Breakup of $^9C$: what can we learn?

Inclusive and exclusive breakup of $^9C$ in nuclear and Coulomb fields for $S_{18} - ^8B(p, \gamma)^9C$

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Three-body systems in reactions with rare isotopes
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Motivation

• $S_{18} = ?$ Astrophysical S-factor for $^8B(p,\gamma)^9C$

• 3-body: $^9C = ^7Be+p+p$ ?
  • Z/N=2
  • $S_p = 1.299$ MeV
  • $S_{2p} = 1.436$ MeV

• BTW: for $^8B$
  • $S_p = 0.137$ MeV
  • $<r^2>^{1/2} = 2.39(4)$ fm
  • $<r^2_p>^{1/2} = 4.20(22)$ fm (LT ea, PRC 63, 054310 (2001))

• Breakup cross sections @285 MeV/nucleon (B. Blank ea NP A624, 242 (1997); targets C, Al, Sn, Pb; Enders ea PRC 67 (2003) on C @78 MeV/nucleon
  – $\sigma_{-1p} = 54(4)$ mb
  – $\sigma_{-2p} = 98(7)$ mb

• Reaction mechanism ?!
The reaction is important in the hot pp chains, in explosive H burning, at large temperatures, for creating alternative paths across the A=8 mass gap (see e.g. M. Wiescher et al., Ap. J. 343 (1989)352.)

$^{9}\text{C} \rightarrow ^{8}\text{B} + p$ breakup for $^{8}\text{B}(p,\gamma)^{9}\text{C}$

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$^{9}\text{C} \rightarrow ^{8}\text{B} + p$ breakup for $^{8}\text{B}(p,\gamma)^{9}\text{C}$

Use breakup of $^{9}\text{C} \rightarrow ^{8}\text{B} + p$ at intermediate energies to obtain $^{8}\text{B}(p,\gamma)^{9}\text{C}$ at astrophysical energies.

Existing data from:
B. Blank et al., Nucl Phys A624 (1997) 242
$^{9}\text{C} @ 285 \text{ MeV/u}$ on C, Al, Sn and Pb targets
Trache et al. ANC from breakup, 2002
Beaumel (ANC from (d,n) reaction)
T. Motobayashi et al. – Coulomb dissociation

$^{8}\text{B}(p,\gamma)^{9}\text{C}$

Astrophysical S-factor

Figure. The results of similar calculations for $^{9}\text{C}$.

Average: $C_{tot} = 1.22 \pm 0.13 \text{ fm}^{-1}$

$S_{18}(E) = 47.3 - 15.1E + 7.34E^2 \text{ eV b}$ ($E$ in MeV)

Trache et al. (ANC)
Beaumel (ANC)

T Motobayashi
$^8\text{Be}(p,\gamma)^9\text{C}$ – astrophysical interest

H-burning in *hot pp chain* (*pp IV* and *rap I*)
at high $T$, $\rho$ in metal-poor environment

$T_9 \sim 0.1-1.0$, $\rho \sim 10^5 \text{ g/cm}^2$

super-massive stars in early Universe?
$^7\text{Li}$ synthesis in novae?

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$E_{\text{Gamow}} \sim 75-350 \text{ keV at } T = 0.1-1.0 \times 10^9 \text{ K}$

$\rightarrow$ capture through continuum dominates
Indirect measurements for nuclear astrophysics

- One-proton-removal reactions at intermediate energies is a tool to study the single particle structure of unstable nuclei and use it in Nuclear Astrophysics:
  - Use inclusive measurements \( \text{X} \rightarrow \text{Y} + \text{p} \) to determine ANC and from there \( Y(p, \gamma)X \) radiative capture rates for nuclear astrophysics \( S_{1Y} \): \( [S_{18}(0) \text{ for } ^9\text{C} \rightarrow ^8\text{B} + \text{p}] \)
  - Use also Coulomb dissociation to determine \( S_{18}(E) \) and compare
  - Use exclusive measurements to check for reaction mechanism for -1p and -2p
  - Part of p-HI series of measurements

- Obtain data to check theoretical models:
  - Momentum distributions
  - Angular distributions
  - \( p-p \) correlations for -2p reaction channel

- **Inclusive and exclusive Nuclear and Coulomb breakup @ 100 and 300 MeV/u**
  - \(^9\text{C} \) one- and two-proton removal on light target: C (or Be)
    - Measure at 100 & 300 MeV/u on C target to obtain ANC (inclusive)
    - Measure nuclear and Coulomb dissociation at 100 & 300 MeV/u (exclusive) to obtain direct and resonant \( S_{18} \)-factor (C and Pb targets) for \( ^{8}\text{B}(p, \gamma)^{9}\text{C} \)
    - Measure momentum distributions for one- and two-proton removal to study the reaction mechanism (exclusive data)
    - Start setup for group of p-HI experiments (smaller dynamic range for signals, easier PID)
Breakup

Transfer or breakup vs proton capt in $^8$R

Model-independent shape w. ANC (Whittaker function)
Example: Summary of the ANC extracted from $^8\text{B} \rightarrow ^7\text{Be}+\text{p}$ with different interactions

Data from:

All available breakup cross sections on targets from C to Pb and energies 27-1000 MeV/u give consistent ANC values!

Summary of results:
LT ea, PRL 87, 2001

$^7\text{Be}(p,\gamma)^8\text{B}$ (solar neutrinos probl.):
p-transfer: $S_{17}(0)=18.2\pm1.7$ eVb
Breakup: $S_{17}(0)=18.7\pm1.9$ eVb
Direct meas: $S_{17}(0)=20.8\pm1.4$ eVb
**E491 exp. @ GANIL**

**Experimental details**

- **32S primary beam**  
  95 MeV/u, ~ 400 W

- **Cocktail beam**  
  (mid-target energies):  
  - $^{24}$Si 53 MeV/u  
  - $^{23}$Al 50 MeV/u  
  - $^{22}$Mg 47 MeV/u  
  - $^{21}$Na 43 MeV/u  
  - $^{20}$Ne 39 MeV/u

- **Gamma-ray detectors:**  
  - 8 EXOGAM clovers 4% effic.  
  - 12 NaI crystals 6% effic.

- **High-resolution spectrometer**  
  - large angular acceptances:  
    4° (horiz. & vertic. planes)  
  - broad momentum acceptance:  
    $\Delta p/p = 7%$

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A. Banu et al., NIC10 2008 & PRC 84, 015803 (2011)
$^{23}\text{Al} \rightarrow ^{22}\text{Mg} + p$

Proton removal
Results from $^{23}$Al breakup

FIG. 1. (Color online) Experimental inclusive momentum distribution of $^{22}$Mg cores (points), in the center-of-mass.

$\Gamma(^{23}\text{Al}) \sim 200 \text{ MeV/ c and } J^\pi = 5/2^+$

If $b^2$ is s.p. ANC:

$C^2 = b^2 \sigma_{\text{exp}} / \sigma_{\text{calc}}$

$= 3.90 \pm 0.44 \times 10^3 \text{ fm}^{-1}$
Ex of complementarities: $^{23}\text{Al}$ Coulomb and nuclear dissociation

$N_A \langle \sigma \nu \rangle = 0.12 T_9^{-3/2} \exp \left(-\frac{4.47}{T_9}\right)$.  

$\Gamma_{\gamma} = 7.2 \pm 1.4 \times 10^{-7}$ eV, which was obtained from the Coulomb dissociation of $^{23}\text{Al}$ at 50 MeV/u [46], is adopted here to evaluate the resonant reaction rate, which is given by.

The reaction is important in the hot pp chains, in explosive H burning, at large temperatures, for creating alternative paths across the A=8 mass gap (see e.g. M. Wiescher et al., Ap. J. 343 (1989)352.)

\[ ^9\text{C} \to ^8\text{B} + p \] breakup for \( ^8\text{B}(p,\gamma)^9\text{C} \)

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**Astrophysical S-factor**

\( ^8\text{B}(p,\gamma)^9\text{C} \)

**Figure.** The results of similar calculations for \(^9\text{C}\).
Setup

$^{16}$O primary beam with two BigRIPS settings for 300AMeV common to other HI-p experiments
DALI2: not necessary for $^9$C$\rightarrow$$^8$B+p, but useful for $^9$C$\rightarrow$Be+2p

The “standard” SAMURAI setting $\Rightarrow$ better for “$k_x$” measurements?
For exclusive measurements or Coulomb and nuclear breakup more demanding?

@65 AMeV (RIPS exp.)

~ 0.1mb/100 keV (Pb target)

c.f. ~100mb for inclusive

⇒ integral rate: 50 s⁻¹

a rough estimate for exclusive

~ 180 at 250 keV ($E_{\text{rel}}$)

~ 20 h⁻¹ at 150 keV

# higher eff. @SAMURAI

lower $\sigma$ at 300 AMeV

A fair tentative estimates

2 days for Coulomb dissociation

(1000 counts at 150 keV with 100 keV bin)
Theoretical analysis (existing):

Fukui, Ogata et al. for exclusive/inclusive breakup (2012);

Fukui, Ogata et al. for ANC (ARIS2014)
$^9$C nuclear breakup @ 100MeV/u. Theor estimates by Glauber calc

Note: $^9$C ->$^7$Be+2p large cs

Calculated momentum distributions from 1p-breakup of $^9$C at 100 MeV/u on a C target. Calculations with two different geometries of the binding potential for the last proton are shown (see text for details).

Interested in the accuracy of absolute values of cross sections. What different models, parameters, codes (and theoreticians) give?!
$^9$C$\rightarrow$$^8$B$+p$ @ 270 MeV/u (0.1mm lead, $E_{rel}=100$keV, field 3T)
AT RIKEN
Secondary beam → target → LI + HI tracking → SAMURAI → proton and HI hodoscopes

Breakup

XY – UV Si planes after target/before SAMURAI

Possible:

a) SSD-SSD --- SSD --- SSD-SSD
b) DSSD ---- SSD ---- DSSD

Problems:

i) Delta e- problem & ii) p threshold issues
Test rigs at WU, TAMU and HIMAC with existing PCB mounting

Test with the 2D TTT (300 µm)

**AREA** ➔ 97.3 x 97.3 mm

**# strips** ➔ 128 x 128 ➔ 256 per Si, 512 per pair

**Pitch** ➔ 756 µm

**Si type** ➔ available in both n and p (intrinsic). We have one of each

**Thickness** ➔ available in both 300 and 500 µm, we have 300 µm.

**pf** ➔ 300 µm: 0.35 pf/mm² = 26 pf/st; 500 µm: 0.21 pf/mm² = 15.4 pf/st

**Si –TTT (WU)**  **Si in chamber (TAMU)**  **External view (WU)**
Breakup (one-nucleon removal r.)

Momentum distributions → $nlj$
Cross section → ANC (only!!!)
Gamma rays → config mixing

Need: $V_p$-target & $V_{core}$-target
and reaction mechanism

Calc: F. Carstoiu (Bucharest); Data: see later
Semi-microscopic double folding potentials for nucleus-nucleus collisions

Double folding procedure:

\[ V(R) = \int d\vec{r}_1 d\vec{r}_2 \rho(r_1) \rho(r_2) v_{\text{eff}}(\rho, E, \vec{s}), \vec{s} = \vec{r}_1 + \vec{R} - \vec{r}_2 \]

- HFB densities (to best match the surfaces)
- tried various effective interactions (M3Y, DDM3Y, JLM, etc...)
- **Settled for JLM**
- **Smearing** w. range parameters \( t_v = 1.2 \) fm, \( t_w = 1.75 \) fm
- **Renormalizations** needed \( N_v, N_w \)

- **JLM** - uses eff inter of Jeukenne, Lejeune and Mahaux (PRC 16, 1977)
- n-nucleus Bauge ea (PRC 58, 1998):
  - energy and density dependent
  - independent geometry for real and imaginary potentials
  - normalization independent of partners
  - reproduces ELASTIC and TRANSFER data
- Checked for loosely bound p-shell nuclei stable beams \( \sim 10 \) MeV/u
  - Found \( N_v = 0.37(2), N_w = 1.0(1) \), \( t_v = 1.20 \) fm, \( t_w = 1.75 \) fm
- Extended to RNB: \(^7\text{Be}, \(^8\text{B}, \(^{11}\text{C}, \(^{12}\text{N}, \(^{13}\text{N}, \(^{17}\text{F on }^{12}\text{C, }^{14}\text{N targets}}\)

\[ U(r) = N_v V(r, t_v) + i N_w W(r, t_w) \]
JLM works for elastic & transfer

JLM works for transfer reactions

E/A = 15-50 MeV/u
Optical Model Potentials for Nucleus-Nucleus collisions for RNBs

Essential to make credible DWBA calc needed in transfer studies
Have established semi-microscopic double folding using JLM effective interaction:
- Established from exps with stable loosely bound p-shell nuclei: $^6,^7\text{Li}$, $^{10}\text{B}$, $^{13}\text{C}$, $^{14}\text{N}$ … @ 10 MeV/u
- Independent real and imaginary parts, energy and density depend.
- Parameters: renormalization coeff. ($N_v\sim 0.4-0.5$, $N_w=1.0$)
- Predicts well elastic scatt for RNBs: $^7\text{Be}$, $^8\text{B}$, $^{11}\text{C}$, $^{12}\text{N}$, $^{13}\text{N}$, $^{17}\text{F}$, $^{14}\text{C}$, …
- Good results for transfer reactions (tested where possible)


TAMU exps @ 12 MeV/ u
G. Tabacaru ea,
PRC 73, 025808 (2006)

ORNL exps @ 10 MeV/ u

$^7\text{Be}$ on melamine

$^12\text{N}$ on melamine

J. Blackmon ea,
PRC 73, 034606 (2005)

Various effective interactions

\[ \sigma_{\text{exp}} = \sum S(c, nlj)\sigma_{sp}(nlj) = \sum C_j^2 \frac{\sigma_{sp}(nlj)}{b_j^2} \]

A. Glauber model with folded potentials

1) JLM - uses the G-matrix effective interaction of Jeukenne, Lejeune and Mahaux (PRC 16, 1977) tested before because:
   - independent geometry for imaginary part
   - normalization independent of partners and energy
   - reproduces ELASTIC and TRANSFER data

for loosely bound p-shell nuclei with experimentally determined renormalizations (\(^{7}\text{Be},^{8}\text{B},^{11}\text{C} and ^{13}\text{N}\) on \(^{12}\text{C},^{14}\text{N}\))

\[
V(W)(R) = N_v [N_w] \int d\vec{r}_1 d\vec{r}_2 \rho(r_1) \rho(r_2) v_{\text{eff}}(\rho, E, \vec{s}), \vec{s} = \vec{r}_1 + \vec{R} - \vec{r}_2
\]

\[
\chi(b) = -\frac{1}{\hbar v} \int dz V(b, z) + \text{high order corr.}
\]

found no renorm for imaginary pot \(N_w=1.0\) at 10 MeV/u. Assumed correct at all energies !!!

2) the free t-matrix NN interactions of Franey and Love (PRC 31, 1985)
Various effective interactions (cont’d)

B. Glauber model calc in the optical limit
Use three ranges for interactions, to check the sensitivity:
3) zero-range $\mu \rightarrow 0$
4) “standard” $\mu = 1.5$ fm for all terms
5) “Ray”, ranges for each term, as determined by L. Ray (PRC 20, 1979)

$$\chi(b) = \frac{1}{2} \sigma_{NN}(i + \alpha_{NN}) \int d\overline{b}_1 d\overline{b}_2 \rho(b_1) \rho(b_2) \overline{v}(\overline{b} + \overline{b}_1 - \overline{b}_2)$$

$$\overline{v}(r) = \frac{1}{\pi^{3/2} \mu^3} e^{-\frac{r^2}{\mu^2}}$$

Test how the calculations reproduce other observables: reaction cross-sections ($p, ^7$Be and $^8$B on a $^{12}$C target) and total cross sections ($p$ on $^{12}$C).
No new parameters!!!
- Astrophysical $S_{18}$ extraction by
  ANC by nuclear and Coulomb dissociation
  with inclusive (for ANC) and
  exclusive (for inverse $(p,\gamma)$ ) measurements
  $^9\text{C} \rightarrow ^8\text{B}+\text{X} / ^9\text{C} \rightarrow ^8\text{B}+\text{p}$

- The easiest among the p-HI experiments being planned at RIBF
  for the 2017 campaign
  light products $\rightarrow$ smaller dynamic range, less atomic electrons …
  $\Rightarrow$ “a good start”

- In addition: mechanism in other channels e.g. $^9\text{C}\rightarrow^7\text{Be}+2\text{p}$
  Goal: improve reliability of calculations for absolute value predictions
Team

- R.E. Tribble, A. Saastamoinen, B. Roeder + 3 students - Texas A&M Univ.
- C. Bertulani – Texas A&M Univ - Commerce
- L. Trache, F. Carstoiu + 3 students – IFIN Bucharest
- Jeff Blackmon, C. Rasco – Louisiana State University
- A. Bonaccorso – INFN Pisa
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- K. Ogata, .. – RCNP Osaka
- Z. Elekes, .. – ATOMKI
- K.I. Hahn,.. – Ewha Womans University