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

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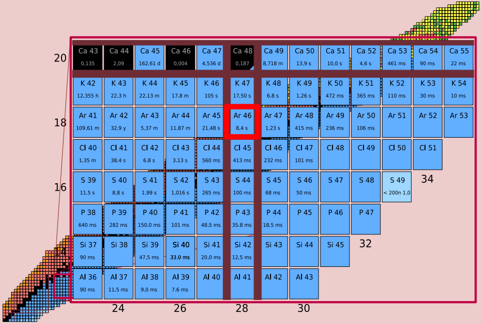
XXIInd COLLOQUE GANIL

Talk Outline

- The Physics Case
- The experiment
    - The Experimental Setup
- Analysis
    - Monte Calo simulations
    - Measured distributions
    - Likelihood fit
    - Comparison with reaction model
    - Cross checks
- Conclusions
- The Collaboration
- Summary

The ^{46}Ar puzzle

^{46}Ar: $-2p$ from ^{48}Ca



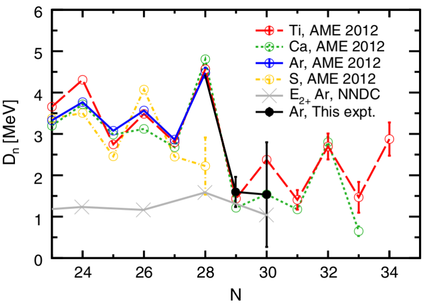
Ca 43 0,135	Ca 44 2,09	Ca 45 162,61 d	Ca 46 0,004	Ca 47 4,536 d	Ca 48 0,187	Ca 49 8,718 m	Ca 50 13,9 s	Ca 51 10,0 s	Ca 52 4,6 s	Ca 53 461 ms	Ca 54 90 ms	Ca 55 22 ms
K 42 12.355 h	K 43 22.3 h	K 44 22.13 m	K 45 17.8 m	K 46 105 s	K 47 17.50 s	K 48 6.8 s	K 49 1.26 s	K 50 472 ms	K 51 365 ms	K 52 110 ms	K 53 30 ms	K 54 10 ms
Ar 41 109,61 m	Ar 42 32,9 y	Ar 43 5,37 m	Ar 44 11,87 m	Ar 45 21,48 s	Ar 46 8,4 s	Ar 47 1,23 s	Ar 48 415 ms	Ar 49 236 ms	Ar 50 106 ms	Ar 51	Ar 52	Ar 53
Cl 40 1.35 m	Cl 41 38.4 s	Cl 42 6.8 s	Cl 43 3.13 s	Cl 44 560 ms	Cl 45 413 ms	Cl 46 232 ms	Cl 47 101 ms	Cl 48	Cl 49	Cl 50	Cl 51	
S 39 11.5 s	S 40 8.8 s	S 41 1.99 s	S 42 1.016 s	S 43 265 ms	S 44 100 ms	S 45 68 ms	S 46 50 ms	S 47	S 48	S 49 < 200n 1.0		
P 38 640 ms	P 39 282 ms	P 40 150.0 ms	P 41 101 ms	P 42 48.5 ms	P 43 35.8 ms	P 44 18.5 ms	P 45	P 46	P 47			
Si 37 90 ms	Si 38	Si 39 47.5 ms	Si 40 33.0 ms	Si 41 20.0 ms	Si 42 12.5 ms	Si 43	Si 44	Si 45				
Al 36 90 ms	Al 37 11.5 ms	Al 38 9.0 ms	Al 39 7.6 ms	Al 40	Al 41	Al 42	Al 43					

The study of the N=28 shell evolution led to the discovery of a peculiar disagreement in ^{46}Ar

- Transition probabilities measured by (intermediate and near-Coulomb-barrier) *coulex* measurements hint at a reduced B(E2) compared to the possibility of an onset of *collectivity* in ^{46}Ar
- Shell model calculations, which account correctly for the breakdown of the shell gap in S and Si are at odds with B(E2) measurements

Neutron observables $\Longrightarrow$ D_n

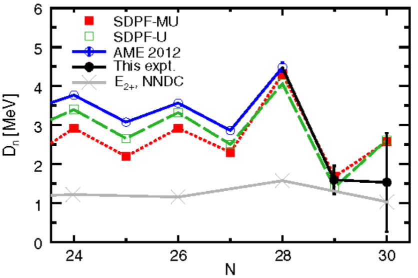
D_n [Z. Meisel et al. PRL 114, 022501 (2015)]



- Mass measurements confirm the N=28 shell closure in ^{46}Ar and its breakdown in the S isotopes (by observing a peaked value of D_n at N=28 with a sudden drop for more neutron-rich ^{46}Ar isotopes)
- **Experimental data and theory well in agreement** ($\Longrightarrow$ SPDF-U describes well the valence-core neutron interaction)

Neutron observables $\Longrightarrow$ D_n

D_n [Z. Meisel et al. PRL 114, 022501 (2015)]



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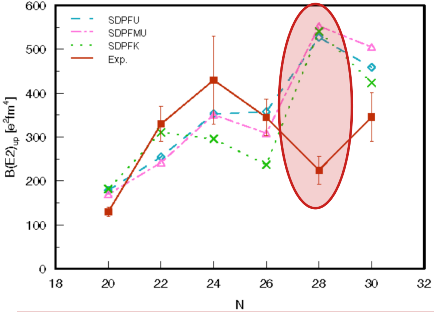
Neutron+Proton observables ⟹ Quadrupole transition probabilities

B(E2) [A. Gade et al., PRC 68, 014302; S. Calinescu et al., PRC 93, 044333]



- **Divergence in trend and in value between shell model calculations and coulomb excitation measurements**
- Other isotopes are well reproduced
- Lifetime measurement shows agreement with SM calculations
- measurement at **LISE**: discrepancy in B(E2) attributed to the contribution on the matrix elements from protons

Is there more to be understood of the proton contribution to the wave-function?

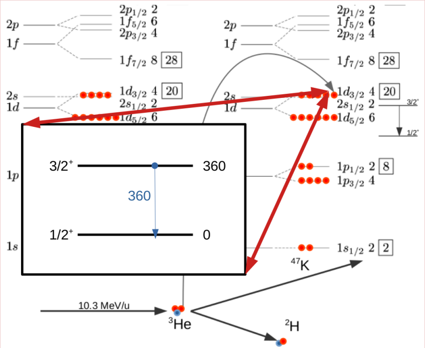
The experiment

- **Spiral1:** ^{46}Ar(^{3}He, d)^{47}K @ 10MeV/u. (primary beam ^{48}Ca) $I_{beam} = 3 \times 10^{4}$ Hz

The aim of the experiment is to probe the proton wavefunction via direct proton transfer reaction in ^{46}Ar

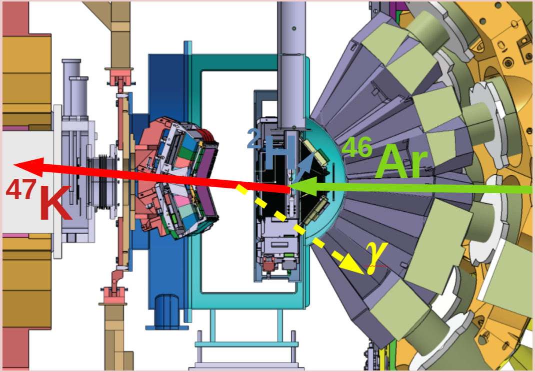
- We are looking into a well studied isotope $\Longrightarrow$ Spin assignments are well established
- The crucial aspect is to investigate the relative *s* and *d* transfer
- Spectroscopic factors are known for ^{48}Ca p removal: what for ^{46}Ar p addition?

(Simplistic) single particle picture



The Experimental Setup

M. Assié et al., NIM A 165743 (2021)



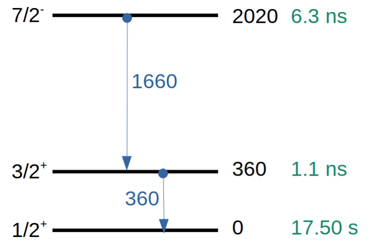
[1] F.Galtarossa et al., NIM A 165830 (2021)

High granularity setup

- **VAMOS**: Reaction fragment identification, Beam and target monitoring
- **MUGAST**: Energy, Position, Particle discrimination
- **AGATA**: Gamma energy, Position
- **CATS2**: TOF for MUGAST and VAMOS
- **HECTOR**[1]: cooled to 7K, density of $\approx 1.5 \times 10^{-3}$ g/cm^{2}, equiv. to $\approx 5.0 \times 10^{-3}$ g/cm^{3}

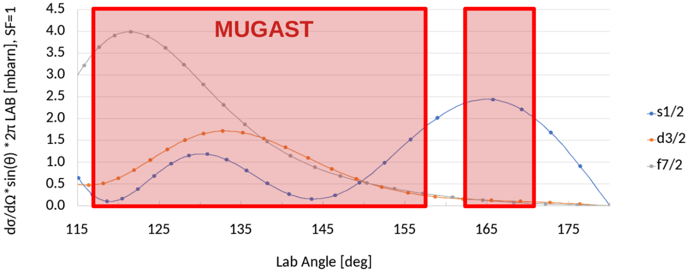
Angular distribution

^{47}K Level Scheme



Well studied spectroscopy [C. A. Ogilvie et al., NPA 465, 3 (1987)]

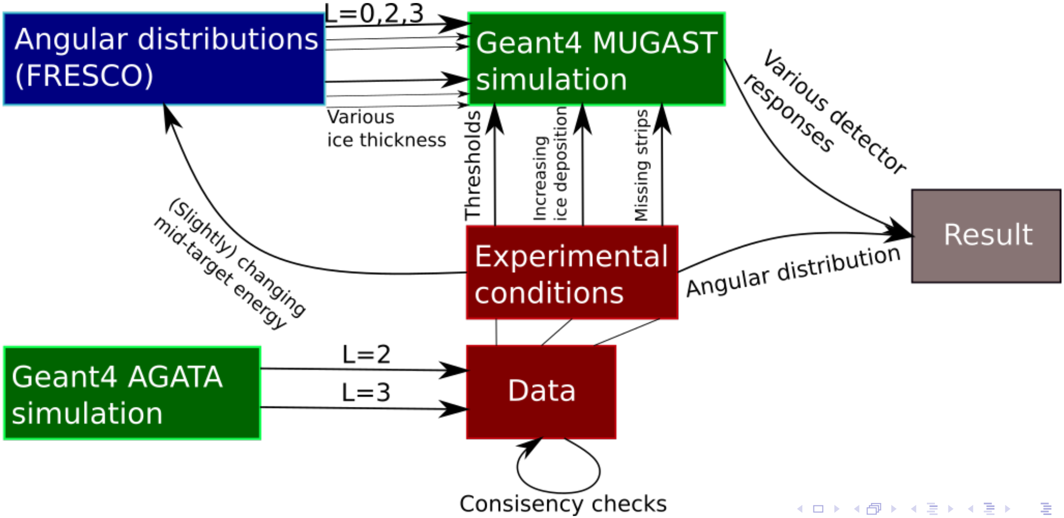
Laboratory Angular distribution



Distributions show a high sensitivity to the transferred wave's L

- We aim to disentangle the L=0 and L=2 distributions which have a very different signature in the angular region of sensitivity

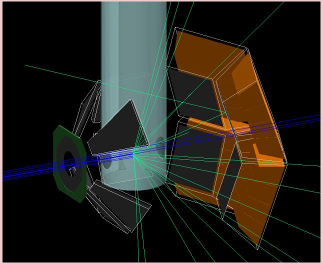
Analysis strategy: interplay of detector response simulation and experiment



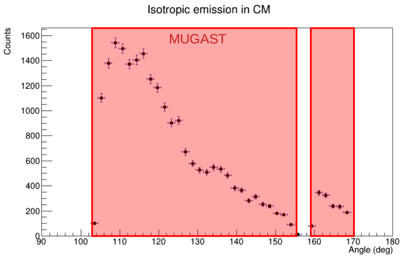
MUGAST: Simulation

- Geant4 Monte Carlo simulation necessary to:
  1. Correct for efficiency as a function of θ, ϕ
  2. Better understand E-Loss in deformed target
  3. Account for missing strips, thresholds, and all other experimental aspects
  4. Angular distribution vary due to growing ice thickness

NPTOOL A Matta et al, J. Phys. G: Nucl. Part. Phys. 43 045113



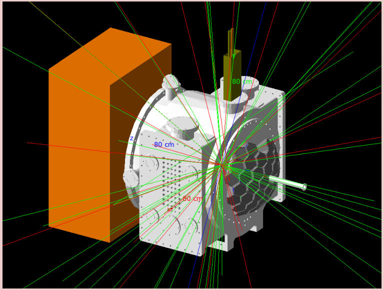
Isotropic CM emission



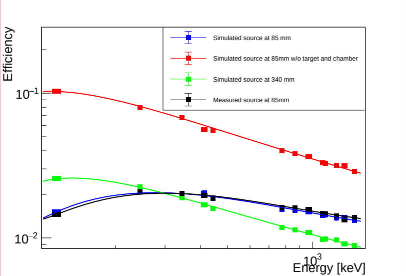
AGATA: Simulation

- Geant4 simulation necessary to:
  1. Simulate response to feeding on 3/2 and 7/2, which have very dissimilar lifetimes
  2. If the deutreron breakup reaction is direct, this reaction channel is interesting due to much higher statistics.

AGATA E. Farnea et al, NIM A 621 1 331-343 + HECTOR

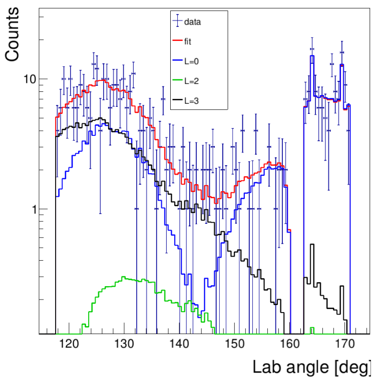


Simulation and source comparison



Angular distributions

Laboratory distribution

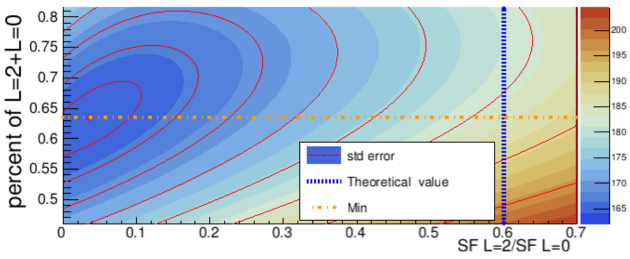


- The detector response to the three different angular distributions is simulated
- Maximizing the likelihood returns a great fit
- The $L = 0$ angular distribution is peaked at backwards angle and fixes the counts in the next peak of the distribution
- Error bars are shown only for guidance since the likelihood approach was chosen
- Little contribution of $L = 2$ transfer
- Discrepancies show no systematic trend

Angular distributions

- Likelihood with multivariate errors is the correct statistical approach for low-count (and empty) bins

Comparison with shell model prediction: **two opposing results**



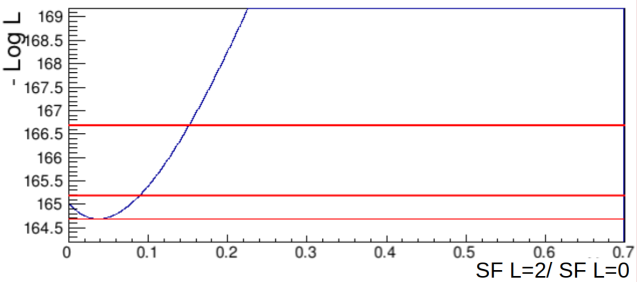
- The contribution of the $L = 3$ transfer does not hinder the sensitivity
- A clear gradient and minimum of $-\log \mathcal{L}$ is present
- Compatible results are obtained with different excitation energy gates and χ^2 test

- **Theory (shell model) and experiments are pointing in different directions**

Angular distributions

- Likelihood with multivariate errors is the correct statistical approach for low-count (and empty) bins

Comparison with shell model prediction: two opposing results



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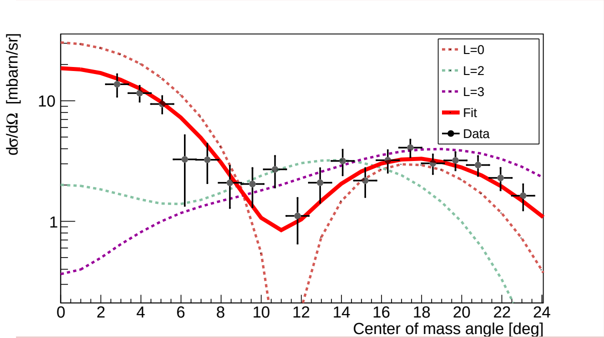
Angular distributions

Center of mass comparison with Fresco calculations

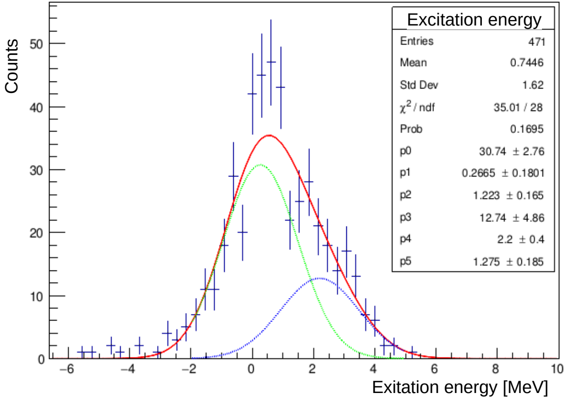


- **Finite-range DWBA** (Fresco)
- The center of mass distribution, shows a remarkable agreement with the fit performed in the laboratory frame of reference.
- Different (global) optical potentials have little effect on the distributions at angles close to zero

- **The peak of the $L = 2$ distribution is located in correspondence of the minimum of the overall distribution**

Excitation energy spectrum

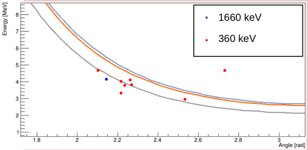
Excitation energy fit



- $L0/(L0 + L3) = 0.78 \pm 0.11$
- Compatible with 0.64 $\rightarrow [0.60, 0.68]$ from angular distribution
- Ex spectrum subject to tricky energy loss calculations
- Fitted sigmas are compatible

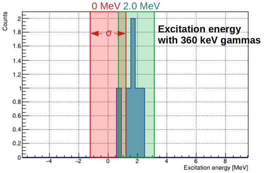
Triple coincidences: AGATA+VAMOS+MUGAST

Kinematic line in coincidence with 360 KeV γ-ray



- 360 keV γ detected by AGATA+^{47}K identified in VAMOS+ deuteron measured in MUGAST $\Longrightarrow$ clear kinematic line
- Narrow γ gate removes background

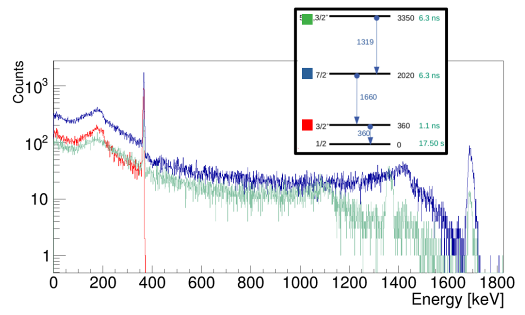
γ-rays in coincidence with d and ^{47}K



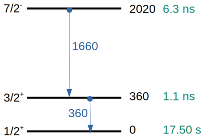
- Despite the majority of counts in the Excitation energy peak are centered at 0 MeV, the only counts in coincidence with AGATA are at 2 MeV
- No gammas seen for Ex$<$ 1MeV
- Suppressed direct transfer to $\frac{3}{2}^{+}$?

γ-ray with ^{47}K in VAMOS

BKG subtracted γ spectrum



^{47}K spectroscopy

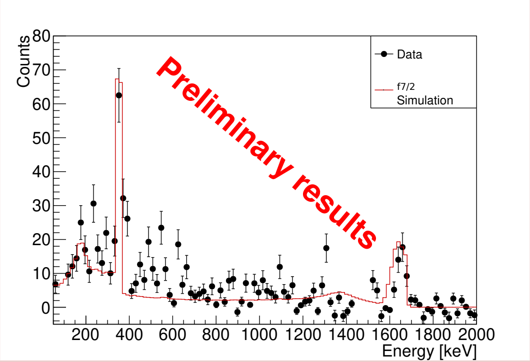


Large difference in lifetime between $7/2^-$ and $3/2^+$

- Due to the long lifetime of the $f7/2$ state, the efficiency of the spectrometer changes drastically
- γ rays at 360 keV are due to the de-excitation of the $7/2^-$ state

γ-ray with ^{47}K in VAMOS

BKG subtracted γ spectrum



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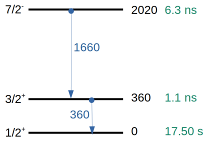

Large difference in lifetime between $7/2^{-}$ and $3/2^{+}$

- Due to the long lifetime of the $f7/2$ state, the efficiency of the spectrometer changes drastically
- γ rays at 360 keV are due to the de-excitation of the $7/2^{-}$ state

Conclusions and future perspectives

- Results indicate a reduced L=2 transfer
- An ongoing collaboration with C. Barbieri, V. Somà et al. aims at investigating the problem with ab-initio methods (calculations performed with NNLO interaction), showing great results
- Other calculations by G. Colò et al. are also being performed (mean field, ...)
- Final minor tweaks and considerations on the analysis are in the works

The Collaboration

- G. de Angelis, E. T. Gregor, **A. Gottardo**, A. Illana, G. Jaworski, D.R. Napoli, M. Siciliano, J.J. Valiente-Dobon, F. Galtarossa, I. Zanon
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Thank you for your attention

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