Colloque GANIL 2021

Book of abstracts

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Neutrons For Science

First beams at the Neutrons For Science facility

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The neutrons for science (NFS) facility is a component of SPIRAL-2. It provides intense neutron beams in the 1-40 MeV range, produced by the interaction of proton or deuteron beams, delivered by the LINEAR accelerator of SPIRAL-2, with lithium or beryllium converters. NFS received its first beam in December 2019 and the commissioning started in the fall of 2020 with proton beams. It will continue in September 2021 with deuteron beams. The first experiments are scheduled between October and December 2021. After a quick reminder of the characteristics of NFS, we will present the results of the first measurements performed during the commissioning and show that measured spectra and neutron fluxes are in agreement with published data. Some of the planned future experiences will also be presented.

(n,xn g) cross section measurements at NFS and nuclear structure needs for nuclear energy applications.

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This last summer, IPHC team has just finished the mounting of the second collimator and its shielding at NFS allowing now measurements at long flight path with a well-defined neutron beam. First tests are planned the week before the "colloque GANIL" to characterize the ambient conditions in this part of the hall to verify the possibility to use the prompt γ-ray spectroscopy method for (n, xn) reactions studies. If possible, very first results will be shown.

In the frame of nuclear data for energy applications, IPHC team with its collaborators (JRC-Geel, IFIN-Bucharest) has proposed an experimental program at NFS dedicated to the study of (n, 2-3n) reactions on actinides with the GAINS and GRAPhEME spectrometers using the prompt γ-ray spectroscopy method. A recall of the experimental methodology and issues that can be tackled at NFS will be presented.

Finally, reflecting a new initiative of the French NEEDS/NACRE project, a brief overview of the nuclear structure needs raised in the problematic of nuclear data for energy applications will be presented beyond the only case of the prompt γ-ray spectroscopy.

Nuclear Structure 1

Status of the S^3 and DESIR experimental installations

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The Super Separator Spectrometer (S^3) in construction at SPIRAL2-GANIL will offer unprecedented intensities of fusion-evaporation products across the nuclear chart, from neutron-deficient nuclei approaching the proton dripline to very heavy and superheavy elements [1]. The new scientific opportunities will be exploited by a series of state-of-the-art experimental installations which are currently in different stages of construction and testing. The decay-spectroscopy station SIRIUS and the low-energy-branch (LEB) setup will be installed at the final focal plane of S^3 for the day-1 measurement program and will allow performing decay, laser spectroscopy and mass spectrometry experiments [2], while the DESIR facility [3] will combine a broad range of low-energy ion manipulation and measurement methods for high-resolution and high-precision experiments with both S^3 and SPIRAL1 beams. This talk will give an overview of the ongoing developments of the different installations, with highlights from recent results, as well as an outlook of the near-term experimental program.

References

[1] F. Déchery *et al.*, Eur. Phys. J. A **51**, 66 (2015).

[2] F. Déchery *et al.*, Nucl. Instrum. Meth. B **376**, 125-130 (2016).

[3] J.-C. Thomas and B. Blank,“The DESIR Facility at SPIRAL2,” Proc. French-Japanese Symposium on Nuclear Structure Problems, 224-229 (2012).

A detection setup for Spectroscopy and Identification of Rare Isotopes Using S3

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on behalf of the SIRIUS collaboration

Very little spectroscopic data[1] is available for the transfermium nuclides that exist because of quantum mechanical nuclear shell stabilization effects. A large body of experimental data is crucial for determining the sequence and spacing of the orbitals in the heavy region to benchmark and refine the theoretical models that aim to describe the underlying nuclear dynamics.

The SIRIUS[2] spectrometer is designed to study rare isotopes produced in fusion-evaporation reactions using stable heavy ion beams of high intensities provided by the SPIRAL2 LINAC. The spectrometer will be installed at the focal plane of S3[3] and consist of tracker detectors, a double-sided silicon strip detector (DSSD), a tunnel detector, 5 Germanium detectors to perform detailed proton, alpha, gamma, and electron spectroscopy. The tracker detectors will be used to track the transmitting ions and measure their time of flight. The ions will then be implanted shallowly in the DSSD, where position and time correlations between the implanted ions and their successive decays can be established. Upstream of the DSSD, the tunnel detector composed of 4 stripy pad silicon detectors will allow detection of the ionizing particles (alphas, electrons, and fission fragments) that escape the DSSD. The Germanium detectors are borrowed from the EXOGAM2 project and will be placed in a close geometry around the silicon detectors for gamma spectroscopy.

The SIRIUS project is a result of a collaboration of GANIL, IJCLab, IRFU, and IPHC. The setup has been recently moved to GANIL from Saclay, and new tests are being performed since then. In this contribution, the latest developments in the project and results from the new tests will be given.

The SIRIUS project is financed by a grant from the CPIER Vallée de Seine and the SoSIRIUS RIN Tremplin grant from Région Normandie.

References

[1] Ch. Theisen *et al.*, Nucl. Phys. A **944**, 333 (2015).

[2] J. Piot, Acta Phys. Pol. B **43**, 285 (2012).

[3] F. Déchery *et al.*, Eur. Phys. J. A **51**, 66 (2015)

Development of Ti:Sa-based laser ion sources for S^3-Low Energy Branch (S^3-LEB) at SPIRAL2-GANIL

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At GANIL (GISELE) [1,2] and LPC Caen [3], the Super Separator Spectrometer-Low Energy Branch (S^3-LEB) [4] is being currently commissioned, which will be installed at the focal plane of the S^3 [5] to study exotic nuclei by In-Gas Laser Ionization Spectroscopy (IGLIS) [6] technique. The S^3-LEB is designed to extract ground-state properties of exotic nuclei, such as nuclear mean-square charge radii $\delta < r^2 >$, magnetic dipole μ and electrical quadrupole Q moments, and nuclear spins I [7].

A crucial aspect for this setup is the laser ion source (LIS), which has to combine high production efficiency and spectral resolution. The final LIS system will consist of Ti:Sa and dye lasers [8] complimenting each other, but commissioning currently is carried out with Ti:Sa systems.

The development work of the Ti:Sa LIS systems has evolved from broad-band (spectral resolution around 5-7 GHz) to mid-band (1.5-2 GHz), and lately narrow-band (40-70 MHz) systems. However, each LIS system comes with it's pros and cons both from a technical and measurement point of view, which will be discussed.

Commissioning work is carried out by performing stable Er I resonant ionization spectroscopy (RIS), which is an S^3-LEB day 1 case. Motivations behind this physics case and latest results will be presented.

References

[1] Grand Accélérateur National d'Ions Lourds, URL: https://www.ganil-spiral2.eu/en/.

[2] Ganil Ion Source using Electron Laser Excitation, URL: http://ipnwww.in2p3.fr/GISELE-Ganil-Ion-Source-using-Electron-Laser-Excitation?lang=fr.

[3] Laboratoire de physique corpusculaire de Caen, URL: http://www.lpc-caen.in2p3.fr/?lang=fr.

[4] F. Déchery *et al.*, Eur. Phys. J A **51**, 66. doi: https://doi.org/10.1140/epja/i2015-15066-3 (2015).

[5] F. Déchery *et al.*, Nucl. Instrum. Meth. B **376**, 125. doi: https://doi.org/10.1016/j.nimb.2016.02.036 (2016).

[6] R. Ferrer *et al.*, Nucl. Instrum. Meth. B **317**, pp: 570-581. doi: 10.1016/J.NIMB.2013.07.028 (2013).

[7] R. Ferrer *et al.*, Nat. Commun. **8**, 14520. doi: 10.1038/ncomms14520 (2017).

[8] S. Raeder *et al.*, Nucl. Instrum. Meth. B **463**, pp. 86–95. doi: https://doi.org/10.1016/j.nimb.2019.11.024 (2020).

Towards superheavy elements: synthesis of heavy nuclei in multinucleon transfer reaction ^{136}Xe + ^{238}U close to 0°*, developmment and characterization of SIRIUS in the S^3 framework

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Information on the heaviest elements have been obtained up to now via fusion-evaporation reactions. It is however well known that the only nuclei one can reach using fusion-evaporation reactions are neutron deficient and moreover in a very limited number (because of the limited number of beam-target combinations). An alternative to fusion-evaporation can be deep-inelastic collisions. Indeed, theoretical calculations [1, 2] predict large cross-sections for neutron-rich heavy elements production close to zero degrees and recent experiments have been performed showing exciting results [3, 4, 5]. In 2019, we have performed a first preliminary test at Argonne National Laboratory (experiment 1786) to investigate deep inelastic reactions mechanisms in the heavy elements region using the Gammasphere germanium array coupled to the AGFA (Argonne gas-filled analyzer) separator with the implantation-decay station (PPAC, DSSD and silicon tunnels) and germanium clover detectors XArray at the focal plane. For the first time, we performed a multinucleon transfer reaction at 0° using AGFA to produce heavy U-like nuclei. The separation with the beam Xe-like nuclei was a great success and we saw the first nucleon exchanges in this process[6]. A new experiment (ANL PAC 2021 - experiment 1930) has been approved and will be scheduled in Fall-Winter 2021 to go further and identify in more details the heavy nuclei produced.

Besides these exciting results on the nuclear structure side, in this talk will also be described the new focal plane detection set-up SIRIUS[7] which is being built in the framework of SPIRAL2 to study heavy and superheavy element. It is coupled with the high-intensity stable beams of the superconducting linear accelerator of GANIL and combined with the new Super Separator Spectrometer S3. In more detail, we will report on the performances and characterisations of the front-end electronics and data acquisition system for the Double-Sided Silicon Strip Detector (DSSD) of SIRIUS[8]. Final results obtained on the CEA-Saclay bench test with the DSSD will be given and the installation of the whole set up at GANIL.

References

[1] V.I. Zagrebaev *et al.*, Nucl. Phys. A **944**, 257-307 (2015).

[2] A.V. Karpov *et al.*, Phys. Rev. C **96**, 024618 (2017).

[3] S. Heinz *et al.*, Eur. Phys. C **52**, 278 (2016).

[4] A. Di Nitto *et al.*, Phys. Lett. B **784**, 199-205 (2018).

[5] J.S. Barrett *et al.*, Phys. Rev. C **91**, 064615 (2015).

[6] Z. Favier *et al.*, in preparation.

[7] F. Déchéry *et al.*, Nucl. Instr. Meth. **376**, 125-130 (2016).

[8] Z. Favier *et al.*, in preparation.

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Nuclear Structure 2

Search for isoscalar pair correlations at the far end of the N=Z line using high-resolution gamma-ray spectroscopy at GANIL*

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and the AGATA, DIAMANT, EXOGAM, Neutron Wall, and NEDA collaborations

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Searches for enhanced neutron-proton correlations in the heaviest, most exotic, $N \approx Z$ nuclei have been carried out at GANIL for more than a decade. The experiments have used the large electrically segmented germanium detector arrays EXOGAM and AGATA in conjunction with the DIAMANT and Neutron Wall/NEDA light-charged-particle and fast neutron multidetector systems. The main focus in this work has been to test theoretical predictions using spectroscopy of low-to-medium spin states in both spherical and deformed systems. The talk will, in particular, highlight recent results on the N=Z nucleus ^{88}Ru [1] and the N=Z+1 nucleus ^{87}Tc [2] from the AGATA-GANIL campaign.

References

[1] B. Cederwall, X. Liu, Ö. Aktas, *et al.*, Isospin Properties of Nuclear Pair Correlations from the Level Structure of the Self-Conjugate Nucleus ^{88}Ru, Phys. Rev. Lett. **124**, 062501 (2020).

[2] X. Liu, B. Cederwall, *et al.*, Neutron-proton correlations from the level structure of the $N = Z + 1$ nucleus ^{87}Tc, submitted to Phys. Lett. B.

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Theoretical and experimental challenges in isospin symmetry breaking studies

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The study of differences in excitation energy between analogue states in isobaric multiplets allows to verify the validity of isospin symmetry and independence as a function of the angular momentum. These differences range from few keV to few hundreds of keV. Several nuclear structure properties can be deduced from these data [1, 2]. In the last years these studies have been extended from the nuclei in the $f_{7/2}$ shell to other mass regions due to the progress in the experimental techniques and the use of radioactive beams [3, 4, 5]. From the theoretical side the research of the origin of the isospin breaking interaction is exploring different scenarios [6, 7, 8].

In this contribution, recent theoretical and experimental achievements will be presented and discussed together with the challenges and future perspectives.

References

[1] A. P. Zuker, S. M. Lenzi, G. Martinez-Pinedo, and A. Poves, Phys. Rev. Lett. **89**, 142502 (2002).

[2] M. A. Bentley and S. M. Lenzi, Prog. Part. Nucl. Phys. bf59, 497 (2007).

[3] K. Wimmer *et al.*, Phys. Lett. B **785**, 441 (2018).

[4] R.D.O. Llewellyn *et al.*, Phys. Lett. B **811**, 135873 (2020)

[5] D. E. M. Hoff *et al.*, Nature **580**, 52 (2020).

[6] J. Bonnard, S. M. Lenzi, and A. P. Zuker, Phys. Rev. Lett. **116**, 212501 (2016).

[7] S. M. Lenzi, A. Poves, and A. O. Macchiavelli, Phys. Rev. C **102**, 031302 (2020).

[8] J. Henderson and S.R. Stroberg, Phys. Rev. C **102**, 031303(R) (2020).

Evidence of isomers in $^{255/256}$No with SHELS

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Nuclei around ^{254}No (Z=102) have been widely studied by means of cold fusion reactions using projectile and targets around the doubly magic ^{48}Ca and ^{208}Pb in order to study the evolution of the single-particle structure both below and above Z=100 and N=152. Numerous rotational structures and high-K isomers could be observed giving valuable information on single particle orbitals present around the Fermi level in theses nuclei (see [1-2] and references therein).

The ^{256}No nucleus has never been successfully studied in detailed spectroscopy, only alpha decay data are available [3]. Since it cannot be produced in cold fusion reactions, separation efficiency is rather low due to slow recoil velocity induced by hot fusion reaction. We report here about two experiments performed in 2019 in order to obtain information on high-K states, which are predicted to exist in this "hard-to-get-to" nucleus. Indeed, decay-spectroscopy techniques are very powerful to pin down high-K isomers and to study their decay path to the ground state as well as to subsequent states fed by radioactive decay of the nucleus of interest and its daughters.

The experiments were performed with the GABRIELA [5] array, at the focal plane of the SHELS [6] separator of the FLNR in Dubna. In the first one, ^{255}No and ^{256}No were produced by means of a hot fusion-evaporation reaction using a ^{22}Ne beam impinging on a ^{238}U target. In order to maximize the transport of slow recoils to the focal plane of SHELS, only one secondary-electron emissive foil was mounted in the Time of Flight (ToF) detector. The separator parameters were optimized for very asymmetric reactions leading to a 6% recoil transmission from SHELS to GABRIELA. The first part of this talk will be dedicated to the setup and to the genetic correlation analysis method used to establish the existence of new isomeric states. We will then discuss the observation of a high-K isomer in ^{256}No [7].

The second part of this talk will focus on a complementary experiment performed using a cold fusion-evaporation reaction ^{48}Ca(^{208}Pb, n) ^{255}No, with the same setup optimized for a ^{48}Ca beam. Thanks to a higher transmission of the separator, this latter reaction allowed the discovery of four isomeric states in ^{255}No, suspected since our first experiment. The lifetime measurements and excitation energies will be presented and a tentative interpretation in terms of high-K isomers and underlying single particles content will then be discussed.

References

[1] M. Asai *et al.*, Nucl. Phys. A **944**, 308-332 (2015).

[2] Ch. Theisen *et al.*, Nucl. Phys. A **944**, 333-375 (2015).

[3] E. D. Donets *et al.*, Sov. Journ. of. Nucl. Physics **723**, (1966).

[4] K. Hauschild *et al.*, Nucl. Instr. Methods A **560**, 388-394 (2006).

[5] A. G. Popeko *et al.*, NIM. B **376**, 140-143 (2016).

[6] K. Kessaci *et al.*, Phys. Rev. C, to be published (2021).

New results on the decay spectroscopy of ^{254}No with GABRIELA@SHELS

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The structure of the ^{254}No nucleus has been studied for more than 20 years: the last publications on the decay spectroscopy are from four experiments performed at LBNL [1], GSI [2], JYFL [3] and ANL [4]. Four decay schemes featuring two isomers have been published. These are interpreted as 2 and 4qp states. Unfortunately, while the authors agree on the excitation energy and decay scheme of the 2-qp ∼260 ms 8- isomer, they disagree on the configuration assignment for both the 8- and the shorter-lived ∼180 µs 4-qp isomer and differ considerably on the excitation energy and decay scheme of the 4qp isomer. These discrepancies have triggered new experiments worldwide, for example the combined prompt and decay spectroscopy performed using SAGE and GREAT [5]. We report here on an experiment performed with the GABRIELA [6] array, at the focal plane of the SHELS [7] separator at the FLNR, Dubna.

The ^{254}No nucleus was produced using the cold fusion-evaporation reaction ^{48}Ca(^{208}Pb, 2n)^{254}No. The first part of this talk will present the experimental setup and the analysis techniques used to reveal the electromagnetic decay of the known isomers in ^{254}No. The second part will focus on the new results obtained. Due to the combination of a higher transmission of the separator (as compared to VASSILISSA [8]) and an increased efficiency of the upgraded GABRIELA array [9], more than 1 million ^{254}No nuclei were implanted in the focal plane detector enabling the electromagnetic decay of the short and long-lived isomers to be studied in more detail. In particular, the internal conversion electron spectrum observed in decay of the 8- isomer has revealed the presence of a strong transition, possibly E0, suggesting low-lying shape coexistence in this nucleus as predicted in [10]. The spectroscopic information extracted from alpha, gamma and electron correlations will be presented and discussed in terms of the likely underlying single-particle structure.

References

[1] R.M Clark *et al.*, Phys. Lett. B **690**, 19 (2010).

[2] F.P. Hessberger *et al.*, Eur. Phys. J. A **43**, 55 (2010).

[3] R.-D. Herzberg *et al.*, Nature **442**, 896 (2006).

[4] S.K. Tandel *et al.*, Phys. Rev. Lett. **97**, 082502 (2006).

[5] A. Ward PhD, University of Liverpool (2016).

[6] K. Hauschild *et al.*, Nucl. Instr. Methods A **560**, 388-394 (2006).

[7] A.G. Popeko *et al.*, NIM B **376**, 140-143 (2016).

[8] O.N. Malyshev *et al.*, Nucl. Instrum. Methods Phys. Res. A **440**, 86 (2000).

[9] R. Chakma *et al.*, Eur. Phys. J. A **56**, 245 (2020).

[10] J.-P. Delaroche *et al.*, Nucl. Phys. A **771**, 103-168 (2006).

Fission Dynamics

Theory of nuclear fission: present and perspectives

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Building theoretical approaches that (i) reproduce quantitatively the measurements of fission observables (ii) give insights into the core of the fission process (iii) are capable of making predictions in exotic regions of the nuclear chart is a long term challenge of nuclear theory. Decades of research in this direction are at the origin of a wide range of theoretical approches attempting the prediction of the fission cross section, fission dynamics and the deexcitation of the fragments [1]. In general, each method is highly specialized into the description of one specific aspect of this process and therefore into the prediction of one or a few observables only. This is in constrast with recent experimental studies turned toward the collection of correlated fission observables [2, 3]. In this context, a major challenge for theory consists in unifying the current approaches so to describe simultaneously the diabatic aspects of fission as well as its large quantum flucutations.

This presentation will first survey the existing theoretical methods used to describe different aspects of fission ranging from cross sections to fission yields and the deexcitation of the fragments. It will especially focus on the strengths and limitations of these state of the art approaches. A last part will be dedicated to the first steps of novel theoretical approches and their preliminary results.

References

[1] M. Bender *et al.* J. Phys. G: Nucl. Part. Phys. **47** 113002 (2020)

[2] A. Chatillon *et al.* Phys. Rev. Lett. **124**, 202502 (2020)

[3] J. N. Wilson *et al.* Nature **590**, 566-570 (2021)

Fission studies at GANIL: Exploiting the inverse-kinematics surrogate and the direct neutron-induced techniques.

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The fission process has intrigued physicist for a long time from both, experimental and theoretical approaches. From a qualitative point of view, it is well known that nuclear structure dominates the production of fission fragments at low excitation energy [1, 2]. However, the large deformation reached by the system and the fission dynamics that drives the system from one single object to two separated fragments prevent, so far, from a quantitave microscopic description of the problem.

A great effort has been made in the last decades in order to modeling the fission process [3, 4, 5], but the accuracy of these models, some of them even under fundamental contradictions [6, 7], could not be experimentally endorsed because of the limited number of avaliable systems as well as a reduced number of physical observables.

The ongoing fission program running at GANIL provided new experimental data from exotic fissioning systems and new fission observables, such as the neutron content of fission fragments that reveals the configuration of the system at the scission point [8, 9, 10]. Nevertheless, the incoming channel that forms the fissioning system —surrogate reactions— is not fully under control. Conversely, neutron-capture reactions is a suitable mechanism to study fission due to the controled incoming channel. The new NFS facility open a new opportunity to study the fission process with unprecent accuracy in such incoming channel with high energy resolution and beam intensity [11, 12].

A global overview of the most relevant results achieved at GANIL, including the first measurement of the fission fragments configuration at scission and the indications of common driving mechanism along a wide range of systems will be presented. The the direct-kinematics neutron-induced fission program starting at NFS and its complementarity with the upgraded inverse-kinematics fission campaing at GANIL/cyclotrons will be also presented.

References

[1] B.D. Wilkins, E.P. Steinberg, and R.R. Chasman, Phys. Rev. C 14, 1832 (1976).

[2] U. Brosa, S. Grossman, and A. Müller, Phys. Reports 197, 167 (1990).

[3] K.-H. Schmidt et al, Nucl. Data Sheets 131, 107 (2016).

[4] G. Scamps and C. Simenel, Nature 564, 382 (2018).

[5] A. Bulgac et al., Phys. Rev. Lett. 116, 122504 (2019).

[6] P. Möller et al., Nature 409, 785 (2001).

[7] D. Regnier et al., Phys. Rev. C 93, 054611 (2016).

[8] M. Caamaño et al., Phys. Rev. C 92, 034606 (2015).

[9] D. Ramos et al., Phys. Rev. Lett. 123, 092503 (2019).

[10] C. Schmitt et al., Phys. Rev. Lett. 126, 132505 (2021).

[11] X. Ledoux et al, Nucl. Data Sheets 119, 353 (2014).

[12] X. Ledoux et al, Submitted Eur. Phys. J. A. (2021).

Indirect measurements of neutron-induced reaction cross-sections at storage rings *

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Obtaining reliable cross sections for neutron-induced reactions on unstable nuclei is a highly important task and a major challenge. These data are essential for understanding the synthesis of heavy elements in stars and for applications in nuclear technology. However, their measurement is very complicated as both projectile and target are radioactive. The best alternative to infer these cross sections is to use the surrogate-reaction method in inverse kinematics, where the nucleus formed in the neutron-induced reaction of interest is produced by a reaction (typically a transfer or an inelastic-scattering reaction) involving a radioactive heavy-ion beam and a stable, light target nucleus. The decay probabilities (for fission, neutron and gamma-ray emission) as a function of excitation energy of the nucleus produced by the surrogate reaction provide precious information to constrain models and enable much more accurate predictions of the desired neutron-induced cross sections [1].

Yet, the full development of the surrogate method is hampered by the numerous long-standing target issues inherent to measurements involving transfer or inelastic scattering reactions. The objective of the NECTAR project is to solve these issues by combining surrogate reactions with the unique and largely unexplored possibilities at heavy-ion storage rings. In a storage ring heavy radioactive ions revolve at high frequency passing repeatedly through an electron cooler, which will greatly improve the beam quality and restore it after each passage of the beam through the internal gas-jet serving as ultra-thin, windowless target. This way, excitation energy and decay probabilities can be measured with unrivaled accuracy.

In this contribution, we will present the conceptual idea of the setup, which will be developed within NECTAR to measure for the first time simultaneously the fission, neutron and gamma-ray emission probabilities at the storage rings of the GSI/FAIR facility. We will also discuss the technical developments that are being carried out towards these measurements.

References

[1] R. Pérez Sánchez, B. Jurado et al., Phys. Rev. Lett. 125 (2020) 122502.

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Investigation of fission modes in ^{176}Os, ^{177}Ir and ^{179}Au

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The spontaneous and low energy fission of actinides is known to indicate the dominance of asymmetric mass division in the measured Fission Fragment (FF) Mass Distributions (MD). This production of FFs of unequal masses is understood to be driven by the microscopic effects in the fragments which is known to evolve along the nuclear chart [1]. A transition from asymmetric fission in actinides towards symmetric fission was observed for nuclei below A∼226, and it was believed that all systems lighter than A∼226 would fission symmetrically.

However, fission of neutron-deficient $^{178-190}$Hg isotopes has revealed prominent asymmetric mass division, despite of the presence of the closed shell in ^{90}Zr (Z=40, N=50) [3, 4, 5]. Similar studies made with ^{179}Au and ^{178}Pt have further proved that the asymmetric mass split is a typical property of the neutron-deficient nuclei in this region [6], thus confirming the theoretical expectations [7] for the existence of a new region of asymmetric fission, in addition to the actinide region.

This work deals with the multi-parameter study of fission modes of highly neutron-deficient nuclei with $N = 100$ below ^{180}Hg namely with ^{176}Os, ^{177}Ir and ^{179}Au. This exotic nuclear matter has been produced in fusion reactions of the ^{35}Cl beam with the ^{144}Sm, ^{142}Nd and ^{141}Pr targets. The experiment was conducted at the Advanced Science Research Center (ASRC) of the Japanese Atomic Energy Agency (JAEA). The major advantage of this measurement is the use of a large array (33 modules) of liquid scintillator detectors capable of detecting neutrons and gammas. The simultaneous measurement of the FFs, neutrons and gamma-rays was done for the three used targets and at different beam energy thus leading to different excitation energy of the Compound Nucleus (CN).

Some preliminary results on FFMD and Total Kinetic Energy (TKE) distribution will be addressed, from the point of view of fission modes coexistence as well as their evolution with the excitation energy of the CN. Preliminary results on the neutron and the gamma ray emission in coincidence with fission events will be given, which is relevant to understanding of the neutron emission from fragments produced in fission of neutron deficient nuclear matter.

References

[1] A. Andreyev *et al.*, Rep. Prog. Phys. **81(1)**, 016301 (2017).

[2] K.-H. Schmidt *et al.*, Nucl. Phys. A **665**, 221 (2000).

[3] A. Andreyev *et al.*, Phys. Rev. Lett. **105(25)**, 252502 (2010).

[4] K. Nishio *et al.*, Phys. Lett. B **748**, 89-94 (2015).

[5] C. Schmit *et al.*, Phys. Rev. C **126**, 132502 (2021).

[6] I. Tsekhanovich *et al.*, Phys. Lett. B **790**, 583-588 (2019).

[7] P. Möller *et al.*, Phys. Rev. C **91**, 044316 (2015).

Preliminary results on Z-, N- fission-yields in inverse kinematics at VAMOS++

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Despite the lately significant progresses in fission studies, fission still has many loose ends to tie up. The complex process of nuclear fission involves extreme deformations, nuclear structure and heat-flows that decide characteristics of emerging fragments. Many physical theories and models try to explain this process from the different points of view: macroscopic and microscopic models, including the interplay between nuclear structure and nuclear dynamics [1-6]. However, the lack of experimental information prevents from a clear understanding of the underling mechanism.

The innovation on experiments to study fission is conducted to reach new physical observables such as isotopic fission-fragment yields. In particular, the fission program running at GANIL since 2007 strongly contributed to increase the experimental information on the topic [7-8]. The last experiment of this program, $e753$, was conducted in Oct-2017 with exotic systems above U produced through transfer and fusion reactions between a ^{238}U beam and light targets. The fissioning system identification was achieved using the *Spider* telescope [9] and the isotopic identification of the full fragment distributions was achieved due to the inverse kinematics technique using the magnetic spectrometer VAMOS++ [10].

This presentation compiles the first results of the physical observables Z-, N- fission yields of the measured fragments achieved with the collected data.

References

[1] Bohr and J.A. Wheeler, Phys. Rev. **56**, 426 (1939).

[2] B.D. Wilkins, E.P. Steinberg, and R.R. Chasman, Phys. Rev. C **14**, 1832 (1976).

[3] U. Brosa, S. Grossman, and A.Müller, Phys. Reports **197**, 167 (1990).

[4] K.-H. Schmidt and B. Jurado, Phys. Rev. Lett. **104**, 212501 (2010).

[5] G. Scamps and C. Simenel, Nature **564**, 382 (2018).

[6] K.-H. Schmidt and B. Jurado, Rep. Prog. Phys. **81**, 106301(2018).

[7] D. Ramos *et al*, Phys. Rev. Lett. **123**, 092503 (2019)

[8] M. Caamaño and F. Farget, Phys. Lett. B **770**, 72 (2017).

[9] C. Rodríguez-Tajes et al., Phys. Rev. C **89**, 024614 (2014).

[10] Rejmund, M., *et al.* VAMOS++, NIM-A, **646**(1), 184–191 (2011).

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Investigation of the response of solar cells to heavy ions at energies close to 10 AMeV *

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Solar cells have been used for several decades to detect fission fragments up to 1 AMeV. In this energy range, they provide an energy resolution of 1-2%, a time resolution of a few ns and better radiation hardness than Si detectors. All these properties, together with their low cost and low sensitivity to light particles, make solar cells an appealing alternative to silicon detectors for the detection of heavy ions.
Since 2018 we have been investigating the possibility to use solar cells for the detection of heavy ions at energies above 1 AMeV. The first exploratory measurements were performed using ^{84}Kr and ^{129}Xe beams at 7-13 AMeV, and ^{238}U at 3.8 MeV at GANIL. These measurements provided us with interesting results in relation to both energy and time resolution, and they evidenced a stable response of the cells when irradiated with beam intensities up to thousands of pps for a few minutes.
These results showed the great potential of solar cells to be used in radioactive ion beam facilities for experiments and beam monitoring [1].
In March 2021 we carried out another experiment at GANIL to further study the response of solar cells of different types and dimensions to a ^{84}Kr beam at 5, 10 and 15 AMeV. In this measurement it was possible to successfully study the evolution of the cell response as a function of the beam energy and perform long radiation resistance tests. Moreover, a Si detector was also irradiated under the same conditions, thus enabling for a direct comparison with the solar cells.

In this contribution we will present the experimental procedure and the main results of the conducted measurements.

References

[1] A. Henriques et al., Nucl. Instrum. Methods A 969 (2020) 163941.

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Nuclear Structure 3

Scientific opportunities at S3 and DESIR in the context of ground-state nuclear structure

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The SPIRAL2 facility at GANIL will produce radioactive isotopes from the lightest to the heaviest elements beyond uranium. A variety of production mechanisms will be utilized to access several key regions throughout the nuclear landscape. Dedicated projects have been proposed and are under construction to utilize the available rare isotopes, two of which are of particular interest for the study of nuclear structure, nuclear astrophysics, fundamental interactions and applications. DESIR is a low-energy experimental hall hosting a suite of complementary technologies including, among others, laser spectroscopy (LUMIERE), beta decay studies (BESTIOL), Penning-trap based mass measurements as well as trap-assisted spectroscopy. High-quality low-energy beams will be provided from the two SPIRAL2 production caves, SPIRAL1 and S3. The Super Separator Spectrometer facility, S3, has been designed to enhance the capability of SPIRAL2 to perform experiments with extremely low production cross sections. Of interest to the nuclear physics community are the areas of research connected to superheavy element synthesis (SHE) and very heavy elements, as well as spectroscopy of neutron deficient nuclei close to the proton drip-line. The S3 low-energy branch as well as REGLIS3 are two pertinent infrastructures which will host in-gas cell and in-gas jet laser spectroscopy, as well as mass measurements using PILGRIM, the multi-reflection time-of-flight mass spectrometer.

In this contribution, I will endeavor to highlight scientific opportunities at DESIR and S3, with a focus on mass measurements, trap-assisted spectroscopy and laser spectroscopy. I will present recent results from the IGISOL facility, Jyväskylä, to illustrate these methods and how the combination thereof provides not only better use of the more limited production rates available at Jyväskylä, but also a more complete picture of the evolution and emergence of structural changes in nuclei. Examples will include the study of nuclei around ^{132}Sn, the vicinity of the magic Z=28, N=28 shell closures, nuclei below ^{100}Sn and the first exploration into decay spectroscopy in the actinide region. The physics cases may be more widely explored in the future at GANIL and many of the developments underway will also be implemented in the future at S3 and DESIR.

Commissioning and recent achievements of ion beam purification devices under development at CENBG in the framework of DESIR/SPIRAL2

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The DESIR (Désintégration, Excitation et Stockage d'Ions Radioactifs) hall is a part of the new extension of the GANIL; the SPIRAL2 facility. This hall will be dedicated to the study of nuclear structure, astrophysics and weak interaction at low energy (30-60 keV). With the low-energy comes the advantage of working with high optical quality ion beams, allowing high-precision experiments. Various experimental setups will take place in the DESIR hall, divided into three main categories, β-decay spectroscopy, laser spectroscopy and mass spectrometry.

In the DESIR hall, ion beams coming from SPIRAL1 and S3 will be available. SPIRAL1 is producing light exotic nuclei by fragmentation and S3 neutron deficient nuclei by fusion evaporation. These two techniques are non-selective and, depending on the region of interest, can produce huge amounts of contaminants. However, one of the major requirements to performing high-precision experiments is the purity of the ion beam. To guaranty such a high purity of the samples, several devices are currently being developed at CENBG, before being moved to GANIL. The first one is the HRS (High-Resolution Separator), constituted mainly of two 90 degrees magnetic dipole and one multipole. It is foreseen to be located in front of the DESIR hall and its resolving power on the order of 10^4 will allow a purification of most isobars from the ion beam. At the entrance of the DESIR hall will be installed the GPIB (General Purpose Ion Buncher), a linear Paul trap for cooling and bunching continuous ion beam and the double Penning trap mass spectrometer PIPERADE (PIèges de PEnning pour les ions RAdioactifs à DESIR). The mass resolving power of PIPERADE is expected to be higher than 10^6 and will allow purification of close isobars and even isomers. The combine use of the HRS, the GPIB and PIPERADE will ensure high quality ion samples to all experimental setups of DESIR.

The HRS, the GPIB and PIPERADE are now fully assembled at CENBG and under commissioning before their transfer to GANIL in 2 or 3 years. Their status will be presented as well as the recent achievements.

Precision mass measurements of neutron-rich refractory nuclei at JYFLTRAP

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The rapid neutron-capture process, in short the r-process [1], is responsible for the production of half of the heavy-element abundances beyond iron. A key input for the r-process path simulations is precise ground-state masses of neutron-rich elements far from the stability. The region of refractory elements is located between the first (A = 80) and the second (A = 130) r-process abundance peaks. This region is also known for the presence of many isomeric states and rapid changes in the deformation of the nuclei. These changes in the deformation of the ground states can be studied for example via looking at the trend exhibited by the two-neutron separation energy of each isotopic chain determined from the masses of the ground states of the relevant nuclei.

The JYFLTRAP double Penning trap mass spectrometer, located at the IGISOL facility of the Accelerator Laboratory of University of Jyväskylä, is used to perform such high-precision mass measurements. At JYFLTRAP two different precision mass measurement techniques are utilized to determine the cyclotron frequency of the ion of interest: the phase-imaging ion-cyclotron-resonance (PI-ICR) technique [3, 4] and the time-of-flight ion-cyclotron-resonance (ToF-ICR) technique [5]. The measured cyclotron frequency is related to the mass of the ion as follows: $\nu_c = qB/2\pi m$, where q is the charge of the ion, B is the magnetic field and m denotes the mass of the ion.

The PI-ICR technique was used to separate and measure the ground states and low-lying isomeric states in ^{110,112,114,116,118}Rh, ^{115}Ru and ^{104}Nb isotopes and to measure the exotic cases of ^{104}Y, ^{106}Zr and ^{111}Mo. To measure the mass of the most exotic cases ^{120}Rh, ^{117}Ru, ^{109}Nb and ^{112}Mo the ToF-ICR technique was used. In total nine masses were measured for the very first time and the precision of several literature values were improved. In this contribution the results of the precision mass measurements are shown and the possible implications for the r-process and nuclear structure studies will be discussed.

References

[1] E.M. Burbidge *et al.*, Rev. Mod. Phys. **29**, 547 (2018).

[2] T. Eronen *et al.*, Eur. Phys. J. A. **48**, 46 (2012).

[3] S. Eliseev *et al.*, Phys. Rev. Lett. **110**, 082501 (2013).

[4] S. Eliseev *et al.*, Appl. Phys. B. **114**, 107 (2014).

[5] M. König *et al.*, Int. J. Mass. Spectrom. Ion Process. **142**, 95 (1995).

Beta-delayed neutron emission from photo-fission fragments produced at ALTO: outlook of the experimental program at TETRA

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TETRA is a decay detection station constructed by collaboration of scientists from JINR, Dubna and IJCLab, Orsay to study the integrated quantities of beta-decay (such as half-live and probability of delayed (multi) neutron emission $P_{1(x)n}$) of neutron-rich species produced at ALTO ISOL facility. TETRA is equipped by the 4π ^{3}He long neutron counter TETRA, a $4\pi\beta$ plastic scintillator detector and a HPGe detector to allow for simultaneous measurements of three types of radioactivity accompanied β-decay of nuclei [1].

In the talk it is reported the outline of a few physical campaigns conducted to study properties of neutron-rich species in the vicinity of the N = 50 and N = 82 closed shells. They proved that TETRA is a versatile tool to study properties of fission fragments produced at ALTO using both almost topicality pure laser ionized beams and merely selective hot plasma ionization extraction sources but which can provide higher extraction efficiency [2]. One of the selected for the talk result is the staggering of P_{1n} for Ga isotopes as crossing the N = 50 shell. From the first glance, this effect is somewhat unexpected. However, concentration of the beta-decay strength in the near proximity of the neutron separation energy, as was shown in our calculations, may be responsible for such a trend [3]. Yet another selected fact which will be reported is the observation of a new β-delayed neutron precursor in the region of the astrophysical nucleus ^{130}Cd: the tentative assignment was done using the lifetime of the recorded neutron activity. This fact is interpreted using the quasiparticle random phase approximation (QRPA) with the self-consistent mean-field derived from the energy density functional (EDF). Taking into account the coupling between oneand two-phonon terms the β-decay rates of neutron-rich nuclei neighbouring to ^{132}Sn are discussed [4].

TETRA@ALTO was considered as the first step in the vast scientific program to be carried out at GANIL (DESIR). The performance of TETRA@ALTO and the importance of the obtained results highlight the advantage of the TETRA installation at DESIR low energy branch of the SPIRAL2 facility.

References

[1] D. Testov, D.Verney, B.Roussiere, et al., Nucl.,Instr.&Meth., A, 815 96 (2016)

[2] D. Testov, A.P. Severyukhin , B.Roussiere at al., Eur. Phys. J. A 57 (2021)

[3] D. Verney, D. Testov, F. Ibrahim et al., Phys. Rev. C 95 054320 (2017)

[4] A.P. Severyukhin et al., Phys. Rev. C 101, 054309 (2020)

Production and decay spectroscopy of neutron-deficient actinides at IGISOL using ^{232}Th(p,X)Y reaction

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The study of the structure of neutron-deficient actinides is of particular interest since several theoretical calculations predicts strong octupole deformations in this region of the nuclear chart [1, 2, 3]. In addition, this region includes the ^{229}Th whose study of the low-lying isomeric state is of great interest [4]. However experimental data are scarce due to very low production rates.

Recently, a program aiming to study the production and decay spectroscopy of actinide isotopes through proton-induced fusion-evaporation reactions on a ^{232}Th target has been started at IGISOL, University of Jyväskylä. A successful experiment was performed in July 2020 where short-lived actinide isotopes were produced, mass separated and guided to a decay spectroscopy station. Using an experimental setup composed of Ge, Si and Si(Li) detectors, α, γ and conversion electrons decay spectroscopy of the selected nuclei can be performed. The aim of the experiment is to measure lifetime, decay scheme and Q-values which are missing or incomplete in the region. First results of the analysis are promising and, in this presentation, I will show preliminary results focusing on the mass 225 and in particular ^{225}Pa for which very little decay information is available. A second goal of this experiment is to measure production yield in order to consider a laser spectroscopy program in the future. Indeed laser ionisation spectroscopy is well established as a powerful tool in nuclear structure studies [5]. It allows the measurement of spins, magnetic dipole moments, electric quadrupole moments and changes in the mean-square charge radii independently of nuclear models.

In the near future, the possibility to perform laser ionisation spectroscopy at S^3-LEB of neutron-deficient actinides produced and selected by S^3 will allow to continue this program towards nuclei further from stability. In particular the SEASON (Spectroscopy Electron Alpha in Silicon bOx couNter) detector will enable the coupling of two approaches : the laser ionisation spectroscopy and the decay spectroscopy. I will conclude my talk discussing perspective offered by SEASON at S^3-LEB.

References

[1] S.E. Agbemava, A.V. Afanasjev, Phys. Rev. C **96**, 024301 (2017).

[2] S.E. Agbemava, A.V. Afanasjev and P. Ring, Phys. Rev. C **93**, 044304 (2016).

[3] L.M. Robledo and R.R. Rodríguez-Guzmán, J. Phys. G: Nucl. Part. Phys. **39**, 105103 (2012).

[4] L. von der Wense, B. Seiferle and P.G. Thirolf, Meas. Tech. **60**, 1178-1192 (2019).

[5] P. Campbell, I.D. Moore and M.R. Pearson, Prog. Part. Nucl. Phys. **86**, 127-180 (2016).

Nuclear Astrophysics

Nucleosynthesis: new perspectives from gamma-ray astronomy

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Measurements of gamma-ray photons from cosmic sources of nuclear radiation have advanced our knowledge of the origin of the chemical elements. Many isotopes are synthesized in exploding stars – novae, supernovae, kilonovae – some of which are radioactive and emit specific gamma-ray lines that can be detected by space telescopes. Radioisotopes with a relatively short lifetime can be used to directly characterize the individual explosion events or the first stages of the stellar remnant, while long-lived radioactivites, with lifetimes much longer than the characteristic time between events that synthesize them, can produce a diffuse gamma-ray emission in the sky. Observations in the MeV gamma-ray band offer a privileged diagnostic tool with respect to other measurements based on atomic spectroscopy, thanks to the penetration power of high-energy photons and the association of gamma-lines to specific isotopes. I will review the progress made in recent years in our understanding of nucleosynthesis thanks to some remarkable gamma-ray observations, and then discuss the prospects that a new, more sensitive gamma-ray space observatory could offer us.

Experimental Study of the ^{30}Si(p,γ)^{31}P via the ^{30}Si(^{3}He,d)^{31}P transfer reaction for understanding elemental anomalies in Globular Clusters.

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Globular clusters are key grounds for models of stellar evolution and early stages of the formation of galaxies. Abundance anomalies observed in the globular cluster NGC 2419, such as the enhancement of potassium and depletion of magnesium [1] can be explained in terms of an earlier generation of stars polluting the presently observed stars [2]. However, the nature and the properties of the polluting sites are still debated. The range of temperatures and densities of the polluting sites depends on the strength of a number of critical thermonuclear reaction rates. The ^{30}Si(p,γ)^{31}P reaction is one of the few reactions that have been identified to have an influence for elucidating the nature of polluting sites in NGC 2419 [3]. The current uncertainty on the ^{30}Si(p,γ)^{31}P reaction rate has a strong impact on the range of possible temperatures and densities of the polluter sites.

Hence, we investigated the ^{30}Si(p,γ)^{31}P reaction with the aim to reduce the associated uncertainties by determining the strength of resonances of astrophysical interest. In this talk I will present the study of the reaction ^{30}Si(p,γ)^{31}P that we performed via the one proton ^{30}Si(^{3}He,d)^{31}P transfer reaction at the Maier-Leinbnitz-Laboratorium Tandem. With the high resolution Q3D magnetic spectrograph, we measured the angular distributions of the light reaction products. These angular distributions are interpreted in the DWBA (Distorted Wave Born Approximation) framework to determine the proton spectroscopic factor information needed to determine the proton partial width of the states of interest. This information was used to calculate the ^{30}Si(p,γ)^{31}P reaction rate. The uncertainties on the reaction rate have been significantly reduced and key remaining uncertainties have been identified.

References

[1] C. Iliadis *et al.*, The Astrophysical Journal, vol. 470, p. 98, Feb. 2016.

[2] R. G. Gratton *et al.*, The Astronomy and Astrophysics Review, vol. 20, p. 50, Feb. 2012.

[3] J. R. Dermigny and C. Iliadis, The Astrophysical Journal, vol. 848, p. 14, Oct. 2017.

The nuclear matter density functional under the nucleonic hypothesis

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Recent development in multi-messenger astronomy leading to a wealth of new observational results through gravitational waves (LIGO/VIRGO) [1] and X-ray spectra (NICER) [2, 3, 4] have opened new possibilities to understand hadronic matter at densities at and beyond our terrestrial reach. Combining this at the same time with precise knowledge on the low density matter from effective field theory and nuclear masses can enable one to constrain the nuclear equation of state through a wide range of densities. A Bayesian analysis taking into account all the information mentioned above reveals that they are fully compatible with a purely nucleonic hypothesis. Under this nucleonic hypothesis we have extracted the behaviour of energy per particle of symmetric nuclear matter and symmetry energy which is consistent with the data. These results can be used as a null hypothesis for future constraints on high density matter to search for possible exotic degrees of freedom.

The nucleonic hypothesis is based on a density expansion of the nuclear potential, where nuclear matter properties serve as the parameters of the model [5]. This so called "meta-modelling" approach has the advantage over conventional nuclear interaction models being free from in-built correlations among the nuclear matter properties. For this reason, the results obtained by this method is rather model independent of any nuclear interaction form. This clearly points to the fact that with all the present constraints, a purely nucleonic star can not be ruled out. This is why the result obtained in this premise is a very important one to the community.

References

[1] B. P. Abbott *et al.*, Physical Review X 9(1), 011001, (2019).

[2] M. C. Miller *et al.*, arXiv:2105.06979 (2021).

[3] T. E. Riley *et al.*, arXiv:2105.06980 (2021).

[4] G. Raaijmakers *et al.*, arXiv:2105.06981 (2021).

[5] J. Margueron *et al.*, Phys. Rev. C 97, 025805 (2018).

Understanding ^{22}Na cosmic abundance by measuring lifetimes in ^{23}Mg

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Simulations of novae explosive nucleosynthesis predict the production of the radionuclide ^{22}Na. Its half life of 2.6 yr makes it a very interesting astronomical observable by allowing space and time correlations with the astrophysical object. This radionuclide should bring constraints on nova models. It may also help to explain abnormal ^{22}Ne abundance observed in presolar grains and in cosmic rays. Its gamma-ray line at 1.275 MeV has not been observed yet by the gamma-ray space observatories. Hence accurate yields of ^{22}Na are required. Within nova thermal range, the main destruction reaction ^{22}Na(p,γ)^{23}Mg has been found dominated by a resonance at 0.213 MeV corresponding to ^{23}Mg at Ex = 7.786 MeV. However the measured strengths of this resonance are in disagreement [1], [2].

An experiment was performed at GANIL facility to measure the lifetime of the key state at Ex = 7.786 MeV with an expected resolution of 1 fs. The principle of the experiment was close to [3]. With a beam energy of 4.6 MeV/u, the reaction ^{3}He(^{24}Mg,α)^{23}Mg* populated the state of interest. This reaction was tagged thanks to particle detectors (spectrometer VAMOS++, silicon detector SPIDER) and gamma tracking spectrometer AGATA. The state of interest decayed either by gamma deexcitation or proton emission. The expected time resolution of 1 fs was made possible with AGATA high space and energy resolutions. Several Doppler based methods were used to analyse the lineshape of gamma peaks. SPIDER detector gave information about the proton branching ratio.

The analysis procedures and preliminary results will be presented. Produced light particles are identified within SPIDER data, as well as Doppler shifted gamma rays from ^{23}Mg excited states. Gamma spectra are improved by coincidence constrains on reconstructed α excited energies with VAMOS. It ensures to suppress feeding from higher states. A new method based on Doppler correction leads to estimate the velocity of the gamma emitting ^{23}Mg ions. Lifetimes in ^{23}Mg are measured with a new approach. Proton decays from unbound levels in ^{23}Mg are also identified, leading to an upper value for the branching ratio of interest. With an higher precision on the lifetime at Ex = 7.786 MeV, a new value of ^{22}Na(p,γ)^{23}Mg resonance strength $\omega\gamma$ is extracted by using also the most accurate measurement in $BR_{\mathtt{p}}$ [4]. The contribution of this new resonance strength to the thermonuclear ^{22}Na(p,γ)^{23}Mg rate is calculated and compared with the latest results [1]. Using the astrophysical code MESA [5] on nova bursts, the impact of the new rate on the predicted ^{22}Na production will be discussed.

References

[1] A.L. Sallaska *et al.*, Phys. Rev. Let. **105**, 152501 (2010).

[2] F. Stegmuller *et al.*, Nuc. Phy. A **601**, 168-180 (1996).

[3] O.S. Kirsebom *et al.*, Phys. Rev. C **93**, 025802 (2016).

[4] M. Friedman *et al.*, Phys. Rev. C **101**, 052802(R) (2020).

[5] B. Paxton *et al.*, APJS **208**, 4 (2013).

Oxygen-15 alpha capture measurements for neutron stars in binary systems through alpha transfer on the SPIRAL-1 ^{15}O RIB

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We present a study of the astrophysical ^{15}O alpha capture reaction [1]. This is a key breakout route from the Hot CNO cycle leading to explosive nucleosynthesis via the rp-process on the surface of neutron stars in binary systems. Determining an accurate cross section for the relevant states is critical for a better understanding of the X-ray burst energy production and light-curves [2], as well as other novel binary stellar systems involving neutron stars and their potential impact on nucleosynthesis [3].

An indirect ^{7}Li(^{15}O,t)^{19}Ne alpha transfer reaction in inverse kinematics is presented. In this reaction we populate the relevant states for temperatures up to 1GK. We take advantage of the post-accelerated ^{15}O Radioactive Ion Beam provided at GANIL and the state-of-the art detection system VAMOS[4] + AGATA[5] + MUGAST[6] coupled together for the first time [7], allowing us an unrivalled selectivity for detecting triple coincidences in this reaction. We will present the experimental set-up and analysis, as well as preliminary results for the strongest populated resonances in ^{19}Ne. We will finally relate this to the higher temperature scenarios for the astrophysical ^{15}O(α,γ)^{19}Ne reaction.

References

[1] M. R. Hall *et al.*, Phys. Rev. C **99**, 035805 (2019).

[2] R. H. Cyburt *et al.*, Astrophys. J. **830**, 55 (2016).

[3] J. Keegans *et al.*, MNRAS, **485**, Issue 1, Pages 620-639 (2019).

[4] M. Rejmund *et al.*, NIMA, **646**, 184 (2011).

[5] S. Akkoyun *et al.*, NIMA, **668**, 26 (2012).

[6] M. Assié *et al.*, J. Phys. Conf. Ser. 1643, 012070 (2020).

[7] M. Assié *et al.*, Submitted to NIMA. arXiv:2104.10707 (2021).

Nuclear Structure 4

Precision γ-ray spectroscopy of neutron-rich C, N and O isotopes as a test-bench of nuclear structure theory

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The structure of light nuclei can be predicted by state-of-the-art *ab initio* and shell model calculations, which aim at probing nuclear interactions and describing nuclear properties in a wide range of nuclei, including exotic systems, *i.e.*, those lying far away from the stability line. With the advent of powerful modern detection instrumentation for γ rays and particles, high-precision spectroscopy measurements become feasible, yielding strong constrains on such theory approaches. In this talk, results will be presented from an experiment performed in GANIL with the AGATA tracking array coupled to the PARIS scintillator array and the VAMOS++ magnetic spectrometer [1]. The main aim of the measurement was the spectroscopy of neutron rich C to O isotopes, with special emphasis on the lifetimes of the second 2^+ states of ^{16}C and ^{20}O. *ab-initio* calculations predict, in fact, a strong sensitivity of the lifetime of such states to the details of the nucleon-nucleon interactions, in particular to the three-body term. The nuclei of interest were populated by deep-inelastic collisions between an ^{18}O beam and a ^{181}Ta target, and the nuclear state lifetimes were determined via a novel approach which allows to access nuclear state lifetimes in the tens-to-hundreds femtoseconds range, in reaction with complex structure of the product velocity distribution [2]. The achieved results on transition probabilities clearly point to the importance of the three-body term of the nuclear force to accurately describe electromagnetic observables in neutron-rich nuclei. In the same experiment, high-resolution γ-ray spectroscopy of ^{18}N was also performed, leading to the complete identification of all negative parity excited states expected in ^{18}N below the neutron threshold. In such case, the comparison with large-scale shell model calculations performed in the *p-sd* space provides strong constrains on cross *p-sd* shell matrix elements based on realistic interactions [3].

References

[1] M. Ciemala *et al.*, Phys. Rev. C 101, 021303(R) (2020).

[2] M. Ciemala *et al.*, Eur. Phys. J. A 57, 156 (2021).

[3] S. Ziliani *et al.*, to be published.

Study of single particle and shape evolution in neutron-rich nuclei produced in fusion-fission reactions using AGATA coupled to VAMOS++ and other devices

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The structure of neutron-rich nuclei from Z $\sim$ 28 to Z $\sim$ 50 and N $\sim$ 50 to N $\sim$ 80 was explored in four fusion-fission experiments performed at GANIL. The fission fragments were produced in inverse kinematics taking advantage of the intense ^{235}U beam which impinged a thick ^{9}Be target. Their mass and atomic number were identified in the large acceptance recoil spectrometer VAMOS++ and the coincident emitted gamma rays were detected in the new generation gamma-ray tracking spectrometer AGATA. Two experiments, e680 [**?**, **?**] and e669 [**?**], were focused on the gamma-ray spectroscopy and lifetime measurements, respectively, for nuclei above ^{78}Ni in the $80 < A < 100$ mass range. Lifetimes in the ps range were obtained with a differential plunger using the recoil distance Doppler shift (RDDS) method. The two other experiments aimed at the study of the structure of $100 < A < 130$ nuclei. Experiment e706 [**?**] used two techniques for lifetime measurements in neutron-rich Zr, Mo and Ru isotopes, the RDDS method for the ps range and FATIMA fast scintillators for the ns range. Experiment e661 [**?**, **?**, **?**] used seven EXOGAM detectors placed at the focal plan of VAMOS++ for about microsecond isomers identification in I and Sb fission fragments. The structures studied were interpreted in the light of large-scale shell-model (e680, e669 and e661) and Hartree-Foch Bogoliubov (e706) calculations. Major results were obtained in all four experiments.

References

[1] J. Dudouet *et al.*, Phys. Rev. Lett. **118**, 162501 (2017).

[2] J. Dudouet *et al.*, Phys. Rev. C **100**, 011301(R) (2019).

[3] C. Delafosse *et al.*, Phys. Rev. Lett. **121**, 192502 (2018).

[4] S. Ansari, *Shape evolution in neutron-rich Zr, Mo and Ru isotopes around mass A=100*, Ph.D. thesis, Université Paris-Saclay, 2019. https://tel.archives-ouvertes.fr/tel-02445759/document

[5] Y.H. Kim *et al.*, Eur. Phys. J A **53**, 162 (2017).

[6] S. Biswas *et al.*, Phys. Rev. C **99**, 064302 (2019).

[7] S. Biswas *et al.*, Phys. Rev. C **102**, 014326 (2020).

Lifetime measurements of 2_2^+ and 3_1^+ states in ^{20}O*

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The oxygen isotopic chain presents a variety of interesting phenomena, such as the appearance of new magic numbers or the unexpected change in the neutron drip line behaviour. From standard shell-model calculations, ^{28}O ($Z = 8$, $N = 20$) was expected to be the last bound isotope of the oxygen chain. However, ^{24}O has been observed to be the last bound oxygen isotope. This anomaly can be explained with the inclusion of three-body forces. Three-body (3N) forces arise from the composite nature of nucleons and are naturally included in the chiral effective field theory [1]. The work of Otsuka *et al.* [2] shows how the contribution of these forces modifies the single particle energies for the neutron-rich oxygen isotopes, changing the expected neutron drip line from ^{28}O to ^{24}O, in agreement with experimental observations. The importance of 3N forces in *ab-initio* calculations is now established, however their contribution has yet to be quantified.

In this context, the ^{20}O is an interesting case of study. The non-yrast states 2_2^+ and 3_1^+ are based on a mixed $(d_{5/2})^3(s_{1/2})^1$ neutron configuration. These orbitals are highly dependent on the contribution of 3N forces. Hence, electromagnetic properties of the 2_2^+ and 3_1^+ states, such as the excitation energies, the branching ratios and the reduced transition probabilities, provide meaningful information on the position of the $d_{5/2}$ and $s_{1/2}$ orbitals.

An experiment aimed at measuring the lifetime of these states was performed at GANIL (France). The ^{20}O was populated via a (d,p) reaction, using a post-accelerated radioactive beam of ^{19}O provided by the SPIRAL complex and a deuterated polyethylene target deposited on a gold degrader. The beam-like and target-like partners were detected using the VAMOS spectrometer [3] and the MUGAST array [4], respectively. The γ rays emitted by the ^{20}O were detected by the AGATA array [5] at backward angles. The lifetimes of the states were measured using the Doppler-Shift Attenuation method. In this contribution, the first lifetime results will be presented.

References

[1] R. Machleidt, D.R. Entem, Phys. Rep. **503**, 1 (2011).

[2] T. Otsuka *et al.*, Phys. Rev. Lett. **105**, 032501 (2010).

[3] M. Rejmund *et al.*, Nucl. Instr. and Meth. A **646**, 184 (2011).

[4] M. Assié *et al.*, Nucl. Instr. and Meth. A, (to be submitted).

[5] E. Clément *et al.*, Nucl. Instr. Meth. A **855**, 1 (2017).

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Shape isomerism in ^{66}Ni?

It was suggested by Leoni et al. [1] that ^{66}Ni shows shape isomerism with B(E2) values between the 0_3^+ and 0_4^+ states and the 2_1^+ state of 0.09(1) W.u. ($T_{1/2}$=134 ps) and 0.21(7) W.u. ($T_{1/2}$=20 ps), respectively. The lifetimes used to deduce the transition strengths were measured at the Horia Hulubei National Institute for Physics and Nuclear Engineering (IFIN-HH) in Bucharest using the ROSPHERE array and a plunger. As the reaction did not produce a well defined recoil direction, an innovative method based on simulations to construct the decay curves and extract the lifetime was invented and used. The unusual point was that only the stopped component of the γ-ray peaks could be observed, and that the intensity of the in-flight component was instead deduced from simulation and intensities of other γ-ray transitions.

In the first experiment performed with AGATA at GANIL in 2015 ^{66}Ni was populated using multi-nucleon transfer in inverse kinematics with ^{238}U beam and a ^{64}Ni target [2]. The reaction products where uniquely identified in the VAMOS Spectrometer. The OUPS plunger was used for RDDS measurements. Data was taken with target degrader distances between 25 μm and 225 μm, corresponding to 1 to 7 ps of flight time. In figure 1 spectra gated in VAMOS on ^{66}Ni are shown for three different distances. Marked in the figure are the (possible) $0_3^+ \rightarrow 2_1^+$, $0_3^+ \rightarrow 2_1^+$ and $0_3^+ \rightarrow 2_1^+$ transitions with their respective half lives from Leoni et al. [1] converted to target-degrader distances. This corresponds to the distance where the intensity for the shifted and unshifted peaks should be equal. The data form the AGATA experiment suggests that this point is reached for a shorter distance and hence that the lifetimes from the Bucharest experimented are overestimated.

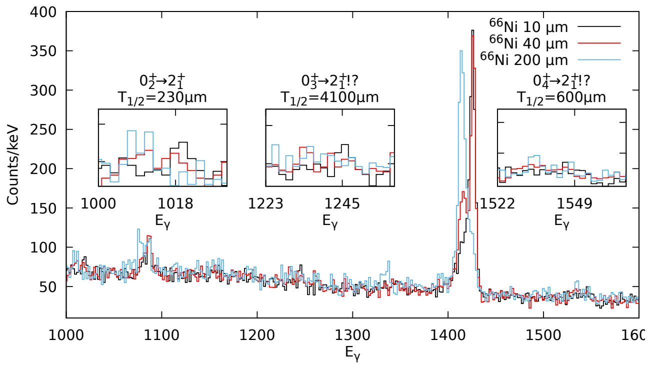

Figure 1: Gamma-ray spectra of ^{66}Ni for three different distances showing the decay of the three exicted 0^+ states in ^{66}Ni.

I will discuss what possible impacts shorter lifetimes would have on the interpretation of ^{66}Ni and present ideas of how to (re)measure the lifetimes in order to resolve this inconsistency in the data.

References

[1] S. Leoni et al., Multifaceted quadruplet of low-lying spin-zero states in ^{66}Ni: Emergence of shape isomerism in light nuclei, Phys. Rev. Lett. 118 (2017) 162502. doi:10.1103/PhysRevLett.118.162502. URL https://link.aps.org/doi/10.1103/PhysRevLett.118.162502

[2] M. Klintefjord et al., Measurement of lifetimes in ^{62,64}Fe,^{61,63}Co, and ^{59}Mn, Phys. Rev. C 95 (2017) 024312. doi:10.1103/PhysRevC.95.024312.
URL http://link.aps.org/doi/10.1103/PhysRevC.95.024312

Decay of the "stretched" resonance in ^{13}C studied by gamma-particle coincidences as a testing ground for Gamow Shell Model

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The stretched excitations are dominated by a single particle-hole component for which the excited particle (proton or neutron) and the residual hole couple to the maximal possible spin value available on their respective shells. Due to the expected low density of other one-particle-one-hole configurations of high angular momenta in the energy region where stretched states appear, their configurations should be relatively simple. This feature makes them attractive as their theoretical analysis could provide clean information about the role of continuum couplings in stretched excitations. The properties of stretched excitations are poorly known, even though they are of key importance for the physics of unbound systems. In light nuclei, as ^{13}C, they appear as high-lying resonances resulting from the $p_{3/2} \rightarrow d_{5/2}$ M4 magnetic transitions. The direct measurement of stretched states properties should provide data which can be used as a very demanding test of state-of-the-art theory approaches. For example, an adequate tool for the theoretical description of the stretched states is Gamow Shell Model, which is being developed within GANIL-IFJ PAN collaboration. The stretched resonances having high energies, relatively narrow widths, and possibly simple structure, thus provide an excellent testing ground for the GSM interaction. Especially, the measurement of the decay patterns is expected to provide a very insightful feedback to the theory by testing the coupling with the component coming from non-resonant continuum and constrain better the weakly determined parameters of the two-body GSM interaction.

An experiment aiming at the investigation of a stretched single-particle M4 state in ^{13}C, located at 21.47 MeV, has been recently performed at the Cyclotron Centre Bronowice at IFJ PAN in Krakow. The data were obtained by measuring inelastically scattered protons (which excite the resonance) in coincidence with charged particles, from the resonance decay, and γ rays from daughter nuclei. The detection setup consisted of: i) the KRATTA telescope array for detection of scattered protons, ii) two clusters of the PARIS scintillator array and an array of $LaBr_3$ detectors for γ-ray measurement, and iii) a thick position-sensitive Si detector for light charged particles detection. In particular, the emitted γ rays give a precise knowledge of the feeding to specific states in daughter nuclei, even in the case of neutron decay from the resonance state. Thus, first experimental information on the proton and neutron decay channels of the 21.47-MeV resonance in ^{13}C, to ^{12}B and ^{12}C daughter nuclei, respectively, could be obtained.

The experimental results on the decay of the 21.47-MeV stretched state in ^{13}C will be compared with the theoretical calculations based on the Gamow Shell Model approach, provided by the IFJ PAN (Y. Jaganathen) - GANIL (M. Płoszajczak) theory group.

Nuclear Structure 5

The Nuclear Shell Model: structure of exotic nuclei, weak processes and astrophysical issues *

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The nuclear shell model, known also as a *(full) configuration-interaction method*, is known to be one of the most successful microscopic tools to understand nuclear properties at low energies. The model is based on the diagonalization of a many-body Hamiltonian containing nucleonic kinetic energies and inter-nucleon interactions in a spherically symmetric basis (typically, in the harmonic oscillator basis). For very light nuclei, the A-body problem can be solved in a model space consisting of many harmonic-oscillator shells, i.e. almost in the full Hilbert space, and therefore such approaches represent a genuine *ab-initio* formulation of the many-body problem [1]. For heavier nuclei, because of very large dimensions involved, calculations are typically done for a few nucleons placed in a model space of several valence space orbitals beyond a closed-shell core. Thus, an *effective Hamiltonian* and *effective transition operators* must be constructed and used to incorporate the effects of excluded correlations.

The recent growth in computation performance and progress in effective interaction theory have preconditioned tremendous success of the shell model in the description of low-energy nuclear structure and decays, making accessible more and more exotic nuclei and heavier nuclei, in first-principle foundation of the model, as well as in numerous interdisciplinary applications (e.g., see Ref. [2] for review).

In this talk, after a brief revision of the shell-model background, we will review the current status of the computational aspects, recent developments in the effective interaction theory and breakthrough achievements in the description of nuclear spectroscopic properties. In particular, we will highlight selected results related to the structure of exotic nuclei, both neutron-rich and neutron-deficient, which shed further light on unexplored before regions of the nuclear chart. A special discussion will be devoted to the calculation of the matrix elements of weak-interaction operators, needed for the tests of the Standard Model in nuclear decays. Finally, we will demonstrate the important role played by shell-model predictions of nuclear-structure ingredients and reaction rate estimations vital for nuclear astrophysics (e.g., nucleosynthesis in r- and rp-process).

References

[1] B.R. Barrett, P. Navrátil, J.P. Vary, Prog. Part. Nucl. Phys. **69**, 131 (2013).

[2] E. Caurier, G. Martínez-Pinedo, F. Nowacki, A. Poves, A.P. Zuker, Rev. Mod. Phys. **77**, 427 (2005).

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Symmetry breaking on the scale of the nuclear chart: exploring the BSkG1 model and its successor

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The description of nuclear reactions, whether earth-based or in astrophysical scenarios, relies critically on the availability of nuclear data across the entirety of the nuclear chart. An overwhelming amount of this data concerns unstable and highly exotic nuclei that are out of experimental reach, especially in the context of nucleosynthesis and the description of the rapid neutron capture process. The chief quantities of interest are the nuclear masses, as these set the energy scales for nuclear reactions.

Nuclear energy density functionals (EDFs) are the tool of choice to respond to this need: they offer a microscopic description of the nucleus that can be applied across the entire nuclear chart. Key to the predictive power of EDFs is the notion of spontaneous symmetry breaking, which allows for a decription of complicated many-body correlations at a reasonable computational cost. The most widely discussed example is an axially symmetric nucleus with a finite quadrupole deformation, which can give rise to a rotational band. A more exotic example is a reflection-asymmetric pear shape, which can explain the observation of rotational bands with alternating parity.

Today, EDF calculations with very little symmetry restrictions can be carried out somewhat routinely for a few nuclei at a time. Nevertheless, virtually all EDF-based models are adjusted on the properties of a few (usually spherical) nuclei. The family of BSk Skyrme-EDF parameterizations is an exception: they have been adjusted to 2408 known nuclear masses [1], resulting in a excellent global description of nuclear masses [2]. Because of the computational demands of considering thousands of nuclei, the BSk family of models was restricted to considering the simple nuclear shapes mentioned above: axially-symmetric, reflection-symmetric and time-reversal invariant.

We are developing the next generation of mass models, aiming to unlock the full power of symmetry breaking for a global description of nuclear properties. To this end, we employ the MOCCa code [3], which represents the self-consistent problem in a three-dimensional coordinate space and allows for great flexibility with respect to the imposed symmetries. We recently presented the first step along this road in Ref. [4]: the BSkG1 model was adjusted to 2408 known masses, while allowing for the first time for triaxial deformation during the adjustment procedure. In order to offset the massive computational cost of repeated 3D calculations for thousands of nuclei, we have developed an adjustment procedure guided by a committee of neural networks. The resulting model achieves an rms deviation of 734 keV on all known nuclear masses and 0.024 fm on the known nuclear charge radii.

In this contribution, we intend to present an overview of the impact of spontaneous symmetry breaking on the global description of nuclear structure. We will report on the impact of triaxial deformation on nuclear masses and radii but also on the fission properties of BSkG1, since its inclusion can significantly lower fission barriers. We will also discuss the next step in our program: developing a mass model that includes the effects of time-reversal breaking to improve the description of odd-A and odd-odd nuclei.

References

[1] M. Wang et al., Chin. Phys. C 41, 3 (2017).

[2] S. Goriely, N. Chamel and J. M. Pearson, Phys. Rev. C **93**, 034337 (2016) and references therein.

[3] W. Ryssens, Symmetry breaking in nuclear mean-field models, Ph.D. thesis, ULB, 2016.

[4] G. Scamps, S. Goriely, E. Olsen, M. Bender and W. Ryssens, arXiv:2011.07904v2 [nucl-th].

Beyond-mean-field calculations of transfermium nuclei*

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Over the past two decades, immense progress has been made in the experimental study of transactinide nuclei. Thanks to the advances in techniques such as in-beam and laser spectroscopy [1, 2], it is now possible to measure their excitation spectra and nuclear moments that provide us with important information on the structure of the nuclei in this mass region.

Complementary to those experimental progresses, it is crucial to develop our theoretical capabilities. In the region of heavy nuclei, the tool of choice to perform theoretical microscopic calculations is the energy density functional (EDF) method† [3]. But while cranked mean-field calculations based on an EDF are able to reproduce reasonably well the moment of inertia observed in this region [4], there exist important discrepancies with experimental results, for example, regarding the low-lying levels of odd-even mass nuclei observed around the Z=100 or N=152 deformed shell gaps [5]. It is yet unclear what are the fundamental reasons of these discrepancies. One possible way to improve the theoretical calculations is to go "beyond-mean-field" (BMF), i.e. to build more sophisticated approximations to the Hamiltonian's exact eigenstates through the restoration of symmetries and the mixing of configurations. The Projected Generator Coordinate Method (PGCM) [3] is a powerful microscopic method that merges these two principles into a single consistent theoretical framework. Importantly, the wave functions built through the PGCM have good quantum numbers such that it is possible to compute matrix elements for the moments and transitions and compare them unambiguously to experimental results. Based on recent formal developments that extended the PGCM method to the description of odd-even mass nuclei [6], we performed first BMF calculations of odd-A nuclei in the transfermium region. In particular, we will present first results of PGCM calculations on ^{251}Md, ^{253}No and ^{255}Lr and present results for the spin-parity of the low-lying states, the moment of inertia of the ground-state rotational band, as well as the magnetic and quadrupole spectroscopic moments of the ground state. These BMF results will be benchmarked against available experimental results and, in order to assess the role of BMF correlations, compared with the outcome of simpler mean-field calculations using the same effective interaction.

The calculations reported here represent a fundamental step towards the systematic application of a fully microscopic and symmetry-restored framework that treats even-even, odd-even, and odd-odd nuclei on the same footing, to the description of spectroscopic properties of very heavy nuclei. Such advanced theoretical calculations will be very beneficial to support the analysis of future experimental results obtained, for example, thanks to the new SPIRAL2 facilities at GANIL.

References

[1] C. Theisen *et al.*, Nucl. Phys **A944**, 333 (2015).

[2] S. Raeder *et al.*, Phys. Rev. Lett. **120**, 232503 (2018).

[3] M. Bender *et al.*, Rev. Mod. Phys. **75**, 121 (2003).

[4] A. Afanasjev *et al.*, Phys. Rev. C **88**, 014320 (2013).

[5] J. Dobaczewski *et al.*, Nucl. Phys **A944**, 388 (2015).

[6] B. Bally *et al.*, Phys. Rev. Lett. **113**, 162501 (2014).

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†Also known as "self-consistent mean-field method".

Nuclear Structure within Shell Model: new frontiers

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The generator coordinate method combining with angular momentum projection (GCM-AMP) will be presented as an alternative approach to the Shell Model (SM) diagonalization. As well known, the major technical difficulty of the Shell Model lies in the dimensionality of the valence space that grows combinatorially when adding particles into valence shells. Accordingly, access to intermediate mass regions far from stability or superheavy nuclei requires tremendous efforts or even impossible. One way out of this problematic is to make use of mean-field such as Hartree-Fock and beyond approaches within the SM valence space where the effective interaction is constructed for an entire given mass region. The latter contains therefore all physical degrees of freedom needed and given the very success of the Shell Model in the description of nuclear spectroscopy properties, reliable predictions could be hoped when applied with an (much less expensive) exact method in unknown regions of the Segré chart. The goal of our work is thus to benefit from the expertise developed especially at Strasbourg regarding the phenomenological ingredients to be incorporated into realistic interactions to make them successful ones, and to have a polyvalent calculational tool that can adapt to various nuclear regions.

In this talk, I will present our current development of the GCM-AMP approach at the SM group at IPHC Strasbourg. The principle of the method consists in the choice of the collective degrees of freedom (known as generator coordinates) to be constrained at the mean-field level (Hartree-Fock in our case) and to perform the mixing of non-orthogonal configurations after symmetry restoration so that spectrum of the full effective SM Hamiltonian is recovered. Due to the non-orthogonality, this turns out to be a delicate matter to control convergence. It requires an efficient method in the selection of a bundle of Slater determinants at hand. A method to deal with it will be presented. I will also present some very preliminary results for superheavy elements where SM calculations are not feasible.

Ab initio description of doubly open-shell nuclei via multi-reference expansion methods

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Ab initio methods aim at providing a unified description of nuclei from realistic two- and three-nucleon interactions. In the last ten years, such calculations have become possible for medium-mass nuclei. In particular, genuine singly- and doubly-open-shell nuclei have become accessible thanks to the formulation of appropriate single-reference expansion many-body methods. Among these methods, a perturbative variant, coined as Bogoliubov many-body perturbation theory (BMBPT), has been formulated [1], implemented and shown to provide accurate description of ground state properties up to Ni isotopes at a low computational cost [2]. In parallel, the multi-reference Projected Generator Coordinate Method (PGCM) has recently experienced a renewed interest within the ab-initio context thanks to its ability to naturally capture collective properties of ground and excited states of nuclei (like deformation, rotation and vibration) that are difficult to grasp through pure particle-hole expansions.

A key objective is to consistently merge the two types of approaches in order to capture simultaneously static and dynamic correlations, both being essential to provide a faithful description of ground and excited properties of mid-mass nuclei independently of their closed or open-shell character. In order to do so, we have adapted to the nuclear context a non-orthogonal multi-reference perturbation theory recently formulated in the context of quantum chemistry [3]. This new formalism, coined as PGCM-PT [4], sheds a new light on both BMBPT and PGCM that are recovered as special limits and provides their coherent merging. Combined with recently introduced many-body reduction of three-body interactions, it offers a promising way to tackle all even-even mid-mass doubly-open-shell nuclei.

A numerical implementation of the new formalism at second-order in the perturbative extension (i.e. PGCM-PT2) has been achieved and tested on open-shell and doubly open-shell nuclei in the O-Ne region [5]. In this presentation, the PGCM-PT2 formalism will be introduced and the connection with both PGCM and BMBPT will be clarified. First numerical results will be presented to illustrate how BMBPT binding energies and PGCM excitation spectra are amended within PGCM-PT2. Eventually, perspectives of this new method will be discussed.

References

[1] T. Duguet and A. Signoracci, *J. Phys. G: Nucl. Part. Phys. 44 (2016) 015103*

[2] A. Tichai, P. Arthuis, T. Duguet, H. Hergert, V. Somá and R. Roth, *Phys. Lett. B786 (2018) 195*

[3] H. Burton and A. Thom, *J. Chem. Theory Comput. (2020), 16, 9, 55865600*

[4] M. Frosini, T. Duguet, J.-P. Ebran and V. Somá, *(2021) to be published*

[5] M. Frosini, T. Duguet, J.-P. Ebran, R. Roth, V. Somá and A. Tichai, *(2021) to be published*

Nuclear dynamics and thermodynamics

Constraining the low-density neutron star equation of state from heavy-ion collisions *

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The present new and very exciting multi-messenger era for the astronomy, nuclear, gravitational and astrophysics community was set by the detection of gravitational wave signals from the collision of two neutron stars (NS) by the LIGO and Virgo interferometers in 2017, followed up by the detection of the gamma-ray burst GRB170817A and the electromagnetic transient AT2017gfo. Later, in 2019, a second and third signals, GW190425 and GW190814, were detected, the first one a larger system than those of any binary NS known to date, and the latter a system involving the collision of a black hole with a 2.5-2.67 Msun compact object, that has not been ruled out yet to be a NS. The NICER collaboration has published new radius and mass measurements from PSRJ0030+0451 [1], and very recently from PSRJ0740+6620 [2], which have been able to set new constraints in NS matter.

In the near future, the large amount of new data that will be made available by SKA will allow us to determine NS properties with much smaller uncertainties and set strong constraints on the equation of state of stellar matter. Neutron stars will, as a consequence, become a real laboratory to test the nuclear force under extreme conditions of density, proton-neutron asymmetry and temperature.

Light (deuterons, tritons, helions, $\alpha-$particles), and heavy (pasta phases) nuclei exist in nature not only in the inner crust of neutron stars (cold $\beta-$equilibrium matter), but also in core-collapse supernova matter and NS mergers (warm nuclear matter with fixed proton fraction). The appearance of these clusters can modify the neutrino transport, and, therefore, consequences on the dynamical evolution of supernovae and on the cooling of proto-neutron stars are expected. However, a correct estimation of their abundance implies that an in-medium modification of their binding energies is precisely derived.

In this review talk, we will address not only from the theoretical point of view how these clusters are calculated for warm stellar matter in the framework of relativistic mean-field models with in-medium effects [3], but also how these models are calibrated to experimental data from heavy-ion collisions [4, 5], measured by the INDRA Collaboration [6]. We show that this in-medium correction, which was not considered in previous analyses from heavy-ion collisions, is necessary, since the observables of the analyzed systems show strong deviations from the expected results for an ideal gas of free clusters. It turns out that the resulting light cluster abundances come out to be in reasonable agreement with constraints at higher density coming from heavy ion collision data. Some comparisons with microscopic calculations are also shown.

References

[1] T.E. Riley et al, ApJ. Lett. 887, L21 (2019); M.C.Miller et al, ApJ. Lett. 887, L24 (2019).

[2] T. E. Riley et al, arXiv:2105.06980; M. C. Miller et al, arXiv:2105.06979.

[3] H. Pais, F. Gulminelli, C. Providência, and G. Röpke, Phys. Rev. C **97**, 045805 (2018).

[4] H. Pais, R.Bougault, F.Gulminelli, C. Providência et al., Phys. Rev. Lett. **125**, 012701 (2020).

[5] H. Pais, R.Bougault, F.Gulminelli, C. Providência et al., J. Phys. G: Nucl. Part. Phys. **47**, 105204 (2020).

[6] R. Bougault et al., J. Phys. G: Nucl. Part. Phys. **47**, 025103 (2020).

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Central heavy-ion collisions around Fermi energies: what your mother never told you

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Central collisions between nuclei at Fermi energies and beyond are an important tool for the study of the nuclear matter Equation of State (EoS), one of the essential ingredients for understanding not only nuclear structure and dynamics but also the later post-bounce stages of evolution of core-collapse supernovae (CCSN), the atmospheres of cooling protoneutron stars (PNS), or the outer crust of the resulting neutron star (NS). The link between EoS and collisions can be made by comparison of data with the results of microscopic transport model calculations, using various effective in-medium nucleon-nucleon interactions which, in the infinite matter limit, map on to the nuclear EoS.

In this talk I will briefly recall the challenges posed by the study of central collisions in experimental data at Fermi energies. A recent advance* in the field allows to characterize any experimental dataset in terms of impact parameter (b) distributions, which are an essential input for unbiased comparison with transport model calculations. Applied to the very large INDRA dataset, the method gives confirmation that there is a finite limit ($b > 0$) to the centrality of any data which we can select, due to the large fluctuations which are inherent to the collisions. At the same time, the method can extract previously inaccessible information from the data which by itself provides new constraints for nuclear transport models.

The outcome of any given collision not being uniquely determined by centrality, the "most central collisions" are not necessarily the most interesting for the study of the EoS. I will present a new method to extract from data sets of events which maximise the degree of isotropy in momentum space. It is possible to isolate in this way homogeneous event samples which, although never strictly isotropic, are more isotropic than all others. The bombarding energy dependence of such events' residual anisotropy is consistent with an increase of nuclear stopping as the Fermi energy is approached, contrary to some previous analyses. The event samples historically used by the INDRA collaboration to characterize the liquid-gas phase transition of nuclear matter are shown to be a representative subset of these "most isotropic" events, which validates *a posteriori* the historic selection method.

*J.D. Frankland, D. Gruyer et al (INDRA collaboration), "Model independent reconstruction of impact parameter distributions for intermediate energy heavy ion collisions", Phys. Rev. C **104**, 034609 (2021)

Asymmetry energy and nuclear matter equation of state: What have we learnt from experiments at GSI ?*

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From several experiments (ALADiN, KaoS, FOPI, ASY-EOS) performed with the SIS accelerator at GSI Darmstadt over the last two decades, a density dependance of the nuclear equation of states can be drawn from 0.4 to 2 times the saturation density, for both the symmetric matter (KaoS, FOPI experiments) and the asymmetric component of the EoS (ASY-EOS and ALADiN). We show that the density dependence of the pressure in neutrons stars deduced by these terrestrial methods confirms that expected from recent gravitational wave and other multimessenger astrophysical measurements, and improves sensitively the constraint on the deduced radii of neutron stars.

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Energy disspiation and cluster correlations in excited light systems at Fermi energies investigated with HIPSE and AMD

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In this work, we will present the results for the **^{32}S/^{20}Ne+^{12}C reactions at 25 and 50 AMeV** beam energies, investigated in the frame of the FAZIA collaboration [1] program at LNS laboratories. The experiment, referred to as **FAZIACor**, employed four FAZIA blocks and is one of the first measurements performed with the FAZIA array.

The results have been studied and compared with MonteCarlo simulations using the **Heavy Ion Phase Space Exploration** (HIPSE) [2] and the **Antisymmetrized Molecular Dynamics** (AMD) [3] models for the dynamical phase. In the latter case, the impact of the clusterization effect to form smaller fragments (2<A<9) is investigated. The models are combined with the **Hauser-Feshbach Light** (HFl) [4, 5] as an afterburner to simulate the decay of the excited primary fragments. In this context several observables, such as angular distributions and energy spectra, have been extracted and compared with the available experimental data. It is found that the cluster correlations take a crucial role into describing the productions of light charged particles and intermediate mass fragments. The AMD model with cluster correlations studied here provides a consistent overall reproduction of the experimental data, especially at 25 MeV/u beam energy where the degree of initial energy dissipation is better reproduced with respect to the higher energy case and with respect to HIPSE.

The comparison of experimental findings with extensive simulations based on different reaction models is essential and indeed is a central point of heavy ion collisions in the Fermi energy range. Such comparisons, and in particular the ones with the dynamical AMD code, is relatively new in this light region as testified by recent papers [6, 7] and up to now applied exclusively to C+C reactions. In fact, these light reaction at these energies are in itself very challenging to study due to the concurring of many effects. First due to the relative small mass and high energy deposition, the reaction evolution is more compressed and the different reactions mechanisms are harder to separate over a broad impact parameter range. Second, finite size fluctuations and structure effects as alpha-clustering (the systems are N=Z) have more influence on the outcome than for heavier systems. In fact, as already found at lower incident energies, the emission of alpha particles is clearly underestimated by models for these N=Z systems also at Fermi energies.

References

[1] The FAZIA Collaboration., R. Bougault, G. Poggi *et al.*, Eur. Phys. J. A **50**, 47 (2014).

[2] D. Lacroix *et al.* Phys. Rev. C **69** 054604, 2004

[3] A. Ono *et al.*, Progress of Theoretical Physics, **87(5)**: 1185–1206, 05, 1992
A. Ono *et al.*, Phys. Rev. Lett. , **68**: 2898–2900, 1992.
A. Ono *et al.*, Journal of Phys. : Conference Series, **420**:012103, 2013

[4] G. Baiocco *et al.*, Phys. Rev. C, **87**:054614, 2013

[5] L. Morelli *et al.*, Journal of Phys. G: Nuclear and Particle Physics, **41(7)**:075107, 2014

[6] G. Tian *et al.*, Phys. Rev. C, **95**:044613, 2017
G. Tian *et al.*, Phys. Rev. C, **97**:034610, 2018

[7] R. Han *et al.*, Phys. RevĊ, **102**:064617, 2020

Femtoscopic probes of jet-fragmentation mechanisms in INDRA and FAZIA campaigns at GANIL

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The systematics of heavy-ion collisions studied with the INDRA multidetector array and, more recently, with its coupling to the new generation FAZIA detector at GANIL, allow one to perform unique studies of nuclear fragmentation phenomena. These can be linked to the equation of state of nuclear matter and can be used to test phenomena predicted by transport models of collisions at Fermi energies and beyond. Studies of violent Ar+Ni collision events at E/A=32-95 MeV have indicated the existence of a forward-backward asymmetry in the multifragmentation of the system. This observation, recently introduced as a new jet-fragmentation mechanism, has been interpreted as a combination of volume and surface instabilities by means of simulations performed with the Boltzmann–Langevin-One-Body (BLOB) model [1]. In order to better investigate on this phenomenon and deepen our understanding of its links to nuclear dynamic properties within transport models, we study particle-particle [2, 3] and more recent fragment-fragment correlation functions in the experimental above mentioned Ar+Ni collision events and in the heavier Xe+Sn reaction system at E/A=50 MeV. The analysis attempts to provide information on the space-time properties and on the topology of the breakup phenomena observed experimentally [4], thus offering new grounds of comparison to model predictions aimed at better understanding in-medium nuclear dynamics, with important implications on the origin of clustering mechanisms in nuclear systems. The assessment of similar studies will offer the opportunity to test the isospin dependence of these phenomena in the ongoing and future INDRA-FAZIA campaigns at GANIL, with its possible links to modeling of the density dependence of the symmetry energy within transport theories.

References

[1] P. Napolitani and M. Colonna, Phys. Lett. B**797**, 134833 (2019)

[2] D. Dell'Aquila, PhD Thesis, University of Naples "Federico II" and Université Paris-Saclay (2018)

[3] G. Verde, A. Chbihi, *et al.*, Eur. Phys. A **30**, 81 (2006)

[4] S. Salou, PhD Thesis, Université de Caen, GANIL (1997)

Study of quasi-projectile breakup in semiperipheral collisions of ^{64,58}Ni+^{64,58}Ni at 32 *A*MeV and 52 *A*MeV with the INDRA-FAZIA apparatus

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Heavy-ion collisions in the Fermi energy regime have been widely employed to probe the properties of nuclear matter far from equilibrium conditions. More specifically, they allow to investigate various phenomena (e.g. isospin transport phenomena) that can be interpreted in the framework of the Nuclear Equation of State (NEoS), which describes the properties of nuclear matter in terms of thermodynamic variables such as temperature, pressure, density.

This presentation concerns the results of the analysis of the E789 experiment, carried out from April to May 2019 in GANIL (Caen, FR): this is the first experiment which exploits the two experimental setups INDRA [1] and FAZIA [2] coupled together. Twelve FAZIA blocks cover the forward polar angles (from 1.5° to 14°) providing good charge and mass identification for the quasi-projectile residue and for most of the reaction products, while the large angular coverage of INDRA (from 14° to 176°) allows for the construction of reaction centrality estimators. In the E789 experiment, we investigate the four different reactions ^{64,58}Ni+^{64,58}Ni at two different energies 32 *A*MeV and 52 *A*MeV. We will focus on the characterization of semiperipheral and peripheral collisions. Two main reaction channels will be selected and examined: the quasi-projectile evaporation channel and the quasi-projectile breakup channel [3]. Special attention will be given to the study of isospin related variables in the breakup (i.e. dynamical fission) channel [4]: a complete characterization of this reaction channel will be presented. The availability of data for all the four projectile-target combinations of ^{64}Ni and ^{58}Ni allow for the evaluation of isospin equilibration phenomena, e.g. by exploiting the isospin transport ratio [5], and the two different energies allow to study the isospin transport phenomena at two different time scales. A comparison between the isospin characteristics of the quasi-projectile in the evaporation channel and the reconstructed quasi-projectile from the two fragments in the breakup channel will also be made, in order to highlight differences and similarities in the equilibration mechanisms [6].

The experimental results will also be compared to the predictions of the transport model AMD [7], coupled with GEMINI [8] as afterburner, in order to check the validity of the event selection procedure and to extract information about the NEoS.

References

[1] J. Pouthas *et al.*, Nucl. Instr. and Meth. in Phys. Res. A **357**, 418 (1995)

[2] R. Bougault *et al.*, Eur. Phys. J. A **50**, 47 (2014)

[3] A.A. Stefanini *et al.*, Z. Phys. A **351**, 167 (1995)

[4] S. Piantelli *et al.*, Phys. Rev. C **101**, 034613 (2020)

[5] F. Rami *et al.*, Phys. Rev. Lett. **84**, 1120 (2000)

[6] A. Camaiani *et al.*, Phys. Rev. C **103**, 014605 (2021)

[7] A. Ono *et al.*, Phys. Rev. Lett. **68**, 2898 (1992)

[8] R.J. Charity *et al.*, Phys. Rev. C **82**, 014610 (2010)

Interdisciplinary research

Nanoengineering of surfaces and 2D materials via electronic excitation

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Ion beams represent an established tool for material modifications as they are easy to use and manipulate. Despite their widespread use for technological and scientific purposes there are still many open questions with respect to the underlying mechanisms which depend on kinetic energy and charge state of the ions [1]. While for singly charged ions with kinetic energies of up to a few 10 keV the dominant process are nuclear collisions, the scattering cross section for nuclear collisions becomes negligible at energies available at accelerators such as GANIL. The main energy loss mechanism, usually called electronic stopping, is then via excitation of the electronic system or ionization of the target atoms. Another option, are slow highly charged ions which also give rise to electronic excitation. The energy of the ions may thus be efficiently used for material modifications in bulk materials, at surfaces [2], and in so-called 2D materials [3, 4, 5], which have attracted much attention lately due to their superior and sometimes even unique properties. In my talk I will present several examples of material modifications in various materials by ion irradiation with a focus on individual impacts.

References

[1] Aumayr et al., J. Phys.: Condens. Matter 23, 393001 (2011)

[2] Akcöltekin et al., Nature Nanotechn. 2 (2007) 290

[3] L. Madauß et al., 2D Materials, 4 (2017) 015034

[4] L. Madauß et al., Nanoscale 9 (2017) 10487

[5] Kozubek et al., J. Phys. Chem. Lett., 10 (2019) 904

Charge reversing multiple electron detachment Auger decay of in-ner-shell vacancies in gas-phase deprotonated DNA

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Biological radiation action is often triggered by the generation of inner-shell vacancies in biomolecular systems and in water. In cancer therapy, these inner-shell vacancies are typically induced by high energy photons or by protons or heavy ions at Bragg-peak energies. Subsequent Auger decay processes lead to emission of low energy electrons, capable of inducing further molecular damage in the vicinity of the initial excitation site. To investigate the molecular mechanisms of inner-shell vacancy decay in DNA we have stored doubly deprotonated model oligonucleotides [dTGGGGT-2H]$^{2-}$ in a radiofrequency ion trap. In the trap, the DNA anions were exposed to monochromatic soft X-rays (BESSY II synchrotron, Helmholtz Zentrum Berlin), to MeV C^{4+} ions (IRRSUD beamline, GANIL, Caen) and to intense femtosecond laser pulses. The ionic products from the interaction processes were mass-analyzized by means of time-of-flight spectrometry. We found that soft X-ray induced inner shell vacancy predominantly decay by detachment of at least three electrons from the initially anionic precursor. Positively charged fragment ions were observed. Also for heavy ion (12 MeV C^{4+}) collisions with [dTGGGGT-2H]$^{2-}$, positively charged fragments were observed. In a radiobiological context, a K-vacancy in DNA that decays by a multiple electron Auger process rather than by a single electron process, has profound consequences. In the multiple electron case, more and lower-energy electrons are emitted and as a consequence secondary electron induced damage will be much more localized. As also found in earlier studies for soft X-ray photoionization of DNA cations [1, 2], the positive-mode fragmentation pattern is dominated by protonated bases. However, fragmentation clearly is not a consequence of the initial K-shell vacancy itself. What drives the process is purely the removal of multiple valence electrons as confirmed by femtosecond laser-induced dissociation experiment, which showed very similar fragmentation patterns.

References

[1] O. Gonzalez-Magaña, Tiemens,G. Reitsma,L. Boschman, M. Door, S. Bari, P. Lahaie, J. Wagner, M. Huels, R. Hoekstra, T. Schlathölter, Physical Review A **87**,032702 (2013).

[2] X. Wang, S. Rathnachalam, K. Bijlsma, W. Li, R. Hoekstra, M. Kubin, M. Timm, B. von Issendorff, V. Zamudio-Bayer, J. Tobias Lau, S. Faraji, T. Schlathölter, Phys. Chem. Chem. Phys. (2021)

Processing of ices in space by energetic particles: synthesis and radiolysis of organics *

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Ices are widely present in the cold regions across the Universe, for example in the interstellar medium as mantles on interstellar and circumstellar dust and on the surfaces of small bodies of the Solar System – beyond the distance around 3-5 AU known as the "snowline" (i.e. below 150-170 K). It is commonly thought that energetic processing of interstellar and planetary ices plays a relevant role in astrochemistry and astrobiology [e.g. 1,2]. Ionizing radiation (UV photons, electrons, ions from cosmic rays or solar wind) induces several physico-chemical processes such as radiolysis and subsequent formation of new molecules, as, for example complex organic molecules (COMs) [3,4]. Once formed in space, COMs are themselves exposed to the complex radiation field, thus, how long can they survive in space? It is necessary to investigate their radiation resistance in order to determine the survival times of complex molecules [4,5].

We have studied the radiolysis of the complex organic molecule pyridine (C_5H_5N) [6], which could play a role in the first steps leading to formation of large nitrogen containing (polycyclic) aromatic hydrocarbons (PNAH) and of prebiotic molecules such as nucleobases [7]. Pure pyridine and mixed pyridine-water ices (T = 12 K) were irradiated with swift ions at two beam lines (SME: 650 MeV Zn^{26+}, ARIBE: 90 keV O^{6+}) of the GANIL facility (Caen, France). The evolution of the IR absorption lines of pyridine in the ices was measured as a function of projectile fluence with a FTIR spectrometer in CIMAP's CASIMIR device. From the exponential decrease of the peak intensities, destruction cross sections of pyridine were calculated in pure and mixed ices. Also, the appearance of radiolytic products were followed by in-situ infrared absorption. The water environment enhances the radiosensitivity of pyridine [6].

References

[1] Y. Oba *et al.*, Nat. Commun. **10**, 4413 (2019).

[2] P. Ehrenfreund *et al.*, Annu. Rev. Astron. Astrophys. **38**, 427 (2000).

[3] G. Strazzulla *et al.*, Rend. Fis. Acc. Lincei **22**, 145-152 (2011).

[4] H. Rothard *et al.*, J. Phys. B At. Mol. Opt. Phys. **50**, 062001 (2017).

[5] P. Ada Bibang *et al.*, Low Temperature Physics **45**, 692-700 (2019).

[6] P. Ada Bibang *et al.*, European Physical Journal D **75**, 57 (2021).

[7] A.R. Soliman *et al.*, J. Am. Chem. Soc. **135**, 155 (2013).

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Radioresistance in Chondrosarcoma using the CIRIL-ARIA biology platform

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INTRODUCTION

Chondrosarcomas are malignant tumors of the cartilage that are chemoresistant and radioresistant to X-rays. The preferred treatment consists of surgical resection, which might cause severe disabilities for the patient; in addition, this procedure might be impossible for inoperable locations, such as the skull base. Carbon ion irradiation (hadron therapy) has been proposed as an alternative treatment, primarily due to its greater biological effectiveness and improved ballistic properties compared with conventional radiotherapy with X-rays.

METHOD

The sensitivity of 4 chondrosarcoma cell lines to X-rays and carbon ion was investigated in vitro [1] in association with PARP inhibitor [2] using the clonogenic survival, the cell cycle progression and proliferation assays. Carbon ion irradiation were performed using the high energy beam line in GANIL, all experiments were performed using the CIRIL-ARIA biology lab.

RESULTS

Chondrosarcoma cells showed a heterogeneous sensitivity toward irradiation. Chondrosarcoma cell lines were more sensitive to carbon ion exposure compared to X-rays. Carbon ions induced more G2 phase blockage and micronuclei in SW1353 cells as compared to X-rays with the same doses. Persistent unrepaired DNA damage was also higher following carbon ion irradiation. PARP inhibitor reduces the clonogenic survival in CH2879 cells after X-rays and carbon ion irradiations.

CONCLUSION

These results indicate that chondrosarcoma cell lines displayed a heterogeneous response to conventional radiation treatment; however, treatment with carbon ion irradiation in association with PARPi was more efficient in killing chondrosarcoma cells.

References

[1] Chevalier F., Hamdi D.H., Lepleux C., Temelie M., Nicol A., Austry J-B., *et al.*, Technol. Cancer Res. Treat. **18**, 1533033819871309 (2019).

[2] Césaire M., Ghosh U., Austry J-B., Muller E., Cammarata F.P., Guillamin M., *et al.*, J. Bone Oncol. **17**, 100246 (2019).

Swift heavy ions induced modification in mesoporous silica materials

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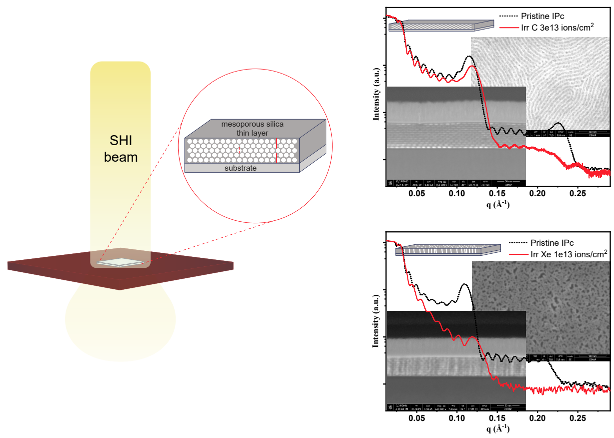
Around the late 1970s, research and case studies began to emerge linking the use of high-silica glasses to nuclear waste management. The work of Simmons[1] in 1979 has demonstrated that the fixation of radioactive wastes is feasible in high-silica glasses of good chemical durability. With the discovery of numerous extraction agents, the concept of ”separation / conditioning process” was brought up as the optimization of the Simmons process in which all porous materials can be used. Furthermore, since the discovery of ordered mesoporous silica material, more recent attention has focused on its potential application as an alternative process for treating radioactive effluents containing actinides and fission products.

Concurrently, studies in the field of irradiation have shown special behavior of mesoporous materials under irradiation. On the one hand, radiation tolerance of mesoporous metallic foam has been reported by Bringa *et al.*[2]. On the other hand, studies[3] [4] have highlighted the collapse of the porous network of silica-based materials induced by the ballistic or electronic radiation damage.

In this way, a precise knowledge of the damage induced due to the radiation in those materials is then required. In this work, thin films (∽60 nm) of mesoporous silica deposited by dip-coating onto silicon wafers were irradiated at IRRSUD (GANIL) with ions having a stopping power between 1 keV/nm to 12 keV/nm. These samples were analyzed before and after irradiation by X-ray reflectometry (XRR) and scanning / transmission electron microscopy (SEM, TEM, STEM) to investigate the evolution of the porous structure and also by spectroscopy (nuclear magnetic resonance, Fourier-transform infrared spectroscopy) to evaluate the modification of the silica network. Possible mechanisms have been proposed and discussed in order to explain and describe the evolution of the mesoporous structure under irradiation.



References

[1] J.H.Simmons *et al.*, Nature **278**, 729-731 (1979).

[2] E.M.Bringa *et al.*, Nano. Lett **12**, 3351-5 (2012).

[3] L.Yu *et al.*, Microporous. Mesoporous. Mater. **251**, 146-154 (2017).

[4] S.Klaumünzer, Nucl. Instrum. Methods. Phys. Res B. **166-167**, 459-464 (2000).

Applications

Harnessing photochemistry in radiotracer synthesis

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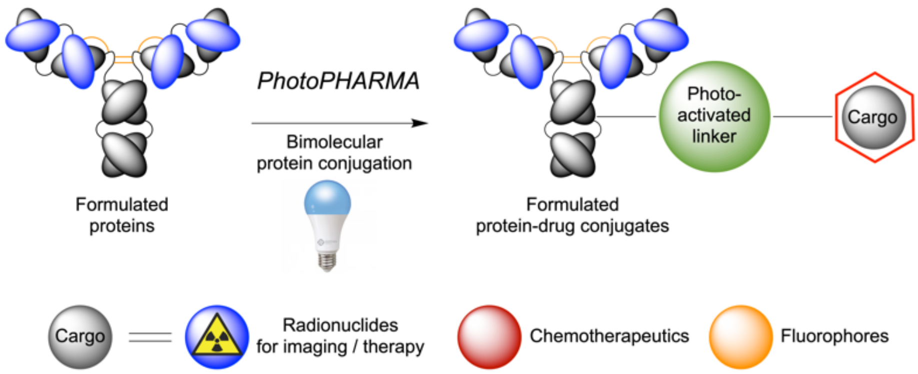
Photochemistry harbours many fascinating reactions and reactive intermediates that hold potential for applications in the synthesis of bioactive compounds. In recent years, my group has been exploring the use of compounds that undergo light-induced activation for the synthesis of protein-conjugates like monoclonal antibodies functionalised with radioactive metal complexes, fluorophores, and drugs. Photolysis typically produces extremely reactive, shortlived intermediates (with lifetimes in the micro-to-nanosecond range) and controlling the experimental conditions to allow productive bioconjugation chemistry is the major challenge in harnessing light-induced chemistry. This presentation will introduce some of our recent synthetic, spectroscopic, computational, radiochemical, and biological studies using (automated) photoradiosynthesis to make viable radiotracers in a flash.



References

[1] Guillou et al., The influence of polyethylene glycol linkers on the metabolism and pharmacokinetics of 89Zrradiolabeled antibodies; Bioconjugate Chem., 2021, 32, 7, 1263–1275.

[2] Fay et al., Tuning tetrazole photochemistry for protein ligation and molecular imaging; Chem. Eur. J., 2021, 27, 4893-4897

[3] Guillou et al., Light-induced synthesis of protein conjugates and its application in photoradiosynthesis of 89Zrradiolabelled monoclonal antibodies; Nat. Protocol, 2020, 15, 3579–3594

[4] Klingler et al., Light-induced radiosynthesis of 89ZrDFO-azepin-onartuzumab for imaging the hepatocyte growth factor receptor; J. Nucl. Med., 2020, 61, 1072-1078.

[5] Holland et al., Photochemical reactions in the synthesis of protein-drug conjugates; Chem. Eur. J., 2020, 26, 33-48. (review)

In vitro dosimetry for assessment of Targeted-Alpha-Therapy*

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Targeted-Radionuclide-Therapy is a cancer treatment method based on the use of radio-labeled molecules showing both interesting properties of specific binding to tumor locations and short range ionizing ray emissions. For the latter matter, while beta-emitting radionuclides are currently mainly used, alpha-particles are of interest for dedicated applications such as the targeting of disseminated brain metastases [1], their radiation range in biological matter covering only a few dozens of micrometers, which is to say only a few cell diameters. Access to alpha-emitting radioisotopes compatible with a clinical use significantly increased the last decade thanks to developments on heavy ions production [2], a research field GANIL is involved in with especially the study of ^{211}At production. However, when alpha-particle based therapies go under *in vitro* and pre-clinical assessment, additional care must be taken compared to beta-particle therapies. In particular, during *in vitro* experiments, because of the high linear energy transfer of alpha-particles, the distribution of the radionuclides in the culture medium must be precisely known to properly assess the energy deposited by the radionuclides into the cell culture, thus allowing a more reliable measurement of the dose received by the cells [3]. Improvement of the reliability of this measurement, which is the main goal of this work, is of utmost importance to perform valid comparisons of the relative biological effectiveness (a quantity based on the cell-survival relative to the dose deposited) between alpha-particle based therapies and other treatments.

The proposed methodology is based on the use of silicon semi-conductor diodes placed below the culture wells, which record energy spectra of the alpha particles passing through the cell layer. A measurement chamber was designed to carry out the measurements inside a cell culture incubator, allowing for the cell cultures to be kept in standard conditions while protecting the electronics. Deconvolution methods, including non-negative matrix regression with relevant tweaks and law-based distribution fits, were tested and implemented to extrapolate the radionuclide spatial distribution from energy spectra during *in vitro* experiments. It is then possible, through Monte-Carlo simulations and the spatial distribution, to determine the dose received by the cells. With the help of simulated spectra obtained from known distributions, the deconvolution methods will be assessed by the agreement of the regressed distributions, spectra, but also, and more importantly, by the consequential differences in terms of delivered dose to the cells. The experimental set-up as well as the analysis methods will be tested with clinically available alpha emitters, such as ^{223}Ra used in treatment of bone metastases and ^{212}Pb, currently under pre-clinical study in association with the VCAM-1 antibody for the treatment of brain metastases [4]. For the latter radionuclide, *in vitro* dosimetry will also allow the evaluation of the efficiency of the proposed radiopharmaceutical, particularly under hypoxic conditions.

References

[1] A. Corroyer-Dulmont *et al.*, Neuro-Oncology **22**(3), 357-68 (2020).

[2] F. Guerard *et al.*, Q J Nucl. Med. Mol. Im. **59**, 161-7 (2015).

[3] A.M. Frelin-Labalme *et al.*, Med. Phys. **47**(3), 1317-26 (2020).

[4] N. Falzone *et al.*, Theranostics **8**(1), 292-303 (2018).

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3-Dimensional Scintillation Dosimetry for Small Irradiation Fields Control in Protontherapy

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The use of proton beams for radiotherapy has many benefits compared to "conventional" photon beams, especially in terms of ballistic properties, in particular for the sparing of healthy tissues, which make the proton therapy treatment less radiotoxic.

However this technique is currently contraindicated for tumors smaller 3 cm in part because of the lack of quality control devices with appropriate spatial resolution. The existing detectors don't combine good spatial, dose resolution and fast 3-dimensional (3D) reconstruction. In order to address this issue, a new dosimetry device is currently under development.

This device, based on the recording by a fast camera of the light emitted by a plastic scintillator, was designed to allow the reconstruction of a 3D map of the absorbed dose for proton beams delivered with the pencil beam scanning (PBS) technique. The final purpose of this device is to provide a quality control of patient treatment plans that employ small fields.

The response of the system was evaluated with clinical proton beams at the Cyclhad proton therapy center, equipped with a Proteus®One (IBA) system.

In a first step, the scintillation signals were recorded for each individual pencil beam of the planned irradiation and compared to the beam characteristics of the treatment plan. This first characterization allowed to design irradiation plans specifically adapted to the dosimetric system evaluation.

In a second step, customized irradiation plans allowed to assess the measurement repeatability for beam spots of 0.02, 0.1 and 1 monitor units (MU – arbitrary machine unit proportional to the dose). The standard deviation of the lateral spot position, the range and the beam intensity was determined for 10 consecutive irradiations performed at each dose.

The measurements showed excellent results with standard deviations lower than 293, 75 and 44 μm on the beam position, 91, 29 and 19 μm on the range (measured at the maximum intensity), and 0.89, 0.26 and 0.17 % on the scintillation intensity at 0.02, 0.1 and 1 MU respectively.

These repeatability measurements showed a very good reliability of the device even at low dose, which is very promising for quality assurance as well as dose distribution measurements.

The next step to achieve accurate quality control of the patient treatment plan is the spatial calibration of the measured spot positions, which will be done in the next experiments. The dose calibration and the scintillation quenching will also have to be studied to be able to control the beam intensity accuracy and reach 3D dosimetry.

Nuclear Structure 6

ACTAR TPC: performances, achievements and future upgrades

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The ACTAR TPC (Active Target & Time Projection Chamber) is a detector developed for nuclear reaction and structure studies as well as exotic decay and proton emission studies. It results from the joint efforts to build a second generation gaseous target and detector that merges the advantages of the first generation active target MAYA based on wire amplification and the CENBG TPC based on GEMs. In addition to specific developments concerning the high density collection plane (with 16k pads) and the active volume, the device is equipped with the GET electronics that allows for time sampling of signal of each pad for a full 3D reconstruction of tracks.

ACTAR TPC is operational since 2018 and was successfully used so far for resonant scattering studies, inelastic and transfer reactions implying lowintensity beams or very-low energy recoils, as well as for studying exotic decays of nuclei.

We will address the performances of ACTAR TPC for the various modes explored so far, and will discuss the planned upgrades of the detector to extend its domain of application.

Looking for 2-proton decay of ^{48}Ni with ACTAR TPC

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The only know $T_Z = -4$ isotope, the doubly-magic ^{48}Ni nucleus, was discovered in a projectile fragmentation experiment at GANIL [1]. A first indication of its ground state 2-proton radioactivity could be observed few years later [2] at GANIL, and this decay mode was established in a tracking experiment performed at NSCL [3]. For the few known ground-state 2-proton emitters ^{45}Fe, ^{48}Ni and ^{54}Zn, available theoretical descriptions were able to reproduced the measured half-lives. This was not the case anymore when the 2-proton radioactivity was established for ^{67}Kr, at RIKEN [4]. with a half-life in the order of 20 times lower than expected.

Two hypothesis have been proposed to explain this discrepancy for ^{67}Kr: either a transitional situation between a direct and a sequential emission of the protons [5] or the influence of the nuclear deformation. This latter hypothesis is based on a Gamow coupled channel approach, that is benchmarked with ^{48}Ni that is expected to be spherical (doubly-magic). Both theoretical frameworks can predict angular distributions of the protons, that need to be confirmed experimentally.

At the time of writting this abstract, we are running an experiment at GANIL / LISE3 facility with the aim to produce ^{48}Ni nuclei, implant them in ACTAR TPC, and perform the tracking of the protons from its decay. At present stage, we do not know what will be the outcome of this experiment, but we have already identified few events. We propose to present the preliminary result of this experiment, for the production and decay of ^{48}Ni, but also for the experimental information that could be extracted for neighbour nuclei.

References

[1] B. Blank *et al.*, Phys. Rev. Lett. **84**, 1116 (2000).

[2] C. Dossat *et al.*, Phys. Rev. C**72**, 054315 (2005).

[3] M. Pomorski *et al.*, Phys. Rev. C**95**, 021601(R) (2017).

[4] T. Goigoux *et al.*, Phys. Rev. Lett. **117**, 162501 (2016).

[5] L. V. Grigorenko *et al.*, Phys. Rev. C**83**, 061303(R) (2011).

[6] S. M. Wang, W. Nazarewicz, Phys. Rev. Lett. **120**, 212502 (2018).

Nuclear Structure 7

Direct reaction studies at GANIL: an overview of recent MUST2 and MUGAST experiments

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Direct reactions has been a staple of radioactive beams studies at GANIL. In this overview talk, recent experimental campaigns using the MUST2[1] array at LISE, and the MUGAST-AGATA-VAMOS [2] setup using SPIRAL1 beams will be presented.

A wide range of physics cases has been explored in both light and medium mass nuclei. From the study of unbound nuclei, to astrophysical implications going through mirror symmetry breaking, nuclear pairing, and of course shell evolution, those experimental campaigns has covered an outstanding field of nuclear structure.

The overview of recent results will highlight the versatility of direct reactions studies when combined to novel technics such as cryogenic target and lifetime measurement as well as the technical challenges associated with such experimental setups.

References

[1] E. Pollaco *et al.*, MUST2: A new generation array for direct reaction studies July 2005European Physical Journal A 25(S1):287-288

[2] M. Assié *et al.*, The MUGAST-AGATA-VAMOS campaign : set-up and performance. arXiv:2104.10707 [physics.ins-det]

The Coulomb force as a magnifying glass of nuclear structure in the A=36 mirror nuclei

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The ^{36}Ca nucleus has been studied at GANIL through ^{37}Ca(p,d) and ^{38}Ca(p,t) reactions at about 50 MeV/A. The ^{37}Ca and ^{38}Ca isotopes, produced in the LISE spectrometer in two different settings, were tracked by two sets of multi-wire devices, before impinging a 9.7 mg/cm^2 Liquid Hydrogen target, which was surrounded by 6 MUST2 telescopes at forward angles (from 3 to 37° in the laboratory frame, i.e. 2 and 160° in the center-of-mass). Each telescope consisted of a 300 μm double-sided Stripped Silicon detector (DSSD) with 128 strips on each side, backed by sixteen 4 cm thick CsI detectors, which provide energy-loss (ΔE) and residual energy (E) of the light d and t particles, as well as protons emitted from the unbound states populated in ^{36}Ca ($S_p = 2599.6(56)$keV). After interaction with the target nuclei, the trajectories of the transfer-like nuclei, their atomic number Z and their time-of-flight were determined by means of a Zero Degree Detection (ZDD) setup, composed of an ionization chamber, a set of XY drift chambers, followed by a thick plastic scintillator. The detection of both light and heavy ejectiles ensured a complete determination of the kinematics of the reaction, an L assignment of all states produced, and a very reduced amount of background.

Besides the confirmation of the spin and energy of the first 2^+ state, as well as the first determination of its proton to γ decay branches [1], the present experiment provides a detailed comparison of excitation energies E^* and C^2S values of states produced in the mirror reactions ^{37}Ca$(p,d)^{36}$Ca and ^{37}Cl$(d,^3He)^{36}$S. This allows to probe the effect of the continuum on E^* and C^2S between ^{36}S, where all states are bound, with ^{36}Ca, where all states except the ground state are unbound. Moreover, the ^{38}Ca$(p,t)^{36}$Ca reaction has allowed the identification of the 0^+_2 ($2p2h$ proton intruder) and the 0^+_3 ($2p2h$ neutron states), the first being proposed to experience a massive shift in energy of about 600 keV between the mirror nuclei [2]. Between the two mirror nuclei, the Coulomb interaction acts as a magnifying glass of the nuclear structure, whose effect will be scrutinized in this presentation. If time allows, other results on ^{35}Ca (atomic mass, spectroscopy, $N = 16$ shell gap) and ^{37}Ca (neutron $d_{5/2} - d_{3/2}$ spin-orbit splitting) can also be presented.

References

[1] L. Lalanne *et al.*, Phys. Rev. C **103**, 055809 (2021).

[2] J. J. Valiente-Dobón *et al.*, Phys. Rev. C **98**, 011302 (2018).

Location of the unbound neutron $0d_{3/2}$ strength in ^{17}C

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The evolution of the N=16 shell gap in neutron-rich oxygen isotopes has been studied extensively over the past years [1, 2, 3, 4]. In neutron-rich carbon isotopes, the N=14 shell gap is shown to collapse [5, 6] however no experimental information on the N=16 shell gap is known. Unbound states in ^{17}C have been populated using one-neutron transfer reaction d(^{16}C,p)^{17}C at a beam energy of 17.2 AMeV [6] with the TIARA Silicon array at GANIL. The excitation energy of the neutron unbound states in ^{17}C was reconstructed using the information from the energy and angle of the proton ejectile. Two resonances have been found at E_x=3.48(31) MeV and E_x=4.83(21) MeV and their neutron-decay widths were deduced. The results show that the $0d_{3/2}$ orbital involved in the development of the N=16 shell gap has been located in ^{17}C. In this talk, I will present the preliminary results and discuss them in the light of recent shell model calculations.

Referencias

[1] O. Sorlin and M.G. Porquet, Prog. Part. Nucl. Phys. 61 (2008) 602.

[2] T. Otsuka et al., Rev. Mod. Phys. 92 (2020) 015002.

[3] Z. Elekes et al., Phys. Rev. Lett. 98 (2007) 102502.

[4] C. R. Hoffman et al., Phys. Rev. Lett. 100 (2008) 152502.

[5] M. Stanoiu et al., Phys. Rev. C 78 (2008) 034315.

[6] X. Pereira-López et al. Physics Letters B, 811, (2020), 135939.

Missing mass spectroscopy of ^{8}C

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The mirror symmetry is one of the basic features in the nuclear system. The mirror nuclei are defined as a pair of nuclei with interchanged numbers of protons and neutrons. The mirror energy difference, the difference of corresponding excitation energies, is known to be small for deeply bound nuclei. Recent study of weekly bound and unbound nuclei suggests the deviation of the mirror energy difference from the systematic trend of deeply bound nuclei [2]. In this study, we investigated excited states of ^{8}C, the most proton-rich even-even nuclei ever observed ($A/Z = 1.33$). No excited state of ^{8}C is experimentally known though its ground state is known to decay by emitting an α particle and four protons with a total decay width of 130 keV [2]. Some excited states of ^{8}He ($A/Z = 4$), the mirror nucleus of ^{8}C, are experimentally known and we can compare the excitation energies of ^{8}C and ^{8}He. The missing mass method was adopted by using MUST2 telescopes to reconstruct the excitation energy spectrum since only one recoil particle detection is needed by this method even if the nucleus of interest, ^{8}C, decays via multi-particle emission.
We performed the experiment in July 2018. A ^{9}C secondary beam containing ^{8}B, ^{7}Be and ^{6}Li was produced by the LISE spectrometer. The beam was bombarded on a liquid hydrogen target of 1.5 mm in thickness. Resonance states in ^{8}C were populated via the (p, d) reaction. An array of six MUST2 telescopes was used to detect recoil deuterons from the target and decay fragments such as α particles and protons. We will report on the experimental result and discuss it.

References

[1] D. Suzuki *et al.*, Phys. Rev. C **93**, 024316 (2016).

[2] R. J. Charity *et al.*, Phys. Rev. C **84**, 014320 (2005).

Study of the ^{46}Ar proton wavefunction by means of direct transfer reaction: ^{46}Ar(^{3}He, d)^{47}K

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The evolution of the nuclear shell closure along N=28 has gathered much interest due to the observed discrepancies between the well established shell model with SDPF-U interaction and measurements of the half-magic ^{46}Ar isotope.

In particular, while remarkable agreement was observed between theoretical and experimental values of S_n, transition probabilities measured with intermediate Coulomb excitation diverge by a factor of two from their predicted values[1, 2]. The reason behind this mismatch has been pinned down to the proton transition matrix elements[2] and hints at an incorrect description of the sd proton space below Z=20 [3].

The experiment we proposed aimed at shedding some light on this peculiar problem by directly probing the proton component of the wavefunction via a proton-pickup direct reaction: ^{46}Ar(^{3}He, d)^{47}K at an energy of 350 MeV.

The experiment, performed at the Spiral 1 facility in GANIL with a post-accelerated radioactive ^{46}Ar beam impinging on a high-density cryogenic ^{3}He target, will assess the amount of d3/2 state relative to the s1/2 relying on a state-of-the-art experimental setup for a precise reconstruction of the kinematics of the reaction.

The heavy reaction fragment was identified by the high acceptance magnetic spectrometer, VAMOS, while the high-granularity silicon DSSSD detector, MUGAST, allowed the measurement of the angular distribution of the light ejectile while also performing particle identification. The AGATA[5] gamma-ray tracking germanium array measured the gamma rays produced by the decay of the ^{47}K excited states.

Experimental results will be compared with theoretical models to infer information on the proton wavefunction of ^{46}Ar.

References

[1] A. Gade *et al.*, Phys. Rev. C 74, 034322 (2006)

[2] S. Calinescu *et al.*, Phys. Rev. C 93, 044333 (2016)

[3] Z. Meisel *et al.*, Phys. Rev. Lett. 114, 022501 (2015)

[4] M.Rejmund *et al.*, Nucl. Inst. Meth. A 646, 184-191 (2012)

[5] S. Akkoyun *et al.*, Nucl. Inst. Meth. A 668, 26-58 (2012)

Investigating the N=28 shell closure below Z=20 through ^{47}K(d,p)^{48}K.

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The N=28 shell gap has long been a topic of interest in the field of nuclear structure. As the first standard magic number that cannot be fully reproduced in theory using only two-nucleon forces, [1] there is considerable need for experimental studies in this region. The nucleus ^{48}K is uniquely situated for this purpose, as it is both one proton below Z=20, and one neutron above N=28. Additionally, the lowest-lying excited states in ^{48}K have been found to result from $\pi(1s_{1/2}) \otimes \nu(fp)$, where the odd proton lies beneath a full $\pi(0d_{3/2})$ orbital [2]. The implications of this interaction extend down the proton-deficient N=28 isotonic chain, where this singly-occupied $\pi(1s_{1/2})$ orbital is expected to couple with neutrons in the orbitals immediately above N=28 in the short-lived ^{44}P nucleus [3].

The first experimental study of states arising from the interaction between $\pi(1s_{1/2})$ and the orbitals $\nu(1p_{3/2})$, $\nu(1p_{1/2})$ and $\nu(0f_{5/2})$ has been conducted, by way of the ^{47}K(d,p) reaction in inverse kinematics. The radioactive beam of ^{47}K from the GANIL-SPIRAL1 facility had a beam energy of 7.7 MeV/nucleon and was of exceptional quality, as it had a typical intensity of 5×10^5 pps (limited primarily by the constraints of the counting system) and was estimated to be $> 99.99\%$ pure. The beam impinged upon a 0.5 mg/cm^2 CD_2 target. The MUGAST + AGATA + VAMOS detection setup [4] allowed for triple coincidence gating, providing a great amount of selectivity. An analysis based both on excitation and gamma-ray energy measurements has revealed a number of previously unobserved states, and preliminary results relating these to the shell model configurations will be presented.

References

[1] J.D. Holt *et al.*, J. Phys. G: Nucl. Part. Phys. **39**, 085111 (2012).

[2] W. Królas *et al.*, Phys. Rev. C, **84**, 064301 (2011).

[3] L. Gaudefroy, Phys. Rev. C, **81**, 064329 (2010).

[4] M. Assié *et al.*, The Mugast-Agata-Vamos Campaign (preprint, submitted to Nucl. Instr. Meth. A), arXiv:2104.10707 [physics.ins-det] (2021).

Fundamental Interactions

Correlation measurements in nuclear beta decay

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Precision measurements in nuclear and neutron beta decay are ideal tools to study the symmetries and the structure of the weak interaction. If the dominance a vector axial-vector form of the interaction coupling to left handed neutrinos with maximal parity violation seems today well established, there is still room for exotic couplings contributions (mediated by W' bosons, leptoquarks, etc..), introduced in several extensions of the standard model (SM). Correlation measurements in beta decay and tests of the CKM matrix unitarity are among the most sensitive probes to search for new physics and large efforts are currently pursued to improve the present limits on exotic couplings. We will discuss the relevance of different experimental observables and give an overview of ongoing projects dedicated to correlation measurements.

Improved Search for CP Violation in ortho-Positronium Decay

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The combined charge and parity symmetry (CP) is only known to be violated in the mixing matrices of quarks and of neutrinos, and has a vanishingly small effect on many physical processes in the Standard Model.

Positronium (Ps) is a purely leptonic system that decays only to photons. The observation of a CP violating correlation in the decay products would be a clear sign of physics beyond the Standard Model.

A CP violating correlation can be built involving the Ps tensor polarization and the momenta of the two highest energy photons in the three-photon decay of Ps.

A new apparatus is being designed and built at the NSCL/MSU, to search for a factor of ten higher precision in the measurement of such correlation compared to previous results. The apparatus consists of a positron source sandwitched between two scintillators for positron detection, and surrounded by a low density powder for Ps formation. This is placed inside an array of photon detectors to measure angular correlations between the decay photons, and the full system is located inside a superconducting solenoid with a large diameter warm bore, to provide tensor polarized Ps. With this design we expect to reach the sensitivity goal in 35 days of continuous running.

Search for CP violation in nuclear beta decay: The MORA project

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Why are we living in a world of matter? What is the reason for the strong matter – antimatter asymmetry we observe in the Universe?
A large CP violation has therefore to be discovered to account for this large matter-antimatter asymmetry, at a level beyond the CP violation predicted to occur in the Standard Model via the quark-mixing mechanism.

The MORA (Matter's Origin from RadioActivity of trapped and oriented ions) project aims to search for new CP violations in beta decay thanks to the measurement of the triple D correlation, with an unprecendented precision to the order of 10^{-5}[1]. The MORA experiment uses an elegant polarisation technique, which implements the high efficiency of ion trapping[2] and the orientation of a laser. A ring of detectors allows the measurement of the coincidences of the beta particles with the recoil ions coming from the trapped radioactive ions. The D parameter can be determined by the asymmetry in the counting rate when inverting the polarisation. This measurement should potentially enable, for the first time, a probe of the Final State Interaction effect which mimics a non-zero D correlation at or below 10^{-4} .

The MORA apparatus is currently tested either at the LPC Caen and at GANIL before moving to JYFL, where adequate lasers are available for the polarization of $^{23}Mg^{+}$ ions. MORA will be installed later in the DESIR hall at GANIL where better production rates are expected, offering the opportunities to reach unprecedented sensitivities to New Physics.
This presentation aims to showcase the current status of the MORA experiment (commissionning, test on detectors ...) and the perspectives beyond it (moving to JYFL, first measurements ...).

References

[1] P. Delahaye et al., Hyperfine Interact 240, 63 (2019).

[2] M. Benali et al., Eur. Phys. J. A 56, 163 (2020).