Status of the Standard Solar Model and Predictions for Solar Neutrino Fluxes

Moshe Gai
University of Connecticut and Yale University

1. **The Standard Solar Model**
   Helioseismology, Chemical Composition

2. **The Standard Solar Model**
   Nuclear Physics/ Radioactive Beam, GSI, RIKEN

3. **Future Prospects for New Physics**
   pp Neutrinos

Korean Physical Society/ LENS, October 20, 2005

The Laboratory for Nuclear Science At Avery Point


Laboratory for
Astrophysics
1084 Shennecossett

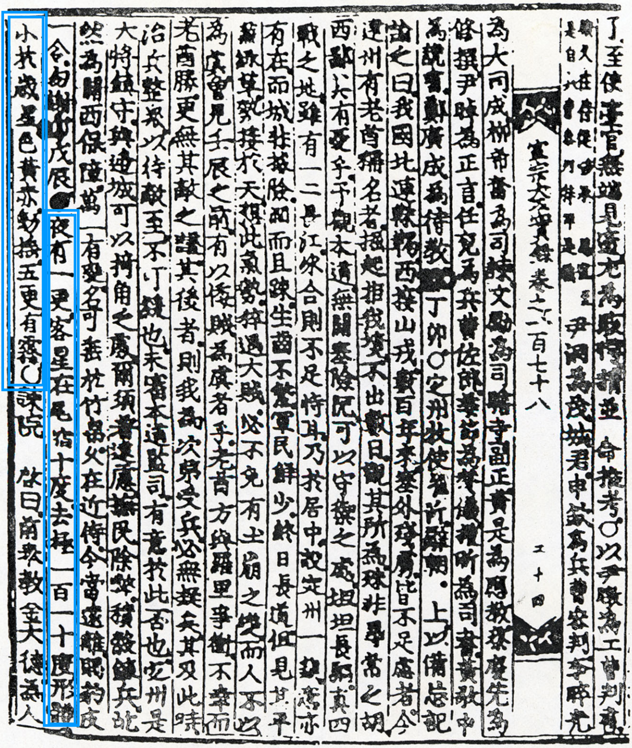


그림 3 손님별(초신성)을 발견한 선조조의 왕조실록의 기록.

객성을 발견한 당시의 생생한 기록이 있다. 즉 〈夜有一更客星在尾宿十度去極一百一十度形體小於歲星色黃赤動搖五更有霧〉(초저녁 손님별이 미수 10도 거극 1백10도 자리에 있었는데 목성보다 작고 적황색 빛깔로 흔들리고 있었으며 이른 새벽녘에는 안개가 끼었다)로 적고 있다. 『조선왕조실록』은 그뒤 약 1년 동안 객성의 관측을 상세히 기

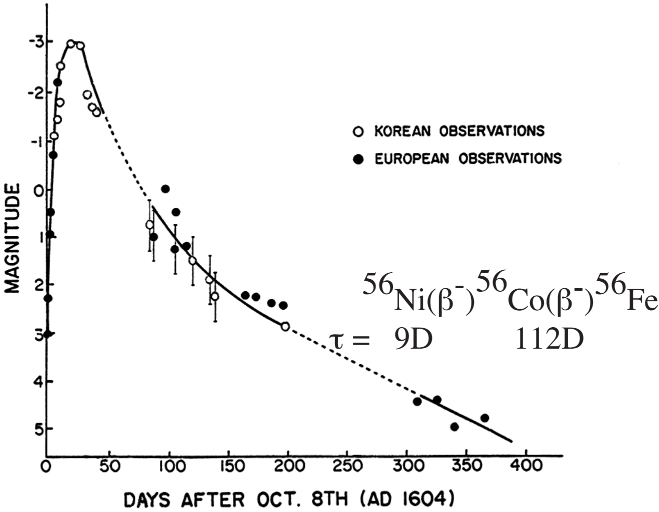

KOREAN OBSERVATIONS
EUROPEAN OBSERVATIONS
MAGNITUDE
-3
-2
-1
0
1
2
3
4
5
0
50
100
150
200
250
300
350
400
DAYS AFTER OCT. 8TH (AD 1604)
56Ni(β-)56Co(β-)56Fe
τ = 9D 112D

그림 3

SNO Salt Phase Result:

$$\Phi_\nu \;=\; 4.94 \pm 0.21\ (\mathrm{stat})\ {}^{+0.38}_{-0.34}(syst)\ \times 10^6\ cm^{-2} sec^{-1} \qquad [1]$$

$$\boxed{\frac{\Phi_{SSM}}{\Phi_\nu} = 1.17} \qquad [2]$$

[1] B. Aharmin *et al.*; nucl-ex/0502021.

[2] J.N. Bahcall and M.H. Pinsonneault; Phys. Rev. Lett. **92**(2004)121301.

SOLAR FUSION

$$^{1}H + {}^{1}H \rightarrow {}^{2}D + e^{+} + \boxed{\nu_e}$$
$$^{2}D + {}^{1}H \rightarrow {}^{3}He + \gamma$$
$$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\,{}^{1}H$$

PPI - 86%

$$^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$$
$$^{7}Be + e^{-} \rightarrow {}^{7}Li + \boxed{\nu_e}$$
$$^{7}Li + {}^{1}H \rightarrow 2\,{}^{4}He$$

PPII - 14%

$$^{7}Be + {}^{1}H \rightarrow {}^{8}B + \gamma$$
$$^{8}B \rightarrow {}^{8}Be + e^{+} + \boxed{\nu_e}$$
$$^{8}Be \rightarrow 2\,{}^{4}He$$

PPIII - 0.01%

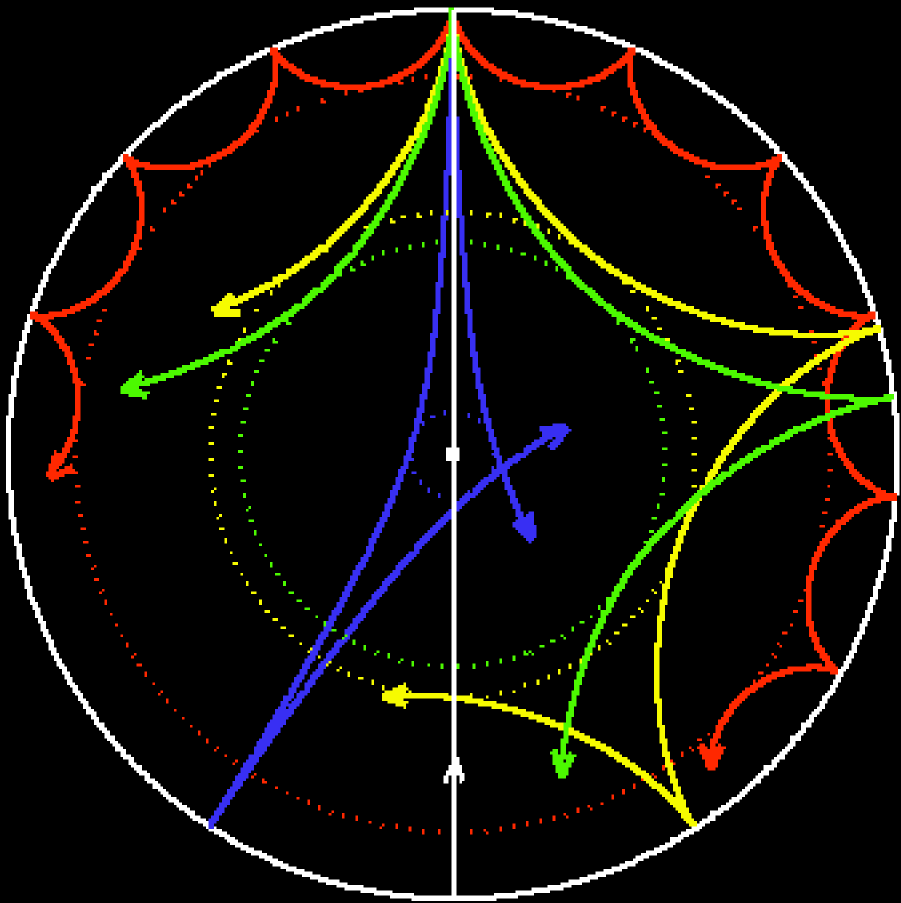
Surface Composition of the Sun:

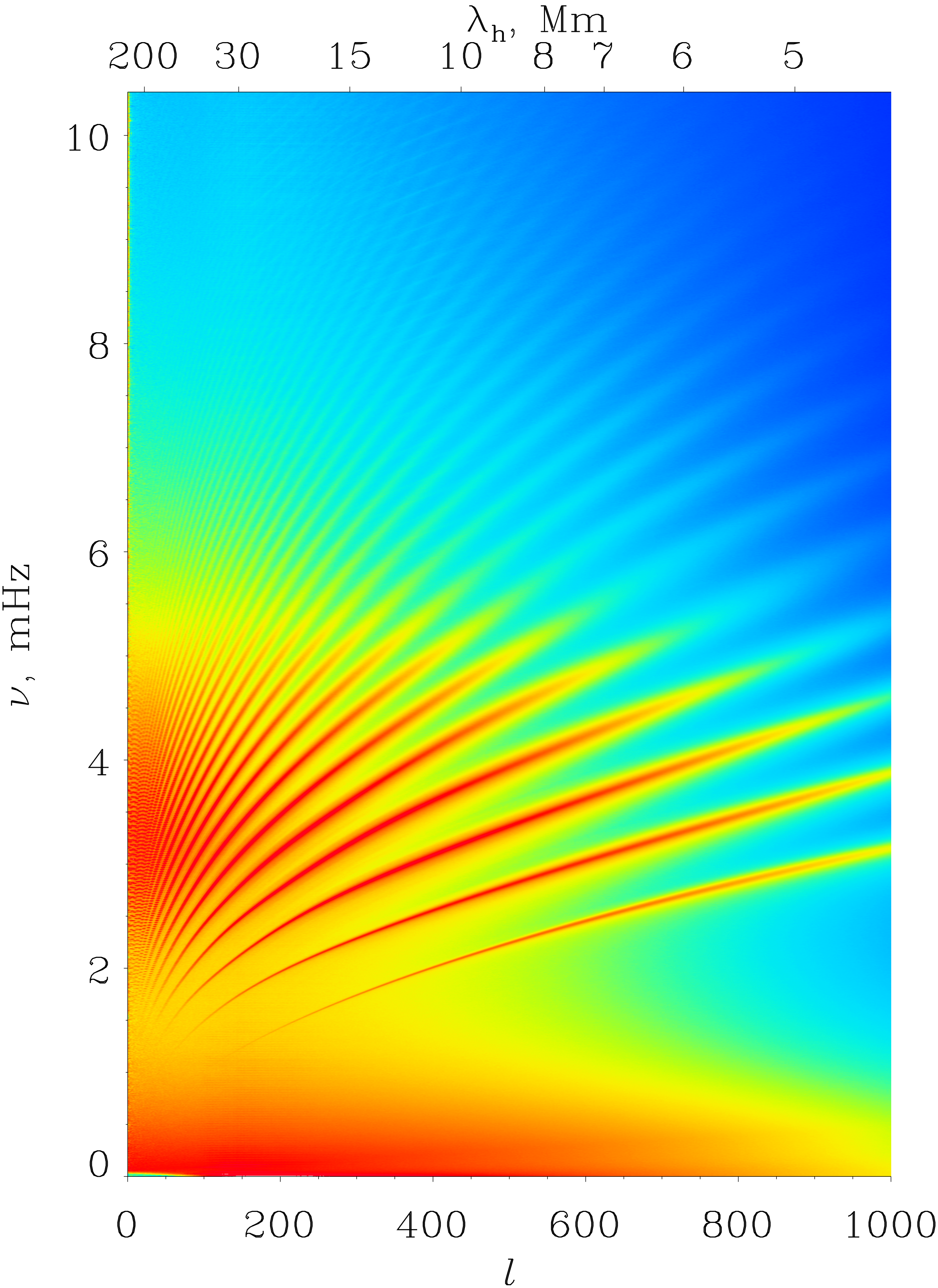
$$X + Y + Z = 1$$

P + He + Heavy

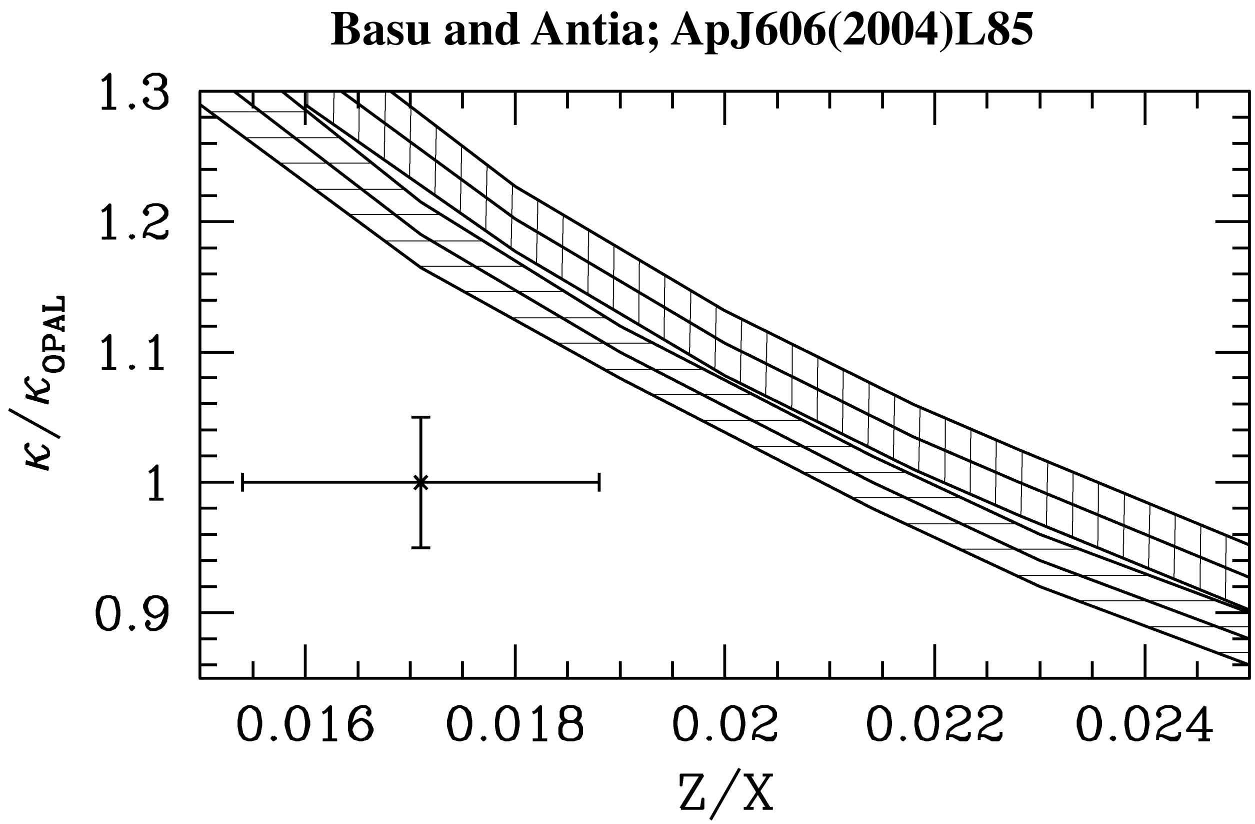
BS05 Fractional Uncertainties

Source	^{8}B	^{7}Be
p-p	0.01	0.004
$^{3}He + ^{3}He$	0.02	0.02
$^{3}He + ^{4}He$	0.08	0.08
$p + ^{7}Be$	0.04	0.00
Composition	0.12	0.05
Opacity	0.05	0.03
Diffusion	0.04	0.02
Luminosity	0.03	0.01





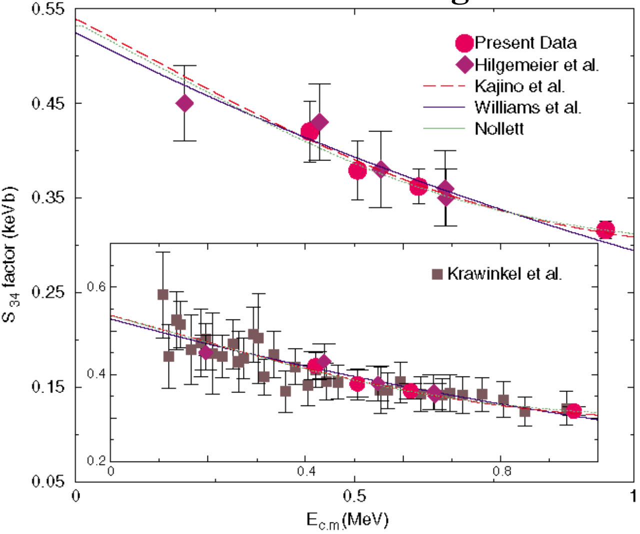
λ_h, Mm
200 30 15 10 8 7 6 5
ν, mHz
0 2 4 6 8 10
0 200 400 600 800 1000
l

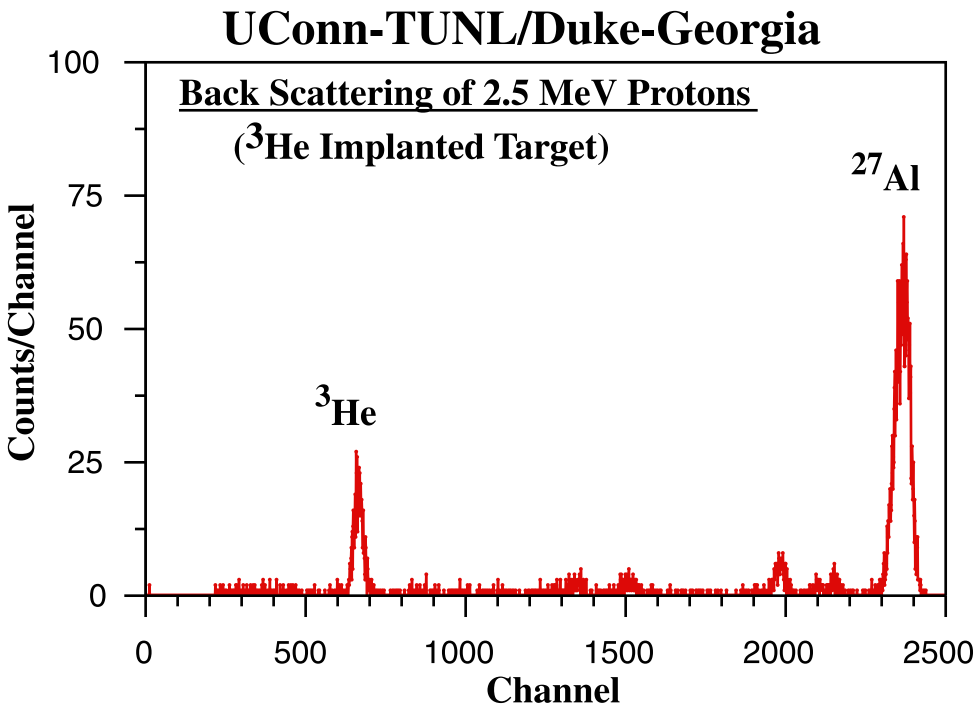


Basu and Antia; ApJ606(2004)L85
1.3
1.2
1.1
1
0.9
κ/κ_OPAL
0.016
0.018
0.02
0.022
0.024
Z/X

Weizmann Result, 2004

$^3He + ^4He \longrightarrow ^7Be + gamma$

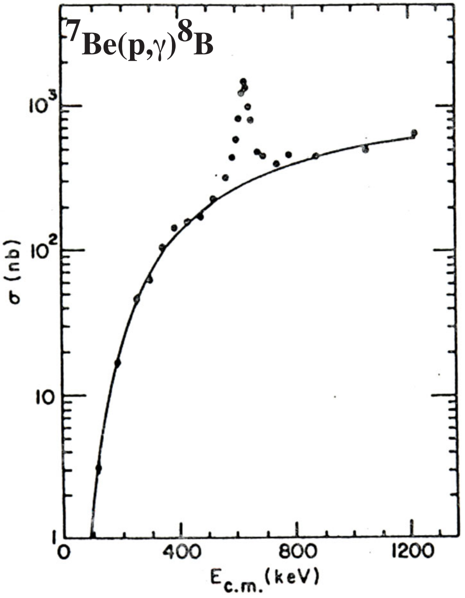



UConn-TUNL/Duke-Georgia
Back Scattering of 2.5 MeV Protons
(3He Implanted Target)
27Al
3He
Counts/Channel
Channel
0
25
50
75
100
0
500
1000
1500
2000
2500

$$\sigma_{17} = S_{17}/E \times e^{-2\pi\eta}$$

$(\eta = Z_1 Z_2 \alpha/\beta)$ $E_{cm} = 18$ keV

Fillipone(1983)



Seattle Result on ^7Be + p $\longrightarrow$ ^8B + γ:

$$S_{17}(0) = 21.4 \pm 0.5 \text{ (expt)} \pm 0.6 \text{ (theory) eV-b} \qquad [1]$$

Previous Compilation:

$$S_{17}(0) = 19 \text{ +4 -2 eV-b} \qquad [2]$$

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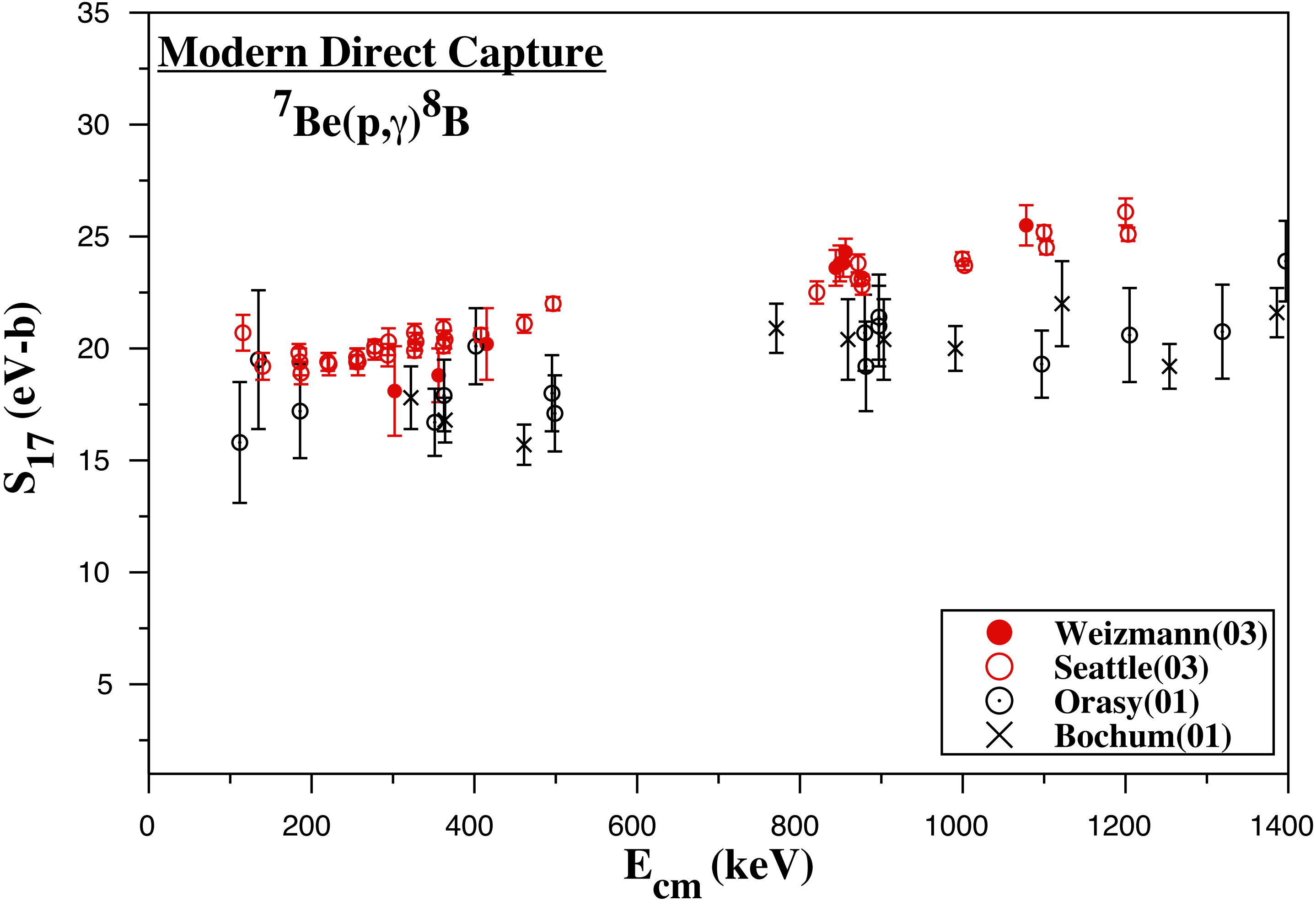
[1] A.R. Junghans *et al.*; Phys. Rev. **C68**(2003)065803.

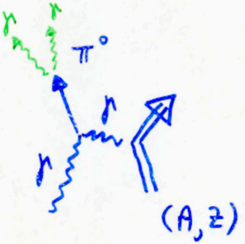
[2] E.G. Adelberger *et al.*; rev. Mod. Phys. **70**(1998)1265.

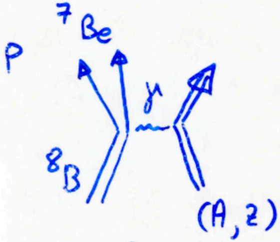


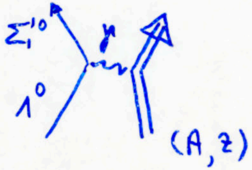
Modern Direct Capture
$^7Be(p,\gamma)^8B$
S_{17} (eV-b)
E_{cm} (keV)
Weizmann(03)
Seattle(03)
Orasy(01)
Bochum(01)
0
200
400
600
800
1000
1200
1400
5
10
15
20
25
30
35

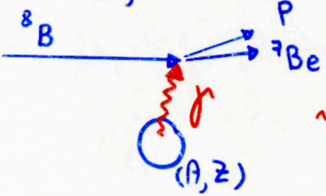
CAPTURE REACTION: $^7Be + p \rightleftarrows {}^8B + \gamma$

PRIMAKOFF (1951):







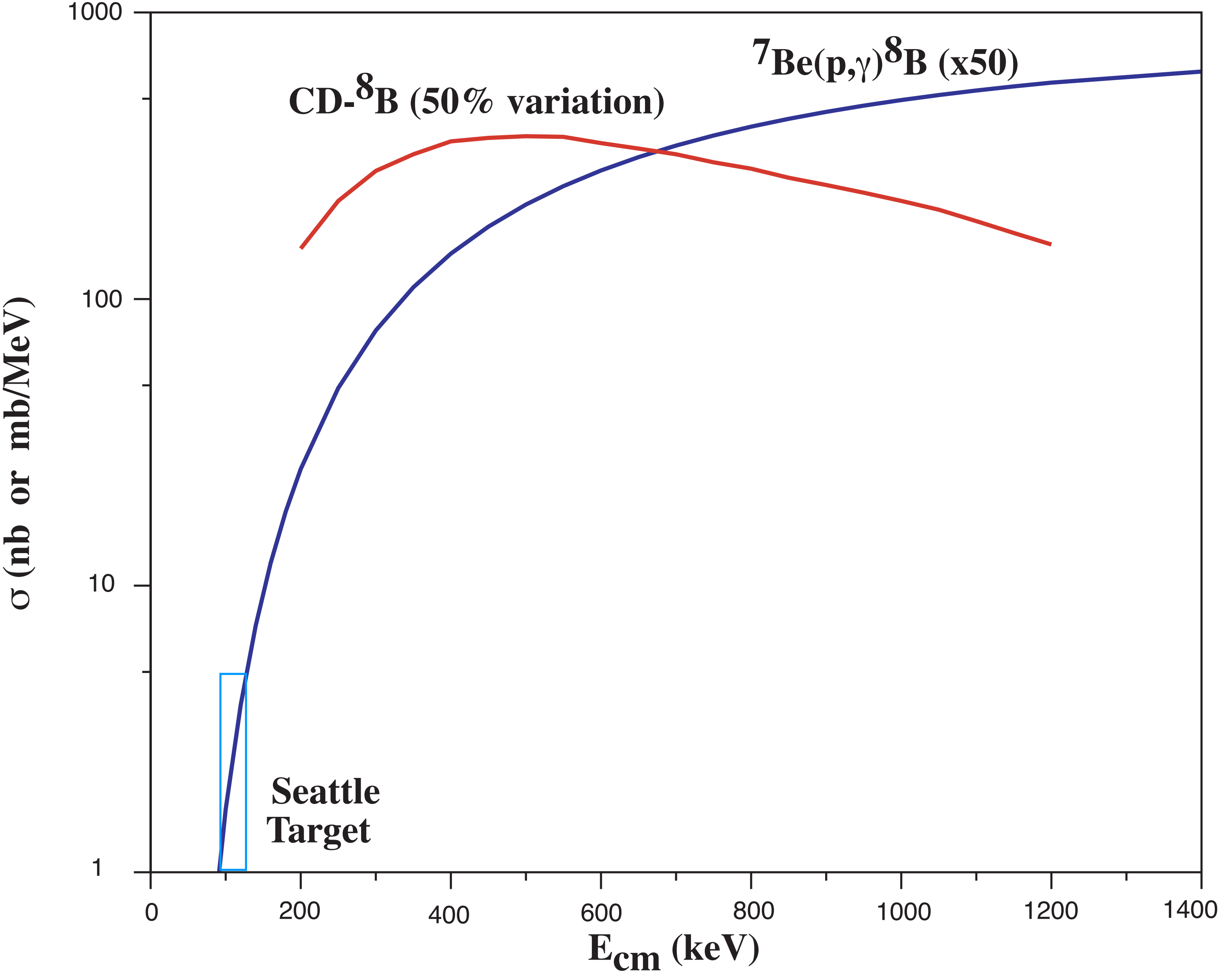


~ 40 fm !!

ENHANCEMENT: (I) $\pi/k^2 \gtrsim 1{,}000$

(II) $n_\gamma(E1) \gtrsim 1000$

BAUR, BERTULANI, REBEL - 1986



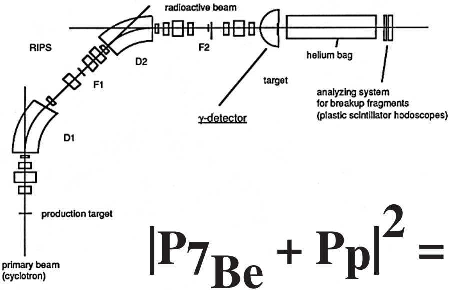
1000
100
10
1
0
200
400
600
800
1000
1200
1400
σ (nb or mb/MeV)
E_{cm} (keV)
CD-^{8}B (50% variation)
^{7}Be(p,γ)^{8}B (x50)
Seattle
Target

^{8}B Breakup 実験覚え書き

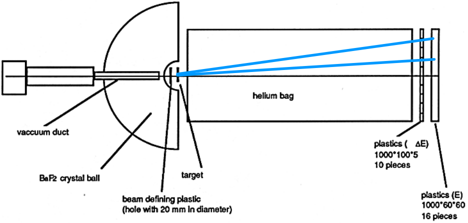
RIKEN - RIPS

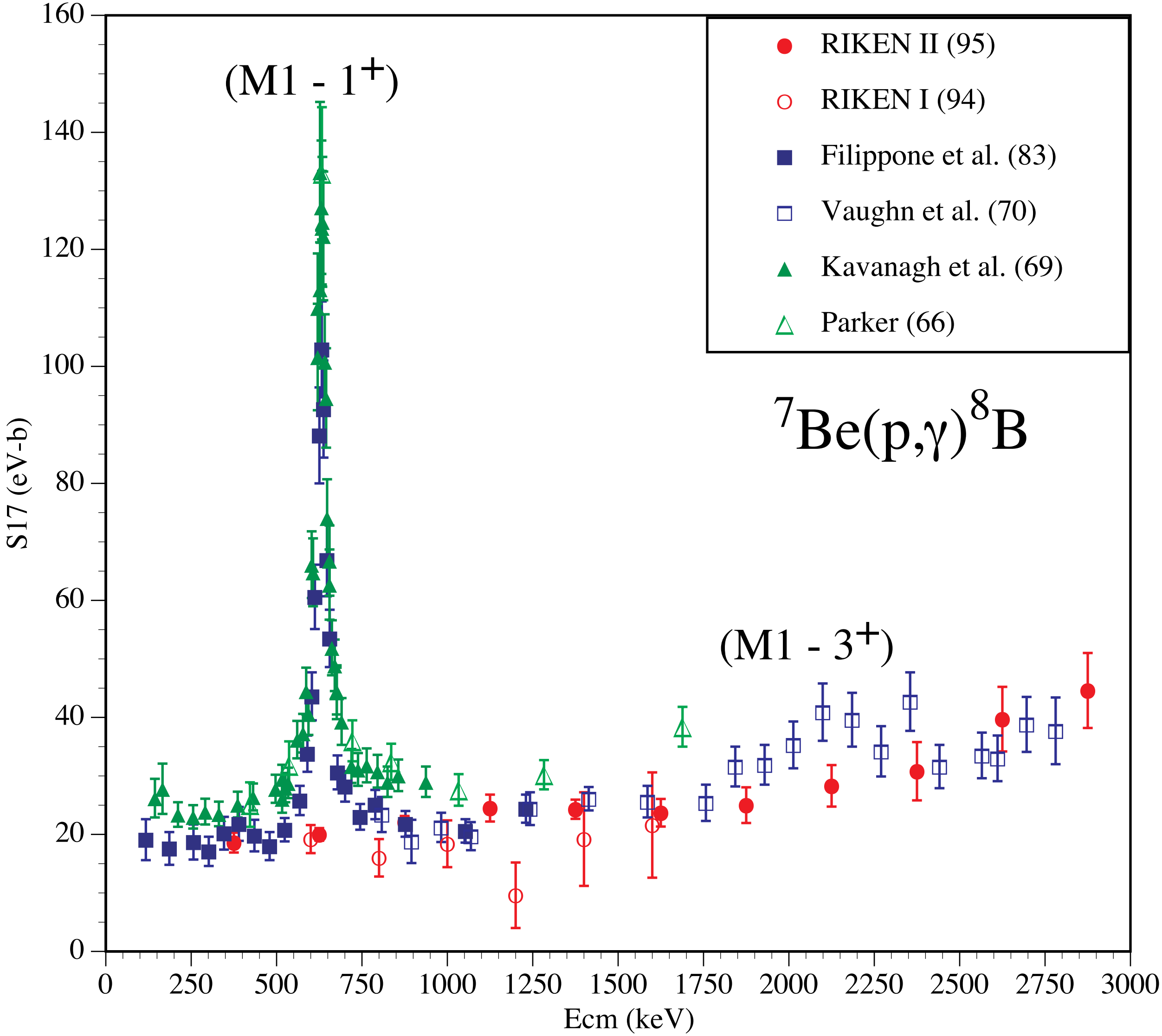
20 Mar. 1992 本林

setup



$$|P_{^7Be} + P_p|^2 = M^2$$

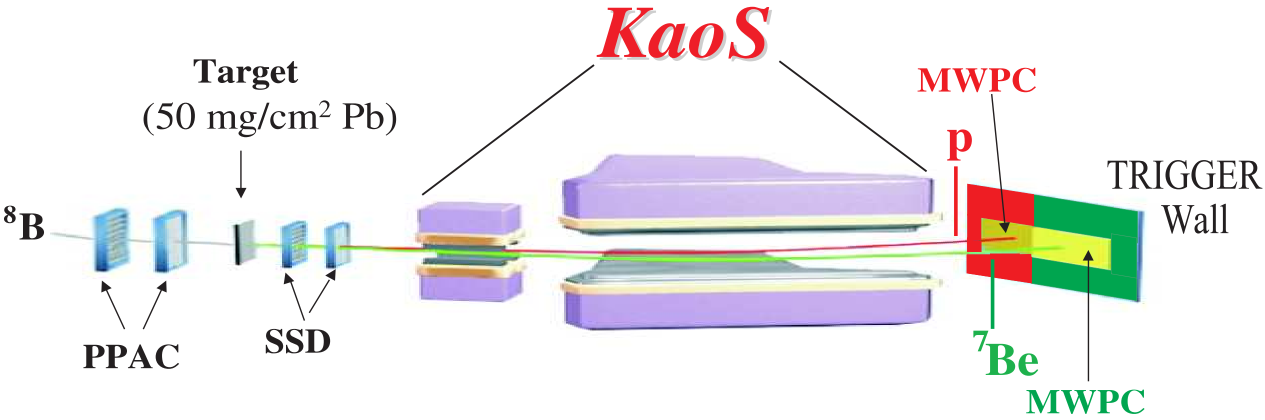


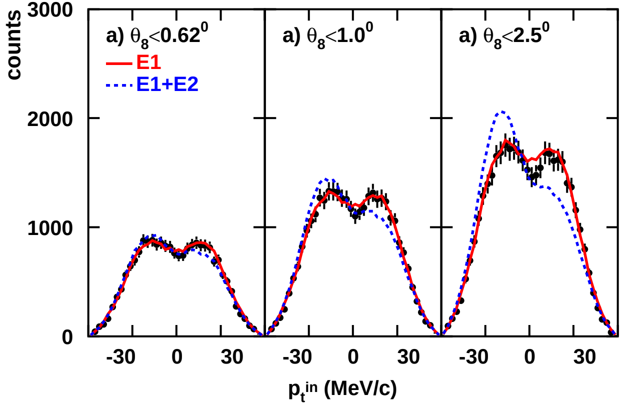


RIKEN II (95)
RIKEN I (94)
Filippone et al. (83)
Vaughn et al. (70)
Kavanagh et al. (69)
Parker (66)
(M1 - 1+)
(M1 - 3+)
7Be(p,γ)8B
S17 (eV-b)
Ecm (keV)
0
20
40
60
80
100
120
140
160
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
2750
3000

When a Dog Speaks it Does Not Matter What it Says.

Igal Talmi


KaoS
Target
(50 mg/cm2 Pb)
8B
PPAC
SSD
MWPC
p
TRIGGER
Wall
7Be
MWPC



counts
3000
2000
1000
0
a) θ8<0.62°
E1
E1+E2
a) θ8<1.0°
a) θ8<2.5°
-30
0
30
pt^in (MeV/c)

COMMENTS

Comments are short papers which criticize or correct papers of other authors previously published in the **Physical Review.** *Each Comment should state clearly to which paper it refers and must be accompanied by a brief abstract. The same publication schedule as for regular articles is followed, and page proofs are sent to authors.*

Comment on "$E2$ contribution to the $^8B \rightarrow p + {}^7Be$ Coulomb dissociation cross section"

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(Received 25 May 1994)

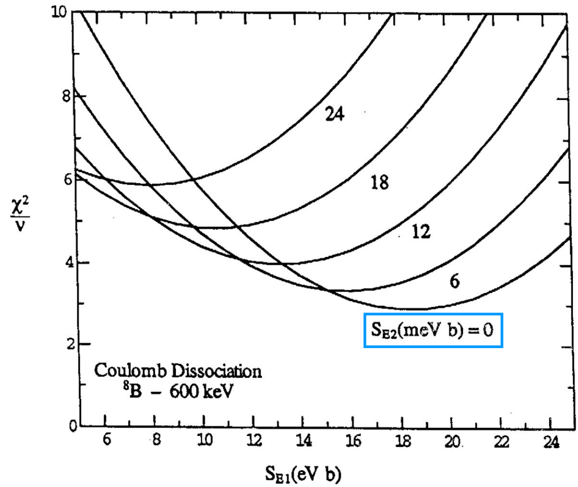
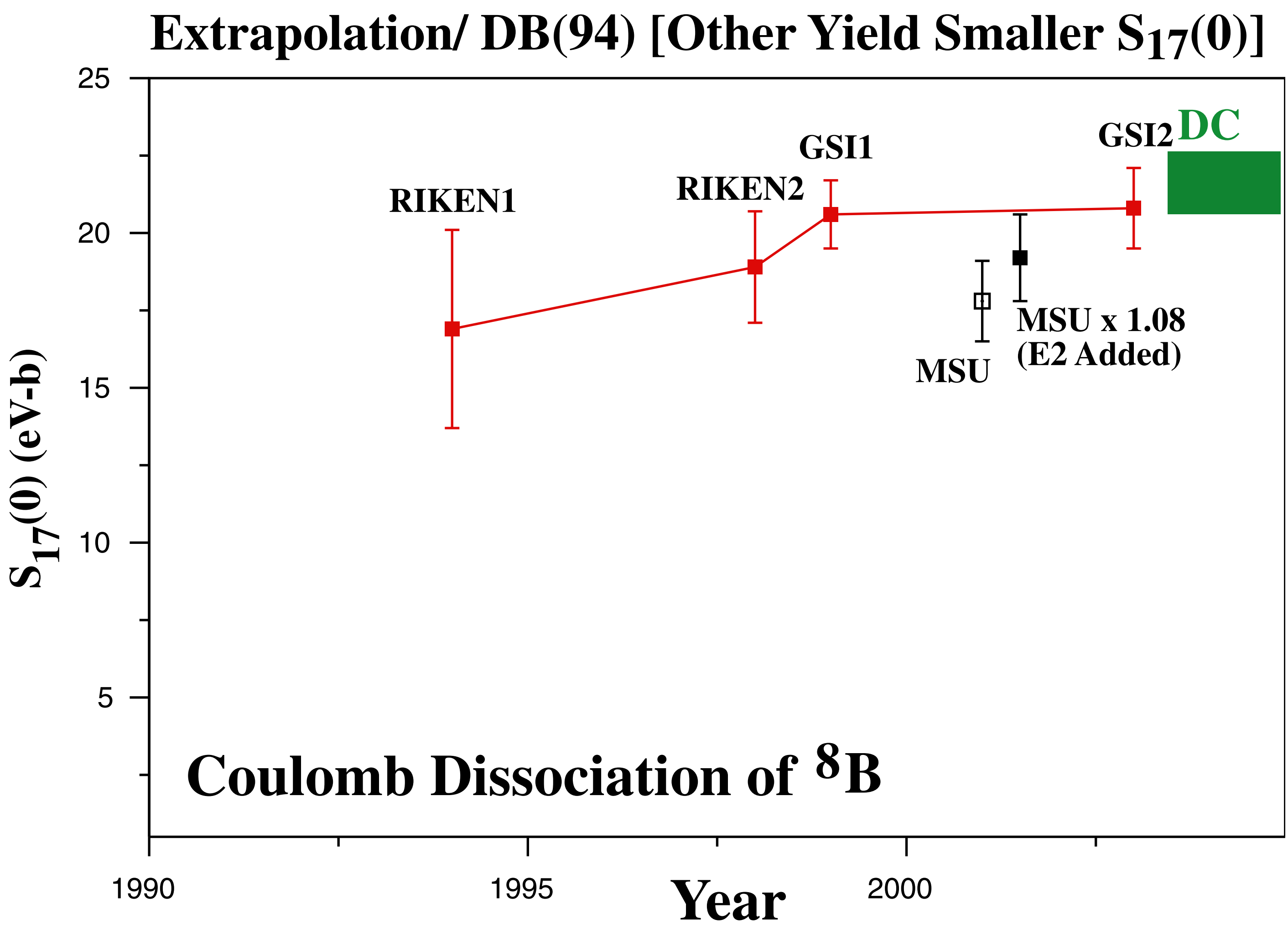
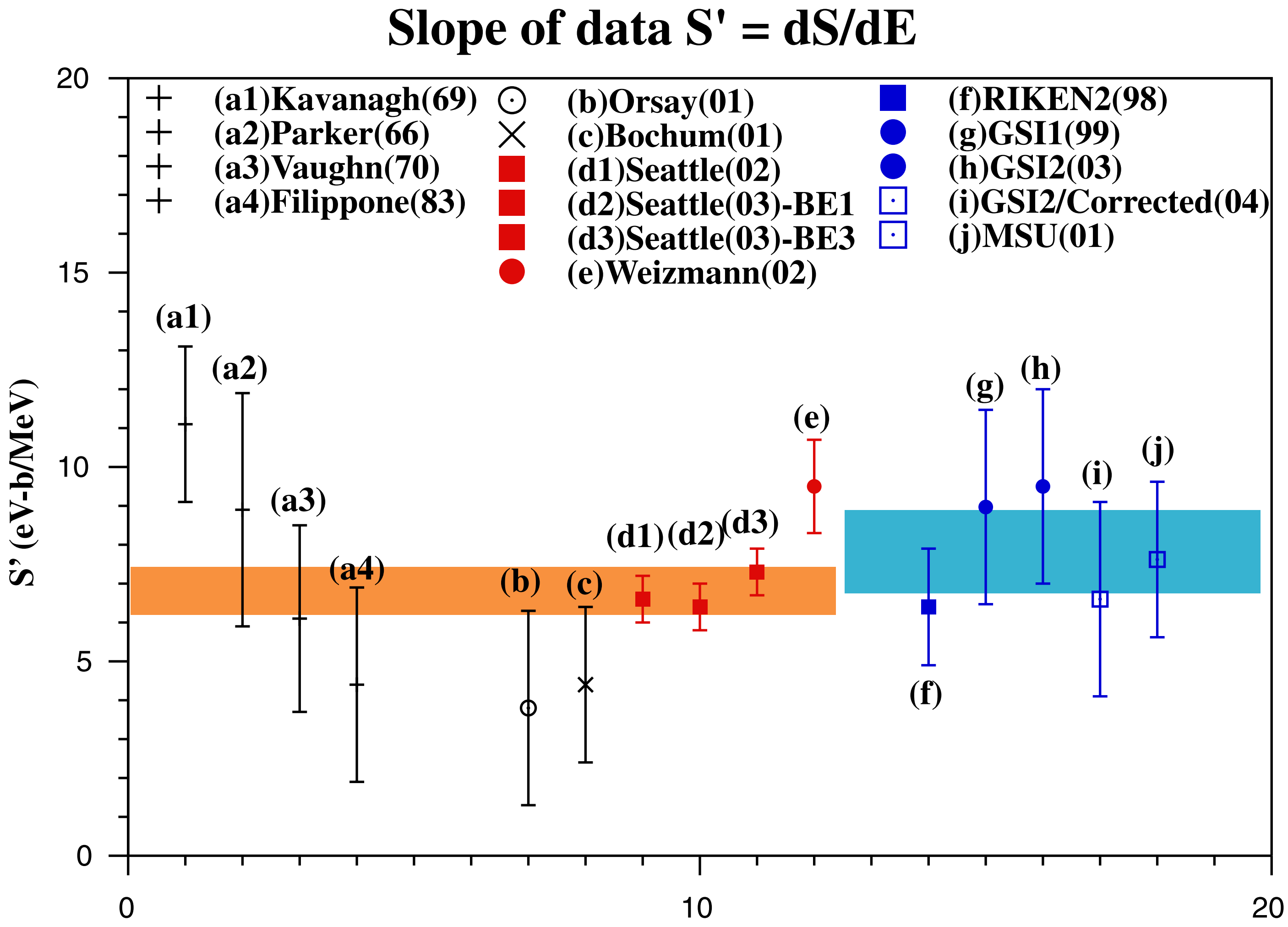


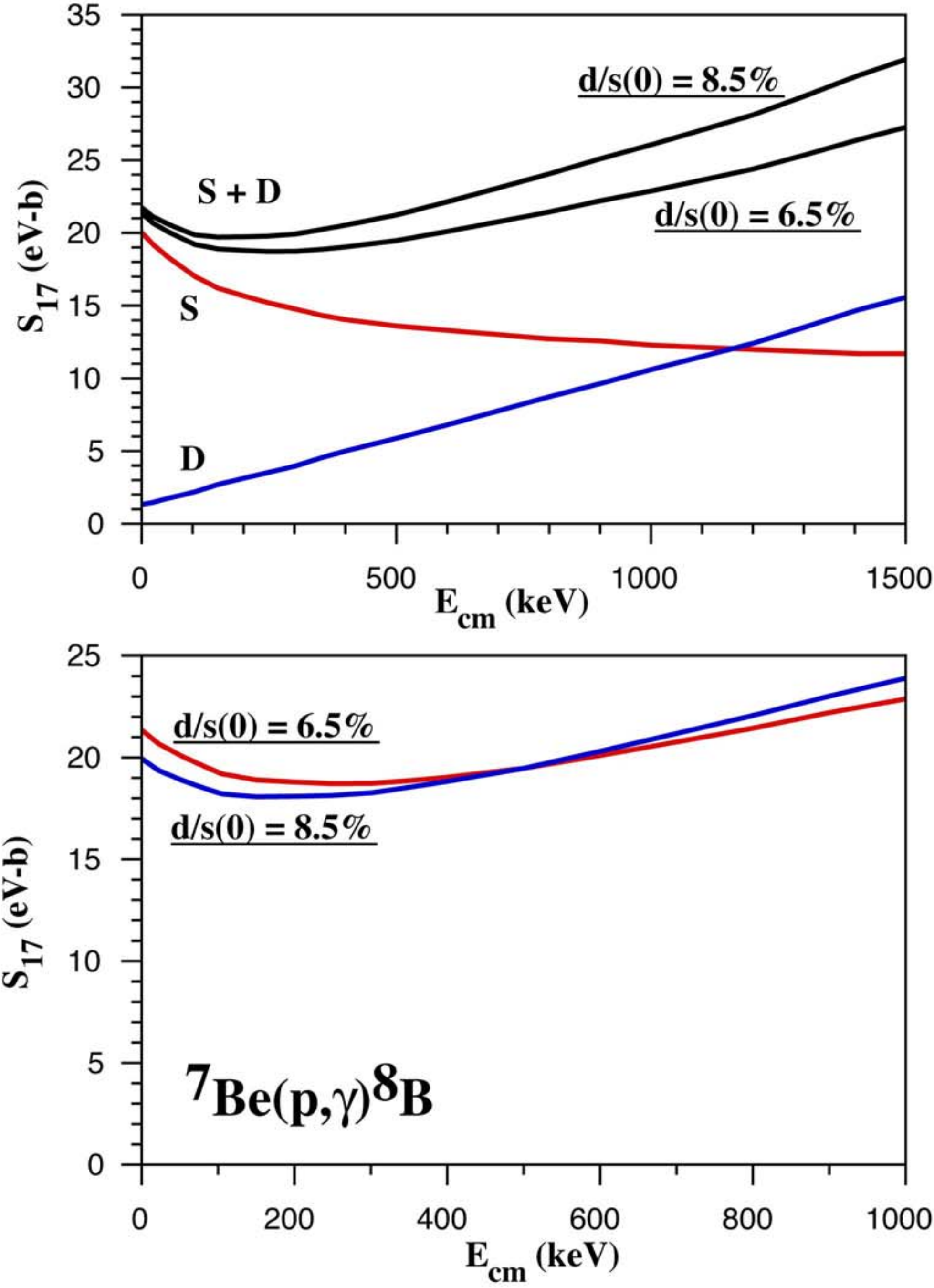
FIG. 1. The reduced χ^2 obtained from fitting the 600 keV angular distribution of the RIKEN data [3] with $\sigma_{CD}(E1) + \sigma_{CD}(E2)$, as discussed in the text.



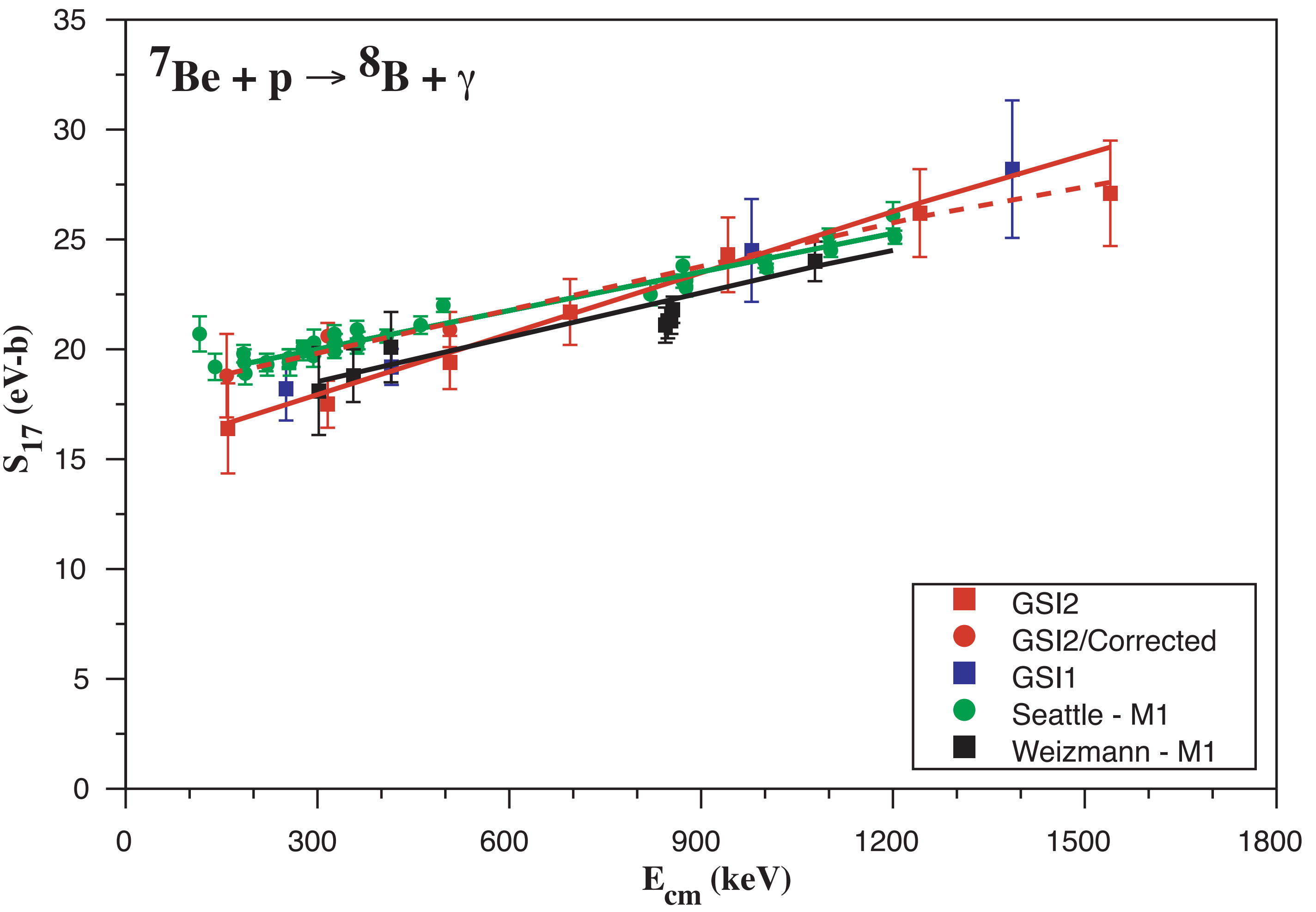
Extrapolation/ DB(94) [Other Yield Smaller $S_{17}(0)$]
25
20
15
10
5
$S_{17}(0)$ (eV-b)
RIKEN1
RIKEN2
GSI1
GSI2
DC
MSU
MSU x 1.08
(E2 Added)
Coulomb Dissociation of ^8B
1990
1995
2000
Year



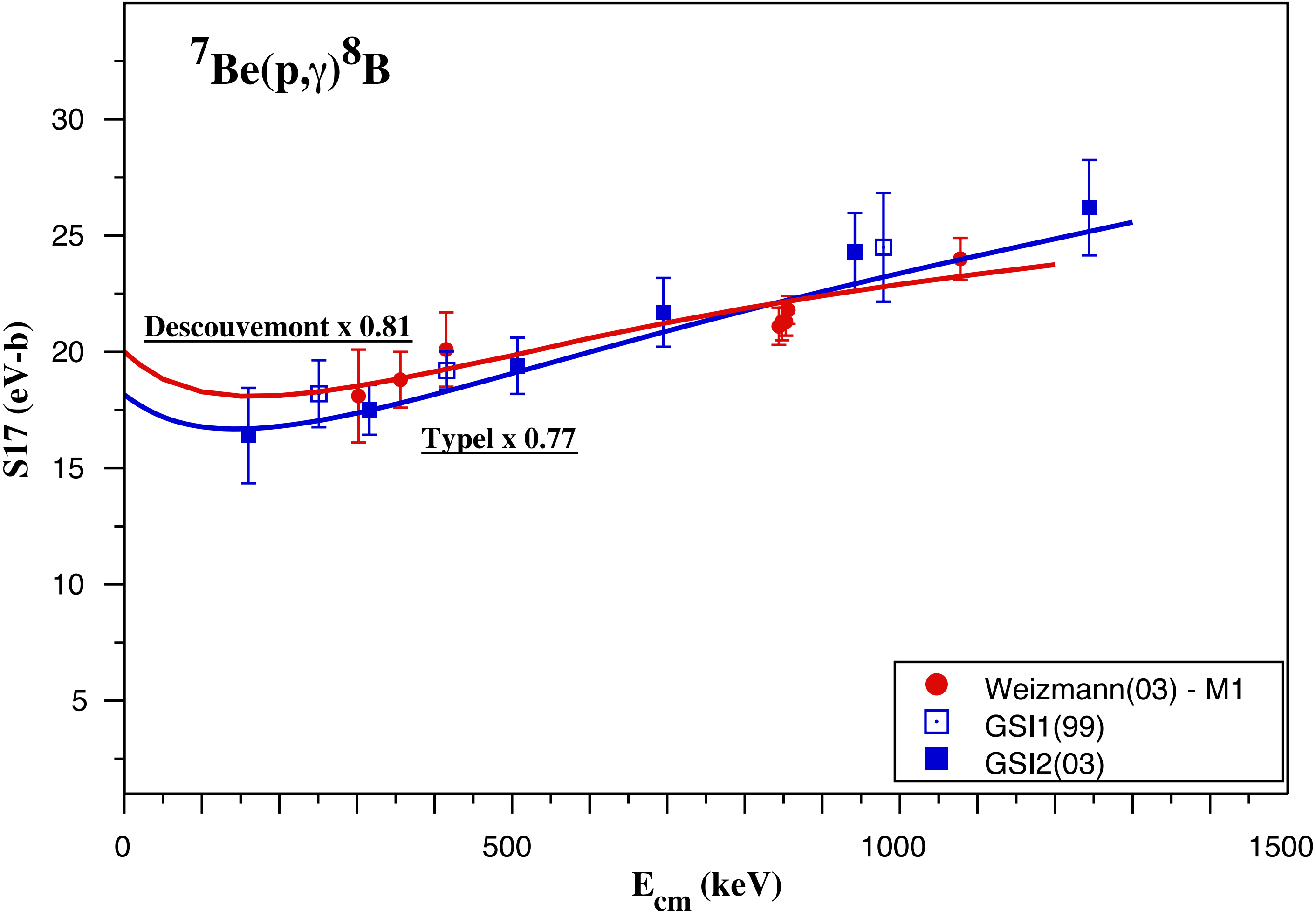
Slope of data S' = dS/dE
S' (eV-b/MeV)
0
5
10
15
20
0
10
20
(a1)Kavanagh(69)
(a2)Parker(66)
(a3)Vaughn(70)
(a4)Filippone(83)
(b)Orsay(01)
(c)Bochum(01)
(d1)Seattle(02)
(d2)Seattle(03)-BE1
(d3)Seattle(03)-BE3
(e)Weizmann(02)
(f)RIKEN2(98)
(g)GSI1(99)
(h)GSI2(03)
(i)GSI2/Corrected(04)
(j)MSU(01)
(a1)
(a2)
(a3)
(a4)
(b)
(c)
(d1)
(d2)
(d3)
(e)
(f)
(g)
(h)
(i)
(j)



d/s(0) = 8.5%
S + D
d/s(0) = 6.5%
S
D
S17 (eV-b)
Ecm (keV)
0
5
10
15
20
25
30
35
500
1000
1500
d/s(0) = 6.5%
d/s(0) = 8.5%
7Be(p,γ)8B
200
400
600
800
1000



$^7Be + p \rightarrow {}^8B + \gamma$
S_{17} (eV-b)
E_{cm} (keV)
0
5
10
15
20
25
30
35
0
300
600
900
1200
1500
1800
GSI2
GSI2/Corrected
GSI1
Seattle - M1
Weizmann - M1



$^7Be(p,\gamma)^8B$
Descouvement x 0.81
Typel x 0.77
Weizmann(03) - M1
GSI1(99)
GSI2(03)
S17 (eV-b)
E_{cm} (keV)
0
500
1000
1500
5
10
15
20
25
30

Seattle Result on ^7Be + p $\rightarrow$ $^8B + \gamma$:

$$S_{17}(0) = 21.4 \pm 0.5 \text{ (expt) } \pm 0.6 \text{ (theory) eV-b} \qquad [1]$$

Previous Compilation:

$$S_{17}(0) = 19 \text{ +4 -2 eV-b} \qquad [2]$$

Reasonable Conservative Estimate:

$$S_{17}(0) = 21.4 \pm 0.8 \text{ (expt) } ^{+0.0}_{-3.0} \text{ (extrap) eV-b} \qquad [3]$$

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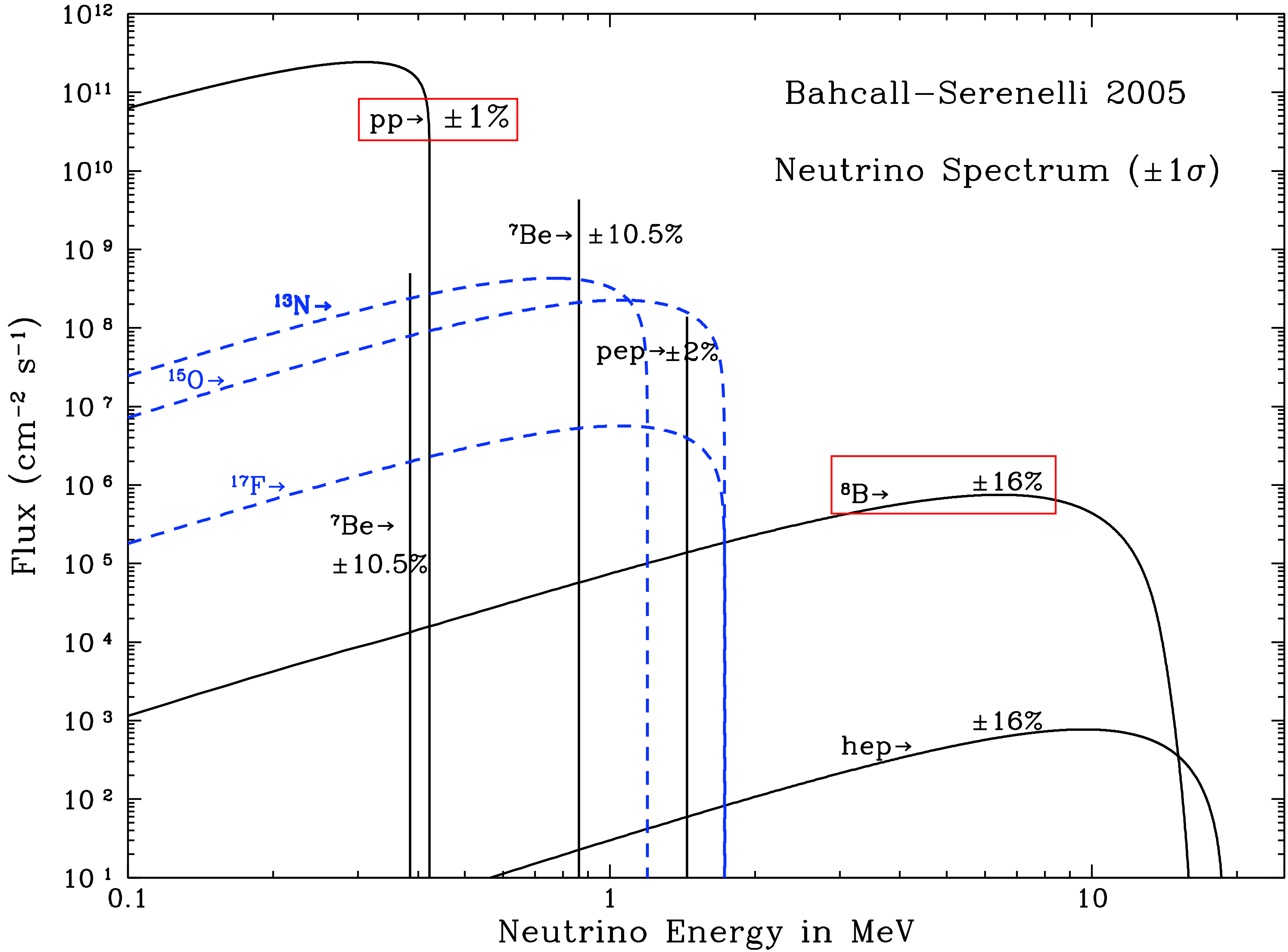
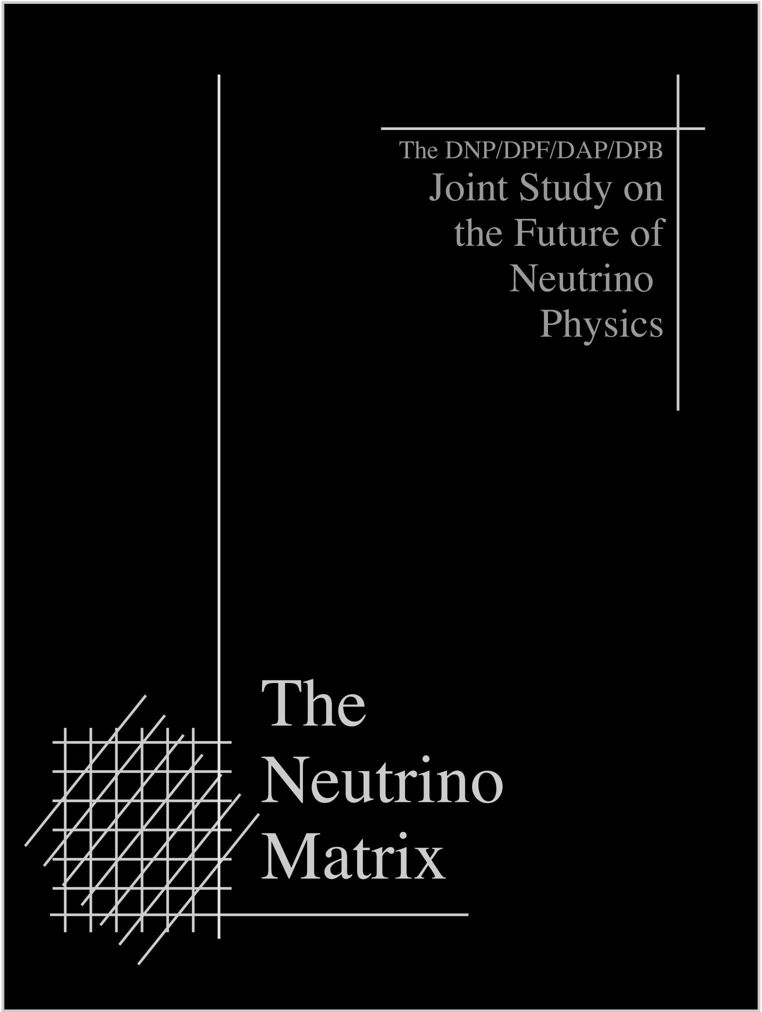
[1] A.R. Junghans *et al.*; Phys. Rev. **C68**(2003)065803.

[2] E.G. Adelberger *et al.*; rev. Mod. Phys. **70**(1998)1265.

[3] M. Gai; nucl-ex/0312003.


Bahcall−Serenelli 2005
Neutrino Spectrum (±1σ)
pp→ ±1%
⁷Be→ ±10.5%
¹³N→
¹⁵O→
¹⁷F→
pep→±2%
⁷Be→
±10.5%
⁸B→ ±16%
hep→ ±16%
Flux (cm⁻² s⁻¹)
Neutrino Energy in MeV
10¹²
10¹¹
10¹⁰
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
10³
10²
10¹
0.1
1
10



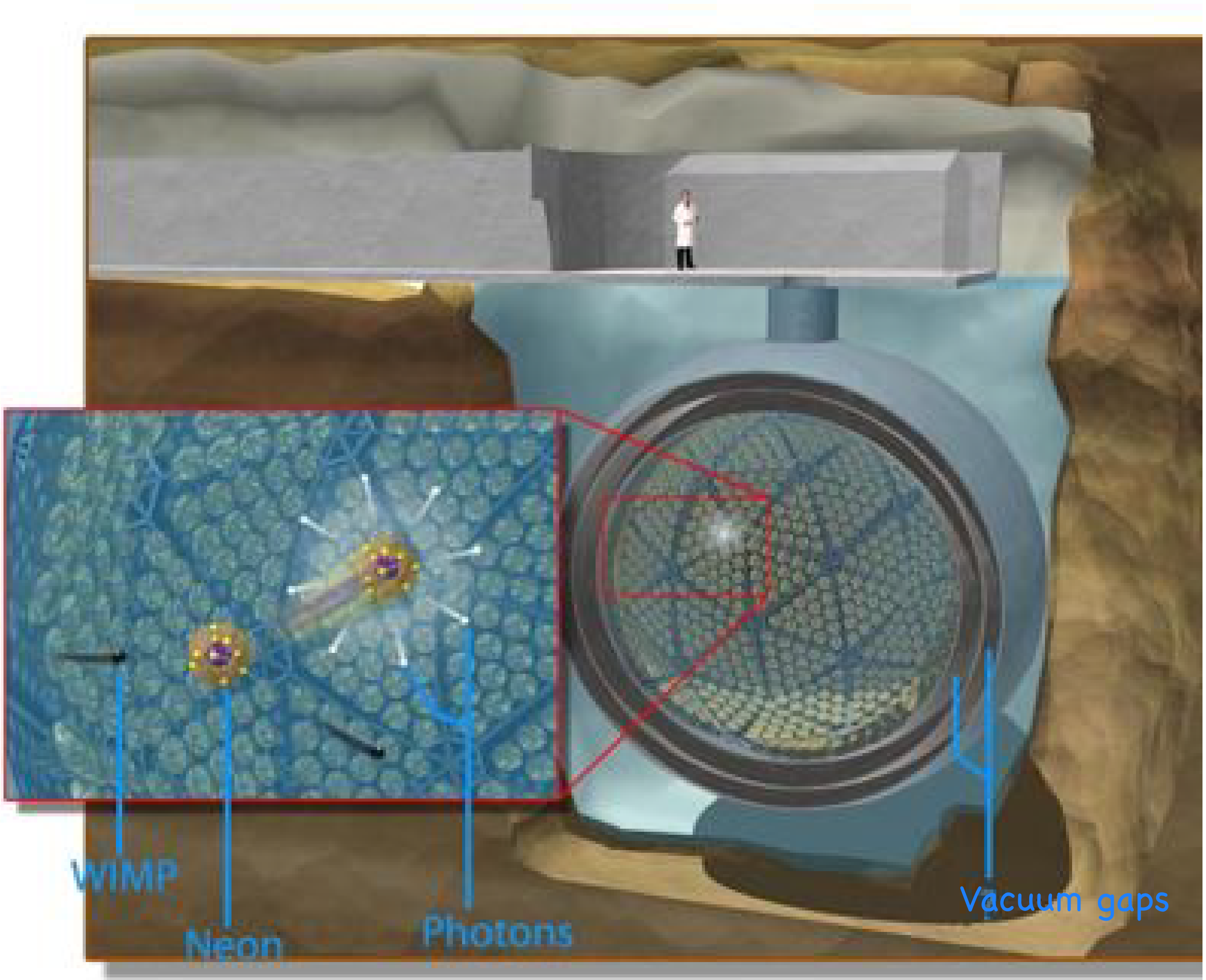
The Neutrino Matrix:

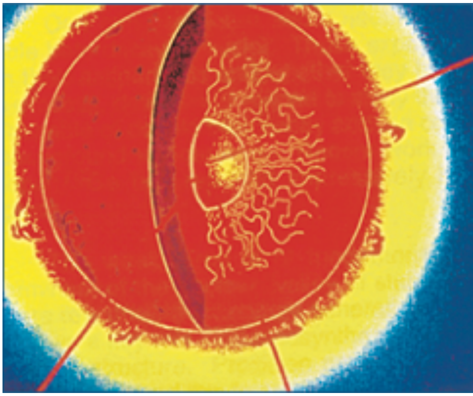
- We recommend, as a high priority, that a phased program of sensitive searches for neutrinoless nuclear double beta decay be initiated as soon as possible.

- We recommend, as a high priority, a comprehensive U.S. program to complete our understanding of neutrino mixing, to determine the character of the neutrino mass spectrum, and to search for CP violation among neutrinos.

- We recommend the development of a spectroscopic solar neutrino experiment capable of measuring the energy spectrum of neutrinos from the primary pp fusion process in the sun.

Artist's Rendition of CLEAN





University of Connecticut
Laboratory for Nuclear Science
at Avery Point

Solar Composition:

^8B Flux error down from 20% to 12%
Confrontation with SSM
Must be resolved

^8B Solar Neutrino Flux:

S_{34} soon will be known (<5%)
S_{17} Seattle result must be checked
Extrapolation must be checked

Is SSM/Flux = 1.17 significant?

pp Solar Neutrino Flux:

Most Exciting Frontier (CLEAN)