Coulomb force as a magnifying glass of shell structure in the \(^{36}\text{S} - {^{36}\text{Ca}}\) mirror nuclei

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Oral contribution Colloque GANIL 2021
Studies of $^{35,36}\text{Ca}$: what is known?

$^{34}\text{Ca}$ is unbound
Only the g.s. of $^{35}\text{Ca}$ and $^{36}\text{Ca}$ are bound
Only first excited state $2^+$ of $^{36}\text{Ca}$ is known
It is above $S_{2p}$ (but considered as quasi-bound as well below $B_c$) $Z=20$

$B_c = 5.5 \text{ MeV}$

The ground and excited states of $^{35,36}\text{Ca}$ studied by (p,d) and (p,t)
Transfer reactions from $^{38}\text{Ca}$ and $^{37}\text{Ca}$ radioactive beams at 50 A.MeV

\[
\begin{align*}
\text{34Ca} & \rightarrow 1/2^+ \\
\text{35Ca} & \rightarrow 3/2^+ \\
\text{36Ca} & \rightarrow 36\text{Ca} + 2p \\
\text{35K} & \rightarrow 34\text{K} + p \\
\text{36K} & \rightarrow 35\text{K} + p \\
\text{37K} & \rightarrow 36\text{K} + p \\
\text{38K} & \rightarrow 37\text{K} + p \\
\end{align*}
\]
### Layout

**Experimental technique and set-up**
- Mirror energy difference: motivation and results
- Double magicity of $^{36}\text{Ca}$

**Not discussed here:** Astrophysical impact *L. Lalanne et al., PRC 103 (2021)*

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### $^{36}\text{Ca}$: a new doubly magic nucleus with colossal breaking of mirror symmetry

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Only first excited state $2^+$ of $^{36}\text{Ca}$ is known

It is above $S_{2p}$ (but considered as quasi-bound as well below $B_C$)

$Z = 20$

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The ground and excited states of $^{35,36}\text{Ca}$ studied by $(p,d)$ and $(p,t)$

Transfer reactions from $^{38}\text{Ca}$ and $^{37}\text{Ca}$ radioactive beams at 50 A.MeV
Experimental set-up and technique

$^{37}\text{Ca} @ 50 \text{ MeV/A} (\text{LISE})$

- CATS
- Liquid H
- MUST2
- ZDD

Drift chamber
Ionization chamber

$^{36}\text{Ca}$

Kine. Lines
$ightarrow$

Energy Loss [MeV]

Total Energy [MeV]

Time Of Flight [a.u.]

$^{35}\text{Ar}$
$^{37}\text{Ca}$
$^{36}\text{Ca}$
$^{35}\text{K}$
$^{32}\text{S}$

Energy Loss [MeV]

Time Of Flight [a.u.]

Energy Loss [MeV]

Energy Loss [MeV]

Fit by slice of $\theta_{cm}$

$d\sigma/d\Omega$

$\sigma \sim 550 \text{ keV}$

$0^+ \rightarrow 2^+$

$L=2$

${\cal L}_p$
Some words about the Mirror Symmetry

Nuclear spectra between mirror nuclei usually very similar -> very small Mirror Energy difference (MED)
Except for unbound states e.g. $^{16}\text{F} - ^{16}\text{N}$ *I. Stefan et al. PRC 90 (2014)* where the MED is of about 650 keV.

Inversion between the ground $1/2^{-}$ and excited state $5/2^{-}$ (separated by 27 keV) of $A=73$ mirror nuclei cannot be explained *Hoff et al. Nature 580 (2020)*

*Lenzi et al. PRC 102 (2020)* calculated a 40-keV MED, explaining why these two levels are inverted. *Henderson and Stroberg PRC 102 (2020)* concur to say that this shift has 30% chance to occur.
Mirror symmetry and shape coexistence

‘Colossal’ MED (-700 keV) predicted between the $0^-_1$ and $0^+_2$ states in $^{36}$S - $^{36}$Ca, Valiente-Dobon et al., PRC 98 (2018).
Due to the very different configuration of the spherical ground state and intruder $0^+_2$ state

Search for $0^+_2$ excited states of $^{36}$Ca to see if such a ‘colossal’ MED exists!
$^{37}\text{Ca}(p,d)^{36}\text{Ca}$ reaction to probe neutron-hole states

- $E^*(^{36}\text{Ca})$ occupancy
- $J^\pi$, $L$ transfer

- $0^+$, $1^+, 2^+$ states
- $1^-$, $4^+$ states
- $2^0, 2^0$ transfer
$^{37}\text{Ca}(p,d)^{36}\text{Ca}$ reaction to probe neutron-hole states

$E^*(^{36}\text{Ca})$ occupancy

J$^\pi$

L transfer

0$^+$

2

1$^+$ - 4$^+$

1$^+$, 2$^+$

2

6

$\pi$

$\nu$

$d_{3/2}$ state

$s_{1/2}$ states

$d_{5/2}$ states

Ca, K, Ar gate

 Counts / 200 keV
$^{37}\text{Ca}(p,d)^{36}\text{Ca}$ reaction to probe neutron-hole states

- $E^*(^{36}\text{Ca})$ occupancy
- $J^\pi$ and $L$ transfer

Diagram showing the reaction process and the excitation energy distribution.
The sequence of L=2, L=0 and L=2 removal from the d_{3/2}, s_{1/2} and d_{5/2} orbitals is found with expected occupancy values $\Delta M ^{^{36}\text{Ca}} = -6480(40)\text{ keV}$ agrees with penning trap measurement of $\Delta M ^{^{36}\text{Ca}} = -6483.6(56)\text{ keV}$.
MED for the $2^+$ and $1^+$ states

$^{37}$Ca(p,d)$^{36}$Ca

$^{37}$Cl(d,$^3$He)$^{36}$S

<table>
<thead>
<tr>
<th>$C^2S$</th>
<th>$E^*$ (MeV)</th>
<th>$J^\pi$</th>
<th>$J^\pi$</th>
<th>$E^*$ (MeV)</th>
<th>$C^2S$</th>
<th>MED (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.28(7)</td>
<td>4.71(9)</td>
<td>$2^+$</td>
<td>2$^+$</td>
<td>4.577</td>
<td>0.25(5)</td>
<td>+133(90)</td>
</tr>
<tr>
<td>0.61(13)</td>
<td>4.24(4)</td>
<td>$1^+$</td>
<td>1$^+$</td>
<td>4.523</td>
<td>0.75(15)</td>
<td>-280(41)</td>
</tr>
<tr>
<td>0.66(14)</td>
<td>3.045(2)</td>
<td>$2^+$</td>
<td>2$^+$</td>
<td>2.295</td>
<td>0.86(17)</td>
<td>-245(5)</td>
</tr>
</tbody>
</table>

Compatible $C^2S$ values between mirror nuclei

Upward shift of the $(1,2)^+$ states in $^{36}$S as they feel more Coulomb repulsion than the g.s. does

The $0^+$ ground state has 2 protons in the $2s_{1/2}$ orbital with rather large radius.
The $(1,2)^+$ state has a proton $(ph)$ structure with one proton in $2s_{1/2}$ and the other in the $1d_{3/2}$ orbits (smaller $r$)
$^{38}\text{Ca}(p,t)^{36}\text{Ca}$ reaction to probe $0^+ \text{ states}$

Very large MED between the $0^+_2$ states $\rightarrow$ first excited state in $^{36}\text{Ca}$
MED for the $0^{+}_2$

Very large MED between the $0^{+}_2$ states -> first excited state in $^{36}$Ca
Closed-shell for $0^+_1$ and deformed $\pi(2p2h) \& \nu(1p1h)$ for $0^+_2$ in $^{36}$Ca
-250 ($^{36}$Ca) & +250 ($^{36}$S) = -500 keV

Colossal shift of the $0^{+}_2$ state as cumulated effects

Coulomb force does not change the structure between the mirror states but highlights their configuration
First mass measurement of $^{35}\text{Ca}$

$\Delta M(^{35}\text{Ca}) = (-4805 \pm 140)\text{keV}$

$\Rightarrow S_n(^{36}\text{Ca}) = 19.36(15)\text{MeV}$

Only one bound state in $^{35}\text{Ca}$

Gap (N=16) $\approx S_n(^{37}\text{Ca}) - S_n(^{36}\text{Ca})$

Gap (N=28) $= 4.8\text{MeV}$

N=28 and N=16 gaps have comparable sizes

$\Rightarrow$ N=16 magic number

Gap (N=34) $\approx 2.28(18)\text{MeV}$

‘Evidence for a new magic number N=34, Magic nature of $^{54}\text{Ca}'
Conclusions

$^{36}$Ca proven to be a doubly-magic nucleus: N=16 gap = 4.60(15) MeV

Its ground and excited states exhibit rather pure configurations

Its Intruder state $0^+_2$ has very different structure from the $0^+_1$ ground state

Coulomb force induces significant changes between the binding energies of states in the mirror $^{36}$Ca-$^{36}$S nuclei

About -250 keV MED for the $2^+$ and $1^+$ states.

About -500 keV for the $0^+_2$ the largest MED ever observed

The breaking of MED is evidenced for the first time in the case of shape coexistence thanks to the double-magicity of $^{36}$Ca
Backup slides
Small MED < 100 keV

- $3/2^+$
- $9/2^+$
- $1/2^+$
- $7/2^+$

$E_x$ [keV]

3000
2500
2000
1500
1000
500
0

$^{23}\text{Na}^{12}$ $^{23}\text{Mg}^{11}$

Large MED > 250 keV

- $2^+$
- $-252 \text{ keV}$
- $-294 \text{ keV}$
- $45 \text{ keV}$
- $2^+$
- $0^+$

$E_x$ [keV]

4000
3000
2000
1000
0

$^{38}\text{Ca}^{18}$ $^{38}\text{Ar}^{20}$
\begin{align*}
E^* & \quad J^\pi \\
4.71(9) & \quad 2^+ \\
4.24(4) & \quad 2^+ \\
3.045(2) & \quad 2^+ \\
\text{S}_{2p} & \quad 0^+ \\
\text{S}_p & \quad 0^+ \\
\end{align*}

\begin{align*}
E^* & \quad J^\pi \\
5.381 & \quad 2^+ \\
4.577 & \quad 2^+ \\
4.523 & \quad 1^+ \\
2.295 & \quad 2^+ \\
\text{MED (keV)} & \quad -671(90) \\
& \quad -280(41) \\
& \quad -280(41) \\
& \quad -245(5) \\
& \quad -516(130) \\
\end{align*}

\begin{align*}
0^+_{^{36}\text{Ca}} & \quad 0^+_{^{36}\text{S}}
\end{align*}
$E_x$
Gate Ca, K and Ar

Excitation Energy [MeV]

Counts / 200 keV

$E_p$
Gate K

Counts / 150 keV

$E_{p\text{cm}} + S_p$ [MeV]
First mass measurement of $^{35}\text{Ca}$

$$\Delta M = (-4805 \pm 140)\text{keV}$$

Discovery of the first $3/2^+$ excited state of $^{35}\text{Ca}$
First mass measurement of $^{35}\text{Ca}$

$\Delta M = (-4805 \pm 140)\text{keV}$

Other arguments in favor of magicity:

- Centroid of $ph$ excitation states at 3.8 MeV
- $C^2S$ close to ‘single-particle’ values

Other nuclei:

- $^{36}\text{Ca}$: a new doubly-magic nucleus
- $^{48}\text{Ca}$ and $^{54}\text{Ca}$

Steppenbeck et al., Nature (2013)
$^{37}$Ca(p,d)$^{36}$Ca reaction to probe neutron-hole states

$(1,2)^+ \text{ states in } ^{36}\text{S have more repulsive Coulomb force than the g.s. due to their proton (ph) structure from } 2s_{1/2} \text{ (large } r) \text{ to } 1d_{3/2} \text{ orbits (smaller } r)$