Spectroscopy of $^{26}\text{F}$ and $^{28}\text{Na}$ to probe proton-neutron forces close to the drip line
Spectroscopy of $^{26}$F and $^{28}$Na to probe proton-neutron forces close to the drip line

- **Motivations**
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- **Experimental study of $^{26}$F**
  $\beta$-decay, unbound by neutron emission state…

- **Experimental study of $^{28}$Na**
  probe the same interaction as in $^{26}$F in another nucleus

- **Interpretations, conclusions and perspectives**
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Stability and limits of stability

- Nuclei close to the drip-lines present a strong asymmetry between the binding energies of their protons and neutrons.

- Evolution of the nuclear interactions far from stability?

\[\begin{align*}
\pi & \quad \nu \\
\text{E} & \quad \text{E} \\
\text{Cd} & \quad \text{Cd} \\
48 & \quad 82 \\
130 & \quad 82
\end{align*}\]
Stability and limits of stability

- Nuclei close to the drip-lines present a strong asymmetry between the binding energies of their protons and neutrons.

- Evolution of the nuclear interactions far from stability?

- Light nuclei are good candidates for such studies as the drip-lines appear faster.
Probing the $\pi d_{5/2} \times \nu d_{3/2}$ interaction along the $N=17$ isotonic chain

<table>
<thead>
<tr>
<th></th>
<th>$^{26}$F</th>
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<th>$^{30}$Al</th>
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<tbody>
<tr>
<td>$S_n$ (MeV)</td>
<td>1</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>$S_p$ (MeV)</td>
<td>16</td>
<td>15</td>
<td>13</td>
</tr>
<tr>
<td>$S_p - S_n$ (MeV)</td>
<td>15</td>
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Probing the $\pi d_{5/2} \times vd_{3/2}$ interaction along the $N=17$ isotonic chain

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$|5/2 - 3/2| = 1 \leq J \leq 4 = |5/2 + 3/2|$
Probing the $\pi d_{5/2} \times v d_{3/2}$ interaction along the $N=17$ isotonic chain

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**$|5/2 - 3/2| = 1 \leq J \leq 4 = |5/2 + 3/2|$**

- $1^+$: ✓  ✓  ✓  ✓
- $2^+$: ✓  ✓  ✓  ✓
- $3^+$: ?  ✗  ✓  ✓
- $4^+$: ✗  ✗  ✓  ✓


$^{26}\text{F}~1^+$: Jurado et al., PLB 649 (2007) 43-48

$^{26}\text{F}~2^+$: Stanoiu et al., PRC 85 (2012) 017303

$^{26}\text{F}~3^+$: Frank et al., PRC 84 (2011) 037302
Spectroscopy of $^{26}\text{F}$ and $^{28}\text{Na}$ to probe proton-neutron forces close to the drip line

- **Motivations**
  Nuclear interactions close to the drip-line

- **Experimental study of $^{26}\text{F}$**
  \[\beta\text{-decay, unbound by neutron emission state}…\]

- **Experimental study of $^{28}\text{Na}$**
  probe the same interaction than in $^{26}\text{F}$ in another nucleus

- **Interpretations, conclusions and perspectives**
Study of the unbound by neutron emission states of $^{26}$F at GSI (2010)
Study of the unbound by neutron emission states in $^{26}$F
Study of the unbound by neutron emission states in $^{26}F$

<table>
<thead>
<tr>
<th>$E_{\text{res}}$ (MeV)</th>
<th>0.35 (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{\text{exp}}$</td>
<td>0.57 (48)</td>
</tr>
<tr>
<td>$\Gamma_{\text{SP}}$(l=0) (MeV)</td>
<td>3.38</td>
</tr>
<tr>
<td>$\Gamma_{\text{SP}}$(l=2) (MeV)</td>
<td>0.07</td>
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Study of the unbound by neutron emission states in $^{26}\text{F}$

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<tbody>
<tr>
<td>$1^+$</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>$2^+$</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>$3^+$</td>
<td>✔</td>
<td>✗</td>
<td>✔</td>
</tr>
<tr>
<td>$4^+$</td>
<td>✗</td>
<td>✗</td>
<td>✔</td>
</tr>
</tbody>
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$^{40}\text{Ar}$ beam $\rightarrow$ $^{27}\text{Ne}$ FRS @GSI

$^{27}\text{Ne}$ $\rightarrow t, x, y, \Delta E$

$^{26}\text{F}$ target

$1n$ $\rightarrow 25\text{F}$

Dipole magnet ALADIN

LAND $t, x, y, z, \Delta E$

Graph showing counts per 200 keV for $^{27}\text{Ne}(-1p)^{26}\text{F} \rightarrow 25\text{F} + n$

Legend:
- Plastic Scintillator
- Position Sensitive Pin Diode
- Fiber Detector
- DSSSD

$E_r = 350(50) \text{ keV}$

$E_r = 1.75(15) \text{ MeV}$
Search for an isomeric $4^+$ state in $^{26}$F at GANIL (2011)
Determination of the $4^+$ isomeric state in $^{26}$F at GANIL (2011)

- 26F implantation
- $\gamma$ [0ms – 2ms]
- $\gamma$ [20ms – 22ms]

Energy (keV) vs Counts/keV graph with peaks at:
- 643.4 keV, gate 643.4 keV
- 2.21 (2) ms

Diagram showing detectors and energy levels:
- $E_1$: 500µm
- $E_2$: 500µm
- Al: 1500µm
- DSSSD: 1000µm
- veto: 5000µm
- $E_3$: 500µm
- Clovers Ge
Determination of the $4^+$ isomeric state in $^{26}$F at GANIL (2011)

Counts/keV

Energy (keV)

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<tbody>
<tr>
<td>$1^+$</td>
<td>✓</td>
<td>*</td>
<td>✓</td>
</tr>
<tr>
<td>$2^+$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$3^+$</td>
<td>✓</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>$4^+$</td>
<td>✓</td>
<td>X</td>
<td>✓</td>
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$\beta$-decay of the ground and isomeric states of $^{26}$F

$\beta$-decay selection rules: $\Delta J = 0, \pm 1$

$^{26}$F

$^{26}$Ne

$2^+ \rightarrow 1^+$

$4^+ \rightarrow 3^+, 4^+, 5^+$

$643.4$ keV

$660$ keV

$2.21$ ms

$7.7$ ms

$3^+$

$2^\pm$ Unbound
\( \beta \)-decay of the ground and isomeric states of \(^{26}\text{F}\)

- \( \beta \)-decay selection rules: \( \Delta J = 0, \pm 1 \)

\( ^{26}\text{F} \):
- \( 3^+ \)
- \( 2^\pm \)
- Unbound
- \( 1^+ \)
- \( 2^+ \)
- \( 4^+ \)
- \( (3^+, 4^+) \)

\( ^{26}\text{Ne} \):
- \( 0^+ \)
- \( 2^+ \)
- \( 1673 \) keV
- \( 2018 \) keV

\( \gamma \) + \( \beta \) [0 ms – 7 ms]
- \( 1499 \) keV
- \( 1673 \) keV
- \( 1797 \) keV

\( \gamma \) + \( \beta \) [35 ms – 210 ms]
- \( 1842 \) keV

- 2018 keV & 1673 keV: Reed et al., PRC 60 (1999)
- \( 2^+ \): Gibelin et al., PRC 75 (2007)
- 1499 keV: Belleguic et al., PRC 72 (2005)
\(\beta\)-decay of the ground and isomeric states of \(^{26}\text{F}\)

\(\beta\)-decay selection rules: \(\Delta J = 0, \pm 1\)

\(26\text{F}\) → \((3^+, 4^+)\) → \(\text{26Ne}\)

Gate 1499 2.4 (2) ms
Gate 1842 2.1 (1) ms
Gate 1797 7.8 (5) ms
Gate 1673 7.7 (2) ms

Energy levels:
- \(2^+\) (660 keV)
- \(4^+\) (643.4 keV)
- \(0^+\) (1842 keV)
- \(3^+\) (1499 keV)
- \(2^+\) (1673 keV)
- \(1^+\) (2018 keV)
- Unbound (2.21 ms)

Times:
- \(2^+\): 7.7 ms
- \(4^+\): 643.4 ms
- \(3^+\): 1499 ms
- \(1^+\): 2018 ms
- Unbound: 2.21 ms
$\beta$-decay of the ground and isomeric states of $^{26}$F

$\beta$-decay selection rules: $\Delta J = 0, \pm 1$

$^{26}$F

$\beta$ decay of the ground and isomeric states

$R_{4+} = 42 \ (8)\%$
$\beta$-decay of the ground and isomeric states of $^{26}$F

Mass measurement from 2007

\[ \approx 0.6 \, \text{BE}(1^+) + 0.4 \, \text{BE}(4^+) \]

Ground state of $^{26}$F more bound by $\sim 270 \, (50) \, \text{keV}$

$R_{4^+} = 42 \, (8)\%$
Spectroscopy of $^{26}\text{F}$ and $^{28}\text{Na}$ to probe proton-neutron forces close to the drip line

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  $\beta$-decay, unbound by neutron emission state…

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  probe the same interaction than in $^{26}\text{F}$ in another nucleus

- Interpretations, conclusions and perspectives
$\beta$-decay of $^{28}$Ne to $^{28}$Na

$\beta$-decay of $^{28}$Ne @ GANIL

$Q_\beta = 12.23 (15) \text{ MeV}$

$\tau_{1/2} = 18.6 (2) \text{ ms}$

A. Lepailleur, K. Wimmer et al., PRC PRC 92 (2015) 05309
In-beam γ–ray spectroscopy of $^{28}$Na

A. Lepailleur, K. Wimmer et al., PRC 92 (2015) 05309
In-beam γ–ray spectroscopy of $^{28}\text{Na}$

In-beam γ–ray spectroscopy of $^{28}\text{Na}$ @ NSCL

$Q_\beta = 12.23 (15)$ MeV
$t_{1/2} = 18.6 (2)$ ms

$^{26}\text{F}$ $^{28}\text{Na}$ $^{30}\text{Al}$

$1^+$ ✓ ✓ ✓

$2^+$ ✓ ✓ ✓

$3^+$ ✓ ✓ ✓

$4^+$ ✓ ✓ ✓

A. Lepailleur, K. Wimmer et al., PRC PRC 92 (2015) 05309
Spectroscopy of $^{26}$F and $^{28}$Na to probe proton-neutron forces close to the drip line

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Evolution of the nuclear interaction for the odd-odd N=17 isotones?

- Systematic study of the odd-odd N = 17 isotones while going from the stability toward the neutron drip-line.
  → Weakening of the residual interaction in $^{26}\text{F}$.
Evolution of the nuclear interaction for the odd-odd N=17 isotones?

- Systematic study of the odd-odd N = 17 isotones while going from the stability toward the neutron drip-line.
  - Weakening of the residual interaction in $^{26}$F.

![Graph showing energy levels](image)
Evolution of the nuclear interaction for the odd-odd $N=17$ isotones?

- Systematic study of the odd-odd $N = 17$ isotones while going from the stability toward the neutron drip-line.
  - Weakening of the residual interaction in $^{26}F$.
  - Effect of the nucleon’s binding energies?

![Diagram](image)
GANIL / LPC
M. Vandebrouck, O. Sorlin, M. Marqués, F. de Oliveira Santos,
J. Gibelin, L. Caceres, J.-C. Thomas, A. Mutschler and the LISE collaboration

GSI
T. Aumann, C. Caesar, M. Holl. V. Panin, F. Wamers and the
LAND collaboration

NSCL / MSU
K. Wimmer, A. Brown, V. Bader, C. Bancroft and the GRETINA collaboration
A candidate for the unbound $3^+$ of $^{26}$F at NSCL

- $^{26}$F produced by charge exchange at NSCL.  
  $^9$Be($^{26}$Ne, $^{26}$F* → $^{25}$F+n)

- $^{25}$F detected and identified after passing through the « large-gap Sweeper Magnet »

- Neutron detected with MoNa (Modular Neutron Array)

$^{26}$Ne → $^{26}$F* → $^{25}$F+n

$E_{res} = 0.271 (32)$ MeV

Franck et al., PRC 84 (2011) 037302
Study of the unbound by neutron emission states of $^{26}$F at GSI (2010)

$^{40}$Ar beam \( // \) \( ^{27}\text{Ne} \) \( t \) \( FRS \) \( @GSI \)

$^{26}$F

NaI sphere $\theta, \phi, \Delta E$

Dipole magnet ALADIN

$\Delta E$

LAND $t,x,y,z,\Delta E$

1n

$^{25}$F

162 NaI crystals
Solid angle covered: $4\pi$

480 vertical fibers
50x50 cm$^2$
Resolution: 1mm

4 DSSSD to track:
incident ions before the target
fragments after the target

Plastic scintillators:
14 horizontal
18 vertical

- 10 planes
- 1 plan = 20 paddles
- 1 paddle (2x2 m$^2$) = 10 plastic scintillator layers
+ 11 iron layers
Etude des états non liés par émission neutron dans le $^{26}\text{F}$

$^{40}\text{Ar}$ beam \(\rightarrow\) $^{27}\text{Ne}$

NaI sphere $\theta, \phi, \Delta E$

Dipole magnet ALADIN

LAND $t, x, y, z, \Delta E$

FRS @GSI

$^{27}\text{Ne} \rightarrow^{1n}$

$^{25}\text{F}$

$t, x, y, \Delta E$

TFW

-1p

-1n

$\pi^-$

$\nu$

$\pi$

$26\text{F}$

$\nu$

$\pi$

$25\text{F}$

$\nu$

$J^\pi = 1^+, 2^+, 3^+, 4^+$

$J^\pi = 5/2^+$

$\pi^-$

$\nu$

$\pi^-$

$\nu$
Study of the unbound by neutron emission states in $^{26}$F

Frank et al., PRC PRC 84 (2011) 037302

This work

$^{26}$Ne $\rightarrow$ $^{26}$F$^*$ $\rightarrow$ $^{25}$F+n

$E_{res} = 0.271 (32) \text{ MeV}$

$^{27}$Ne(-1p)$^{26}$F $\rightarrow$ $^{25}$F+n

$E_r = 350(50) \text{ keV}$

$E_r = 1.75(15) \text{ MeV}$
Search for an isomeric $4^+$ state in $^{26}\text{F}$ at GANIL (2011)

$^{26}\text{F}$: $10.4/s$

$^{26}\text{F}$: $5.5/s$

$^{24}\text{O}$: $0.058/s$

$^{26}\text{F}$

$E1$: $500\mu\text{m}$

$E2$: $500\mu\text{m}$

$\text{Al}$: $1500\mu\text{m}$

$\text{DSSSD}$: $1000\mu\text{m}$

$veto$: $5000\mu\text{m}$

$E3$: $500\mu\text{m}$

Clovers

Ge

$^{28}\text{Ne}$

$^{30}\text{Na}$

$^{29}\text{Na}$

$^{26}\text{F}$

$^{28}\text{Ne}$: $10.4/s$

$^{26}\text{F}$: $5.5/s$

$^{24}\text{O}$: $0.058/s$
$\beta$-decay of the ground and isomeric states of $^{26}$F

Implantation of an ion

Ion-$\beta$ correlation area

Implantation pixel
- Determination of the $4^+$ isomeric state and isomeric ratio (~40%).
- Complete spectroscopy of $^{26}$Ne (two new states, tentative spin assignment $J = 0^+_1$ et $4^+_2$).
- Observation of $^{25}$Ne through the $\beta$-n branch of the $\beta$–decay of $^{26}$F.

*Lepailleur et al., PRL 110 (2013) 082502*
- $\beta$-decay of $^{28}\text{Ne} + \gamma$-decay on flight of $^{28}\text{Na} \Rightarrow J = 3, 4$ previously missing in $^{28}\text{Na}$.

- Determination of all the states $J = 1-4$ arising from the $\pi d_{5/2} \times nd_{3/2}$ coupling.
Conclusions and perspectives

- All the $J = 1-4$ states arising from the $\pi d_{5/2} x \nu d_{3/2}$ coupling are now known for $N = 17$
  - $\beta$-decay of $^{28}\text{Ne} + \gamma$-decay in-flight of $^{28}\text{Na} \Rightarrow 3^+ \text{ et } 4^+ \text{ du } ^{28}\text{Na}$
    Evidences of low lying negative parity states found
  - Study of the unbound by neutron emission states of $^{26}\text{F} \Rightarrow 3^+ \text{ du } ^{26}\text{F}$

To go further

- $\gamma$ : excitation energy
- $p$ : k-o orbital energy
- momentum distributions of the fragments: $l$ of the k-o orbital

- $\beta$-decay of $^{26}\text{F} \Rightarrow 4^+$ state of $^{26}\text{F}$ + isomeric ration
  Required: precise determination of the $^{26}\text{F}$ mass in order to
  → confirm the applied adjustment regarding the mass
  → reduce the uncertainties

- Proton-neutron binding energy asymmetry
  - Real effect or USDA calculation artifacts?
    → « Current » interaction
Conclusions and perspectives

- All the J = 1-4 states arising from the $\pi d_{5/2} \times \nu d_{3/2}$ coupling are now known for N = 17
  - $\beta$-decay of $^{28}$Ne + $\gamma$-decay in-flight of $^{28}$Na => 3$^+$ et 4$^+$ du $^{28}$Na
    Evidences of low lying negative parity states found
  - Study of the unbound by neutron emission states of $^{26}$F => 3$^+$ du $^{26}$F
    To go further
    - $\gamma$ : excitation energy
    - $p$ : k-o orbital energy
    - momentum distributions of the fragments: $l$ of the k-o orbital

- $\beta$-decay of $^{26}$F => 4$^+$ state of $^{26}$F + isomeric ration
  Required: precise determination of the $^{26}$F mass in order to
  - confirm the applied adjustment regarding the mass
  - reduce the uncertainties

- Proton-neutron binding energy assymmetry
  - Real effect or USDA calculation artifacts?
    - « Current » interaction
    - Interaction readjusted on $^{26}$F
Conclusions et perspectives

- All the $J = 1-4$ states arising from the $\pi d_{5/2} \times \nu d_{3/2}$ coupling are now known for $N = 17$
  - $\beta$-decay of $^{28}\text{Ne}$ + $\gamma$-decay in-flight of $^{28}\text{Na} \rightarrow 3^+$ et $4^+$ du $^{28}\text{Na}$
    Evidences of low lying negative parity states found
  - Study of the unbound by neutron emission states of $^{26}\text{F} \rightarrow 3^+$ du $^{26}\text{F}$
    To go further
    - $\gamma$ : excitation energy
    - $p$ : $k_o$ orbital energy
    - momentum distributions of the fragments: $l$ of the $k_o$ orbital

- $\beta$-decay of $^{26}\text{F} \rightarrow 4^+$ state of $^{26}\text{F}$ + isomeric ration
  Required: precise determination of the $^{26}\text{F}$ mass in order to
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  - Real effect or USDA calculation artifacts?
    - « Current » interaction
    - Interaction readjusted on $^{26}\text{F}$
    - Interaction readjusted on $^{30}\text{Al}$