Astrophysical S-factors for radiative capture reactions from transfer measurements

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LENA, SINP, Kolkata Jan 17, 2006

Plan of talk

1. Introduction
2. Measurements of ^{2}H(^{7}Be, ^{7}Be)^{2}H and ^{2}H(^{7}Be, ^{8}B)n angular distributions
3. Analysis and extraction of $S_{17}(0)$
4. Summary and outlook

Radiative capture reactions such as (p, γ) and (α, γ) important in astrophysics

$d + p \rightarrow {}^{3}He + \gamma$

$d + d \rightarrow {}^{4}He + \gamma$

$d + {}^{4}He \rightarrow {}^{6}Li + \gamma$

${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

$p + {}^{7}Be \rightarrow {}^{8}B + \gamma$

$p + {}^{14}N \rightarrow {}^{15}O + \gamma$

${}^{4}He + {}^{12}C \rightarrow {}^{16}O + \gamma$

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 σ_γ ~ pb)

- Indirect methods

  Coulomb dissociation (Virtual photons from high Z target for photo-dissociation of projectile e.g. $^{8}B+^{208}Pb \rightarrow ^{7}Be+p+^{208}Pb$)

  Shortlived (> 100 nsec) projectiles, range of $E_{c.m.}$ in one run

  Asymptotic normalization coefficient (ANC) method using proton (alpha) transfer reaction

  Shortlived (> 100 nsec) nuclei, large cross sections (σ_{tr}~ 10s mb)

Recent transfer measurements for radiative capture S-factors

- (^{3}He,d) on ^{14}N for ^{14}N(p, γ)^{15}O – Texas A&M

  Measured S-factor was about 2 times smaller than then accepted value. Confirmed by later direct (p, γ) measurement.

- ^{9}Be(^{7}Be,^{8}B)^{8}Li for ^{7}Be(p, γ)^{8}B – S_{17} factor - Texas A&M

High energy ν_e from sun mostly from ^8B decay

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

SNO has very likely solved the solar neutrino problem. (*2001*)
$\phi_{expt}(\nu_x) \sim 1.03 \pm 0.05(\text{stat}) \pm 0.07(\text{sys})\ \phi_{th}(\nu_e)$ (*May 2004)*

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

Theory : Standard solar model

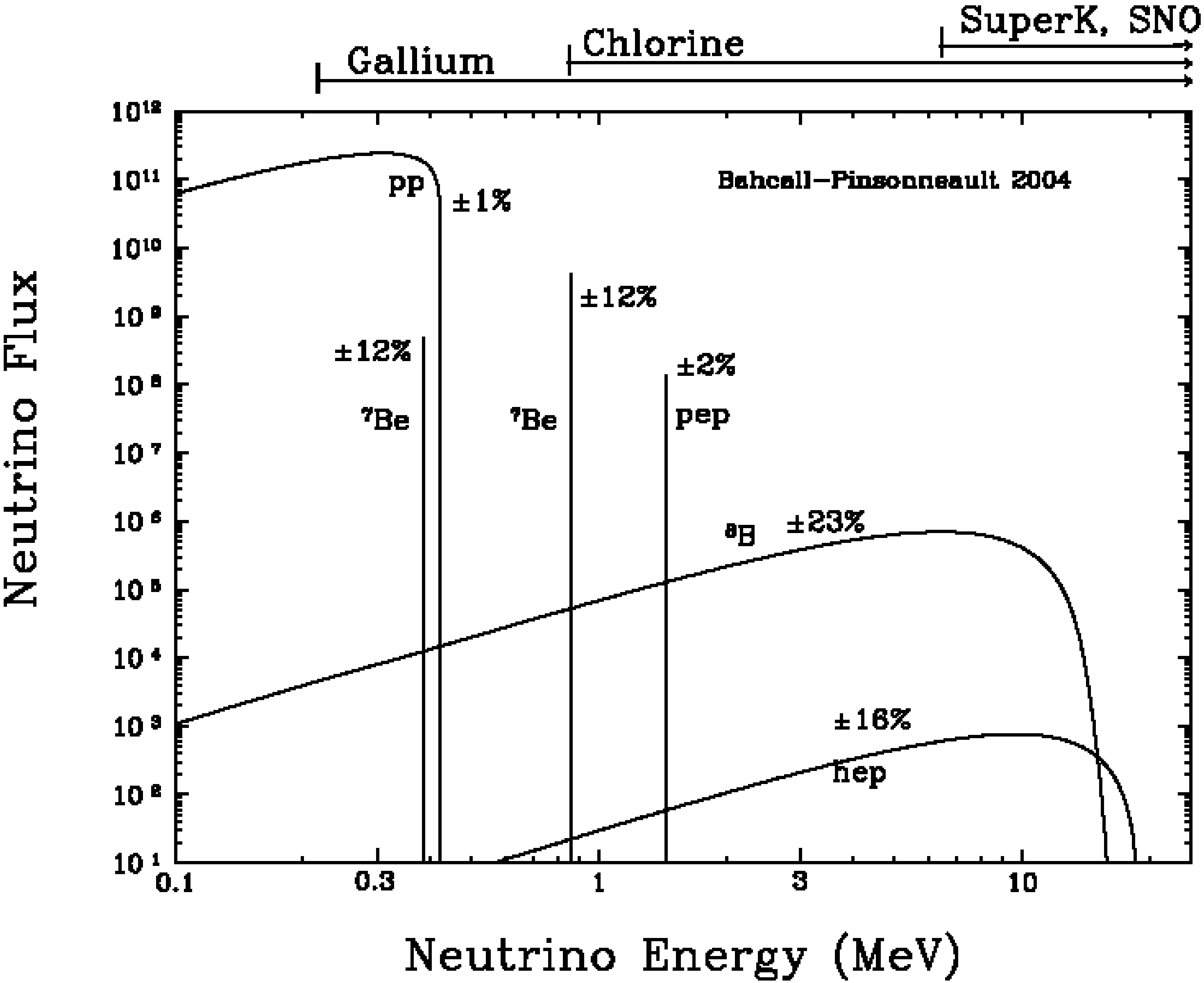
Nuclear cross sections

Neutrino mixing

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

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

(Adelberger 1998, Angulo 1999)



from Bahcall, Pinsonneault (2004), ϕ_ν in #/(cm^2.sec.MeV)

$S_{17}(0)$ measured by

- Direct method (p,γ) for E_p= 700 keV down to 110 keV and

  extrapolate to ~10 keV

- Indirect methods

  Coulomb dissociation ($^8B+^{208}Pb \rightarrow ^7Be+p+^{208}Pb$)

  Asymptotic normalization coefficient (ANC) method using

  proton transfer reaction

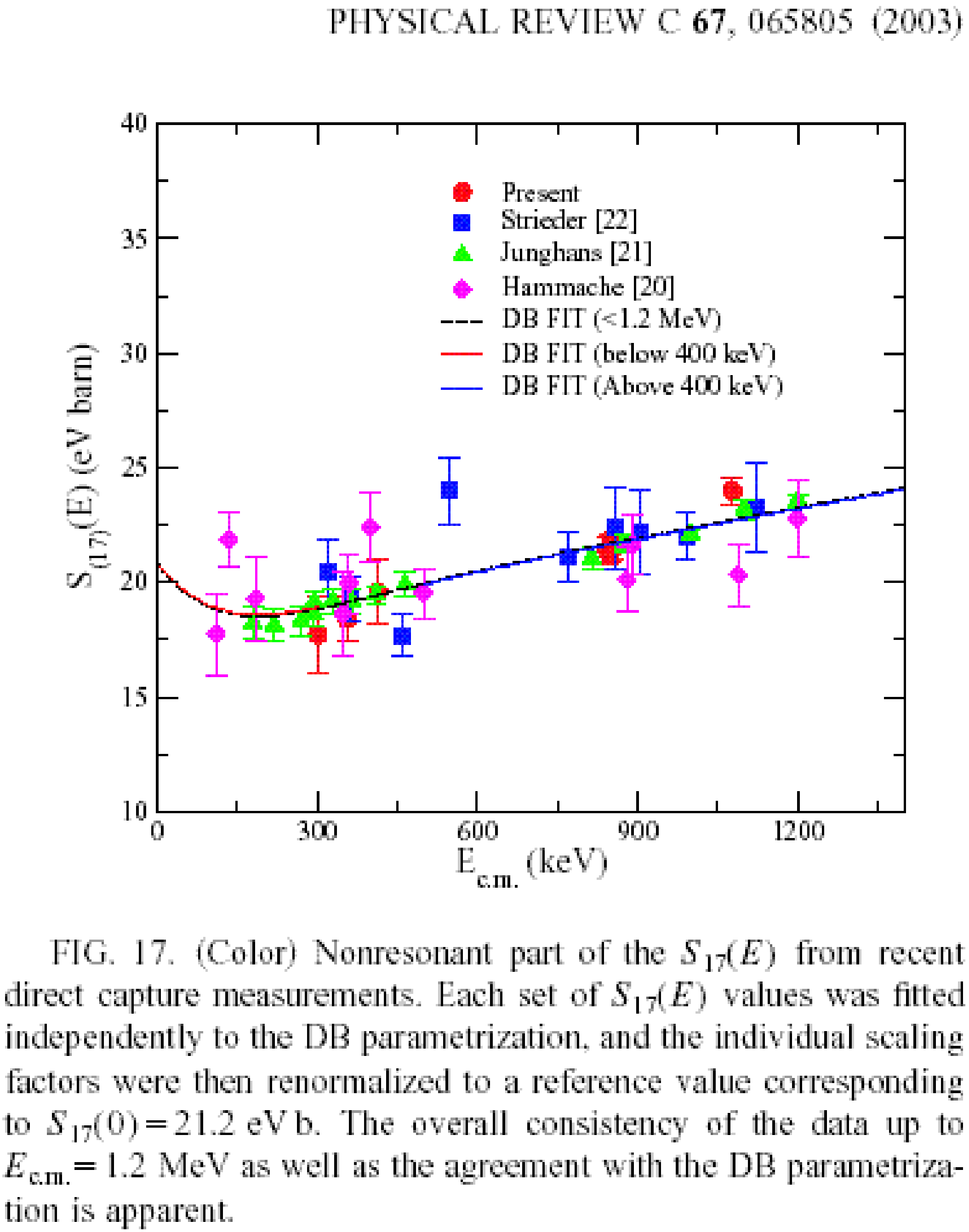
Direct precision S_{17} clustered ~ 21.3 and 18.5 eV.barn

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 $S_{17}(0) = 18.6 \pm 1.2(\mathrm{exp}) \pm 1.0\ (\mathrm{th})$ eV.b

F. Schumann et al, PRL **90**, 232501 (2003) Bochum-GSI-RIKEN-…collaboration

L.T. Baby et al.



PHYSICAL REVIEW C **67**, 065805 (2003)

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.

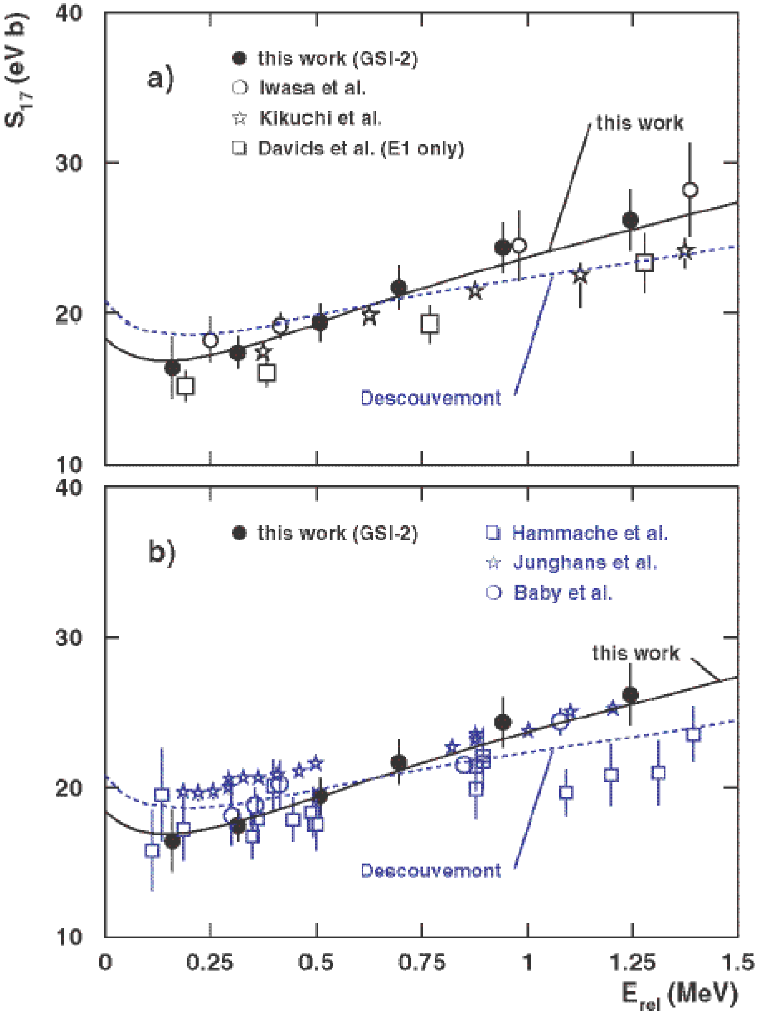


FIG. 4 (color online). (a) Comparison between S_{17} values from Coulomb-dissociation experiments. The full (open) circles indicate the present (previous) GSI CD experiment. Open stars depict Ref. [12], and open squares Ref. [13] ($E2$ contribution subtracted). The theoretical curves are described in the text. (b) S_{17} from this work in comparison with the (p, γ) 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.

--- Descouvement (1994)

E_{cm} ≤1.5 MeV gives 20.8 ± 1.3 eV.b

≤0.6 MeV gives 19.6 ± 1.4 eV.b

__ Potential model (Schumann 2003)

Full E_{cm} range 18.6 ± 1.2 eV.b

Fit to Lagy et al 18.1 ± 0.3 eV.b

What is the ANC method ? (Xu et al. PRL 73 (1994) 2027)

$d\sigma/d\Omega \propto |M_{fi}|^2$

where $M_{fi} = <\Psi_f^{(-)} I^{8B}{}_{p7Be} \,|\, V_{np} \,|\, I^{d}{}_{np} \Psi_i^{(+)}>$

$I^{8B}{}_{p7Be}(r) = C_{nlj}\ u_{nlj}(r)$

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

$u_{nlj}(r) = W_{-\eta,l+1/2}(2\kappa r)$ *is the Whittaker function*

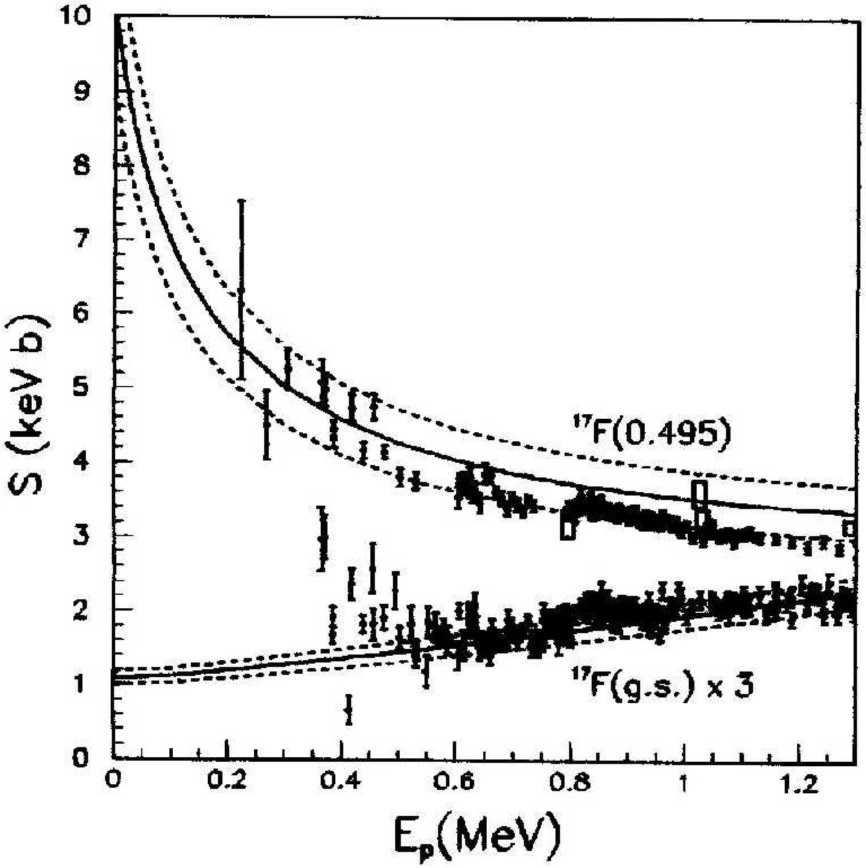
$S_{exp} = (d\sigma/d\Omega)_{expt} / (d\sigma/d\Omega)_{FRDWBA}$

$S_{17}(0) = S_{exp}\,\beta^2{}_{113/2} / 0.026$

ANC method works when reaction ***peripheral***

It works!

Measured $^{16}O(p,\gamma)$ ⇔ $^{16}O(^{3}He,d)$ *Gagliardi et al (1999)*



ANC measurement using

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

$^{14}N(^{7}Be,^{8}B)^{13}C$ $\Rightarrow S_{17}(0) = 16.6\pm1.9$ 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 $E_{c.m.} < 6$ MeV reaction peripheral (*Fernandes et al 1999*)

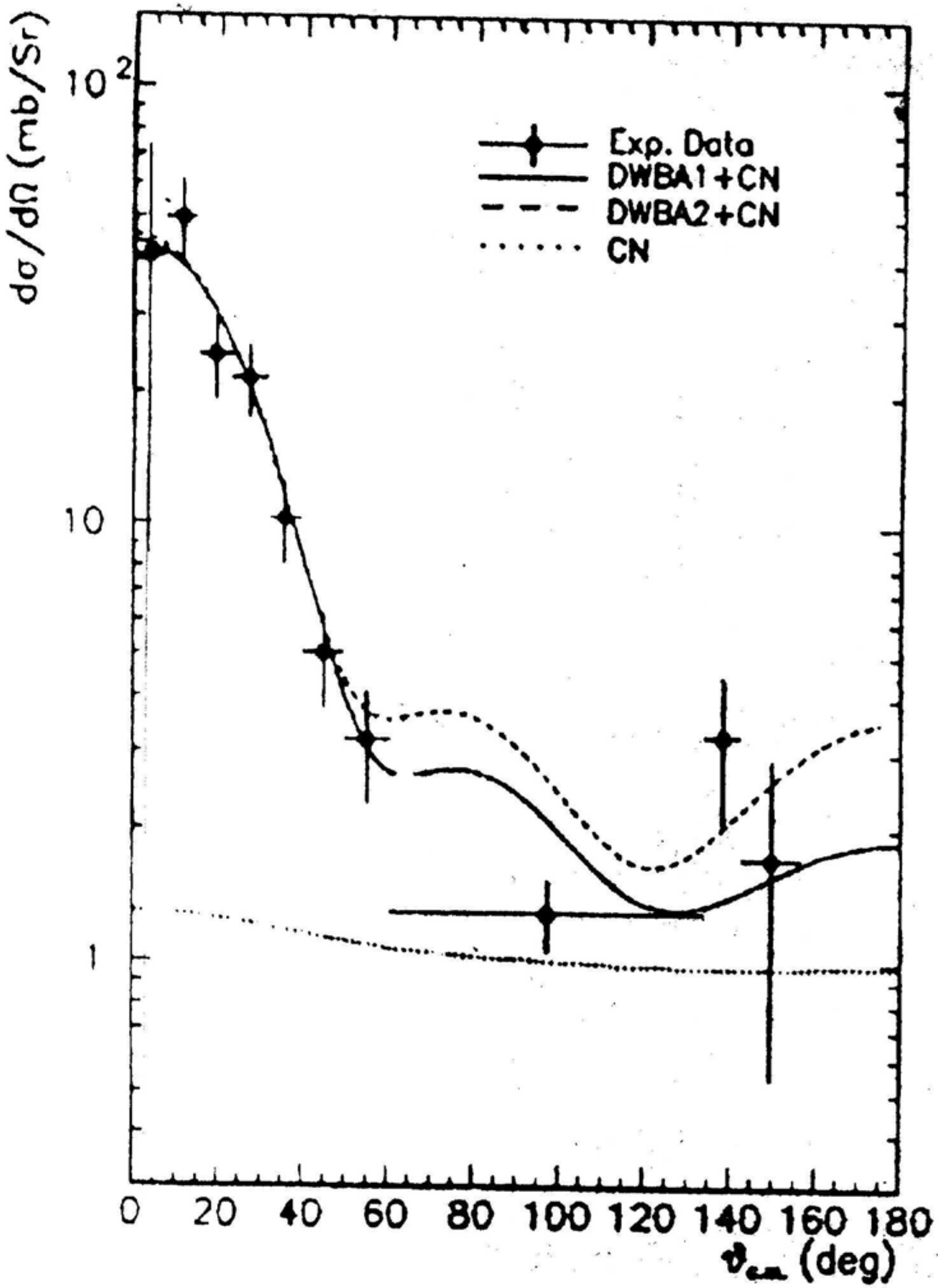
Liu et al PRL **77**, 611 (1996) at 5.8 MeV extracted

$S_{17}(0) = 27.4 \pm 4.4$ eV.barn

Other analyses gave 23.5 ± 3.7 eV.barn (*Gagliardi*) and

23.5 ± 6.7 eV.barn (*Fernandes*). Difference attributed to entrance & exit channel OMP

Also low statistics experiment (total # of ^{8}B events ≈ 300)


dσ/dΩ (mb/Sr)
10²
10
1
Exp. Data
DWBA1+CN
DWBA2+CN
CN
0
20
40
60
80
100
120
140
160
180
ϑcm (deg)

$^{7}\mathrm{Be}$ $T_{1/2} = 53.3$ days, $S_n/S_p/S_\alpha = 10.677 / 5.606 / 1.587$ MeV

E_x(MeV)	J^π
0.000	$3/2^-$
0.429	$1/2^-$
4.57	$7/2^-$

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

E_x(MeV)	J^π
0.000	2^+
0.774	(1^+)
2.32	3^+

$^{7}\mathrm{Be} + \mathrm{d} \rightarrow {}^{8}\mathrm{B} + \mathrm{n}$ $Q_{\mathrm{val}} = -\ 2.087$ MeV

$\rightarrow {}^{8}\mathrm{Be} + \mathrm{p}$ -16.675 MeV

$\rightarrow {}^{6}\mathrm{Be} + \mathrm{t}$ $-\ 4.419$ MeV

$\rightarrow {}^{6}\mathrm{Li} + {}^{3}\mathrm{He}$ $-\ 0.112$ MeV

$\rightarrow {}^{5}\mathrm{Li} + {}^{4}\mathrm{He}$ $+14.801$ MeV

In inverse kinematics $\mathrm{d}({}^{7}\mathrm{Be},{}^{8}\mathrm{B})\mathrm{n}$, at $E({}^{7}\mathrm{Be})_{\mathrm{lab}} = 21$ MeV,

$\theta_{\mathrm{max}} \approx 8°$

For elastic scattering $\mathrm{d}({}^{7}\mathrm{Be}, {}^{7}\mathrm{Be})\mathrm{d}$

$\theta_{\mathrm{max}} \approx 17°$

Substantial improvement over the earlier measurement

- Superior ^{7}Be beam (>99.9% pure, size ≈ 3 mm, $\Delta\theta = 1°$)
- Integrated ^{7}Be flux ≈ 8 times higher ⇒ 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}Be

  I(^{7}Be) ≈ 3000 sec^{-1}

- Si telescopes at ±30° at production target to monitor recoil protons

- Stopper (4 mm dia Ta disc) to reduce main ^{7}Be beam (by ~8) and pileup in detector system at 0°

- MWPC before stopper to count incident ^{7}Be (in MCA)

- Gas ΔE (60 mm deep, 50 mbar isobutane) – Si E detector (50 x 50 mm^2) for particle ID, E, X/Y ⇒ θ

- 3 mm dia graphite collimator upstream

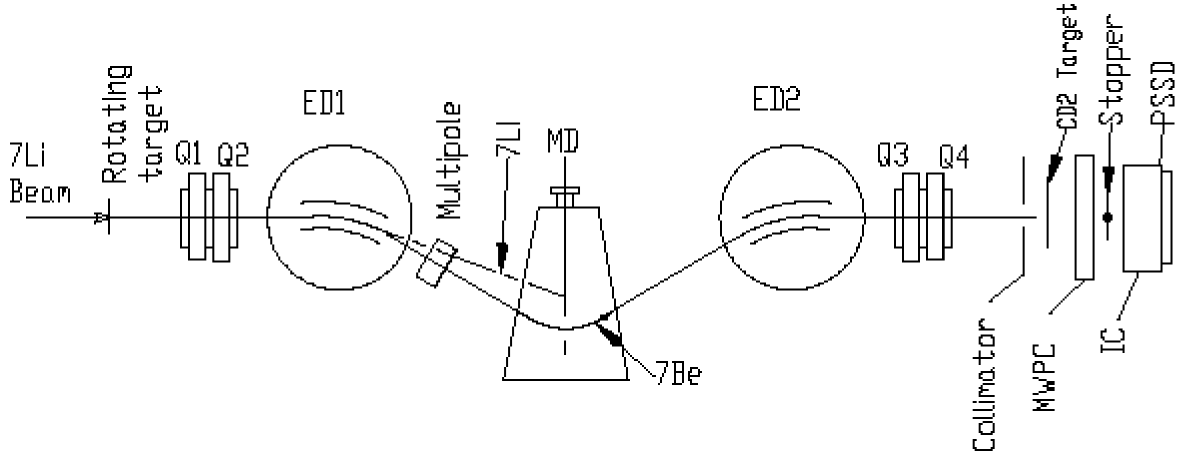
- Event by event data in CAMAC based DAS

  Parameters : E, X, Y, Pileup, TOF (Si 2D), ΔE , TOF, Pileup (IC), Monitors ÷N, TOF(RF-MWPC)

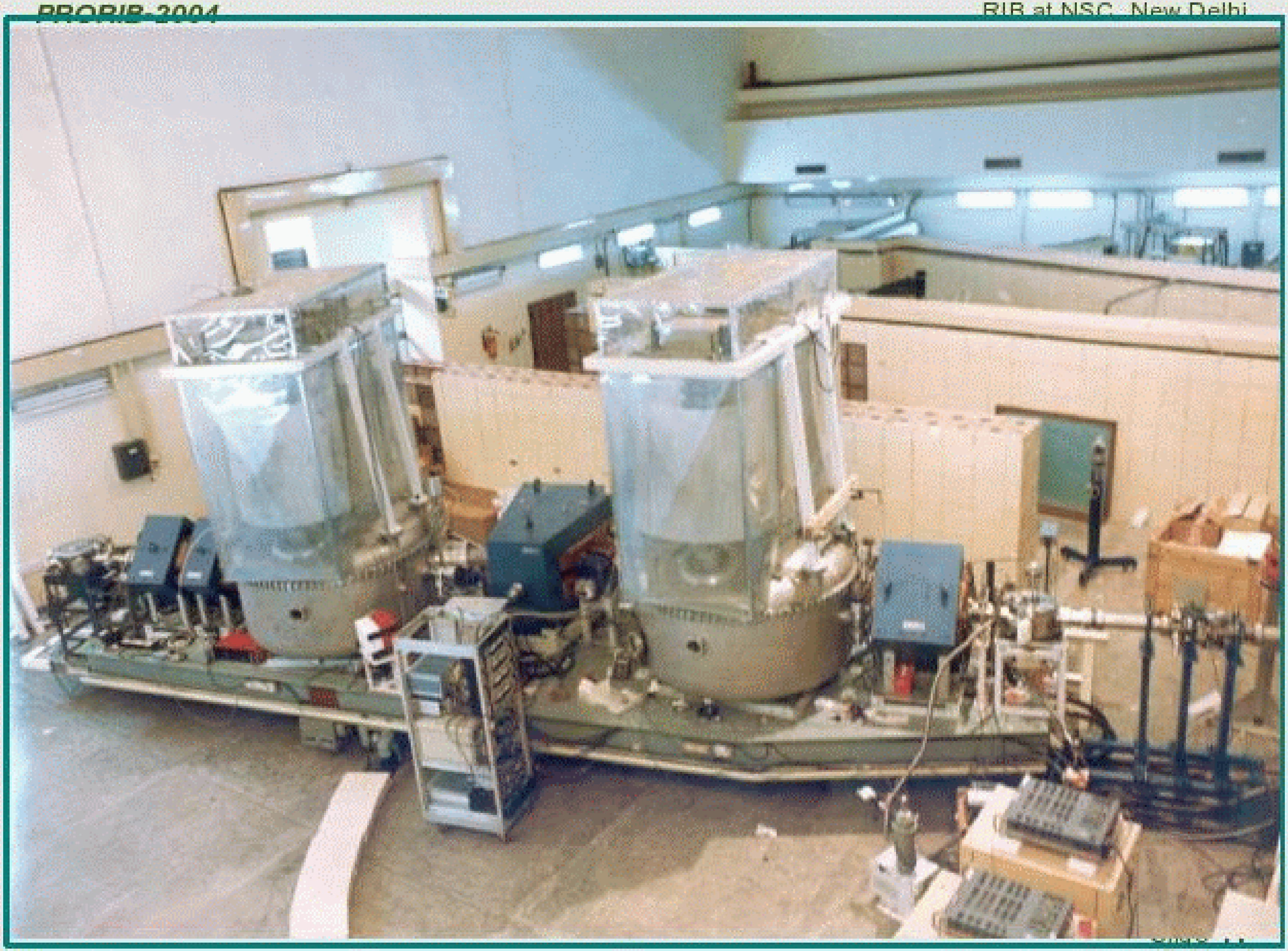
- Total N(^{7}Be) incident on targets

	N(^{7}Be)	
Target	with stopper	without stopper
$(CD_2)_n$	4×10^8	8×10^7
$(CH_2)_n$	1.5×10^8	2×10^7

- PID calibration with scattered ^{7}Li, ^{7}Be, ^{12}C with HIRA at 2°



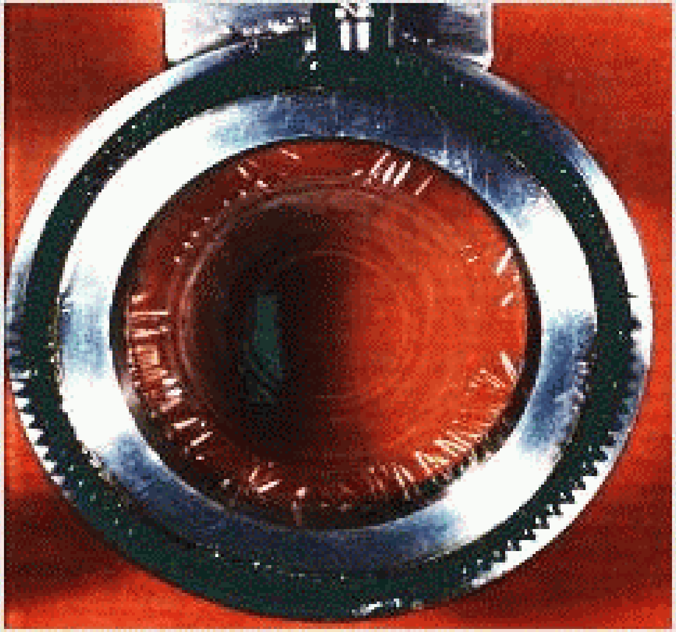
Schematic of HIRA for production of ^{7}Be beam and setup for (^{7}Be,^{8}B) transfer angular distribution measurement

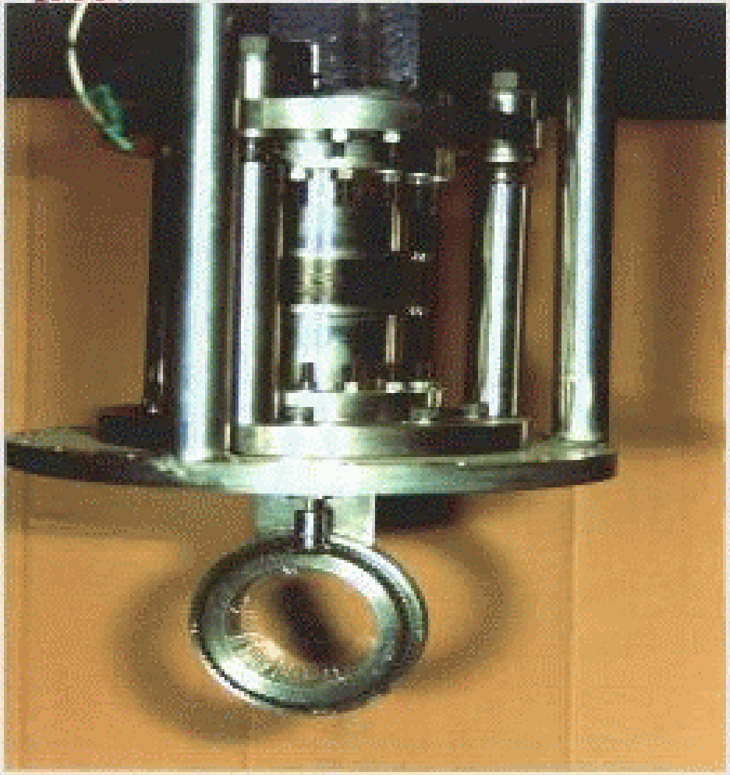


Rotating Target Wheel

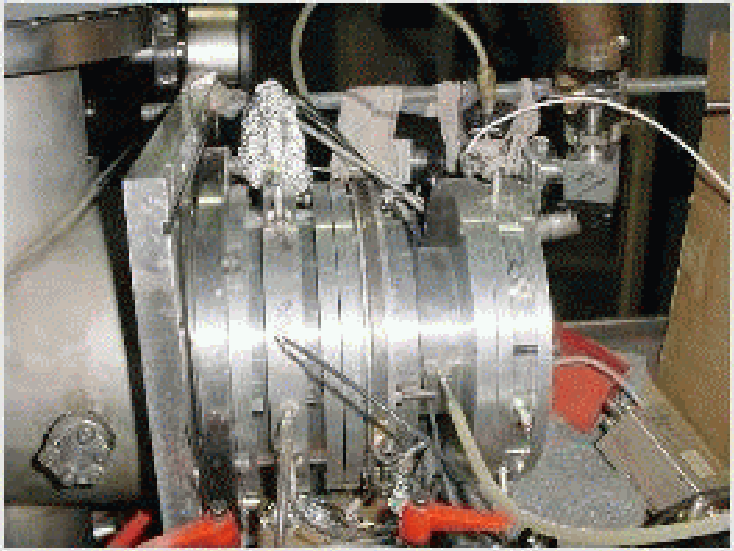
Rotary + linear motion in vacuum

CH_2 foil Life time ~ 120 hours with 5 pna current

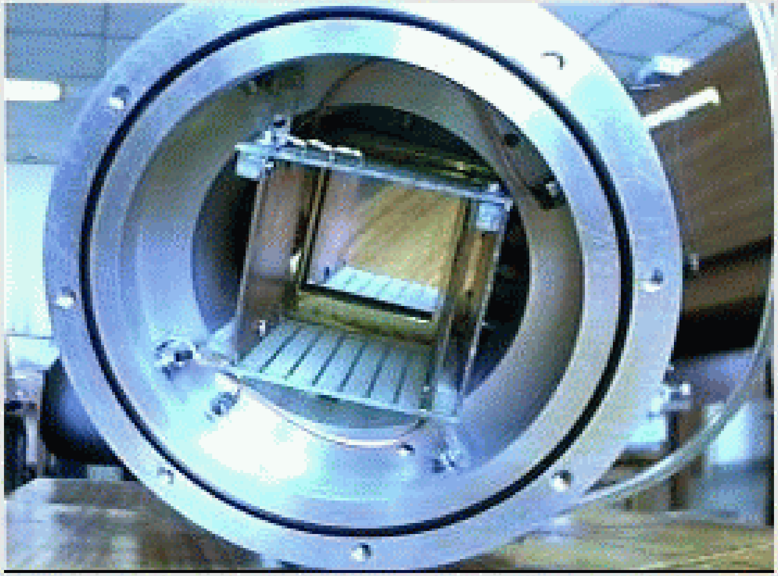




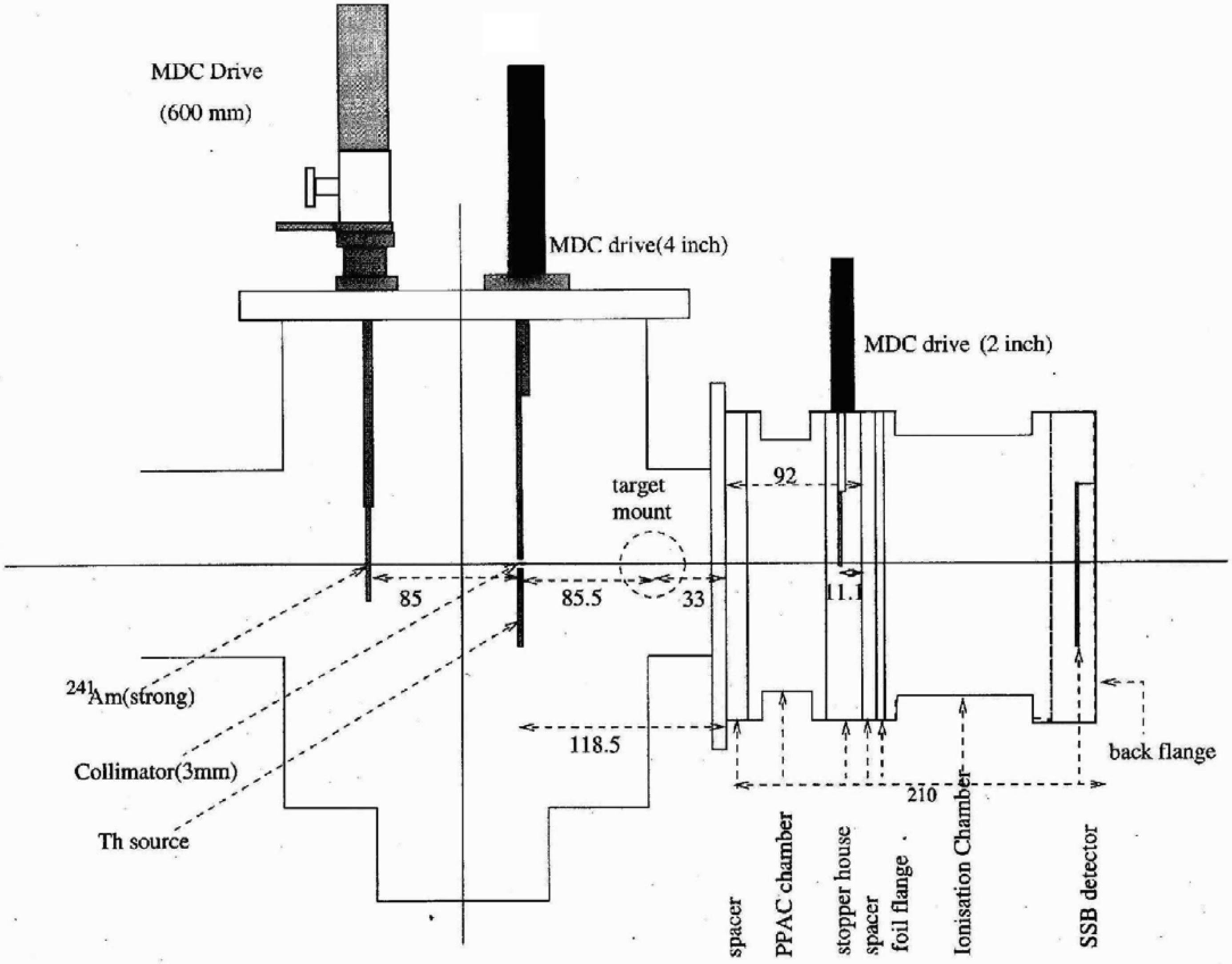
Focal Plane Setup



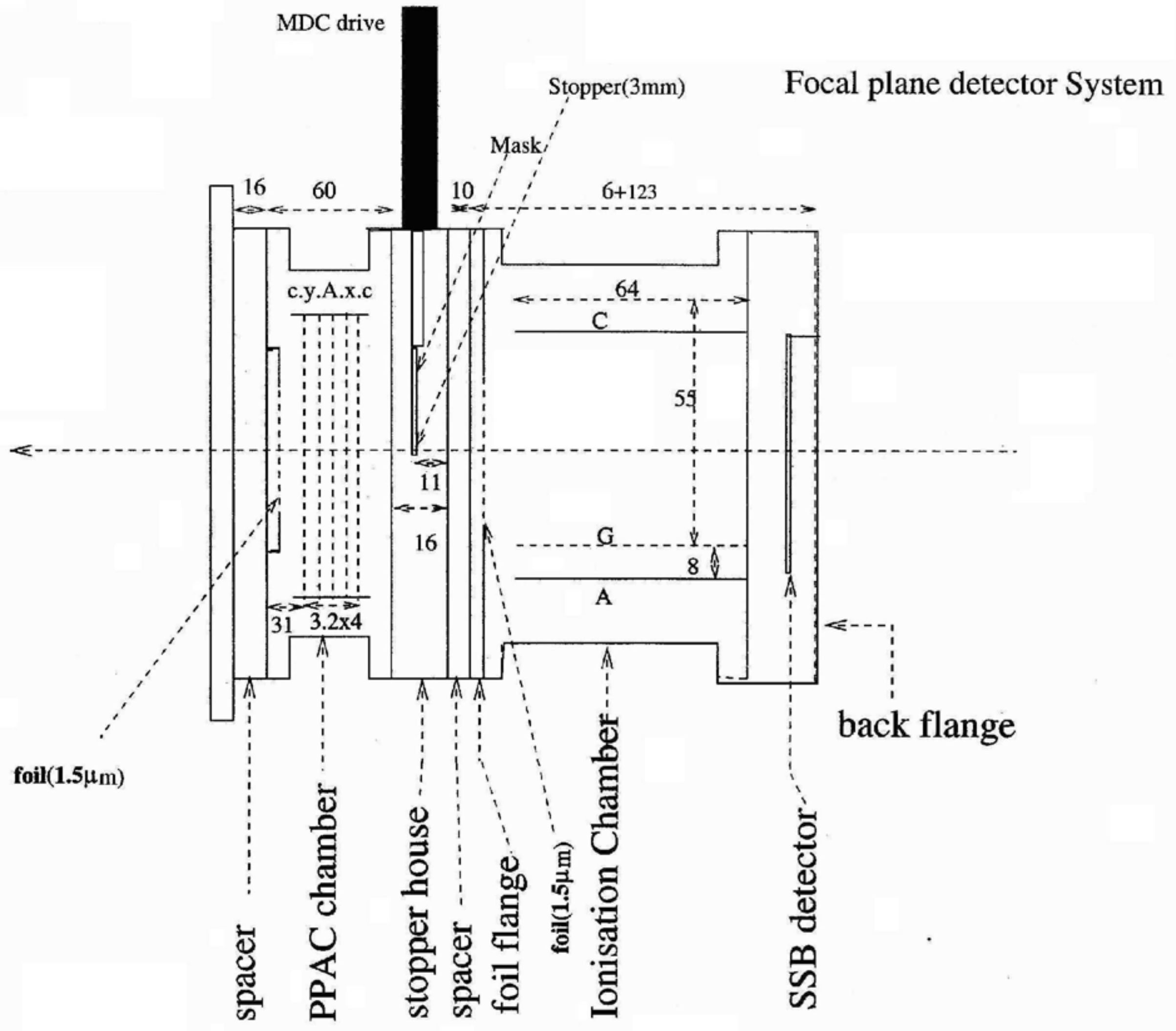
IC



Silicon PSD



Focal plane chamber and the detector system


Focal plane detector System

Position spectrum in Si detector

Figure 2a

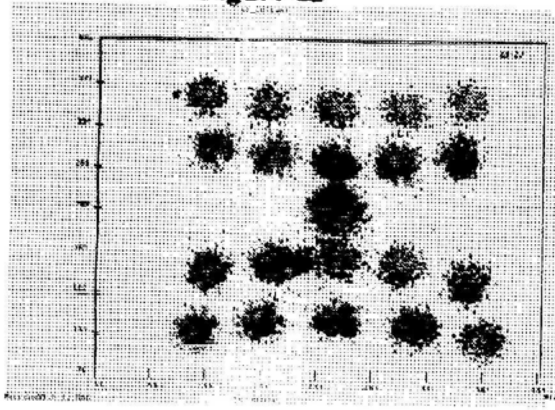
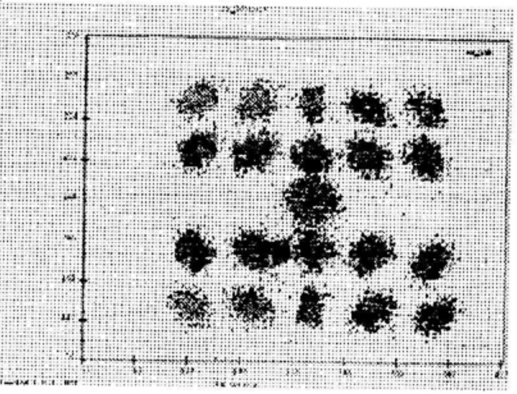


Figure 2b

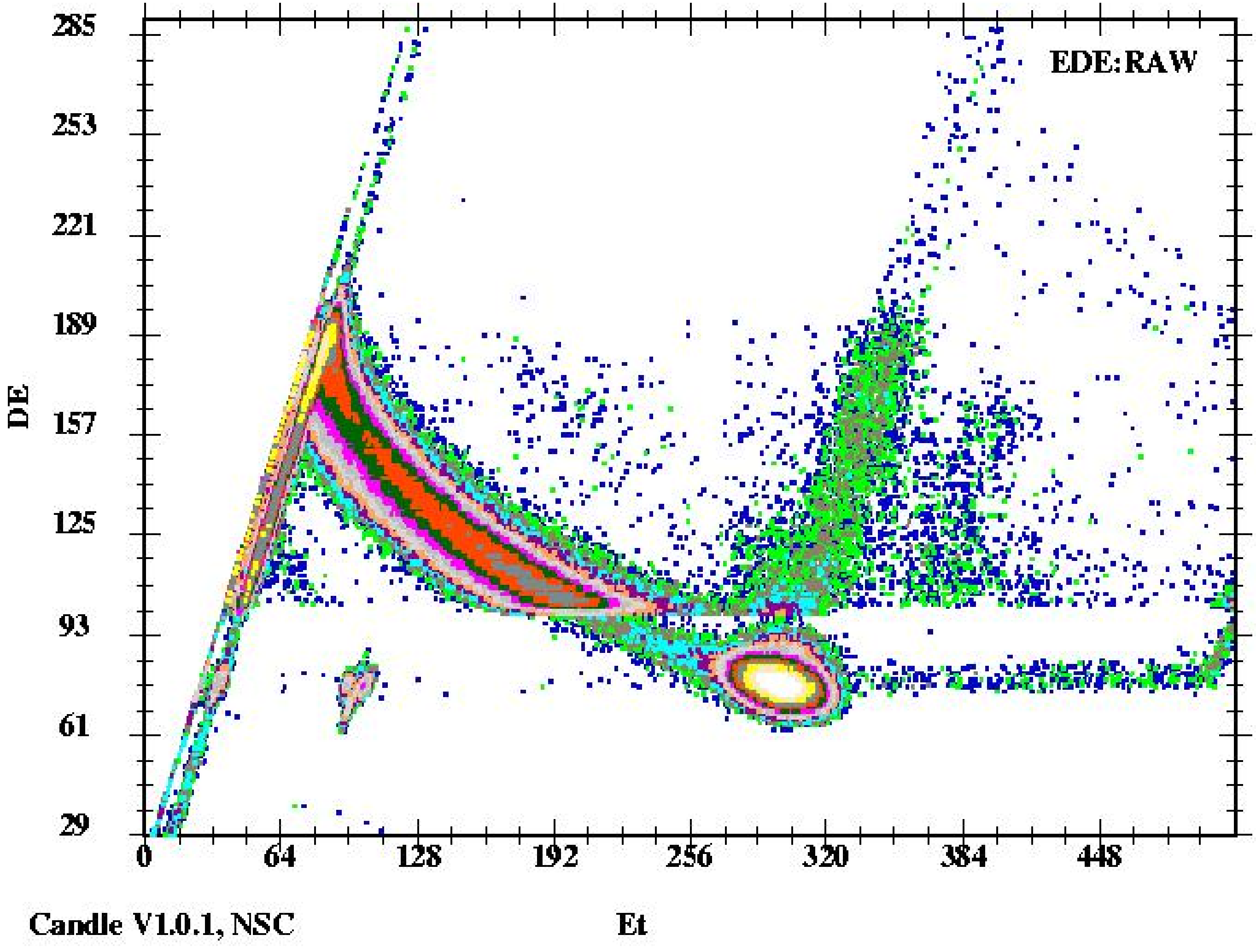


dist. between holes : 8 mm

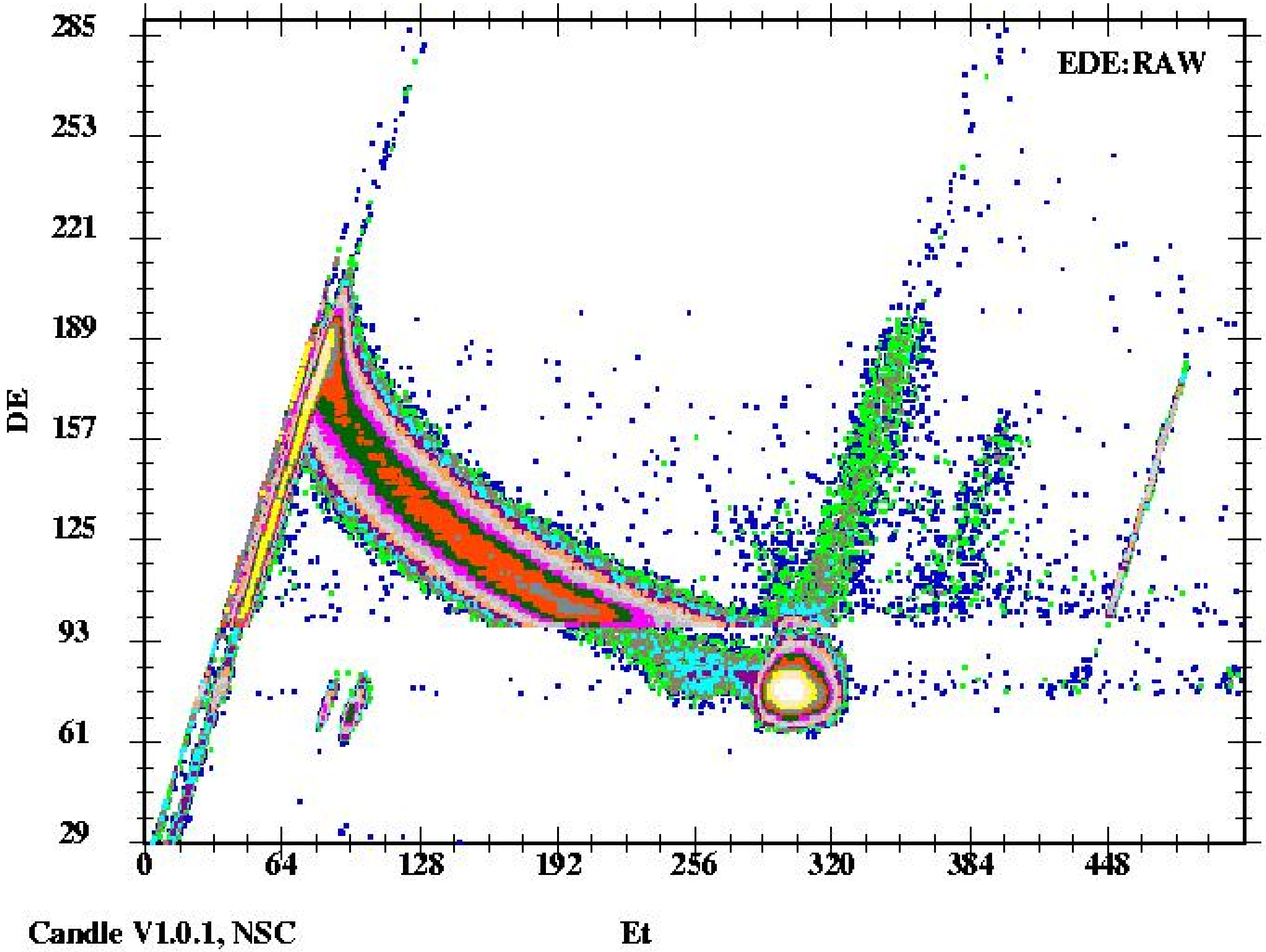
dia of holes 1 mm

except central ~ 2 mm

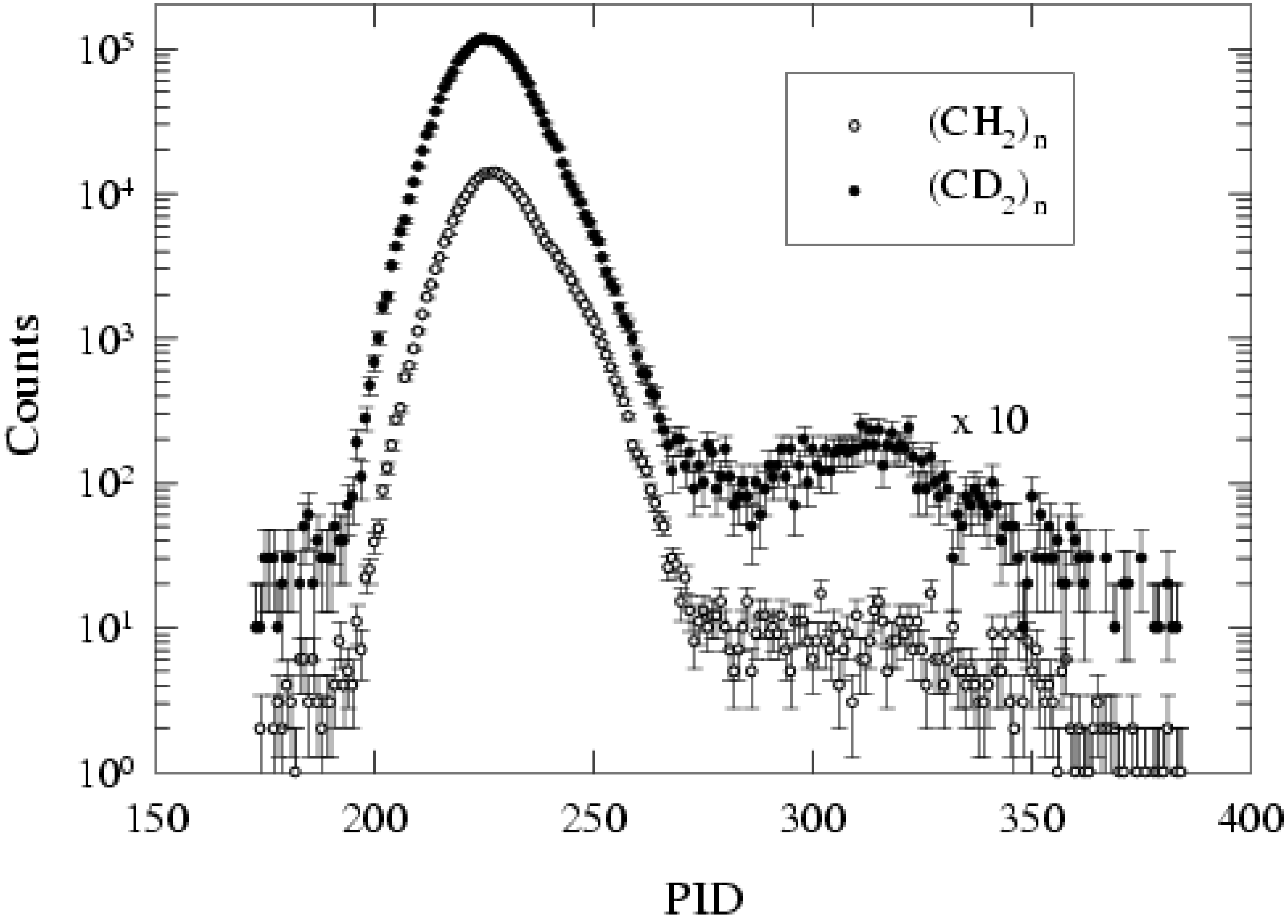
E-DE SPK (raw): CD2 target N(7Be)=13.57 x 10^7

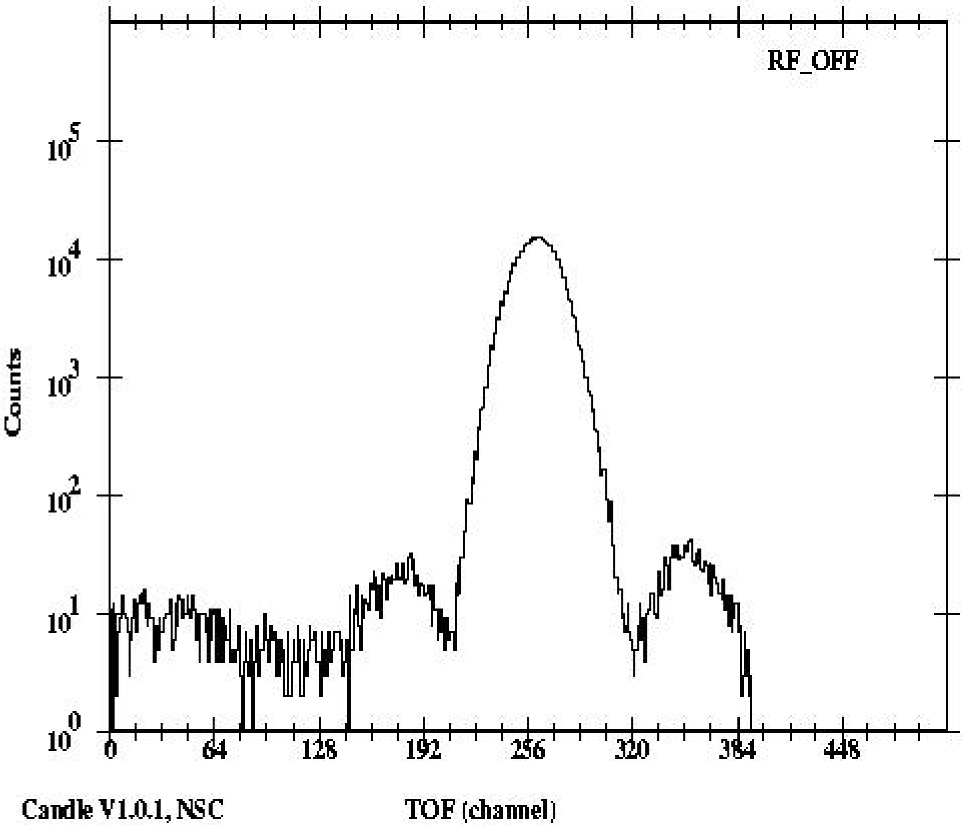


E-DE SPK (raw): CH2 target N(7Be)=13.95 x 10^7

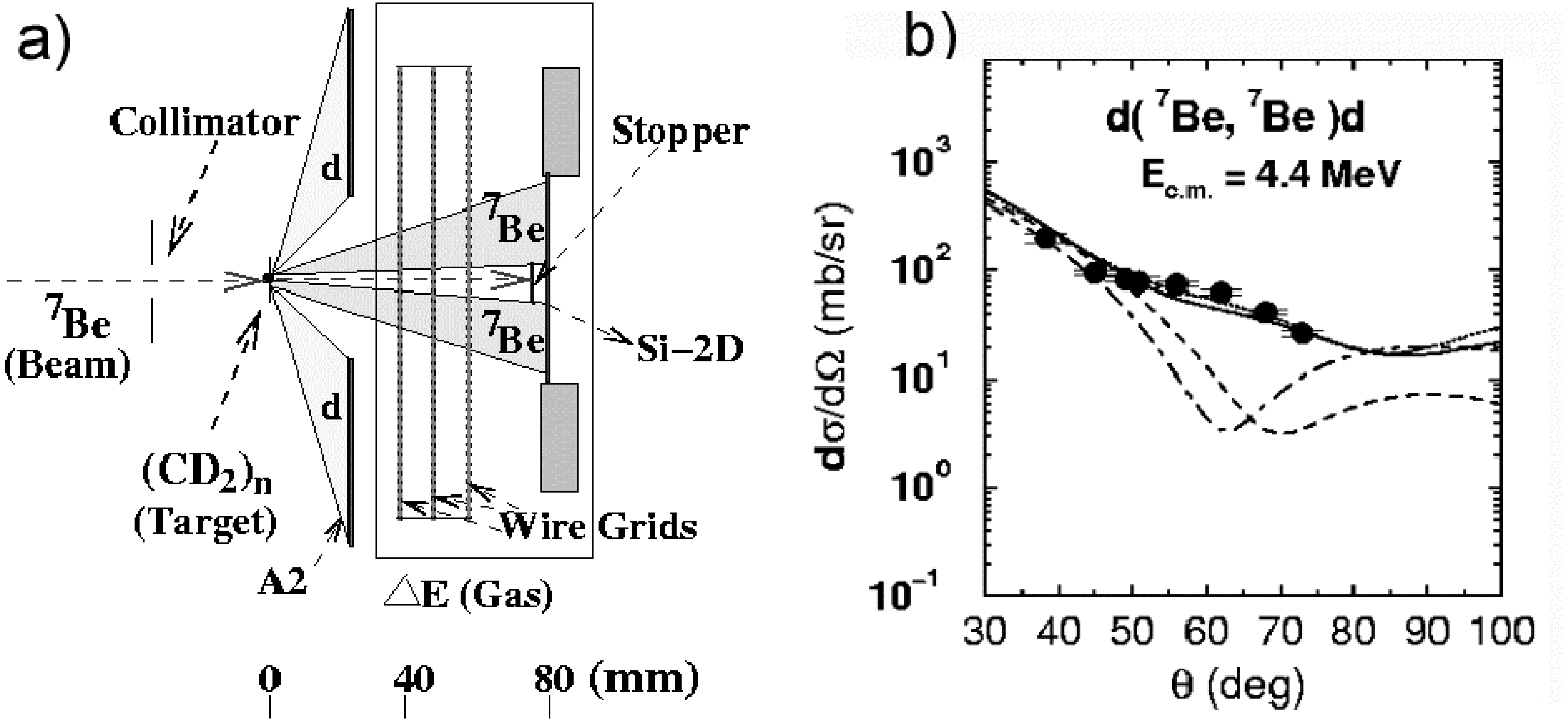


Particle identification spectra for $(CD_2)_n$ and $(CD_2)_n$ targets





TOF Spectra from target to Focal plane of RMS



(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-^{7}Be coincidence eliminates collimator and ^{12}C scattering

- Inelastic excitation to 429 keV state in ^{7}Be not resolved (ΔE~1MeV)
- 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 ($E_{c.m.}$ = 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.

Pot.	V_0	r_0	a_0	$4W_s$	r_s	a_s
	(MeV)	(fm)	(fm)	(MeV)	(fm)	(fm)
S1	103.12	2.23	0.62	79.03	2.37	0.17
S2	107.87	2.17	0.61	58.84	2.28	0.25
S3	92.54	2.41	0.57	117.50	2.45	0.14
S4	121.49	1.97	0.66	54.88	2.38	0.28

n-^{8}B OMP parameters

****

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

****

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+^{9}Be @ 5, 6 MeV, D.N. Loyd, W. Haeberli, NP **A148**, 236 (1970)

Single particle wave function of p - ^{7}Be in ^{8}B

F. C. Barker, Aust. J. Phys. **33**, 177 (1980)

H. Esbensen and G.F. Bertsch, Nucl. Phys. **A600**, 66 (1996)

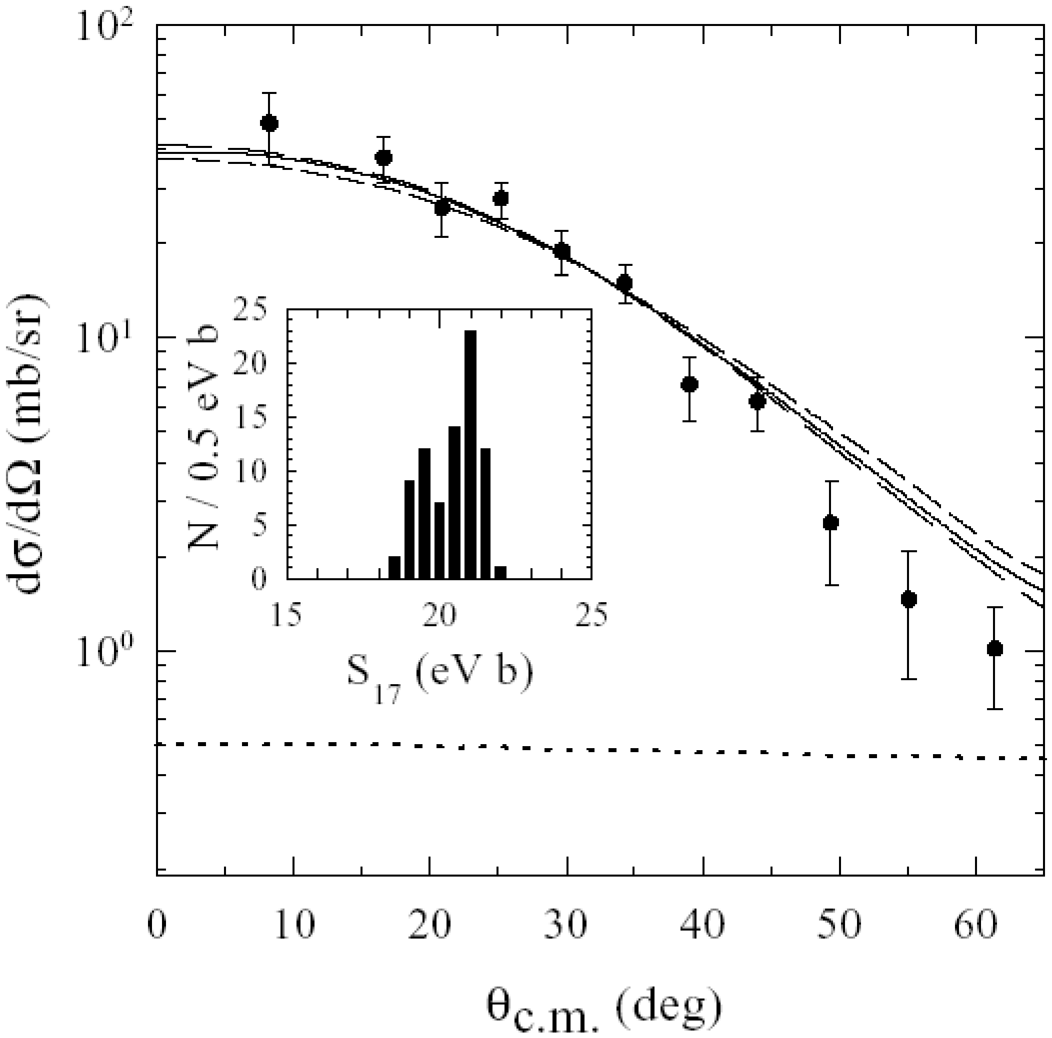
R. G. H. Robertson, Phys. Rev. C **7**, 543 (1973).

T. A. Tombrello, Nucl. Phys. **71**, 459 (1965)

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 (d OMP) x 4 (n OMP) x 5 (p-^{8}Be bound state pot.) ⇒ 80 calc.

- Only data at $\theta_{c.m.} \leq 45°$ used
- Compound nuclear contribution to d(^{7}Be,^{8}B)n calculated using Hauser Feshbach code (Suresh Kumar). Uncertainty in σ_{CN} estimated to be ±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}Be,^{8}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*

# of data points	$S_{17}(0)$ expt.
3	22.32±2.66 ±0.58
5	22.72 ±1.78 ±0.67
8	20.66 ±1.33 ±0.86
11	18.45 ±1.20 ±1.04

Including correction from p-^{7}Be scattering length (~1%)

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

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

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

$S_{17}(0) = 19^{+4}_{-2}$ eV.barn

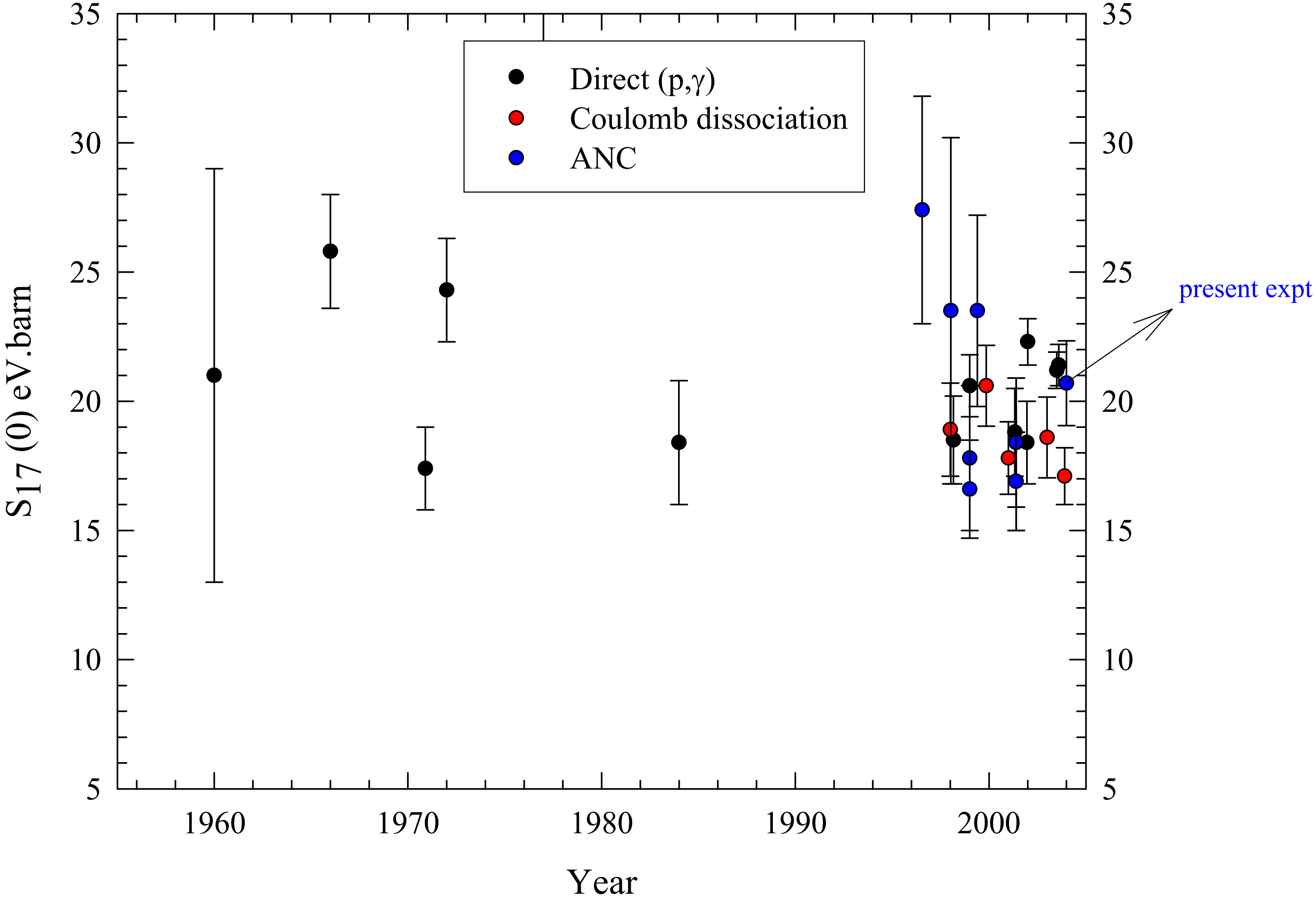
Not included

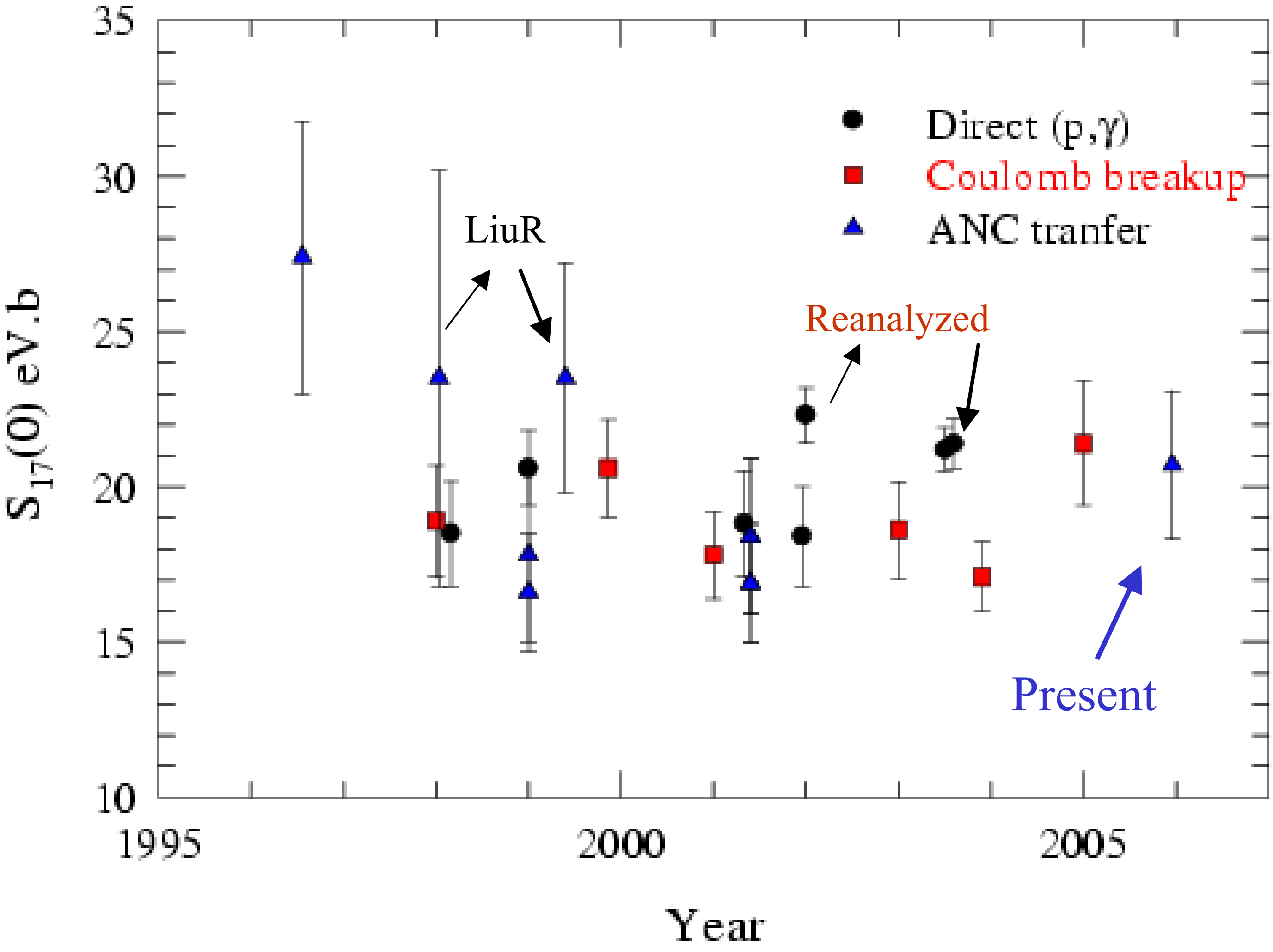
- multistep processes (inelastic+transfer, breakup fusion)
- core excitation

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

Accepted for publication in Phys. Rev. C

$S_{17}(0)$ from direct and indirect measurements





Direct (p,γ)
Coulomb breakup
ANC tranfer
LiuR
Reanalyzed
Present
$S_{17}(0)$ eV.b
Year
35
30
25
20
15
10
1995
2000
2005

- Possible improvements ?

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

Conclusions of S_{17} (0) measurement

- Extracted S_{17} (0) competitive with other methods
- Useful for other (p,γ) S-factors with short lived nuclei with precision ~ direct capture measurements

Other possibilities

- $^{13}C(p,\gamma)$ through $^{13}C(d,n)^{14}N$ reaction
- $^{15}N(p,\gamma)$ and $^{15}N(p,\alpha)$ through proton transfer reaction
- $^{16,17,18}O(p,\gamma)$,,
- $^{19}F(p,\gamma)$ and $^{19}F(p,\alpha)$,,
- $^{20}Ne(p,\gamma)$,,

Remember the case of ^{14}N(p,γ) where new S-factor was

about half of then accepted value.

Schroder et al., Nucl.Phys. **A467**, 240 (1987) *(p,γ) expt.*

Angulo et al., Nucl.Phys. **A690**, 755 (2001) *reanalysis with res.*

Mukhamedzhanov et al., Phys. Rev. **C67**, 065804 (2003) ANC

Runkle et al., arXiv:nucl-ex/0408014 for rad.capture *(p,γ) expt.*

Collaboration

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A. Ray – *Variable Energy Cyclotron Centre, Kolkata*

R.G. Kulkarni – *Saurashtra University, Rajkot*

R. Shyam – *Saha Institute of Nuclear Physics, Kolkata*

Acknowledgements

G.K. Mehta, C.V.K. Baba, E.T. Subramaniam, R.K. Bhowmik, S.K. Datta, A. Roy (IUAC),

D. Beaumel (IPN), Suresh Kumar, D.R. Chakrabarty, S. Kailas (BARC, Mumbai)

Thank you