Neutron $sd$-shell excitations in exotic nuclei near $N=8$


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Evolution of $1s_{1/2} - 0d_{5/2}$ splitting outside $N=8$

Gross behavior from p-n tensor attraction/repulsion

- $^{17}\text{O}$: $\pi(p_{1/2})^2$, $S_n=4.144$
- $^{16}\text{N}$: $\pi(p_{1/2})$, $S_n=2.49$
- $^{15}\text{C}$: $\pi(p_{3/2})^4$, $S_n=1.22$
- $^{14}\text{B}$: $\pi(p_{3/2})^3$, $S_n=0.97$
Neutron configurations around N=8

N=8 (13B)
Positive-parity states are $v(p_{1/2})^{-1}(sd) \otimes \pi(p_{3/2})^{-1}$

$^{12}$B(d,p)$^{13}$B
$^{12}$B from $^{11}$B(d,p)
At 6 MeV/u

N=9 (14B)
Negative-parity states are $v(sd) \otimes \pi(p_{3/2})^{-1}$

$^{13}$B(d,p)$^{14}$B
$^{13}$B from $^{14}$C(9Be,$^{10}$B)
At 15.7 MeV/u

N=10 (16C)
Positive-parity states are $v(sd)^2 \otimes ^{14}$C

$^{15}$C(d,p)$^{16}$C
$^{15}$C from $^{14}$C(d,p)
At 8.5 MeV/u
The HELIOS approach to inverse kinematics

We measure: $E_{lab}, z, TOF$

We deduce: $E_{CM}, \theta_{CM}$

We deduce:

1. $E_{lab} = E_{CM} - A + Bz$
2. $\Delta E_{lab} = \Delta E_{CM}$

For a given state

For two states at fixed $z$
HELICAL ORBIT SPECTROMETER - HELIOS

$B_{\text{MAX}} = 2.85\ T$

2.35 m

0.9 m

BEAM

X-Y-\(\theta\) POSITIONING STAGE

SILICON ARRAY

TARGET

LASER RANGEFINDER


J. C. Lighthall et al, NIMPRA 622, 97 (2010)
Producing secondary beams: “In-flight” production at ANL*

Gas cell: $D_2$
1.4 Atm.

Primary $^{11}$B, $^{14}$C beam
1 X $10^{11}$ particles/sec

Focusing solenoid

Re/De-bunching resonator

Magnetic separator

Secondary beam to experiment

$^{12}$B intensity ~ $6 \times 10^5$ /sec at 6.25 MeV/u
$^{15}$C intensity ~ $1.5 \times 10^6$ /sec at 8.2 MeV/u

Producing secondary beams: “In-flight” production at ANL*

- Be foil 15 mg/cm²
- Primary ¹⁴C beam 1 x 10¹¹ particles/sec
- Focusing solenoid
- Re/De-bunching resonator
- Magnetic separator
- Secondary beam to experiment

¹³B intensity ~ 4 x 10⁴ /sec at 15.7 MeV/u

Physics of $^{13}$B

Lowest $l = 0, 2$

$\nu(p)^{-1}(sd)^{1}$ states in some $N=8$ nuclei

Study with $^{12}$B($d,p$)$^{13}$B

Increasing $N/Z$
First HELIOS RIB results with $^{12}\text{B}(d,p)^{13}\text{B}$

H. Y. Lee et al., PRC 81, 015802 (2010)

B. B. Back et al., PRL 104, 132501 (2010)
$^{11,12}\text{B}(d,p)^{12,13}\text{B}$ angular distributions

B. B. Back et al., PRL 104, 132501 (2010)
Theory versus experiment for $^{13}$B

Blue: L=0
Red: L=2

$5/2^+$ L=2 is reduced, no nearby $3/2^+$ is observed

B. B. Back et al., PRL 104, 132501 (2010)
Exotic behavior in $^{16}$C?

Valence neutrons

Core $^{16}$C

Study with $^{15}$C(d,p)$^{16}$C

No hindrance, and no exotic behavior.
$^{15}\text{C}(d,p)^{16}\text{C}$ with HELIOS

Proton energy-position correlation

$(d,p)$ samples the $\gamma(1s_{1/2})$ content of the wave functions for positive-parity states

$^{16}\text{C}$ Excitation-energy spectrum

PRL 105, 132501 (2010)
$^{15}\text{C}(d,p)^{16}\text{C}$ angular distributions

Curves are DWBA calculations with various optical-model potentials.

Spectroscopic factors obtained from the average over four sets of OMP.

Relative uncertainties in SF dominated by OMP variations

Absolute uncertainty (~30%) from beam-integration uncertainty

PRL 105, 132501 (2010)
$^{15}\text{C}(d,p)^{16}\text{C}$

Spectroscopic factors

Excitation energies and relative spectroscopic factors from the shell model

Blue: $L=0$
Red: $L=2$

Agreement for SF is excellent!
No need for exotica

PRL 105, 132501 (2010)
**Preliminary** excitation-energy spectrum

\[ ^{13}\text{B}(d,p)^{14}\text{B} \]

- \( S_n = 0.969 \)
- \( 3^- (1.38) \Gamma \leq 150 \text{ keV} \)
- \( 4^- (2.08) \Gamma \sim 200 \text{ keV} \)
- Broad \( l=0 \) and 2 states expected with \( J^n=(0,1,2,3)^- \)

Red – \(^{14}\text{B}\)

Blue – \(^{13}\text{B}\)
Preliminary

$^{13}$B($d,p)^{14}$B angular distributions

Blue: $L=0$
Red: $L=2$
Violet: $L=0 + L=2$

$2^-(0.00)$: $S_0=0.71$  $S_2=0.17$
$1^-(0.65)$: $S_0=0.96$  $S_2=0.06$
$3^-(1.38)$: $S_2=1.00$ (fixed)
$4^-(2.08)$: $S_2=1.00$

OMPs fit 30 MeV $d+^{12}$C, $p+^{12,13}$C elastic scattering
$^{13}\text{B}(d,p)^{14}\text{B}$

Spectroscopic factors

Excitation energies and relative spectroscopic factors from the shell model

Blue: $L=0, 1s_{1/2}$
Red: $L=2, 0d_{5/2}$

Reasonable agreement
But caveaet emptor!
Summary

• HELIOS provides a new approach to studying reactions in inverse kinematics
• Alleviates problems with light particle identification and gives improved excitation-energy resolution and straightforward determination of CM quantities
• Around N=8, \((d,p)\) nicely probes the evolution of the \(1s_{1/2}-0d_{5/2}\) orbitals and the p-n/n-n residual interactions
• \(^{14}\text{B}(1^-)\) \((S_n = .319\ \text{MeV})\) is mostly s-wave, so is as good or better a halo state than \(^{11}\text{Li}_{\text{g.s.}}\) or \(^{11}\text{Be}_{\text{g.s.}}\).
• Structure aspects seem reasonably well in hand, BUT: we still worry about DWBA and weakly (or un-) bound s states.
Acknowledgements

The HELIOS Collaboration

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Advantages to the HELIOS approach for \((d,p)\)
Empirical $v(sd')^2$ residual interaction for $O^+$

$$|0_i^+\rangle = \alpha |(1s_{1/2})^2\rangle + \beta |(0d_{5/2})^2\rangle$$

$$|0_2^+\rangle = -\beta |(1s_{1/2})^2\rangle + \alpha |(0d_{5/2})^2\rangle$$

$$\alpha = \sqrt{S(0^+_i)\times[J_f]/[J_i]} = 0.55$$

$$\beta = \sqrt{S(0^+_2)\times[J_f]/[J_i]} = 0.84$$

$$\begin{pmatrix}
E^0_{1/2} + \delta_{1/2;1/2} & \delta_{1/2;3/2} \\
\delta_{1/2;5/2} & E^0_{5/2} + \delta_{5/2;3/2}
\end{pmatrix}
\begin{pmatrix}
\alpha \\
\beta
\end{pmatrix} = E_x
\begin{pmatrix}
\alpha \\
\beta
\end{pmatrix}$$

Single-particle energies $E^0$ from $^{15}$C.

| $<j_1 j_2 |\nu |j'_1 j'_2>$ | $(1/2 \ 1/2, 1/2 \ 1/2)$ | $(5/2 \ 5/2, 5/2 \ 5/2)$ | $(1/2 \ 1/2, 5/2 \ 5/2)$ |
|----------------|------------------|------------------|------------------|
| Exp           | -0.92(28)        | -3.60(28)        | -1.39(12)        |
| LSF           | -1.54            | -2.78            | -1.72            |
| WBP           | -2.12            | -2.82            | -1.32            |

PRL 105, 132501 (2010)
$^{13}\text{B}$ and friends... from $^{14}\text{C} + ^{9}\text{Be}$
\(^{13}\text{B}\) beam quality

From \(d(^{14}\text{C}, ^{13}\text{B})^{3}\text{He}\)

\(2 \times 10^4\) pps

From \(^{9}\text{Be}(^{14}\text{C}, ^{13}\text{B})^{10}\text{B}\)

\(4 \times 10^4\) pps
Recoil particle identification

\[ E(\text{Residual}) \text{ (channels)} \]

\[ \Delta E \text{ (channels)} \]

- $^{13}\text{B}$
- $^{14}\text{B}$
- $^{10}\text{Be}$
- $^{11}\text{Be}$
1s\textsubscript{1/2} and 0d\textsubscript{5/2} neutron form factors

Woods-Saxon potential, \( r_0 = 1.35 \), \( a = 0.6 \), \( V_0 \) adjusted for BE

s-wave tail may cause problems for DWBA!

But: Don’t forget history- $^{10}\text{Be}(d,p)^{11}\text{Be}$

L=0

$S_n = 0.503 \text{ MeV}$
No problem?!

L=1

$S_n = 0.183 \text{ MeV}$
No problem?!

Zwieglinski, Benenson, Robertson, Coker – NP A315, 124 (1979)
But: Don’t forget history-

\[ S_n = 0.503 \text{ MeV} \]

No problem?!

\[ S_n = 0.183 \text{ MeV} \]

No problem?!
$(d,p)$ momentum mismatch at $0^\circ$

$(A_{tgt}=13)$

$\Delta q(1\hbar) \sim 65$ MeV/c
(d, p) momentum mismatch at 0°

\( A_{\text{tgt}} = 132 \)

\[ \Delta q(1\hbar) \sim 30 \text{ MeV/c} \]
Single-particle widths for $^{13}$B+n
Spectrometer completed in August 2008
$^{28}\text{Si}(d,p)^{29}\text{Si}$: Seems to work!

J. C. Lighthall et al, NIMPRA 622, 97 (2010)
$^{28}\text{Si}(d,p)^{29}\text{Si}$ Excitation-energy spectrum

Typical resolution $\sim 120$ keV FWHM
Best resolution $\sim 80$ keV FWHM

J. C. Lighthall et al, NIMPRA 622, 97 (2010)
Towards $^{132}\text{Sn}(d,p)^{133}\text{Sn}$ with CARIBU

B. P. Kay et al, PRC in press
$^{19}\text{O}(d,p)^{20}\text{O}$: Further into the $sd$ shell

C. R. Hoffman, Submitted to PRC
ν(sd) + ν(d_{5/2})^3_{5/2+} states in $^{20}$O
Proton beam impurity: p-d elastics
E vs Z, data and Monte-Carlo

Red: n bound, p$^{14}$B
Green: n-unbound p$^{13}$B

$^{13}$B(d,p)$^{14}$B in HELIOS
Ab initio nuclear structure simulations: The speculative $^{14}$F nucleus

P. Maris, 1 A. M. Shirokov, 1,2,* and J. P. Vary 1

FIG. 3. (Color online) Negative-parity $^{14}$B spectrum obtained with JISP16 at fixed $\hbar \Omega = 25$ MeV in successive basis spaces and extrapolated to infinite basis space using extrapolation B. Experimental (exp.) data are taken from Ref. [13].
Simple considerations for $^{12}\text{B}(d,p)^{13}\text{B}$

+ parity states are p-h excitations out of the p shell
Simple considerations for $^{15}$C($d,p)^{16}$C

$(d,p)$ samples $\nu(1s_{1/2})$ content of states in $^{16}$C
Simple considerations for $^{13}\text{B}(d,p)^{14}\text{B}$

$(d,p)$ populates single-neutron states in $^{14}\text{B}$
HELIcal Orbit Spectrometer - HELIOS

$B_{\text{MAX}} = 2.85 \text{T}$

J. C. Lighthall et al, NIMPRA 622, 97 (2010)
This you have seen...
But maybe not this...
Lowest $l=0,2$ $\nu(sd)^1$ states in some $N=7$ nuclei

Physics of $^{13}$B

Increasing N/Z

Descent of the $sd$ shell
Energy vs Position Boron gated
$^{13}\text{B}(d,p)^{14}\text{B}$

Spectroscopic factors

Excitation energies and relative spectroscopic factors from the shell model

Blue: $L=0, 1s_{1/2}$
Red: $L=2, 0d_{5/2}$

2$^-$ mixed $L=0+2$,
1$^-$ pure $L=0$

Reasonable agreement
But caveat emptor!
$^{13}\text{B}(d,p)^{14}\text{B}$

Spectroscopic factors

Excitation energies and relative spectroscopic factors from the shell model

Blue: $L=0, 1s_{1/2}$
Red: $L=2, 0d_{5/2}$

Reasonable agreement
But *caveat emptor*!
What's in your beam?

$^{15}\text{N} \sim 9 \times 10^3 / \text{s}$

$^{15}\text{C} \sim 1.5 \times 10^6 / \text{s}$