Astrophysical S-factors for radiative capture reactions from transfer measurements

V.M. Datar

*Nuclear Physics Division,*
*Bhabha Atomic Research Centre,*
*Mumbai-400 085*

LENA, SINP, Kolkata Jan 17, 2006
Plan of talk

1. Introduction

2. Measurements of $^2\text{H}(^7\text{Be}, ^7\text{Be})^2\text{H}$ and $^2\text{H}(^7\text{Be}, ^8\text{B})n$ angular distributions

3. Analysis and extraction of $S_{17}(0)$

4. Summary and outlook
Radiative capture reactions such as (p, $\gamma$) and (\(\alpha\), $\gamma$) important in astrophysics

\[ d + p \rightarrow ^3\text{He} + \gamma \]
\[ d + d \rightarrow ^4\text{He} + \gamma \]
\[ d + ^4\text{He} \rightarrow ^6\text{Li} + \gamma \]
\[ ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \]
\[ p + ^7\text{Be} \rightarrow ^8\text{B} + \gamma \]
\[ p + ^{14}\text{N} \rightarrow ^{15}\text{O} + \gamma \]
\[ ^4\text{He} + ^{12}\text{C} \rightarrow ^{16}\text{O} + \gamma \]
S-factor measured by

- **Direct** method – radiative capture cross-section measured to lowest energy possible and *extrapolated* to Gamow energies
  Long lived targets (> 10 days), beams ~ 100 µA, small $\sigma_\gamma \sim \text{pb}$

- **Indirect** methods

  Coulomb dissociation (Virtual photons from high Z target for photo-dissociation of projectile e.g. $^8\text{B}+^{208}\text{Pb} \rightarrow ^7\text{Be}+\text{p}+^{208}\text{Pb}$)
  Shortlived (> 100 nsec) projectiles, range of $E_{\text{c.m.}}$ in one run

  Asymptotic normalization coefficient (ANC) method using proton (alpha) transfer reaction
  Shortlived (> 100 nsec) nuclei, large cross sections ($\sigma_{\text{tr}} \sim 10\text{s mb}$)
Recent transfer measurements for radiative capture S-factors

- \(^{3}\text{He, d)}\) on \(^{14}\text{N}\) for \(^{14}\text{N}(p, \gamma)^{15}\text{O}\) – Texas A&M
  
  Measured S-factor was about \textit{2 times smaller} than then accepted value. \textbf{Confirmed} by later direct \((p, \gamma)\) measurement.

- \(^{9}\text{Be}(^{7}\text{Be}, ^{8}\text{B})^{8}\text{Li}\) for \(^{7}\text{Be}(p, \gamma)^{8}\text{B}\) – \(S_{17}\) factor - Texas A&M
High energy $\nu_e$ from sun mostly from $^8$B decay

Solar neutrino problem: $\phi_{\text{expt}}(\nu_e) \sim 0.3 - 0.6 \phi_{\text{th}}$

SNO has very likely solved the solar neutrino problem. (2001)

$\phi_{\text{expt}}(\nu_x) \sim 1.03 \pm 0.05(\text{stat}) \pm 0.07(\text{sys}) \phi_{\text{th}}(\nu_e)$ (May 2004)

However, detailed understanding of observed $\nu$ flux requires a theoretical prediction of better accuracy. (e.g. sterile $\nu$ ?)

Theory: Standard solar model

  Nuclear cross sections

  Neutrino mixing

$S_{17}(E_{\text{c.m.}}) = E \cdot \sigma(E_{\text{c.m.}}) e^{2\pi\eta}$

$\sigma(p + ^7\text{Be} \rightarrow ^8\text{B} + \gamma)$ at stellar energies $\sim 10$ keV known to $\pm 15\%$

(Adelberger 1998, Angulo 1999)
from Bahcall, Pinsonneault (2004), $\phi_\nu$ in $#/\text{(cm}^2\text{.sec MeV)}$
$S_{17}(0)$ measured by

- **Direct** method ($p,\gamma$) for $E_p = 700$ keV down to 110 keV and extrapolate to $\sim 10$ keV
- **Indirect** methods
  
  Coulomb dissociation ($^8\text{B}+^{208}\text{Pb} \rightarrow ^7\text{Be}+p+^{208}\text{Pb}$)
  Asymptotic normalization coefficient (ANC) method using proton transfer reaction

Direct precision $S_{17}$ clustered $\sim 21.3$ and 18.5 eV.barn
In view of disagreement between different precision ‘direct’ measurements other methods to measure $S_{17}(0)$ of great importance -

*Adelberger et al* RMP 70, 1265 (1998)

Latest Coulomb dissociation $S_{17}(0) = 18.6 \pm 1.2(\text{exp}) \pm 1.0 \text{ (th) eV.b}$

FIG. 17. (Color) Nonresonant part of the $S_{17}(E)$ from recent direct capture measurements. Each set of $S_{17}(E)$ values was fitted independently to the DB parametrization, and the individual scaling factors were then renormalized to a reference value corresponding to $S_{17}(0) = 21.2$ eV b. The overall consistency of the data up to $E_{c.m.} = 1.2$ MeV as well as the agreement with the DB parametrization is apparent.
--- Descouvement (1994)

$E_{cm} \leq 1.5$ MeV gives $20.8 \pm 1.3$ eV.b

$\leq 0.6$ MeV gives $19.6 \pm 1.4$ eV.b

--- Potential model (Schumann 2003)

Full $E_{cm}$ range $18.6 \pm 1.2$ eV.b

Fit to Lagy et al $18.1 \pm 0.3$ eV.b

---

FIG. 4 (color online). (a) Comparison between $S_{17}$ values from Coulomb-dissociation experiments. The full (open) circles indicate the present (previous) GSI CD experiment. Open stars depict Ref. [12], and open squares Ref. [13] ($E2$ contribution subtracted). The theoretical curves are described in the text. (b) $S_{17}$ from this work in comparison with the $(p, \gamma)$ experiments of Ref. [4] (squares), Ref. [6] (stars), and Ref. [7] (open circles). The latter data were corrected for the contribution of the $M1$ resonance by the authors.
What is the ANC method? (Xu et al. PRL 73 (1994) 2027)

\[ \frac{d\sigma}{d\Omega} \propto |M_{fi}|^2 \]

where \( M_{fi} = \langle \Psi_f(\cdot) | I^{8B} p_{7Be} | V_{np} | I^{d}_{np} \Psi_i^{(+)} \rangle \)

\[ I^{8B}_{p_{7Be}} (r) = C_{nlj} u_{nlj} (r) \]

and \( C_{nlj} = S^{1/2} \beta_{nlj} \) where \( \beta_{nlj} \) is asymptotic normalization of \( u_{nlj} (r) \)

\[ u_{nlj} (r) = W_{-\eta, l+1/2} (2kr) \text{ is the Whittaker function} \]

\[ S_{exp} = \frac{(d\sigma/d\Omega)_{expt}}{(d\sigma/d\Omega)_{FRDWBA}} \]

\[ S_{17}(0) = S_{exp} \beta_{113/2}^2 / 0.026 \]

ANC method works when reaction \textit{peripheral}
It works!

Measured $^{16\text{O}}(p,\gamma) \leftrightarrow ^{16\text{O}}(^3\text{He},d)$  Gagliardi et al (1999)
ANC measurement using

$^{10}\text{B}(^{7}\text{Be},^{8}\text{B})^{9}\text{Be} \Rightarrow S_{17}(0) = 17.8\pm2.8 \text{ eV.barn (Texas A&M)}$

$^{14}\text{N}(^{7}\text{Be},^{8}\text{B})^{13}\text{C} \Rightarrow S_{17}(0) = 16.6\pm1.9 \text{ eV.barn (Texas A&M)}$

+ Peripheral reaction, OMP in entrance channels measured

− Uncertainties from ANC of p in target, two step processes…
d($^7$Be,$^8$B)n : proton wave function known precisely
simpler exit channel
For $E_{\text{c.m.}} < 6$ MeV reaction peripheral (Fernandes et al 1999)
Liu et al PRL 77, 611 (1996) at 5.8 MeV extracted
$S_{17}(0) = 27.4 \pm 4.4$ eV.barn
Other analyses gave $23.5 \pm 3.7$ eV.barn (Gagliardi) and
$23.5 \pm 6.7$ eV.barn (Fernandes). Difference attributed to
entrance & exit channel OMP
Also low statistics experiment (total # of $^8$B events $\approx 300$)
**$^7\text{Be}$**  \( T_{1/2} = 53.3 \text{ days} \), \( S_n/S_p/S_\alpha = 10.677 / 5.606 / 1.587 \text{ MeV} \)

<table>
<thead>
<tr>
<th>( E_x (\text{MeV}) )</th>
<th>( J^\pi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>3/2^-</td>
</tr>
<tr>
<td>0.429</td>
<td>1/2^-</td>
</tr>
<tr>
<td>4.57</td>
<td>7/2^-</td>
</tr>
</tbody>
</table>

**$^8\text{B}$**  \( T_{1/2} = 770 \text{ msec} \), \( S_n/S_p/S_\alpha = 13.018 / 0.137 / 4.824 \text{ MeV} \)

<table>
<thead>
<tr>
<th>( E_x (\text{MeV}) )</th>
<th>( J^\pi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>2^+</td>
</tr>
<tr>
<td>0.774</td>
<td>(1^+)</td>
</tr>
<tr>
<td>2.32</td>
<td>3^+</td>
</tr>
</tbody>
</table>
\[ ^7\text{Be} + \text{d} \rightarrow ^8\text{B} + \text{n} \quad Q_{\text{val}} = -2.087 \text{ MeV} \]
\[ \rightarrow ^8\text{Be} + \text{p} \quad -16.675 \text{ MeV} \]
\[ \rightarrow ^6\text{Be} + \text{t} \quad -4.419 \text{ MeV} \]
\[ \rightarrow ^6\text{Li} + ^3\text{He} \quad -0.112 \text{ MeV} \]
\[ \rightarrow ^5\text{Li} + ^4\text{He} \quad +14.801 \text{ MeV} \]

In inverse kinematics d(\(^7\text{Be}, ^8\text{B}\))n, at E(\(^7\text{Be}\))_{\text{lab}} = 21 \text{ MeV},
\[ \theta_{\text{max}} \approx 8^\circ \]

For elastic scattering d(\(^7\text{Be}, ^7\text{Be}\))d
\[ \theta_{\text{max}} \approx 17^\circ \]
Substantial improvement over the earlier measurement

- Superior $^7$Be beam (>99.9% pure, size ≈ 3 mm, $\Delta \theta = 1^\circ$)
- Integrated $^7$Be flux ≈ 8 times higher $\Rightarrow$ larger # of $^8$B events
- Elastic scattering measurement in entrance channel at similar energy

Experimental details

- 25 MeV $^7$Li(p,n)$^7$Be at 15 UD Pelletron at Nuclear Science Centre, New Delhi
- $^7$Li beam pulsed – 2nsec FWHM at 4 MHz
- Rotating 20 µm thick polyethylene (production) target
• Recoil mass analyser HIRA operated in novel mode to separate $^7\text{Be}$ I($^7\text{Be}$) $\approx$ 3000 sec$^{-1}$

• Si telescopes at $\pm30^\circ$ at production target to monitor recoil protons

• Stopper (4 mm dia Ta disc) to reduce main $^7\text{Be}$ beam (by $\sim8$) and pileup in detector system at $0^\circ$

• MWPC before stopper to count incident $^7\text{Be}$ (in MCA)

• Gas $\Delta E$ (60 mm deep, 50 mbar isobutane) – Si E detector ($50 \times 50$ mm$^2$) for particle ID, E, X/Y $\Rightarrow \theta$

• 3 mm dia graphite collimator upstream
- Event by event data in CAMAC based DAS
  Parameters: E, X, Y, Pileup, TOF (Si 2D), ΔE, TOF, Pileup (IC), Monitors ÷N, TOF(RF-MWPC)

- Total N(⁷Be) incident on targets

<table>
<thead>
<tr>
<th>Target</th>
<th>with stopper</th>
<th>without stopper</th>
</tr>
</thead>
<tbody>
<tr>
<td>(CD₂)ₙ</td>
<td>4 x 10⁸</td>
<td>8 x 10⁷</td>
</tr>
<tr>
<td>(CH₂)ₙ</td>
<td>1.5 x 10⁸</td>
<td>2 x 10⁷</td>
</tr>
</tbody>
</table>

- PID calibration with scattered ⁷Li, ⁷Be, ¹²C with HIRA at 2°
Schematic of HIRA for production of $^7$Be beam and setup for ($^7$Be,$^8$B) transfer angular distribution measurement
Rotating Target Wheel

Rotary + linear motion in vacuum

$\text{CH}_2$ foil Life time $\sim$ 120 hours with 5 pna current
Focal Plane Setup

IC

Silicon PSD
Focal plane chamber and the detector system
Position spectrum in Si detector

dist. between holes: 8 mm
dia of holes: 1 mm
except central ~2 mm
E-DE SPK (raw): CD2 target \( N(7\text{Be}) = 13.57 \times 10^7 \)
E-DE SPK (raw): CH2 target  N(7Be)=1.395 \times 10^7
Particle identification spectra for \((\text{CD}_2)_n\) and \((\text{CD}_2)_n\) targets
TOF Spectra from target to Focal plane of RMS

Counts

Candle V1.0.1, NSC  TOF (channel)
(a) Schematic of detector setup used for elastic scattering measurement

(b) Measured elastic differential cross sections along with optical model fits (dashed lines show Liu 1 & 2)

d-\textsuperscript{7}Be coincidence eliminates collimator and \textsuperscript{12}C scattering
- Inelastic excitation to 429 keV state in $^7$Be not resolved ($\Delta E \sim 1$MeV)
- Expected to be small on basis of low energy $^7$Li + $^{12}$C measurement at FOTIA, Mumbai
- Elastic differential cross sections fit using code SNOOPY
Parameters of the Woods-Saxon OMPs extracted from the d + $^7$Be ($E_{\text{c.m.}} = 4.4$ MeV) elastic scattering data. Spin orbit term with $V_{so} = 8.60$ MeV, $r_{so} = 2.17$ fm, and $a_{so} = 0.61$ fm added to all potential sets. Light ion convention for the radius used.

<table>
<thead>
<tr>
<th>Pot.</th>
<th>$V_0$ (MeV)</th>
<th>$r_0$ (fm)</th>
<th>$a_0$ (fm)</th>
<th>$4W_s$ (MeV)</th>
<th>$r_s$ (fm)</th>
<th>$a_s$ (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>103.12</td>
<td>2.23</td>
<td>0.62</td>
<td>79.03</td>
<td>2.37</td>
<td>0.17</td>
</tr>
<tr>
<td>S2</td>
<td>107.87</td>
<td>2.17</td>
<td>0.61</td>
<td>58.84</td>
<td>2.28</td>
<td>0.25</td>
</tr>
<tr>
<td>S3</td>
<td>92.54</td>
<td>2.41</td>
<td>0.57</td>
<td>117.50</td>
<td>2.45</td>
<td>0.14</td>
</tr>
<tr>
<td>S4</td>
<td>121.49</td>
<td>1.97</td>
<td>0.66</td>
<td>54.88</td>
<td>2.38</td>
<td>0.28</td>
</tr>
</tbody>
</table>
### n-\(^8\)B OMP parameters

<table>
<thead>
<tr>
<th>Pot.</th>
<th>(V_0)</th>
<th>(r_0)</th>
<th>(a_0)</th>
<th>(4W_s)</th>
<th>(r_s)</th>
<th>(a_s)</th>
<th>(V_{so})</th>
<th>(r_{so})</th>
<th>(a_{so})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(MeV)</td>
<td>(fm)</td>
<td>(fm)</td>
<td>(MeV)</td>
<td>(fm)</td>
<td>(fm)</td>
<td>(MeV)</td>
<td>(fm)</td>
<td>(fm)</td>
</tr>
<tr>
<td>N1</td>
<td>46.44</td>
<td>1.316</td>
<td>0.66</td>
<td>33.64</td>
<td>1.264</td>
<td>0.48</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N2</td>
<td>45.56</td>
<td>1.31</td>
<td>0.66</td>
<td>36.32</td>
<td>1.26</td>
<td>0.48</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N3</td>
<td>47.10</td>
<td>1.31</td>
<td>0.66</td>
<td>33.52</td>
<td>1.26</td>
<td>0.48</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N4</td>
<td>50.0</td>
<td>1.38</td>
<td>0.65</td>
<td>47.60</td>
<td>1.50</td>
<td>0.37</td>
<td>7.3</td>
<td>1.35</td>
<td>0.33</td>
</tr>
<tr>
<td>N5</td>
<td>50.7</td>
<td>1.38</td>
<td>0.65</td>
<td>16.10</td>
<td>1.50</td>
<td>0.37</td>
<td>6.5</td>
<td>1.35</td>
<td>0.33</td>
</tr>
</tbody>
</table>

N1 : D. Wilmore, P.E. Hodgson, global neutron OMP in HF calc., NP 55, 673 (1964)

N2, N3 : n\(^+\)\(^{10,11}\)B @ 9.72 MeV, J. Cookson, J.G. Locke, NP A146, 417 (1970)

N4, N5 : p\(^+\)Be @ 5, 6 MeV, D.N. Loyd, W. Haeberli, NP A148, 236 (1970)
Single particle wave function of p - \(^7\)Be in \(^8\)B


FRDWBA calculations using DWUCK5. Neutron (in deuteron)
wave function (s and d states) generated using Reid soft core
potential. \(0p_{3/2}\) for p\(^+\)\(^7\)Be used but \(0p_{1/2}\) gives very similar results

\[4 \text{(d OMP)} \times 4 \text{(n OMP)} \times 5 \text{(p-}^8\text{Be bound state pot.)} \Rightarrow 80 \text{ calc.}\]
• Only data at $\theta_{c.m.} \leq 45^\circ$ used

• Compound nuclear contribution to $d(\text{^7Be},\text{^8B})n$ calculated using Hauser Feshbach code (Suresh Kumar). Uncertainty in $\sigma_{CN}$ estimated to be $\pm 50\%$

• FRDWBA transfer cross sections folded using a Monte Carlo simulation which includes spatial, angular and energy spread of beam, target thickness and spatial resolution of detector

• (Data – folded CN) compared with folded DWBA to derive $S_{exp}$ hence $S_{17}(0)$ extracted

• Mean and rms deviation derived from 80 “exptl” values of $S_{17}(0)$ to estimate systematic error due to OMP
Measured $d(^7\text{Be},^8\text{B})n$ angular distribution and folded theoretical calculation which includes FRDWBA transfer and compound nuclear contributions (dashed line). Inset shows histogram of extracted $S_{17}(0)$
Systematic error 2 from *analysis of 3, 5, 8, 11 data points*

<table>
<thead>
<tr>
<th># of data points</th>
<th>$S_{17}(0)$ expt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>22.32±2.66 ±0.58</td>
</tr>
<tr>
<td>5</td>
<td>22.72 ±1.78 ±0.67</td>
</tr>
<tr>
<td>8</td>
<td>20.66 ±1.33 ±0.86</td>
</tr>
<tr>
<td>11</td>
<td>18.45 ±1.20 ±1.04</td>
</tr>
</tbody>
</table>
Including correction from p-\(^7\)Be scattering length (\(\sim 1\%\))

\[ S_{17}(0) = 20.7 \pm 1.4 \text{ (stat)} \pm 2.0 \text{ (sys)} \text{ eV.barn} \]

Combining errors \( S_{17}(0) = 20.7 \pm 2.4 \text{ eV.barn} \)

consistent with recommended value of Adelberger et al RMP 70, 1265 (1998)

\[ S_{17}(0) = 19^{+4}_{-2} \text{ eV.barn} \]

Not included

- multistep processes (inelastic+transfer, breakup fusion)
- core excitation

Measurement of d+\(^7\)Li, \(^7\)Be at \(E_{\text{c.m.}} = 4.4\text{ MeV}\), p-\(^8\)B,\(^8\)Li elastic scattering at \(\sim 2\text{ MeV}\) necessary to lower uncertainty due to entrance and exit channel OMPs (\(\sim 3.5\%\) presently)

*Accepted for publication in Phys. Rev. C*
$S_{17}(0)$ from direct and indirect measurements

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{17}(0)$ eV.barn</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>25</td>
</tr>
</tbody>
</table>

- **Direct (p,γ)**
- **Coulomb dissociation**
- **ANC**

Present expt
•Possible improvements?

Full angular distribution (neutrons?) and better elastic and inelastic $d + ^7\text{Be}$ data

**Conclusions of $S_{17}(0)$ measurement**

- Extracted $S_{17}(0)$ competitive with other methods
- Useful for other $(p,\gamma)$ S-factors with short lived nuclei with precision $\sim$ direct capture measurements
Other possibilities

- $^{13}\text{C}(p,\gamma)$ through $^{13}\text{C}(d,n)^{14}\text{N}$ reaction
- $^{15}\text{N}(p,\gamma)$ and $^{15}\text{N}(p,\alpha)$ through proton transfer reaction
- $^{16,17,18}\text{O}(p,\gamma)$
- $^{19}\text{F}(p,\gamma)$ and $^{19}\text{F}(p,\alpha)$
- $^{20}\text{Ne}(p,\gamma)$
Remember the case of $^{14}$N(p,γ) where new S-factor was about half of then accepted value.


Runkle et al., arXiv:nucl-ex/0408014 for rad.capture \textit{(p,γ) expt.}
Collaboration


V.M. Datar, A. Navin – Bhabha Atomic Research Centre, Mumbai

P.V. Madhusudhana Rao, D.L. Sastry – Andhra University, Visakhapatnam

S.K. Dhiman – Himachal Pradesh University, Shimla

S. Barua – Gauhati University, Jalukbari-Guwahati

A.K. Sinha – IUC-DAEF Kolkata Centre, Kolkata

R. Singh – Delhi University, New Delhi

A. Ray – Variable Energy Cyclotron Centre, Kolkata

R.G. Kulkarni – Saurashtra University, Rajkot

R. Shyam – Saha Institute of Nuclear Physics, Kolkata

Acknowledgements

Thank you