

<http://esic.ciae.ac.cn>



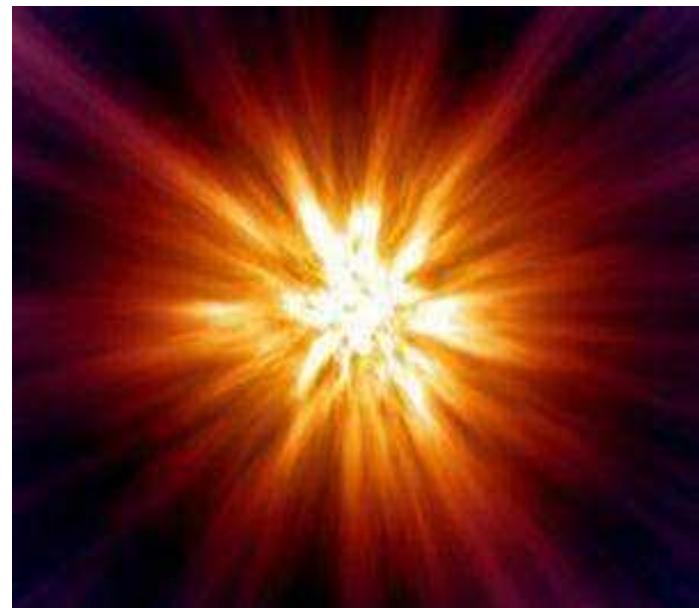
原初锂丰度研究进展

李志宏



报告内容

- 锂元素及其应用
- 大爆炸核合成简介
- 原初锂丰度疑难
- 最近完成的几个核反应
 - $^6\text{He}(\text{p}, \gamma)^7\text{Li}$, $^7\text{Li}(\text{n}, \gamma)^8\text{Li}$
 - $^7\text{Be}(\text{d}, ^3\text{He})^6\text{Li}$, $^8\text{Li}(\text{p}, \gamma)^9\text{Be}$
 - $^4\text{He}(\text{pn}, \gamma)^6\text{Li}$
- 结果讨论



锂元素及其应用

- 第三种元素, 第一种金属元素
- In 1817 , Lithium element was discovered by Swedish chemist Johan August Arfwedson.
- Exists in the body fluid, affect *central nervous system*
- Widely applied in the glass and ceramics field.
- Power resource, Fusion Materials
- Lithium has become important in human life.

锂元素伴我们每一天



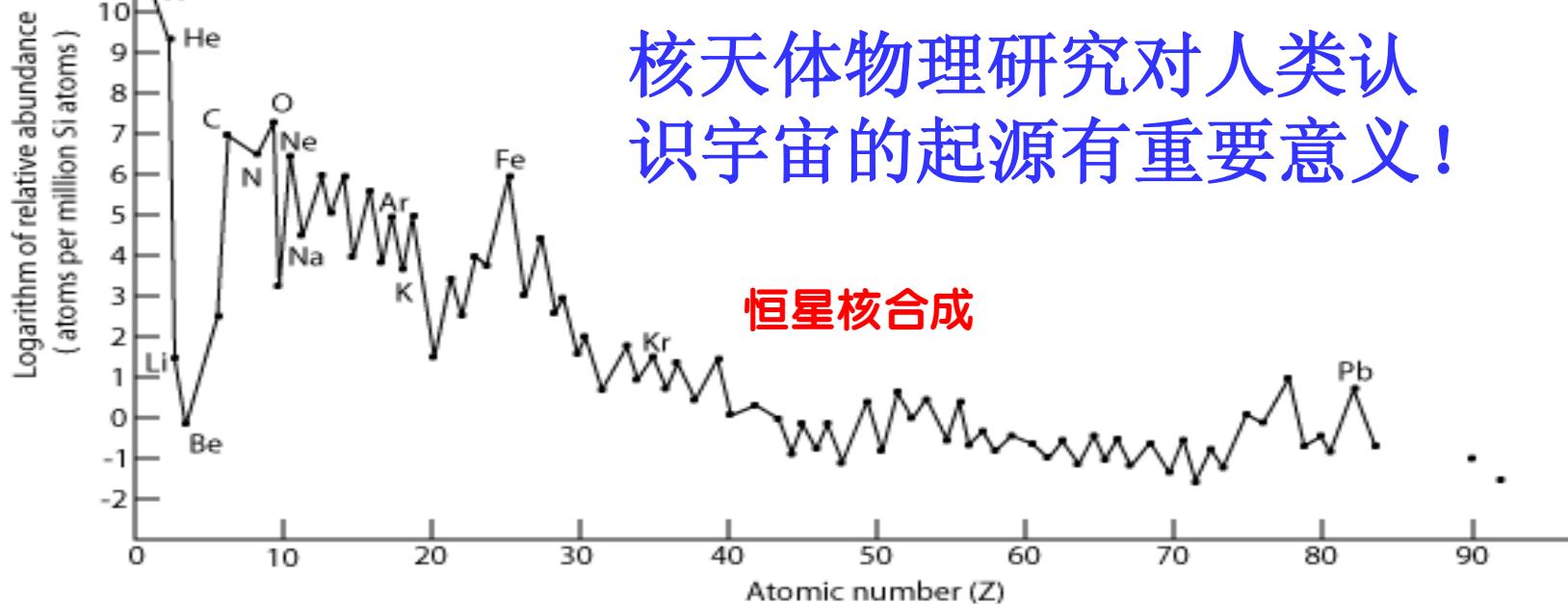
物质世界的来源

Periodic Table of the Elements																			
Abundance of Elements in Seawater near the Surface																			
all values are in mg/L																			
1A	2A	3B	4B	5B	6B	7B	8B	1B	2B	3A	4A	5A	6A	7A	8A				
1 H 100000 Hydrogen	4 Be 5×10^4 Boron	21 Sc 6×10^7 Scandium	22 Ti 1×10^2 Titanium	23 V 2.5×10^3 Vanadium	24 Cr 3×10^4 Chromium	25 Mn 2×10^4 Manganese	26 Fe 2×10^5 Iron	27 Co 2×10^6 Cobalt	28 Ni 5.5×10^4 Nickel	29 Cu 2.5×10^4 Copper	30 Zn 4.9×10^4 Zinc	31 Ga 3×10^5 Gallium	32 Ge 5×10^4 Germanium	33 As 3.7×10^4 Arsenic	34 Se 2×10^4 Selenium	35 Br 6.7×10^3 Bromine	36 Kr 3×10^3 Krypton	2 He 7×10^6 Helium	
3 Li 1.8×10^{-1} Lithium	12 Mg 1.2×10^0 Magnesium	20 Ca 4.12×10^1 Calcium	21 Sc 6×10^7 Scandium	22 Ti 1×10^2 Titanium	23 V 2.5×10^3 Vanadium	24 Cr 3×10^4 Chromium	25 Mn 2×10^4 Manganese	26 Fe 2×10^5 Iron	27 Co 2×10^6 Cobalt	28 Ni 5.5×10^4 Nickel	29 Cu 2.5×10^4 Copper	30 Zn 4.9×10^4 Zinc	31 Ga 3×10^5 Gallium	32 Ge 5×10^4 Germanium	33 As 3.7×10^4 Arsenic	34 Se 2×10^4 Selenium	35 Br 6.7×10^3 Bromine	10 Ne 1.2×10^4 Neon	
11 Na 10000 Sodium	12 Mg 1.2×10^0 Magnesium	19 K 3.99×10^1 Potassium	20 Ca 4.12×10^1 Calcium	21 Sc 6×10^7 Scandium	22 Ti 1×10^2 Titanium	23 V 2.5×10^3 Vanadium	24 Cr 3×10^4 Chromium	25 Mn 2×10^4 Manganese	26 Fe 2×10^5 Iron	27 Co 2×10^6 Cobalt	28 Ni 5.5×10^4 Nickel	29 Cu 2.5×10^4 Copper	30 Zn 4.9×10^4 Zinc	31 Ga 3×10^5 Gallium	32 Ge 5×10^4 Germanium	33 As 3.7×10^4 Arsenic	34 Se 2×10^4 Selenium	35 Br 6.7×10^3 Bromine	18 Ar 4.5×10^1 Argon
19 K 3.99×10^1 Potassium	20 Ca 4.12×10^1 Calcium	38 Sr 1.2×10^4 Strontium	39 Y 1.3×10^4 Yttrium	40 Zr 3.4×10^4 Zirconium	41 Nb 1×10^5 Niobium	42 Mo 1×10^4 Molybdenum	43 Tc 7×10^7 Technetium	44 Ru 7×10^7 Ruthenium	45 Rh 7×10^7 Rhodium	46 Pd 4×10^4 Palladium	47 Ag 4×10^4 Silver	48 Cd 1.1×10^4 Cadmium	49 In 2×10^4 Indium	50 Sn 4×10^4 Tin	51 Sb 2.4×10^4 Antimony	52 Te 1.9×10^4 Tellurium	53 I 6×10^4 Iodine	54 Xe 5×10^4 Xenon	
55 Cs 3×10^4 Cesium	56 Ba 1.3×10^4 Barium	57-71 5.3×10^4 Lanthanides	72 Hf 7×10^4 Hafnium	73 Ta 2×10^4 Tantalum	74 W 1×10^4 Tungsten	75 Re 4×10^4 Rhenium	76 Os 1×10^4 Osmium	77 Ir 1×10^4 Iridium	78 Pt 1×10^4 Platinum	79 Au 3×10^4 Gold	80 Hg 1.9×10^4 Mercury	81 Tl 1.9×10^4 Thallium	82 Pb 3×10^4 Lead	83 Bi 2×10^4 Bismuth	84 Po 1.6×10^4 Polonium	85 At 1×10^4 Astatine	86 Rn 6×10^3 Radon		
87 Fr 6.9×10^1 Francium	88 Ra 6.9×10^1 Radium	89-103 6.9×10^1 Actinides	104 Rf 105 Db 106 Sg 107 Bh 108 Hs 109 Mt 110 Ds 111 Rg 112 Cn 113 Uut 114 Uuuq 115 Uup 116 Uuh 117 Uus 118 Uuo																

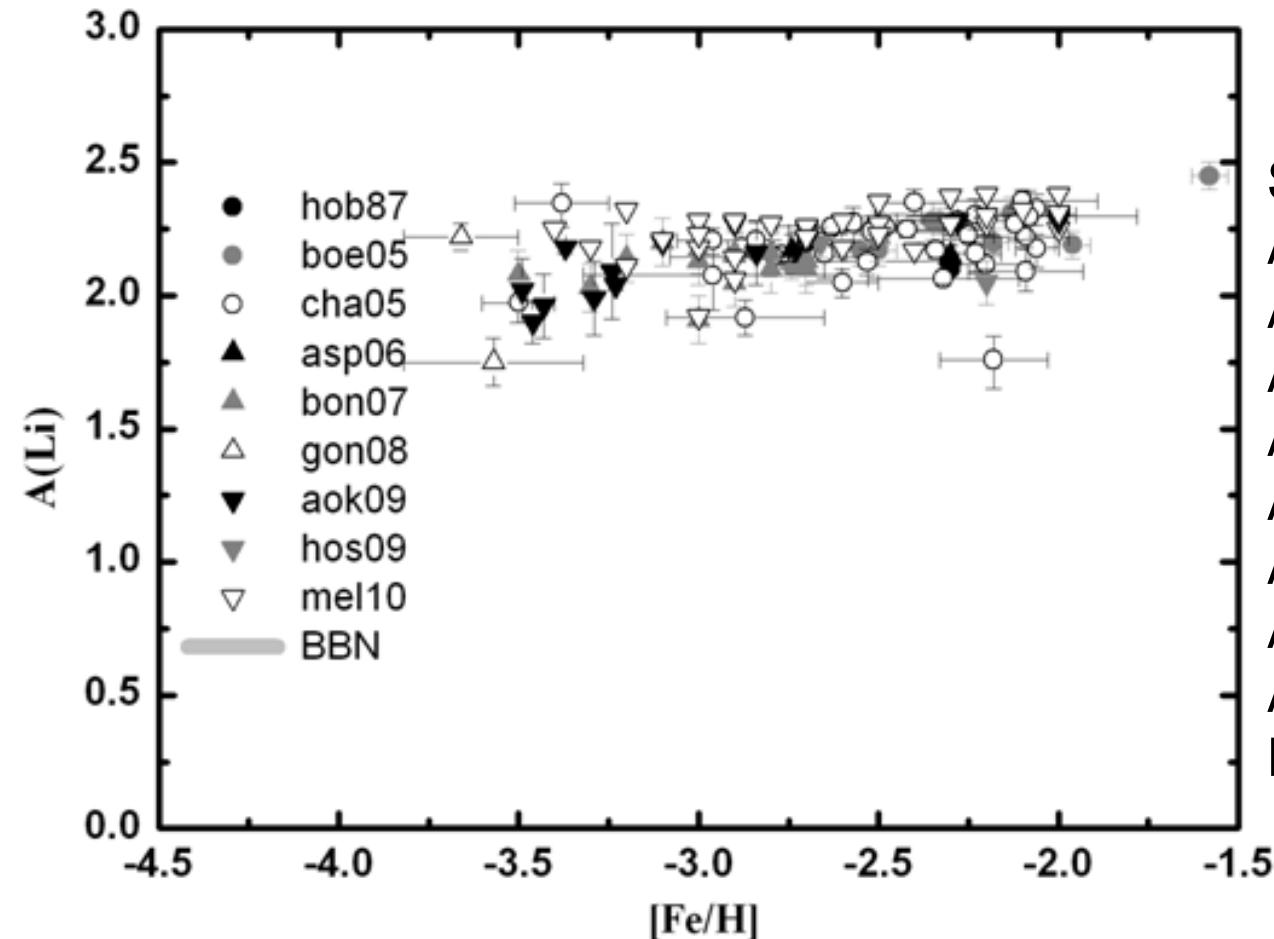
大爆炸核合成

核天体物理研究对人类认识宇宙的起源有重要意义！

恒星核合成



贫金属星中的锂平台



Spite, Nature 297(1982)483
APJ: 319 (1987) 796.
APJ: 633 (2005) 398.
A&A: 442 (2005) 961.
APJ: 644 (2006) 229.
A&A: 462 (2007) 851.
A&A: 480 (2008) 233.
APJ: 698 (2009) 1803.
A&A: 493 (2009) 601.
PIAUS : 268 (2010).

Widely accepted interpretation: Lithium is produced in BBN

大爆炸核合成计算用的微分方程组

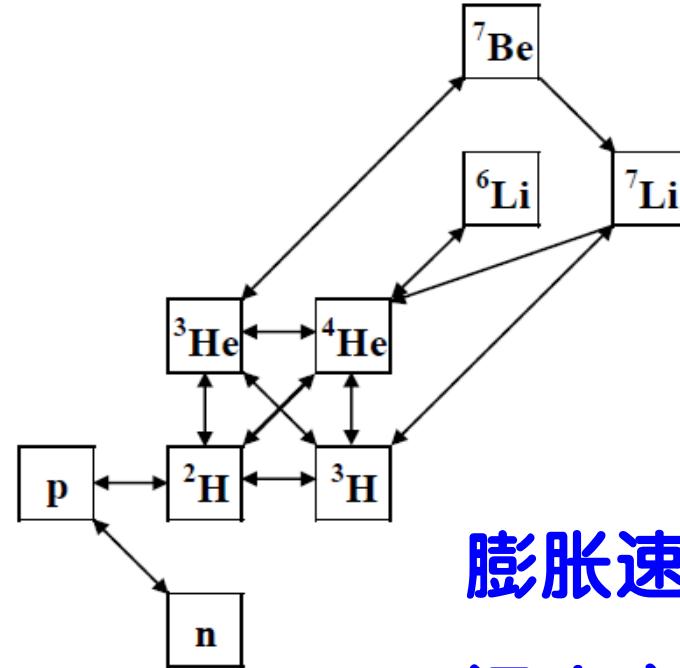
$$\frac{1}{R} \frac{dR}{dt} = \sqrt{\frac{8\pi G}{3}\rho - \frac{k}{R^2} + \frac{\Lambda}{3}}$$

$$\frac{1}{n_b} \frac{dn_b}{dt} = -3 \frac{1}{R} \frac{dR}{dt}$$

$$L\left(\frac{m_e}{T}, \phi_e\right) = \frac{n_b q_b}{T^3}$$

$$\frac{d\rho}{dt} = -3H(\rho + p)$$

$$\frac{dY_i}{dt} = \sum_{j,k,l} N_i \left(-\frac{Y_i^{N_i} Y_j^{N_j}}{N_i! N_j!} [ij]_k + \frac{Y_l^{N_l} Y_k^{N_k}}{N_l! N_k!} [lk]_j \right)$$



膨胀速率

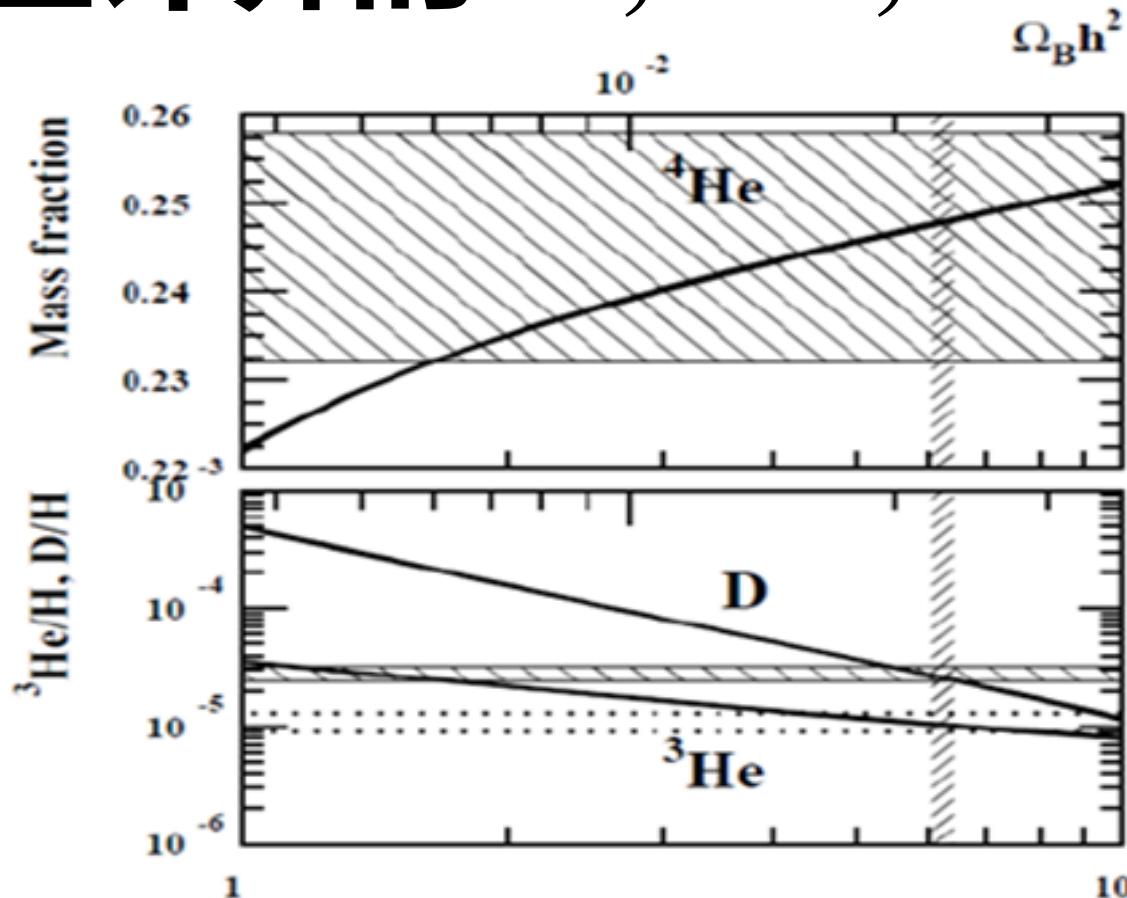
温度变化

元素丰度

基本输入参数：重子光子数密度比

.....

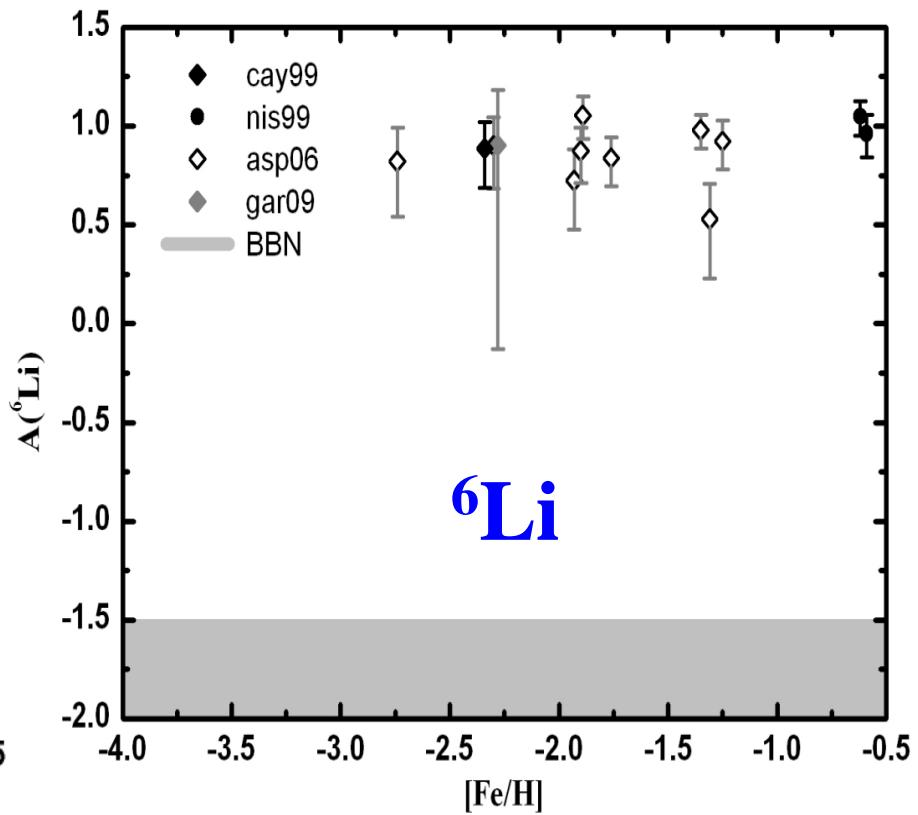
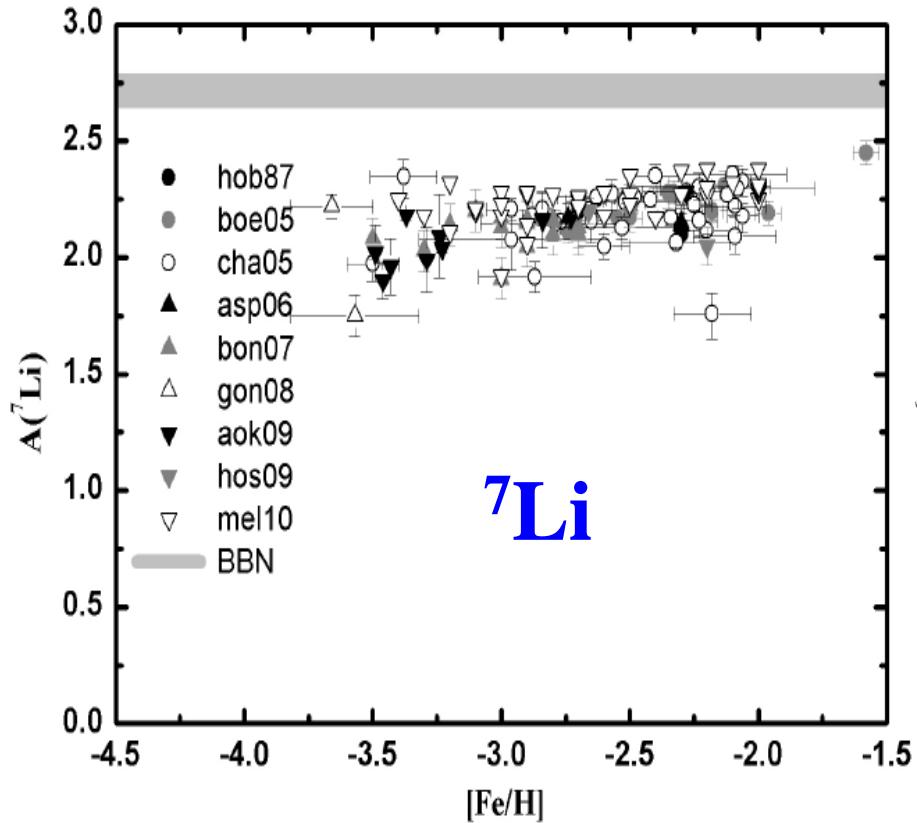
模型计算的 ^2H , ^3He , ^4He 丰度



^2H 、 ^3He 、 ^4He 的丰度与 η 的关系曲线

- ^2H 、 ^3He 、 ^4He 元素的理论丰度与天文观测结果精确一致。
- 宇宙大爆炸的证据：原初核合成、微波背景辐射、星系红移

模型计算与天文观测的锂元素丰度



锂丰度异常： ^7Li 相差3倍 ^6Li 相差3个量级！！！

宇宙大爆炸模型错了吗！

How to solve lithium problem?

Astronomy

Instrument

Improvement

Corrections of ionization

Stellar model

.....

Cosmology

BBN model

Dark matter

.....

particle physics

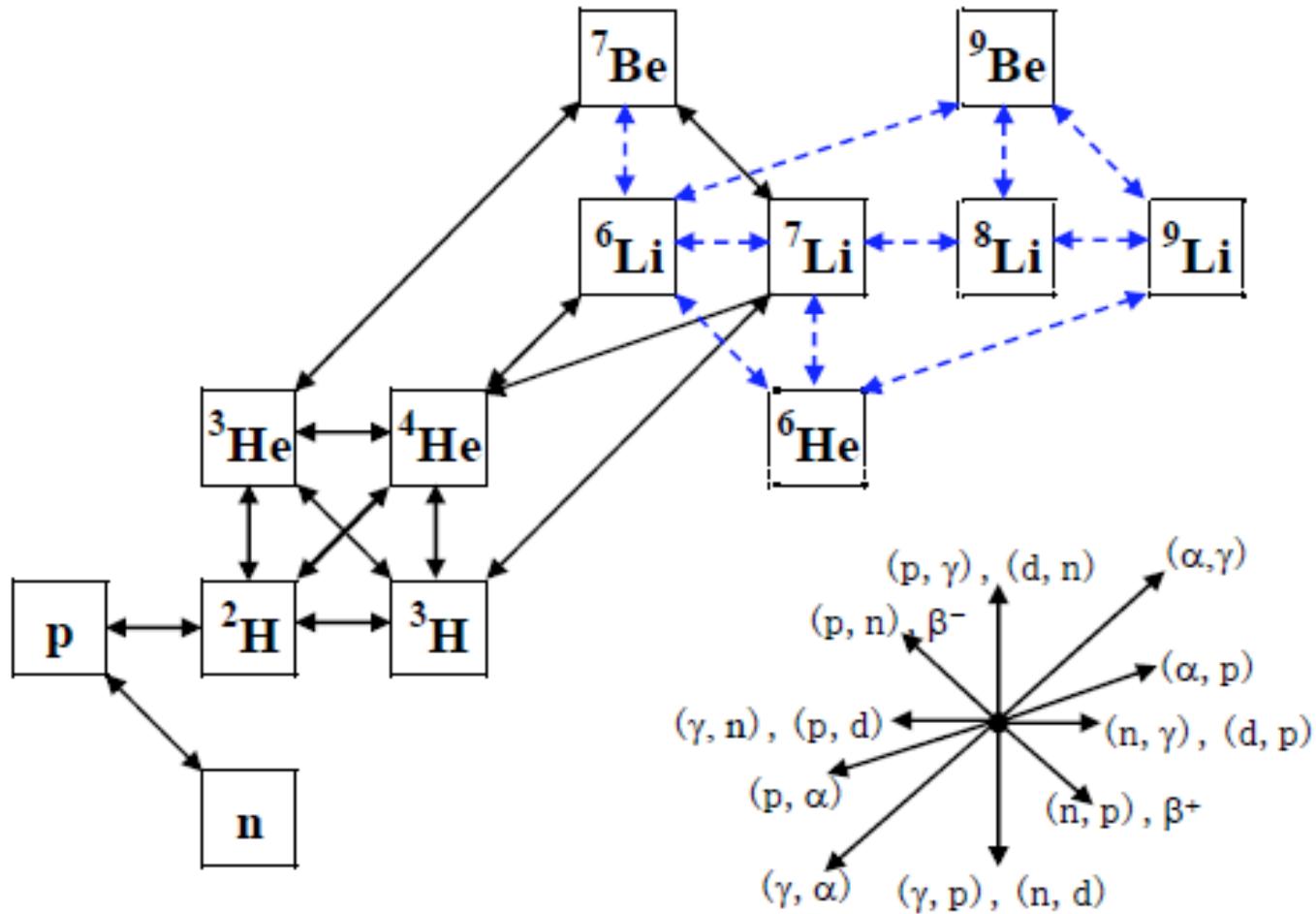
Supersymmetry

strange particle and decay

Nuclear physics

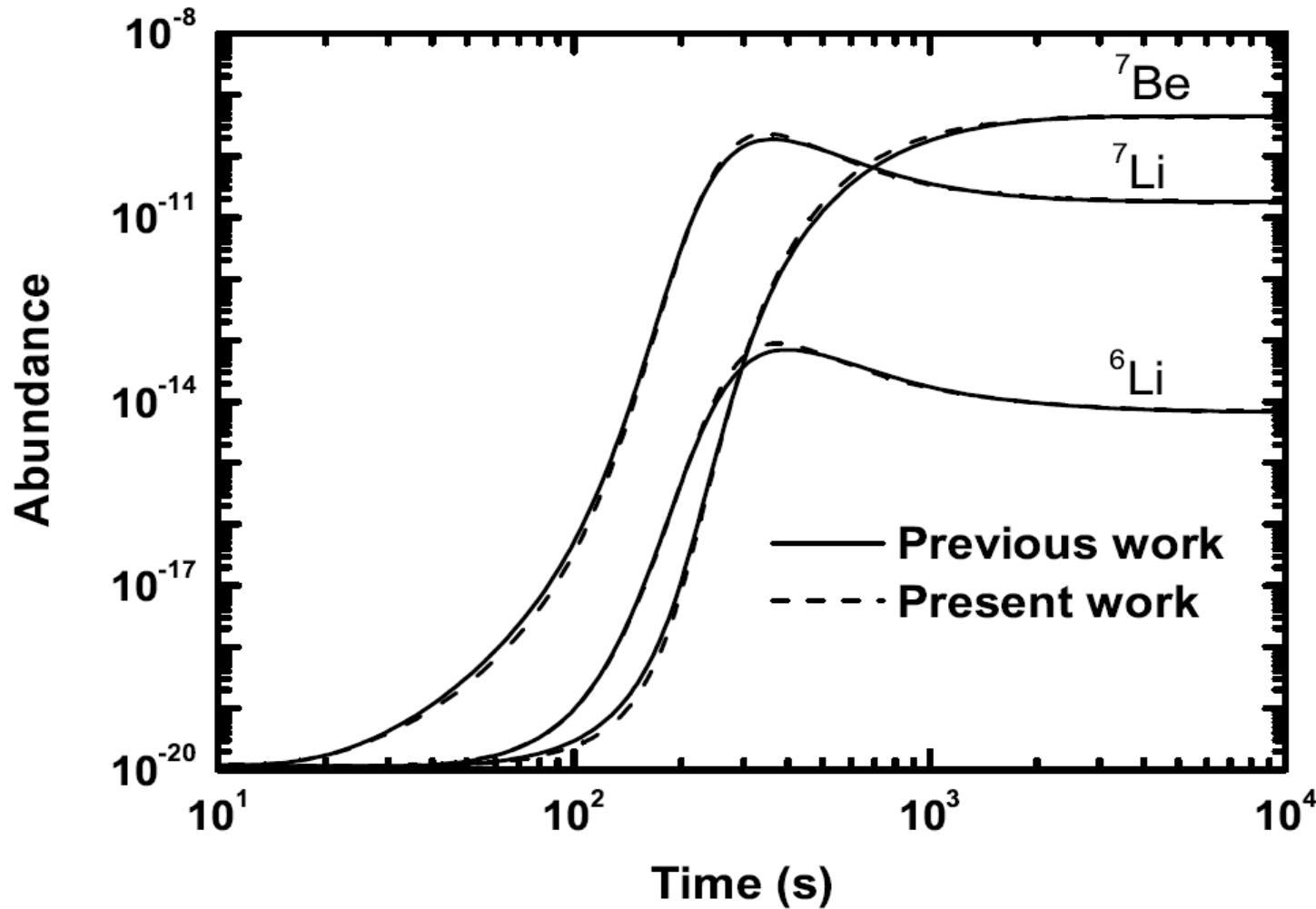
Determine the reaction
rates precisely

CIAE锂丰度的研究现状

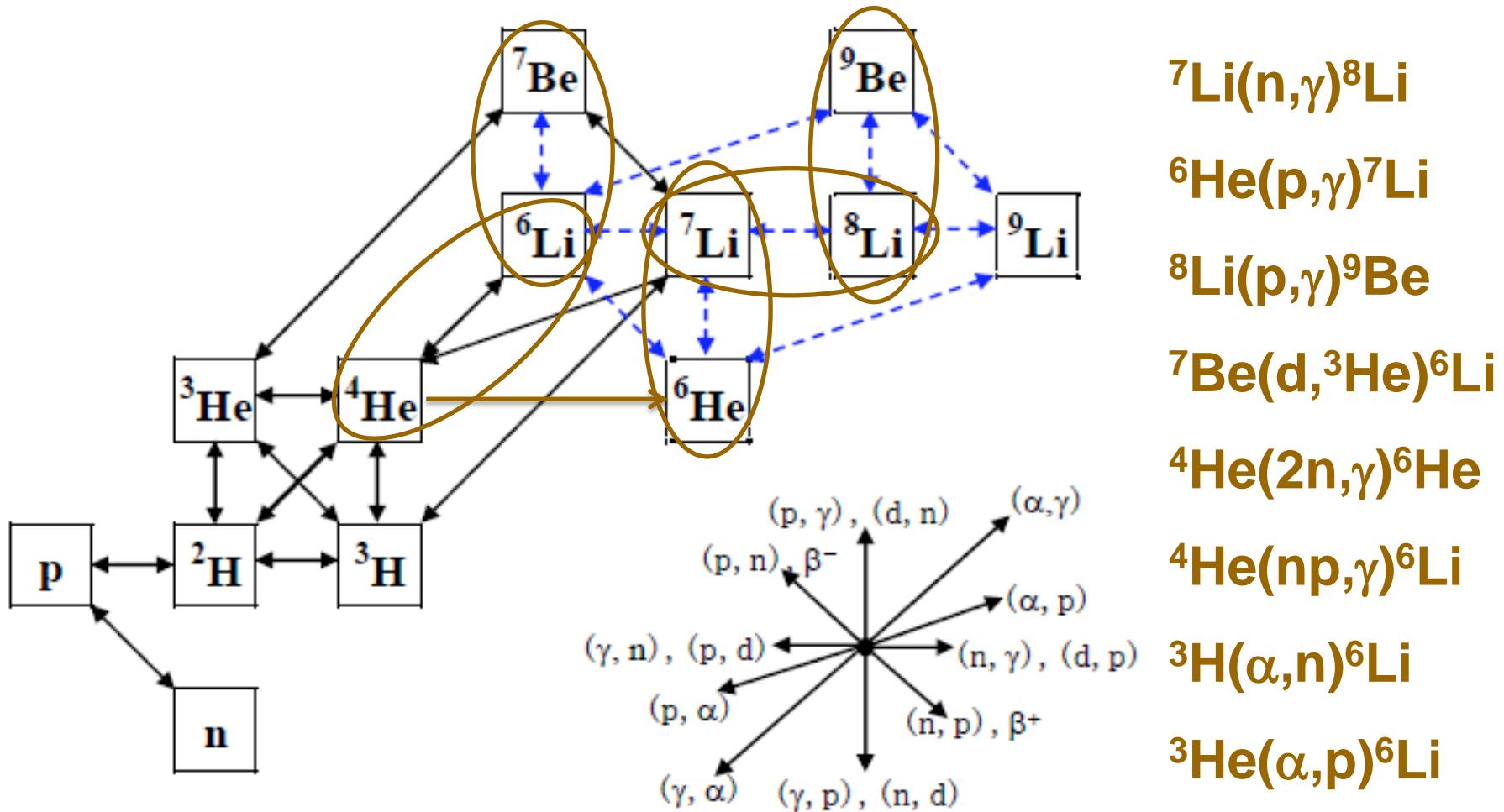


${}^6\text{Li}(\text{p},\gamma){}^7\text{Be}$
 ${}^6\text{Li}(\text{n},\gamma){}^7\text{Li}$
 ${}^6\text{Li}(\text{d},\text{p}){}^7\text{Li}$
 ${}^6\text{Li}(\alpha,\text{p}){}^9\text{Be}$
 ${}^6\text{He}(\text{p},\text{n}){}^6\text{Li}$
 ${}^6\text{He}(\text{d},\text{n}){}^7\text{Li}$
 ${}^7\text{Li}(\text{d},\text{p}){}^8\text{Li}$
 ${}^7\text{Li}(\text{n},\gamma){}^8\text{Li}$
 ${}^8\text{Li}(\text{d},\text{p}){}^9\text{Li}$
 ${}^8\text{Li}(\text{n},\gamma){}^9\text{Li}$
 ${}^8\text{Li}(\text{p},\text{d}){}^7\text{Li}$
 ${}^8\text{Li}(\text{p},\text{t}){}^6\text{Li}$
 ${}^8\text{Li}(\text{p},\gamma){}^9\text{Be}$

网络计算的初步结果

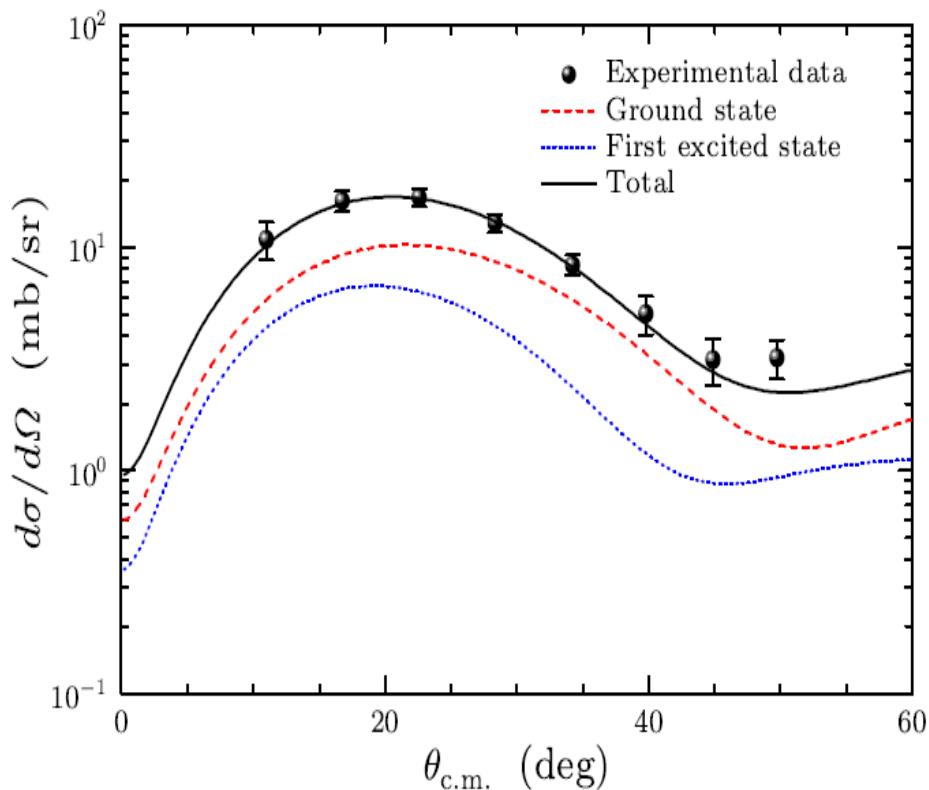


可能影响锂丰度的其它反应

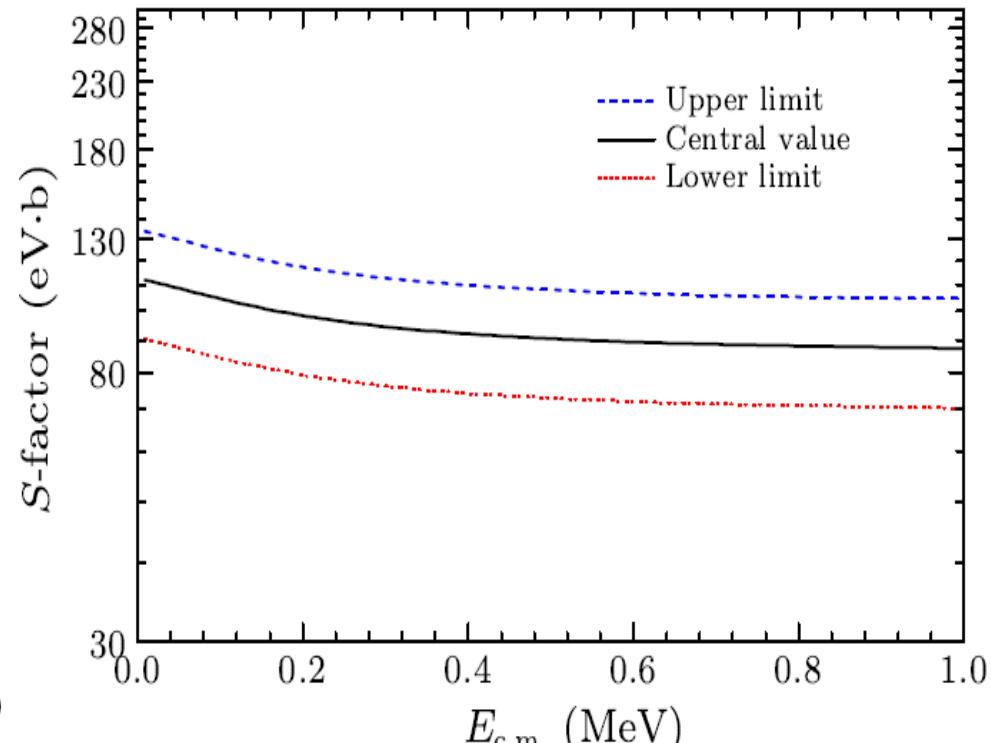


${}^6\text{He}(\text{p},\gamma){}^7\text{Li}$ 反应的天体物理S因子

由 ${}^6\text{He}(\text{d},\text{n}){}^7\text{Li}$ 反应的角分布导出了 ${}^6\text{He}(\text{p},\gamma){}^7\text{Li}$ 反应的天体物理S因子

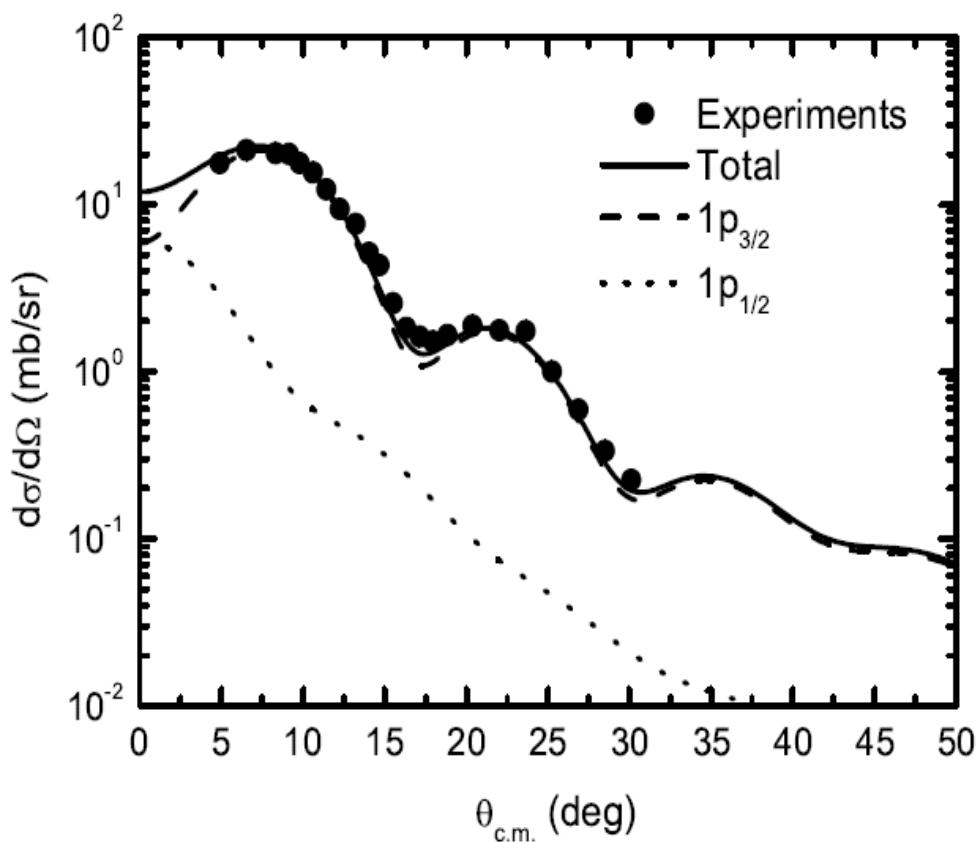


${}^6\text{He}(\text{d},\text{n}){}^7\text{Li}$ 反应的角分布

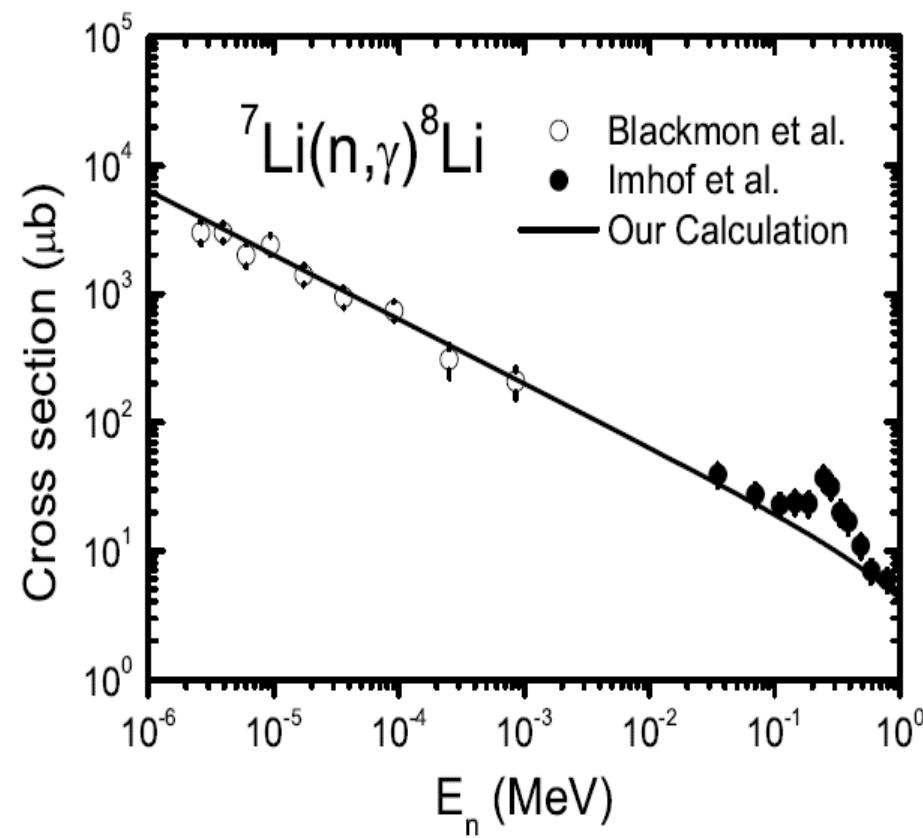


${}^6\text{He}(\text{p},\gamma){}^7\text{Li}$ 反应的天体物理S因子

原初核合成相关的 ${}^7\text{Li}$ (n,γ) ${}^8\text{Li}$ 反应截面

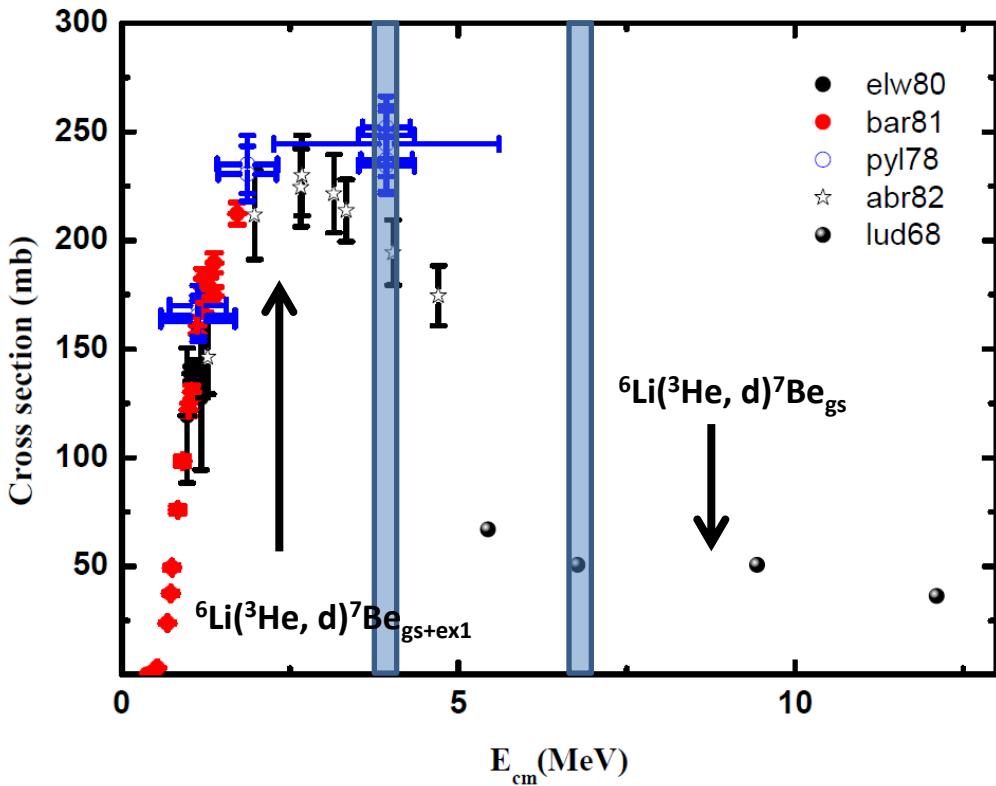


${}^{13}\text{C}({}^7\text{Li}, {}^8\text{Li}){}^{12}\text{C}$ 反应的角分布



${}^7\text{Li} (n, \gamma){}^8\text{Li}$ 反应截面

$^2\text{H}(^7\text{Be}, ^6\text{Li})^3\text{He}$ 反应研究现状



- 迄今没有 $^2\text{H}(^7\text{Be}, ^6\text{Li})^3\text{He}$ 的实验结果。
- 美国等几家实验室测量了 $^6\text{Li}(^3\text{He}, \text{d})^7\text{Be}$ 反应到 ^7Be 基态和第一激发态的总截面。
- 无法得到 $^2\text{H}(^7\text{Be}, ^6\text{Li})^3\text{He}$ 反应的截面。
- 稍高能点的实验给出了 $^2\text{H}(^7\text{Be}, ^6\text{Li})^3\text{He}$ 反应角分布。

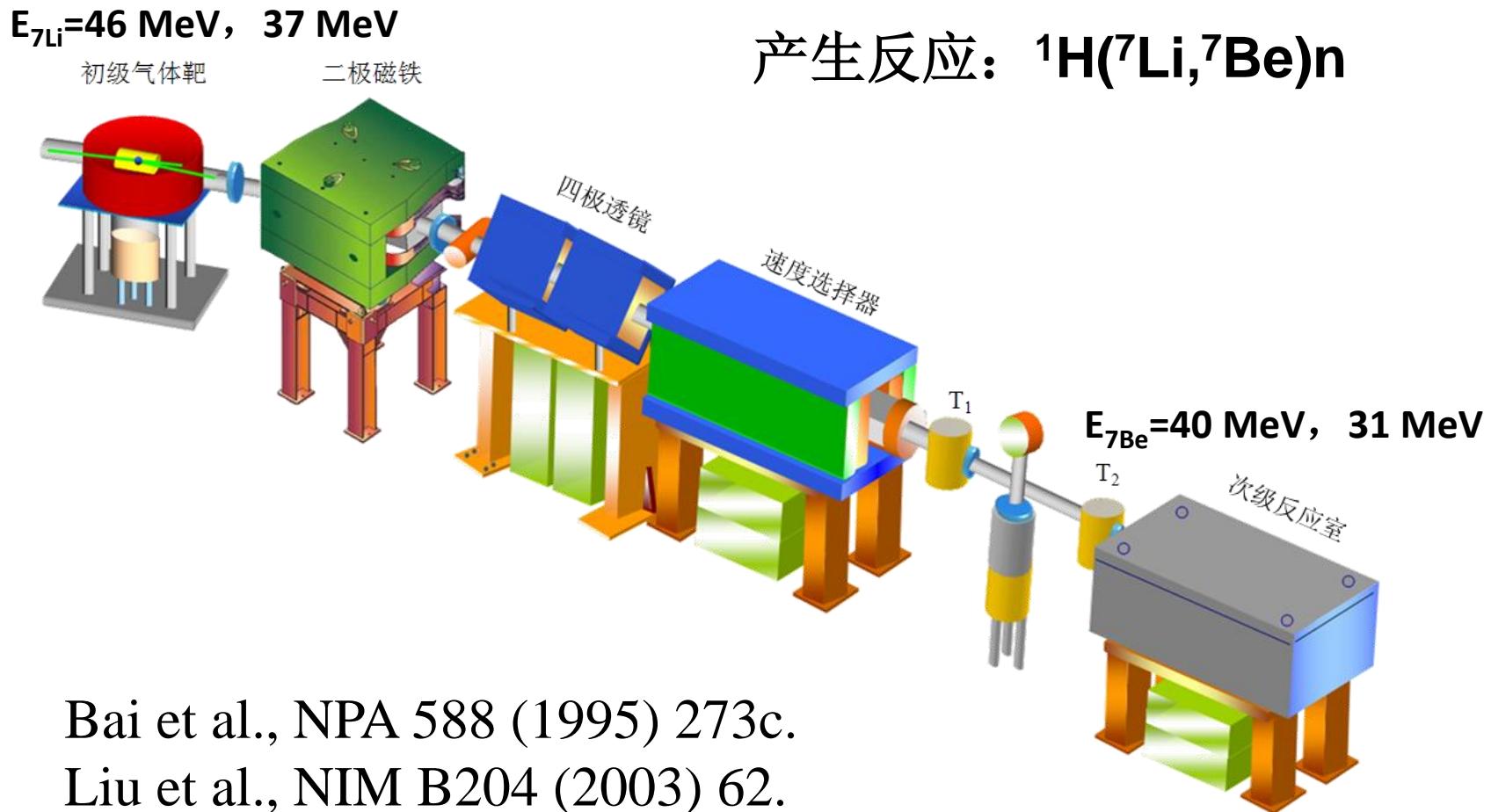
TANS: 30 (1978) 623.

PRC: 22 (1980) 1406.

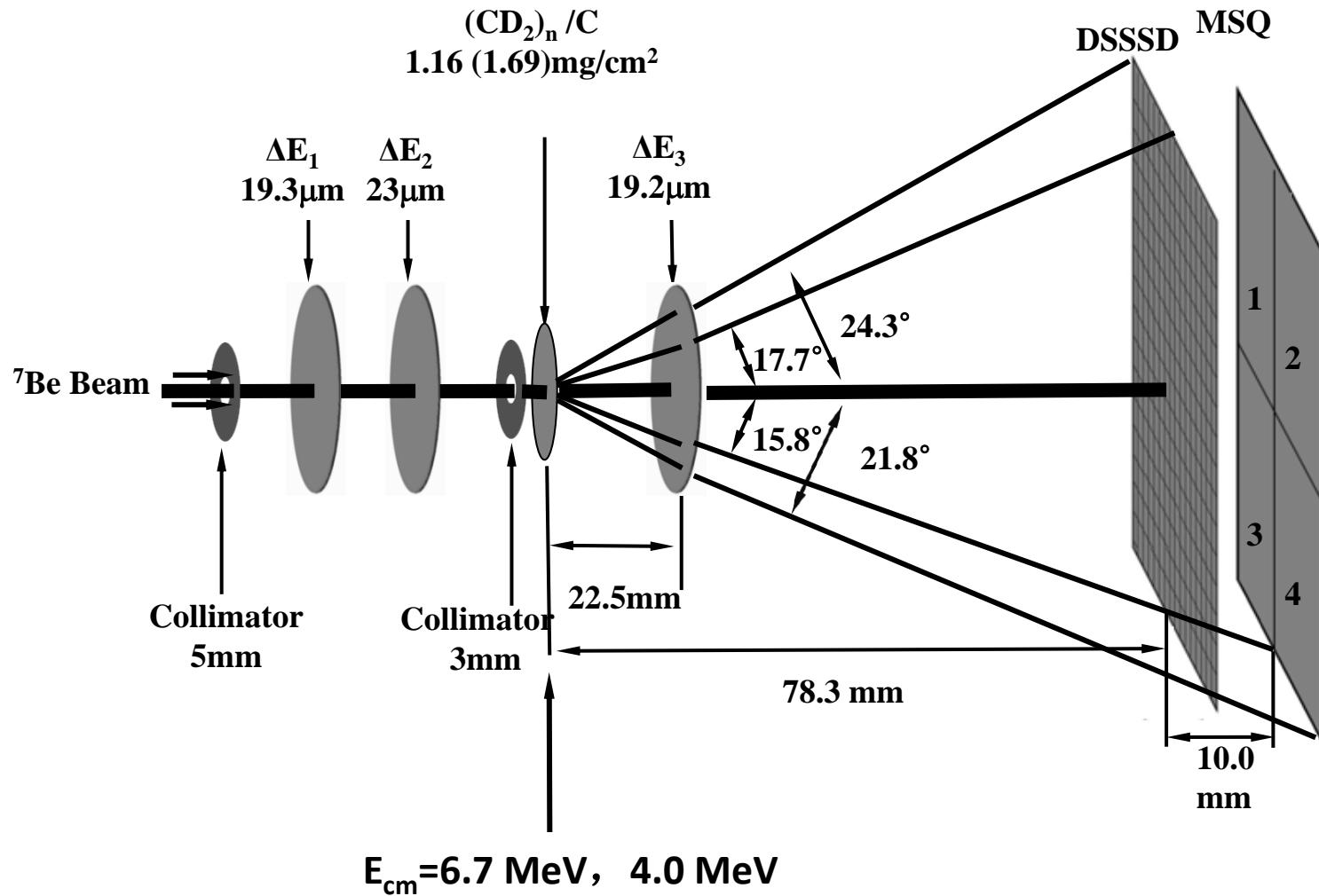
IEEEETNS: 28(1981) 1344.

ANTSYK: 1982 (1982) 21.

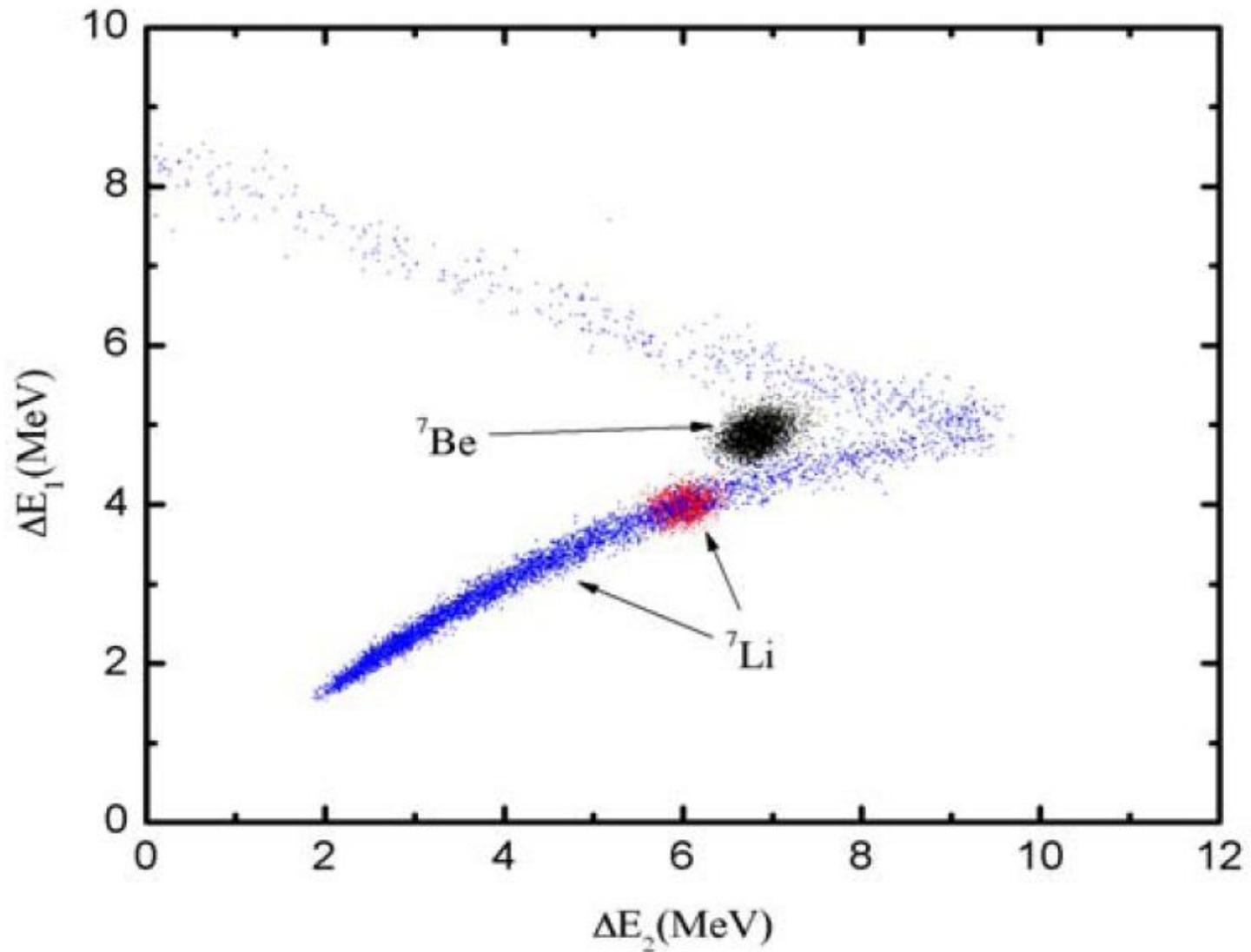
串列加速器次级束流线



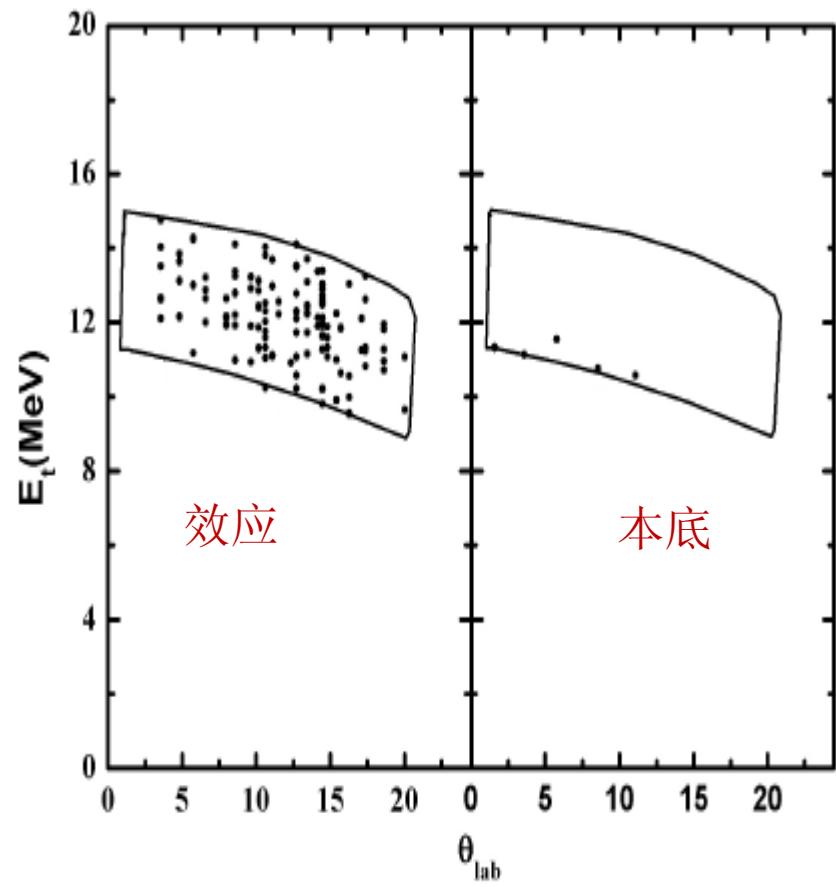
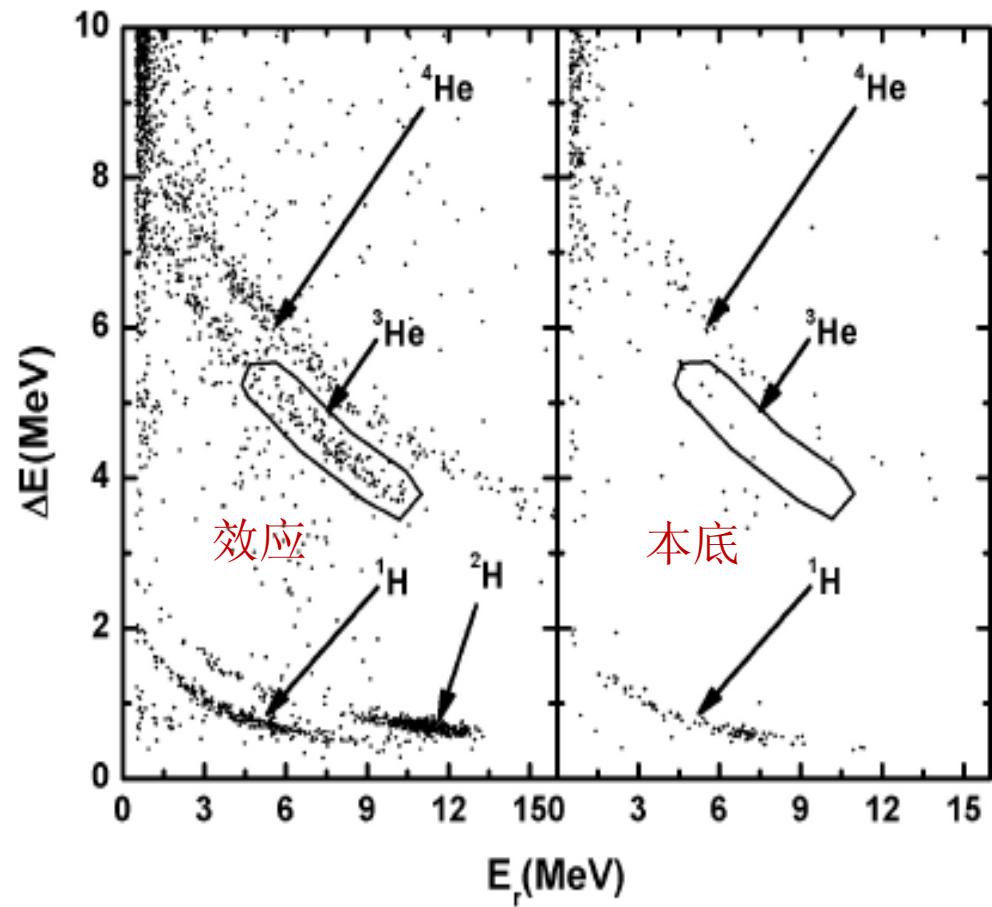
探测器设置



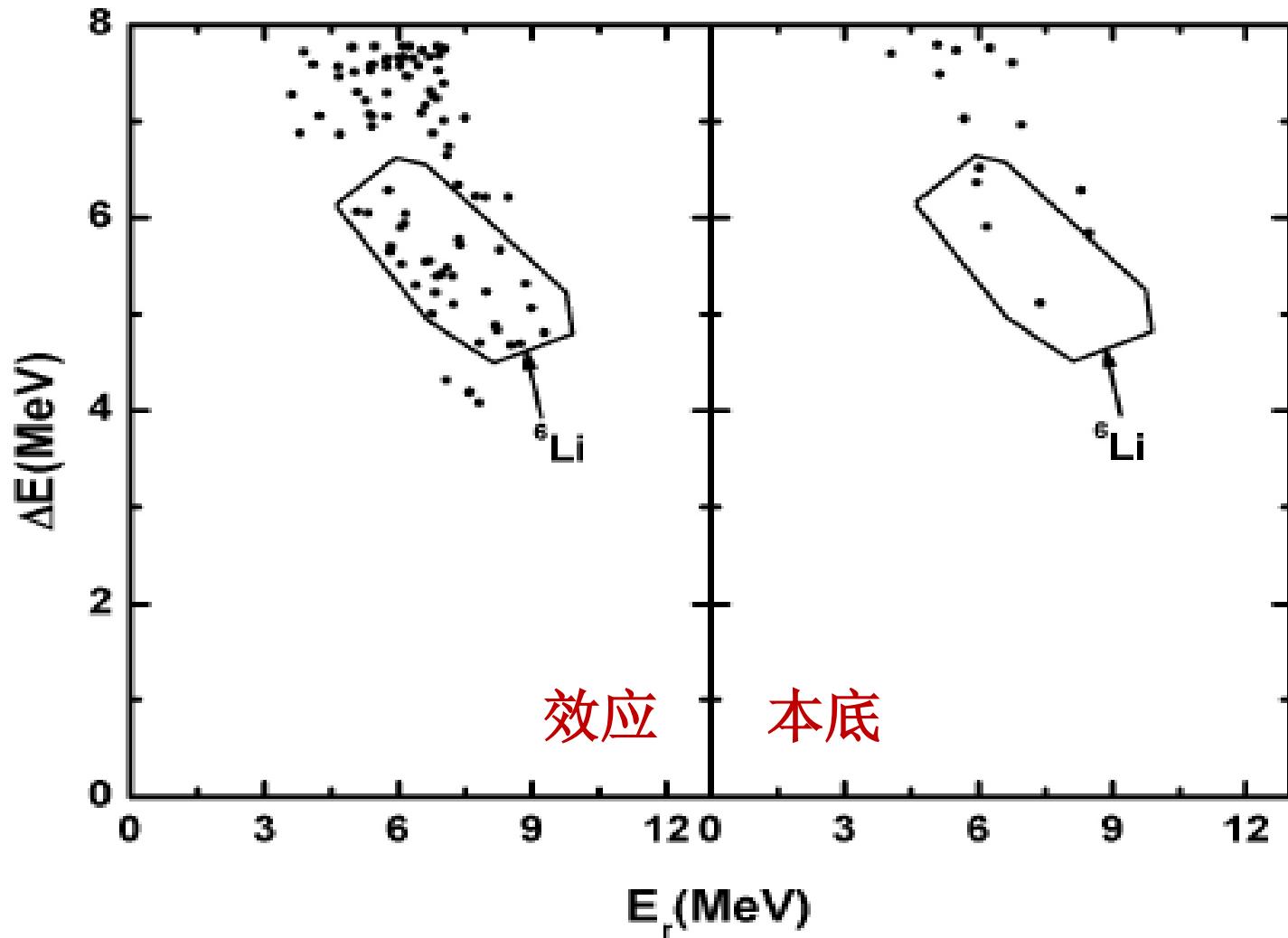
靶前两个 ΔE 探测器效果图



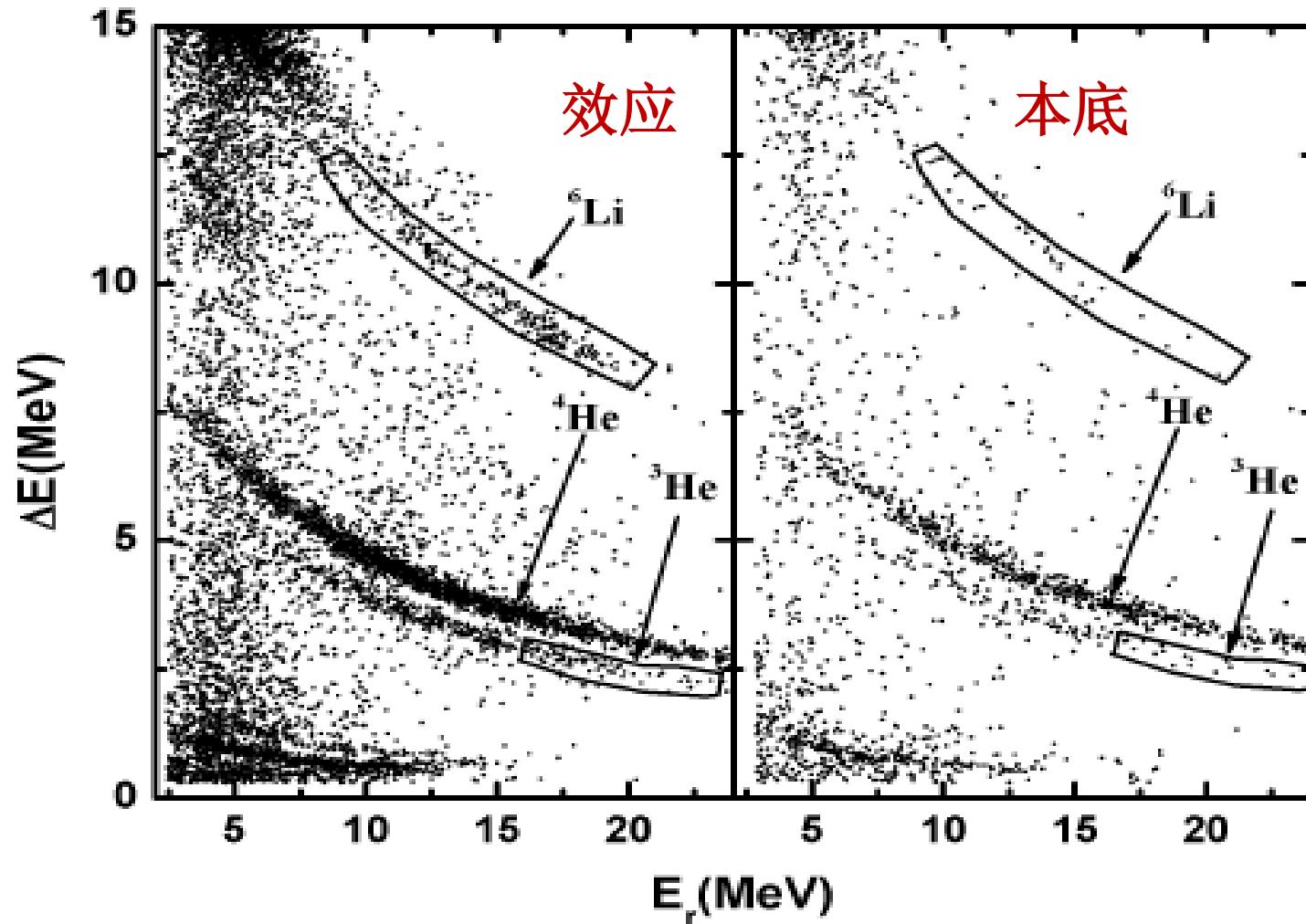
$E_{cm}=4.0$ MeV时的 ${}^3\text{He}$ 鉴别谱



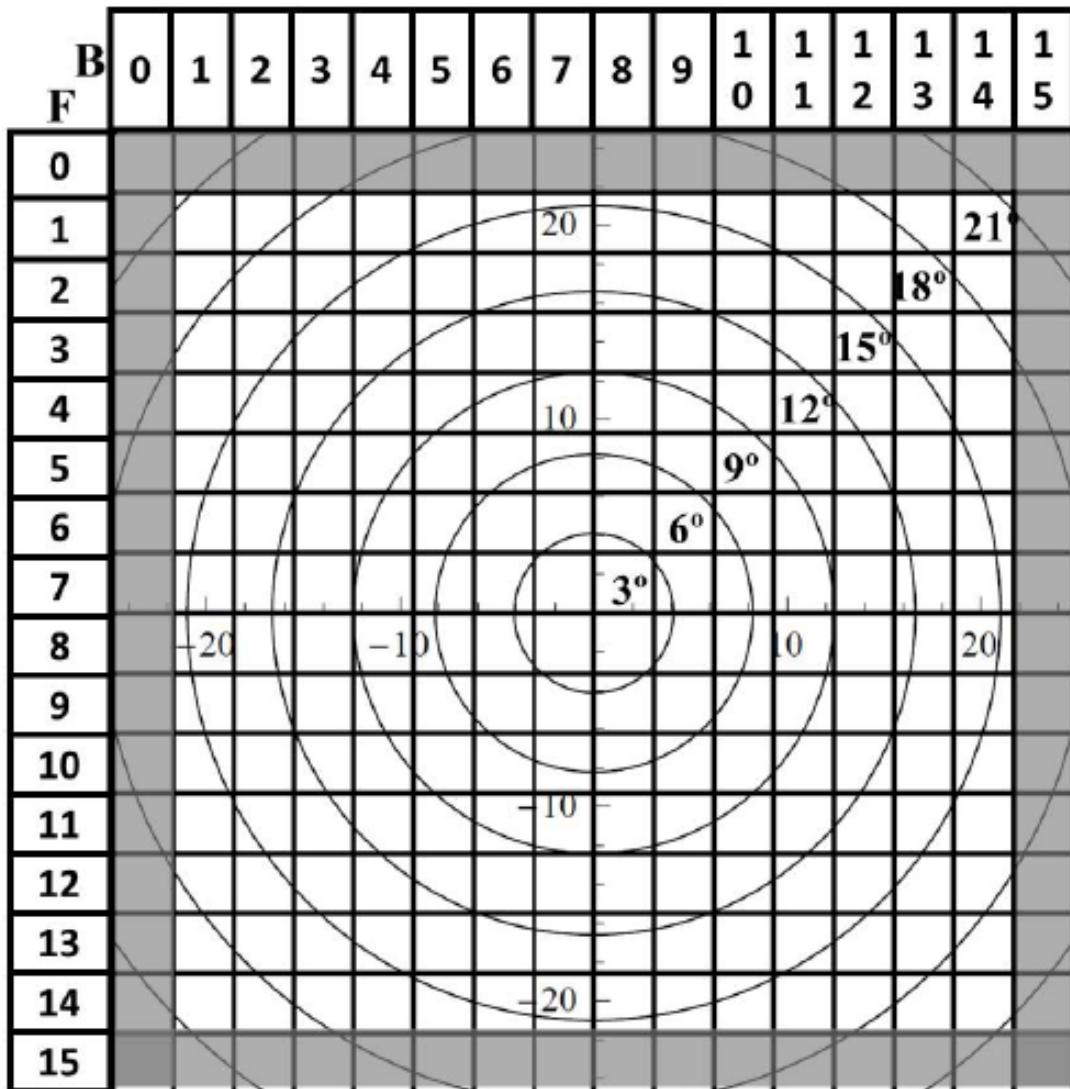
$E_{cm}=4.0$ MeV时的 ${}^6\text{Li}$ 鉴别谱



$E_{cm}=6.7$ MeV时的 $\Delta E-E_r$ 二维谱



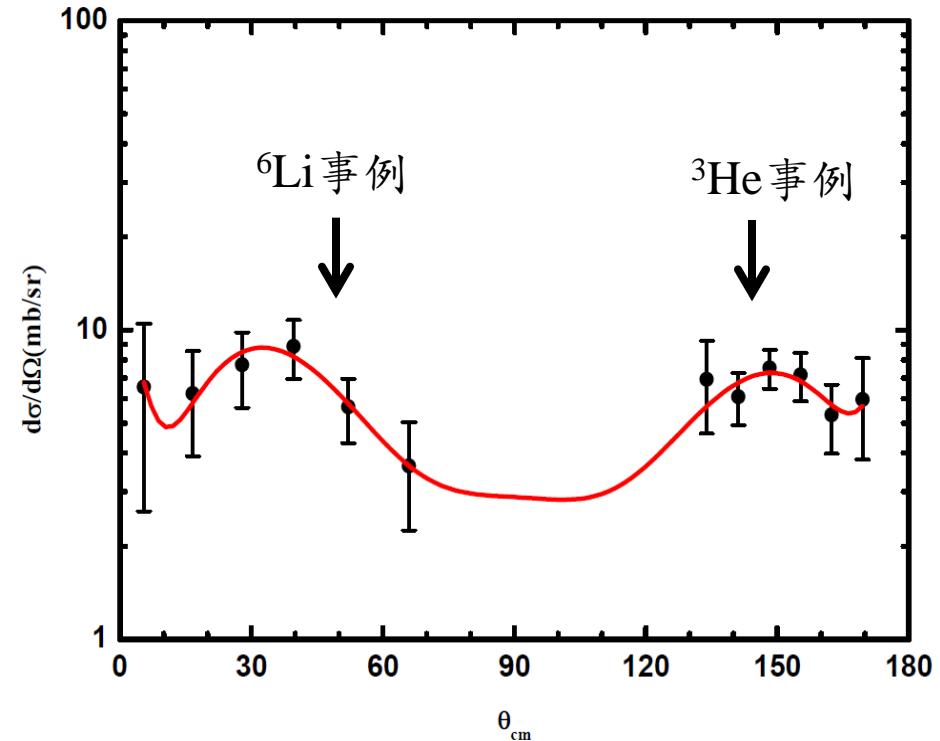
微分截面的导出



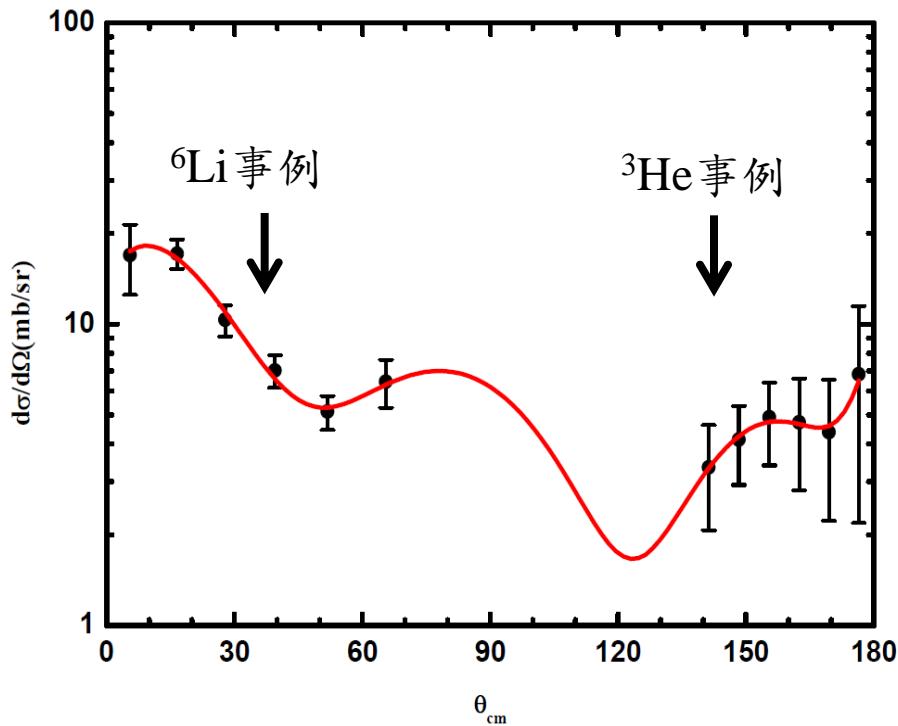
$$\left(\frac{d\sigma}{d\Omega}\right)_i = \frac{\Delta N_i}{IN_s \Delta\Omega_i}$$

ΔN_i : 第*i*环探测到的 ^3He 或 ^6Li 事件数
 I : 入射的 ^7Be 计数
 N_s : 单位面积的靶核数
 $\Delta\Omega_i$: 第*i*环覆盖的立体角

$^2\text{H}(^7\text{Be}, ^6\text{Li})^3\text{He}$ 反应角分布

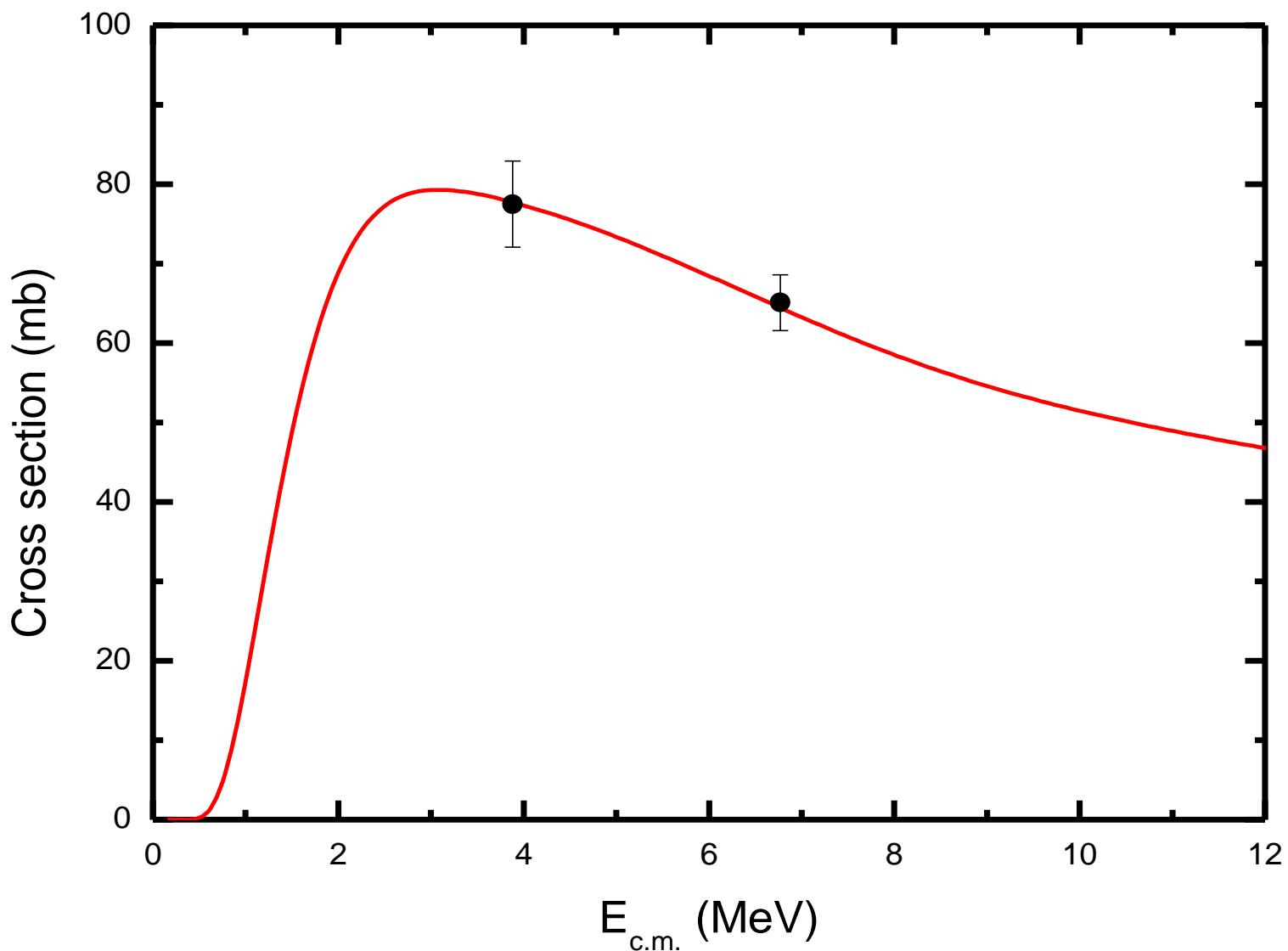


$E_{\text{cm}}=3.9 \text{ MeV}$
总截面为: $77.5 \pm 5.4 \text{ mb}$

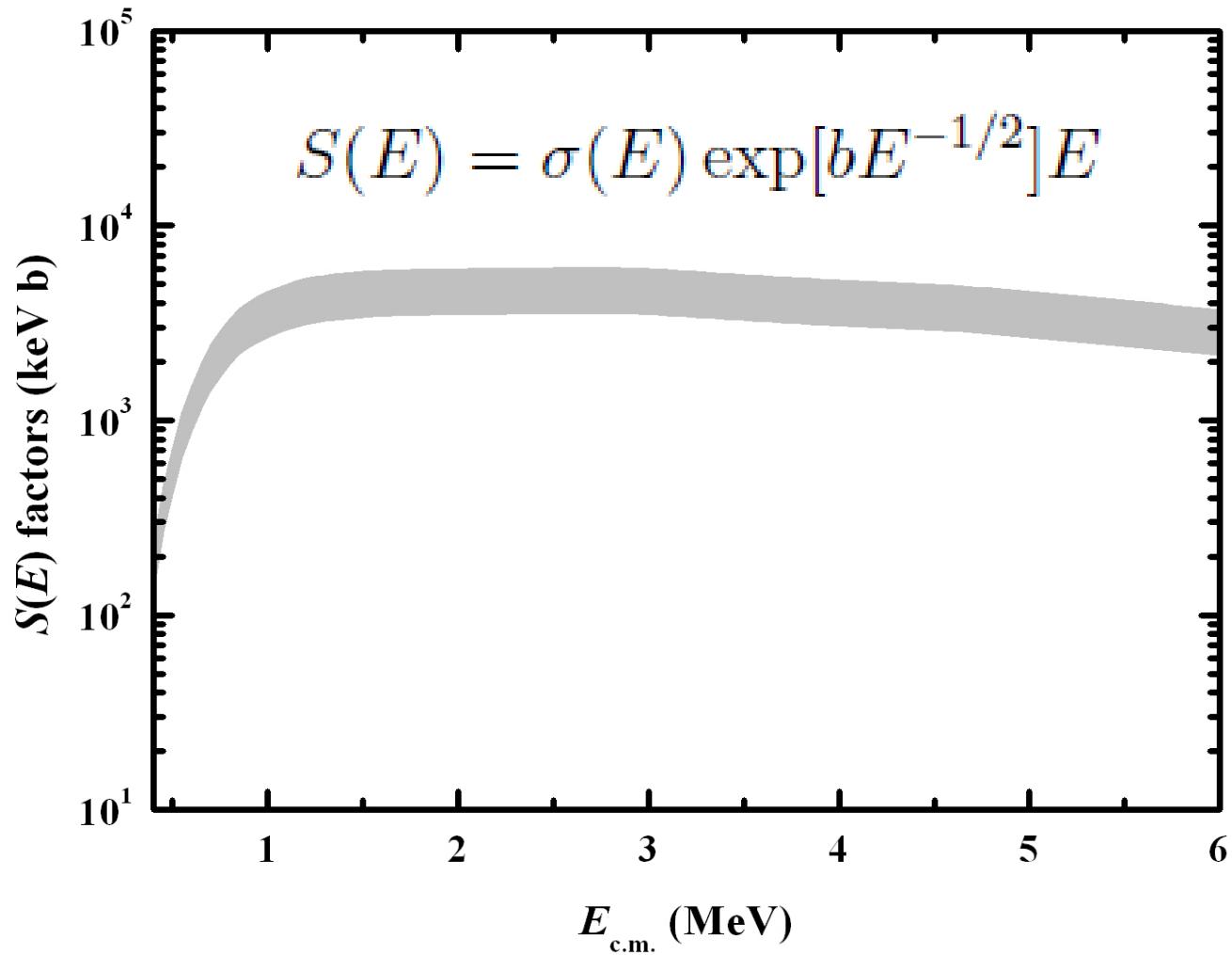


$E_{\text{cm}}=6.8 \text{ MeV}$
总截面为: $65.1 \pm 3.5 \text{ mb}$

$^2\text{H}(^7\text{Be}, ^6\text{Li})^3\text{He}$ 反应的激发函数

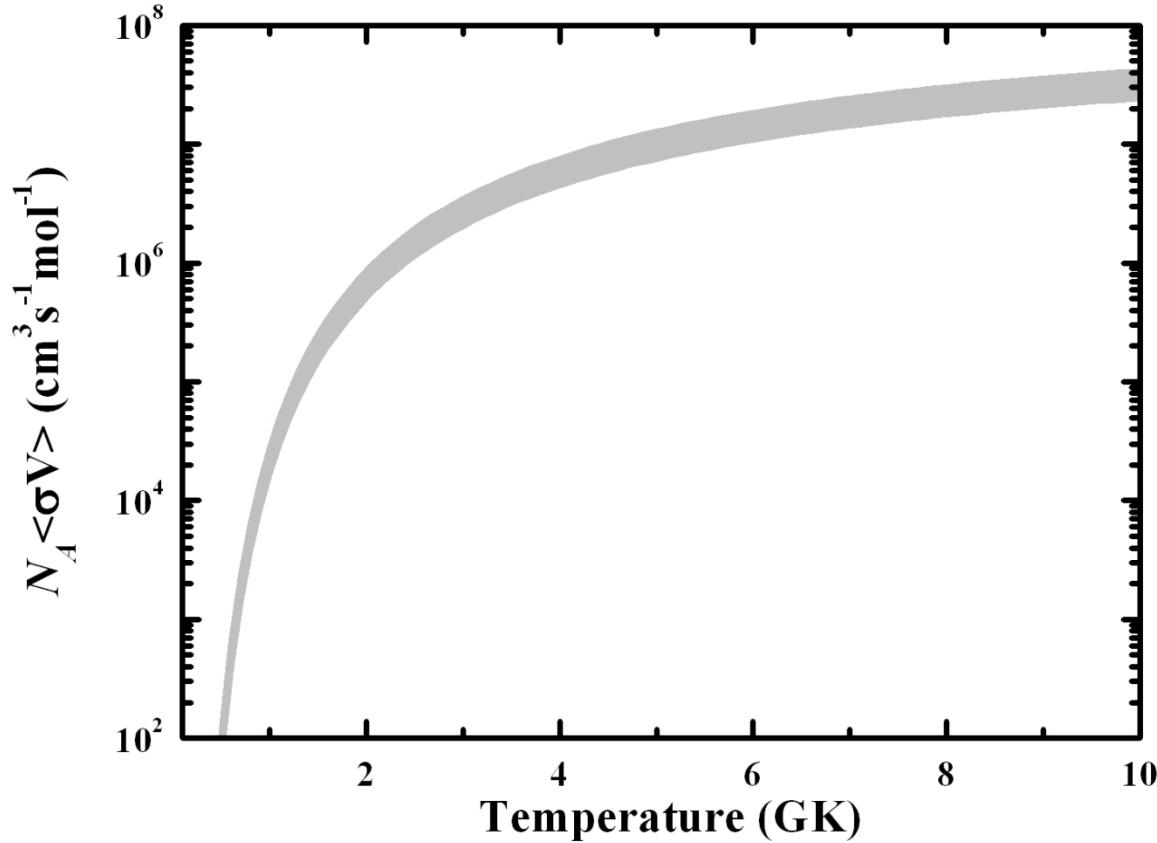


$^2\text{H} (^7\text{Be}, ^6\text{Li}) ^3\text{He}$ 天体物理S因子



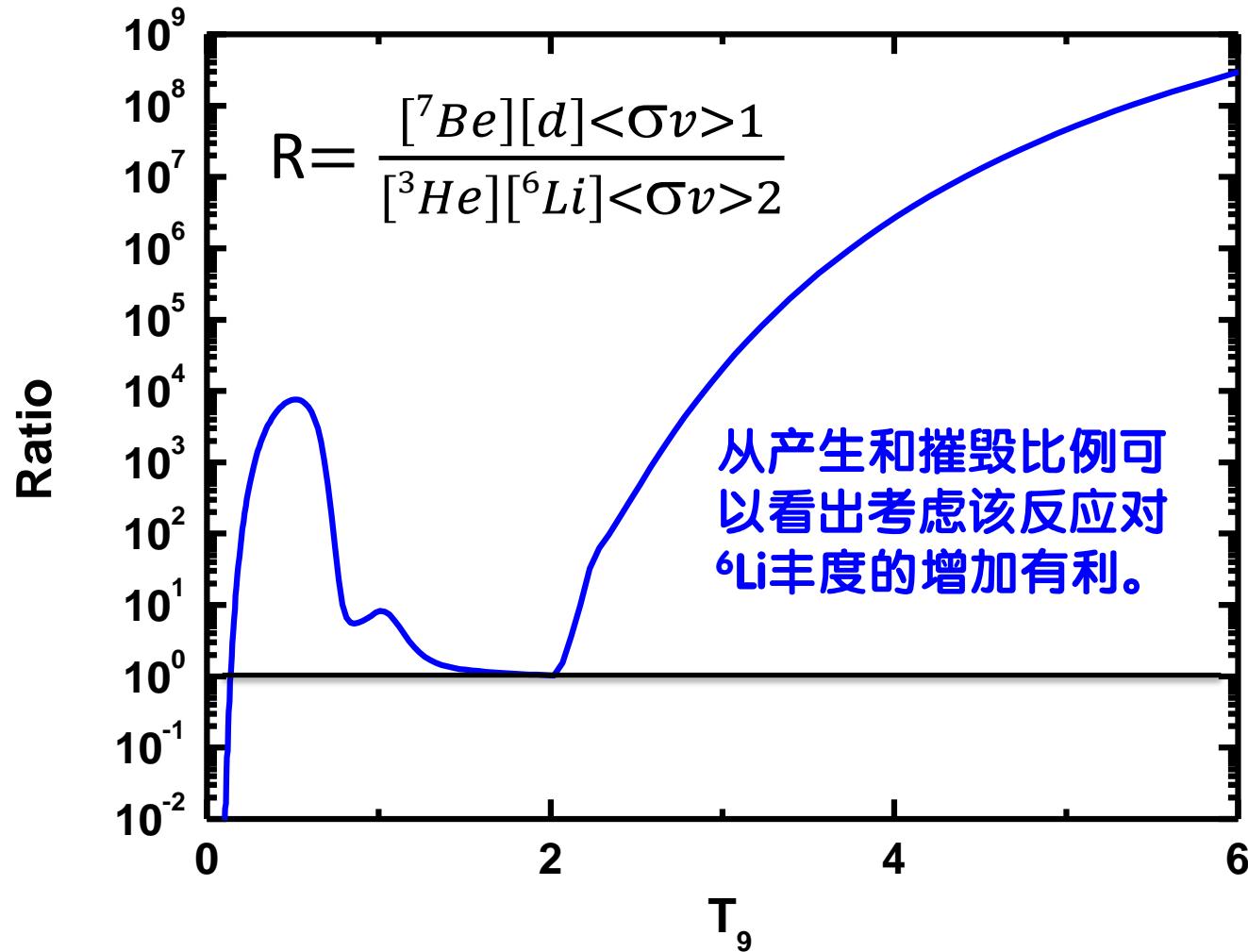
$^2\text{H}(^7\text{Be}, ^6\text{Li})^3\text{He}$ 天体物理反应率

$$N_A \langle \sigma v \rangle = N_A \left(\frac{8}{\pi \mu} \right)^{1/2} \left(\frac{1}{kT} \right)^{3/2} \int_0^\infty S(E) \exp \left(-\frac{E}{kT} - bE^{-1/2} \right)$$

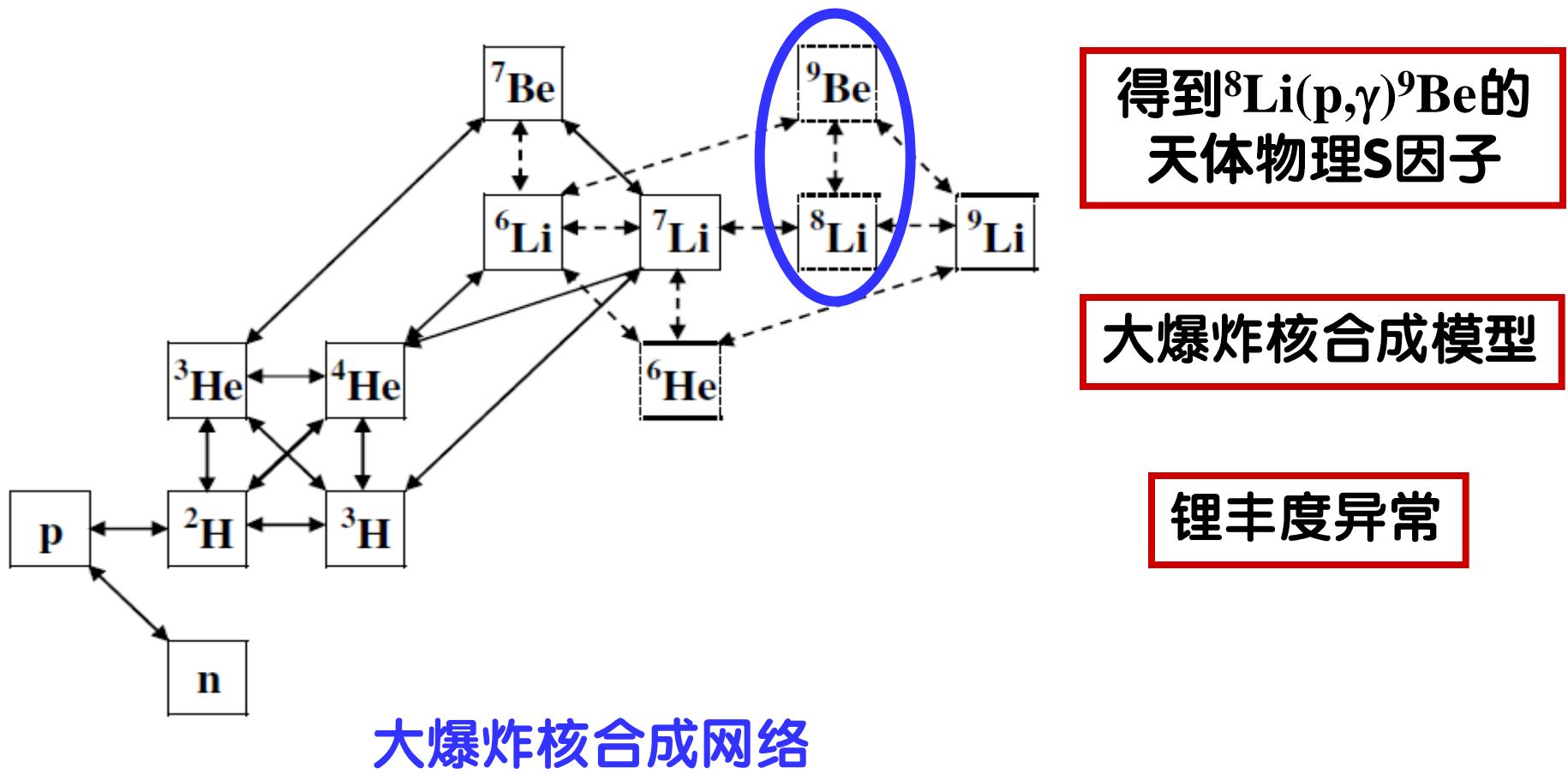


$$\begin{aligned} N_A \langle \sigma v \rangle &= \exp(23.9178 - 5.41899 T_9^{-1} + 58.0574 T_9^{-1/3} - 69.4566 T_9^{1/3} \\ &\quad + 3.0522 T_9 - 0.153952 T_9^{5/3} + 40.4537 \ln T_9) \end{aligned}$$

$^{7}\text{Be}(\text{d}, ^3\text{He})^6\text{Li}$ 对锂丰度影响的分析

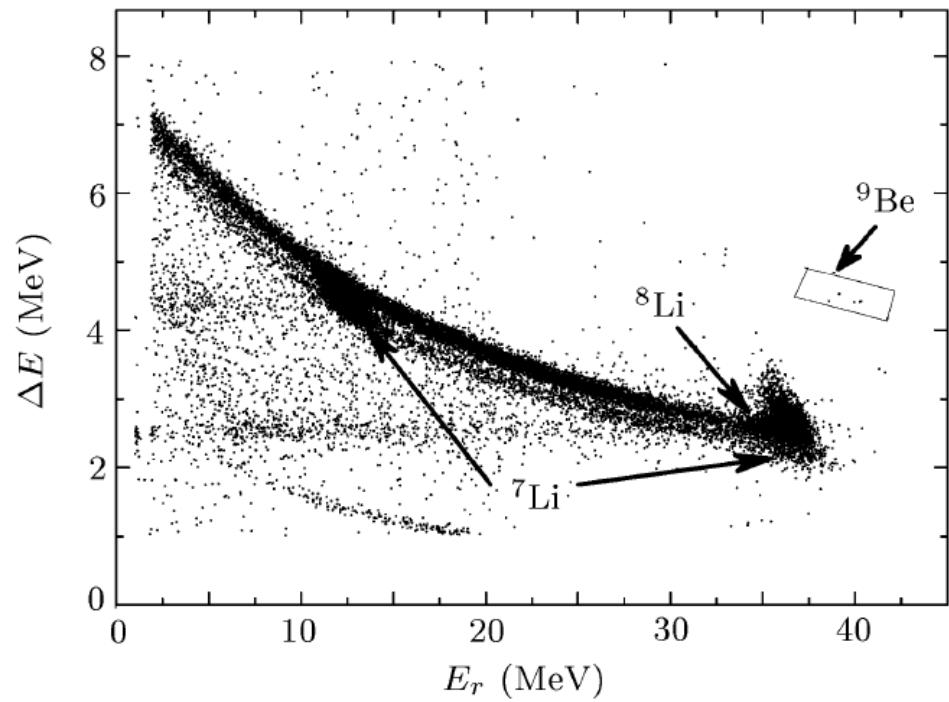
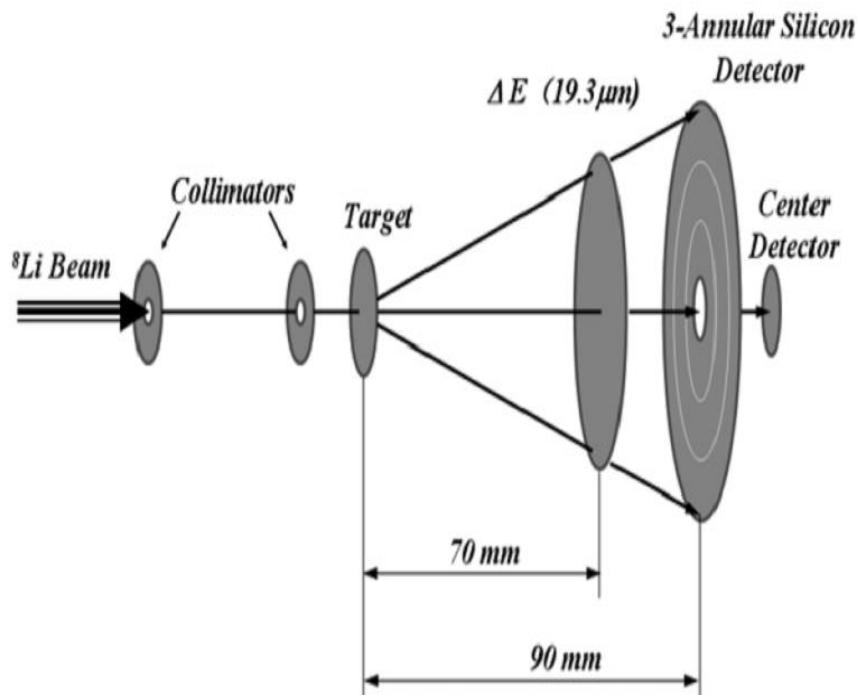


测量 ${}^9\text{Be} \rightarrow {}^8\text{Li} + \text{p}$ 核谱因子的意义



$^2\text{H}(^{8}\text{Li},^{9}\text{Be})\text{n}$ 实验 (2005年)

Zeng et al., Chin. Phys. Lett. 22 (2005) 2219

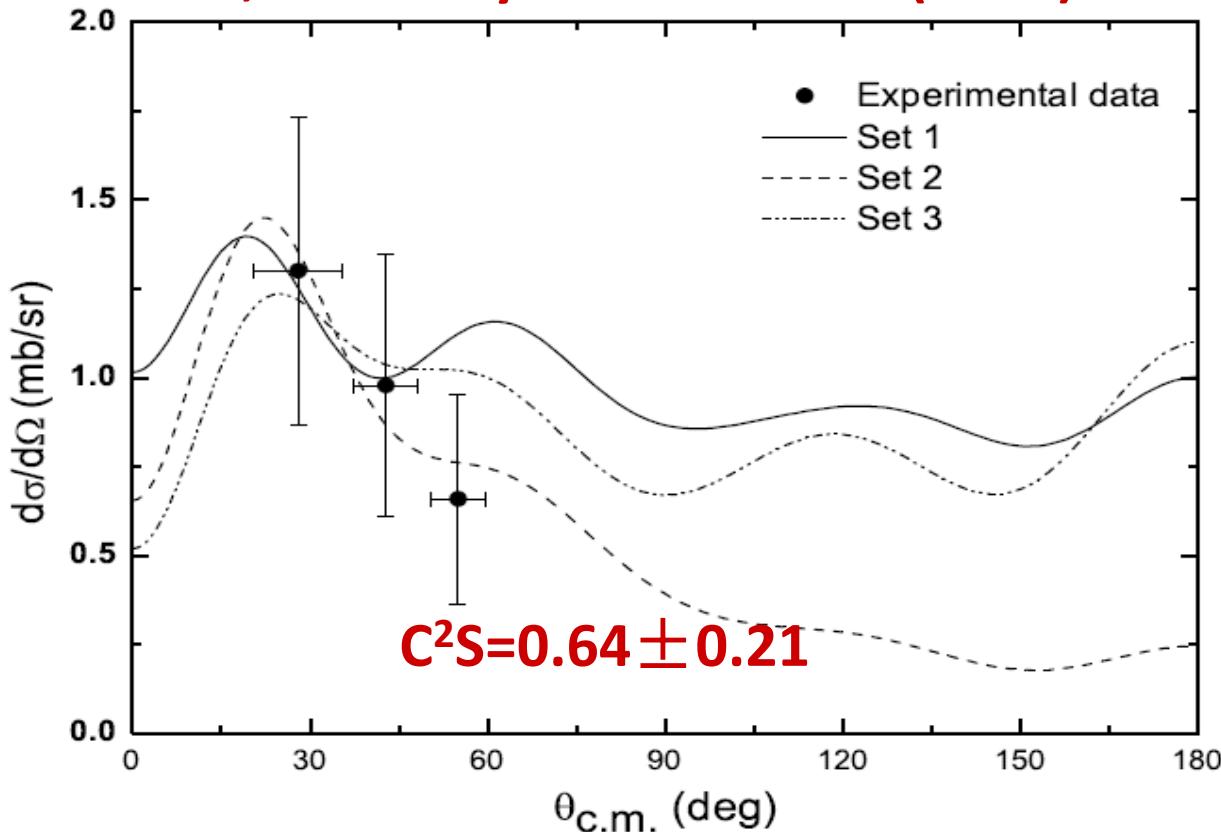


实验设置

ΔE - E_r 二维谱

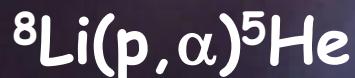
$^2\text{H}(^8\text{Li}, ^9\text{Be})\text{n}$ 反应的角分布

SU Jun et al., Chin. Phys. Lett. Vol. 23 (2006) 55



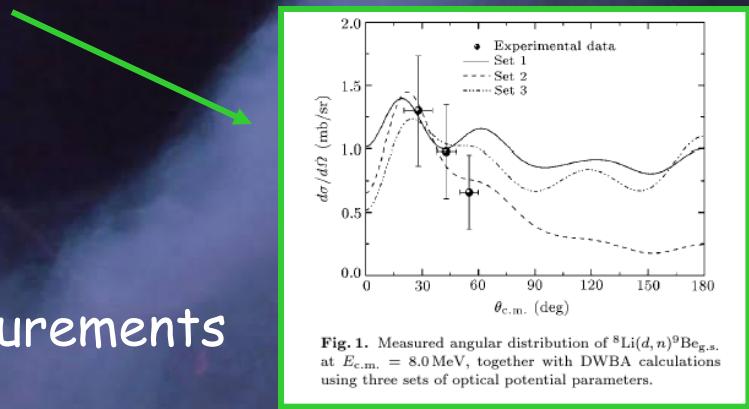
缺点：点数少，误差大！

Production and Destruction of ${}^8\text{Li}$



Indirect ANC ${}^8\text{Li}(\text{d}, \text{n}){}^9\text{Be}$ reaction.
J.Su et al. Chinese PL 23(2006)55

No measurements



Djalma Mendes (Phd Thesis)
At São Paulo (RIBRAS)
Alinka Lepine's talk

Reflection Nebula NGC 1999

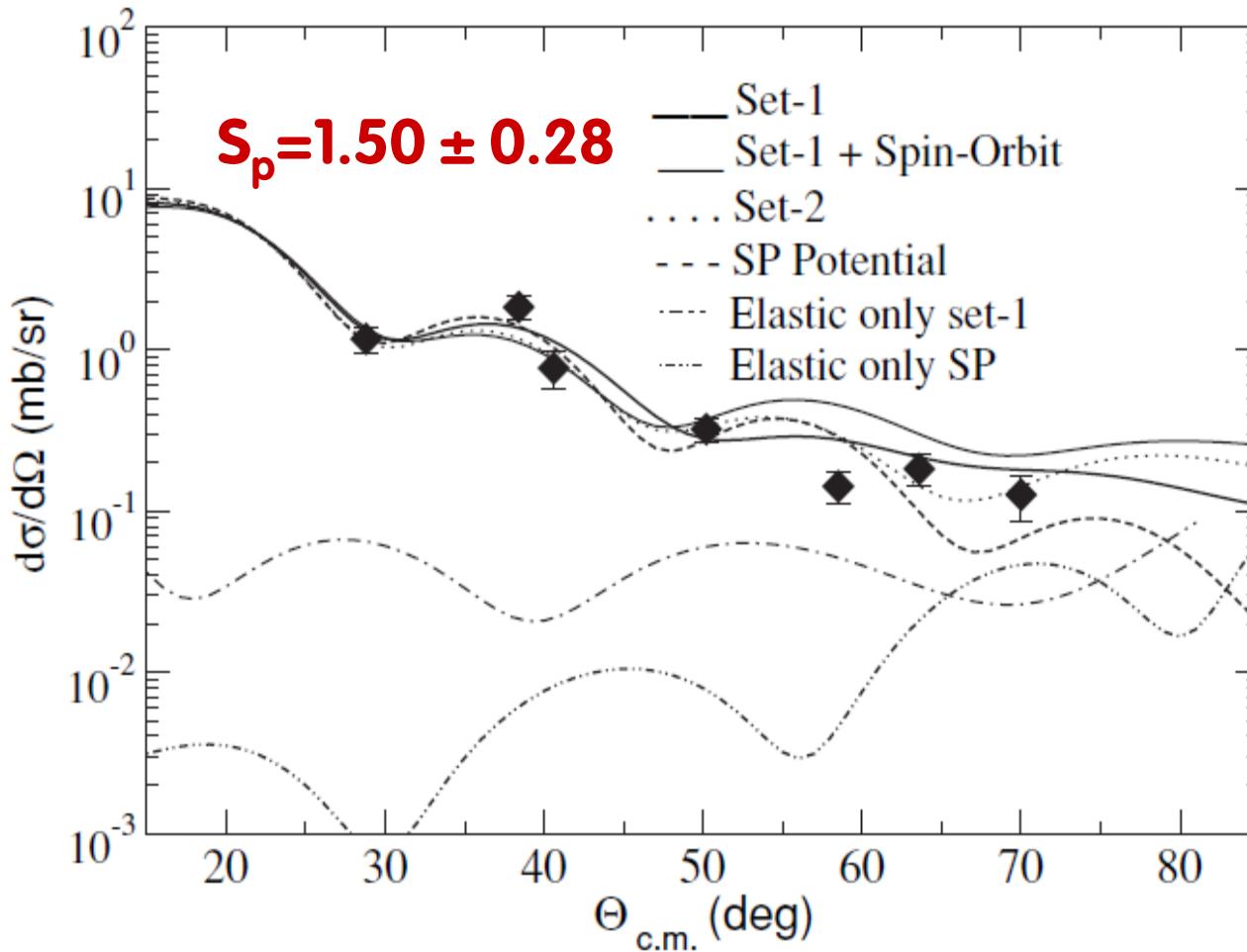


HUBBLE SITE.org

${}^9\text{Be}({}^8\text{Li}, {}^9\text{Be}) {}^8\text{Li}$ 反应 (2008)

University of Notre Dame

O. Camargo et al., Phys. Rev. C 78 (2008) 034605



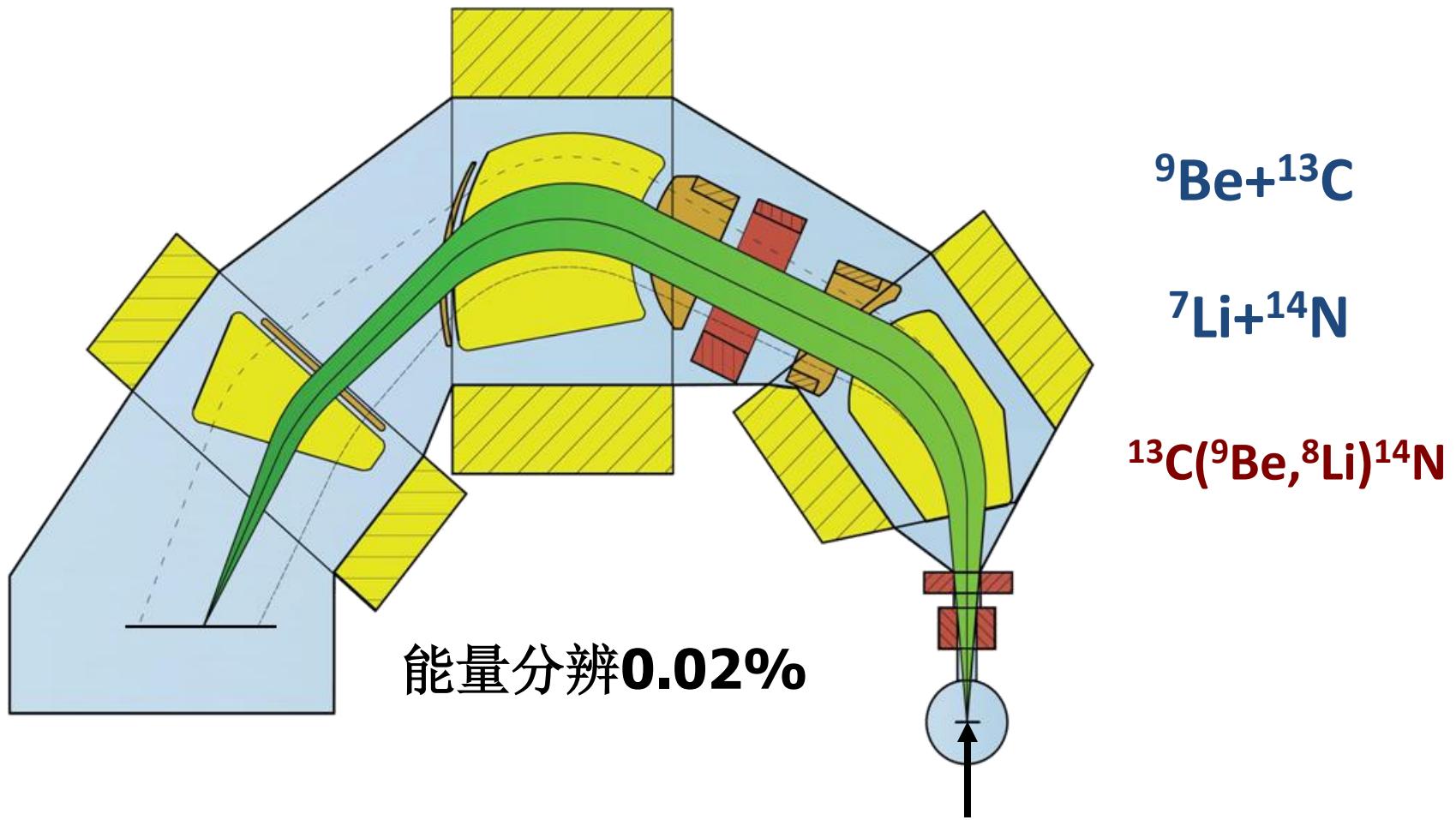
Ours: 0.64 ± 0.21

Theory: 1.0

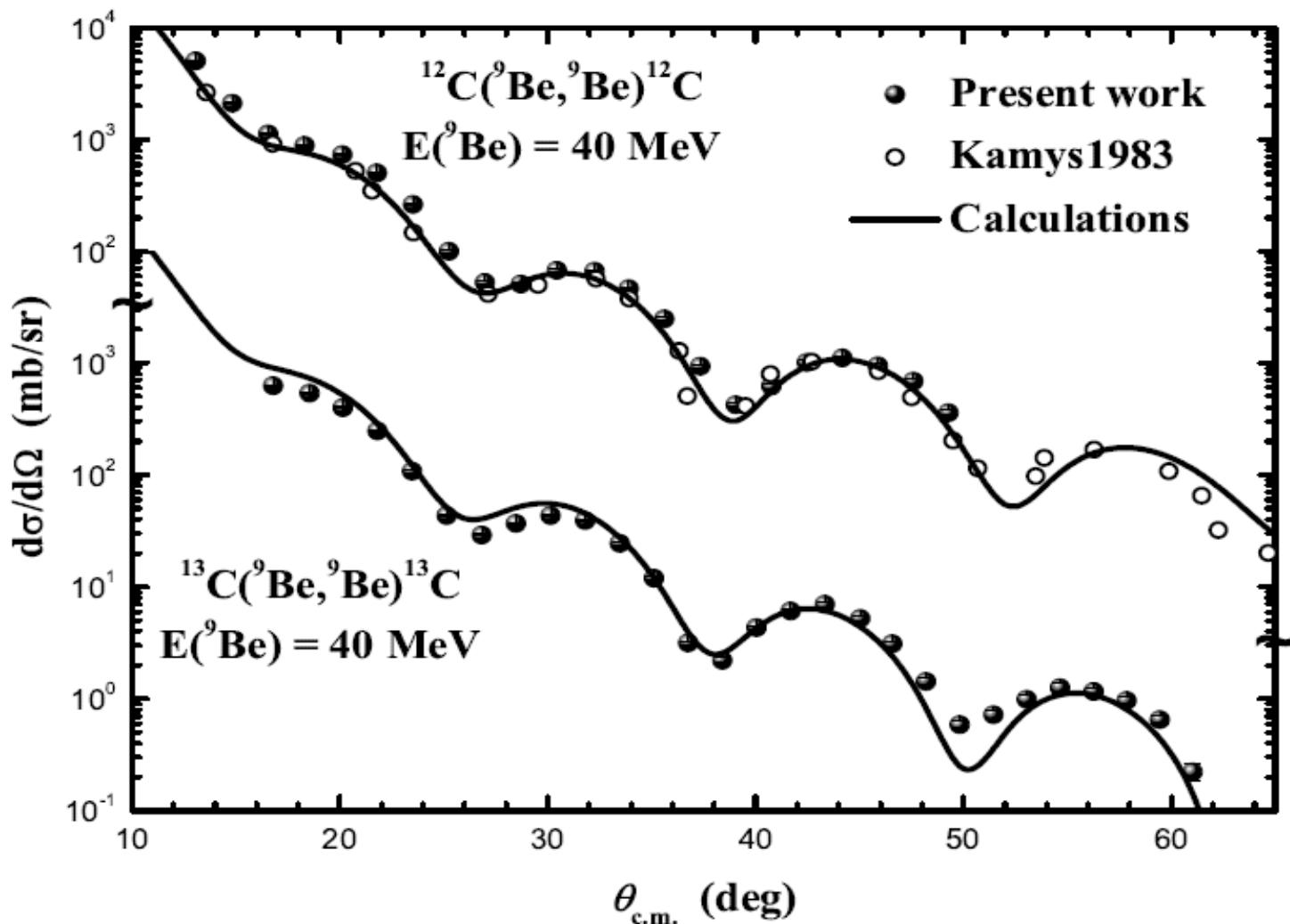
哪一个测错了?

缺点：没有测到角分布的第一个峰！

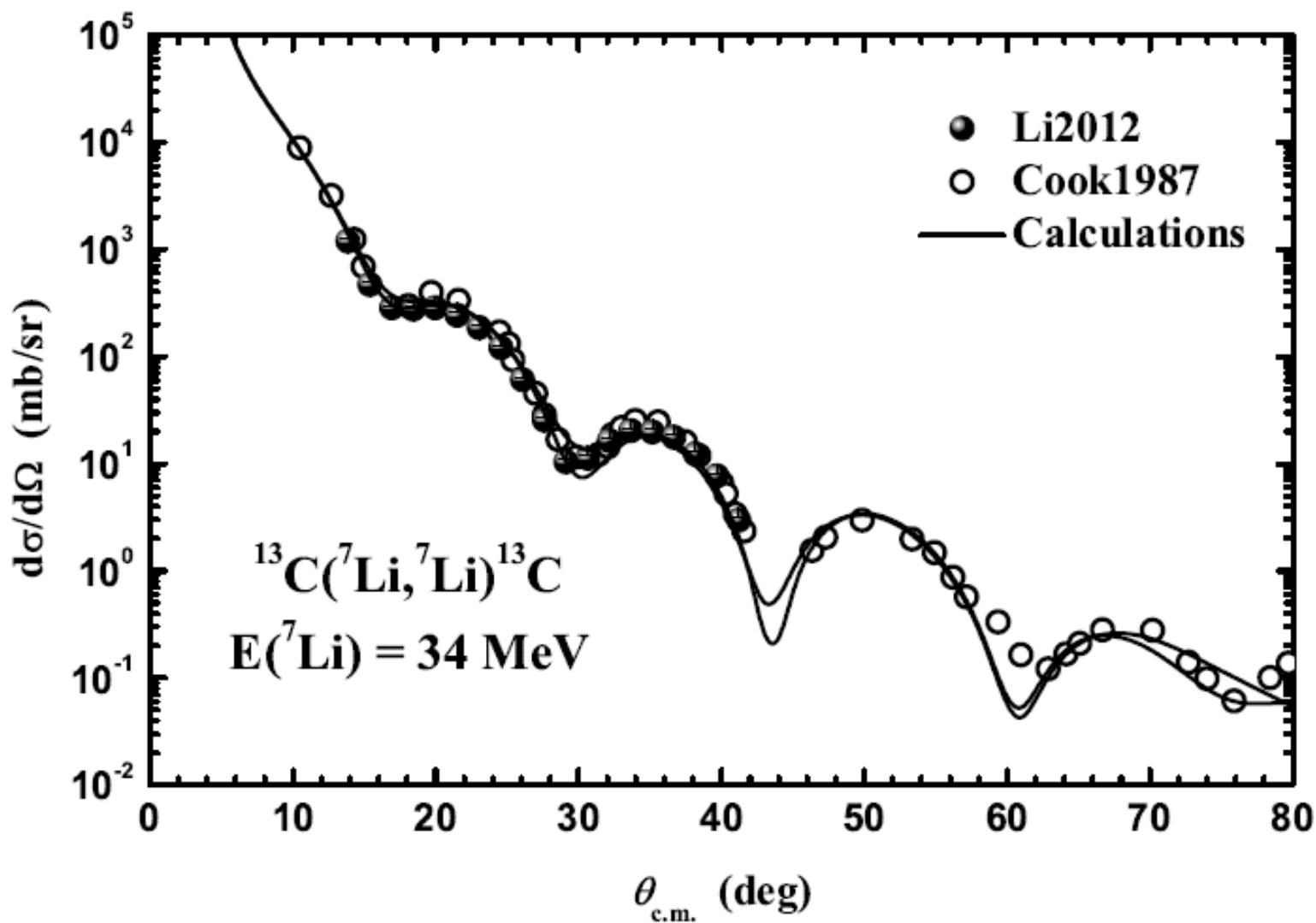
实验计划—Q3D磁谱仪



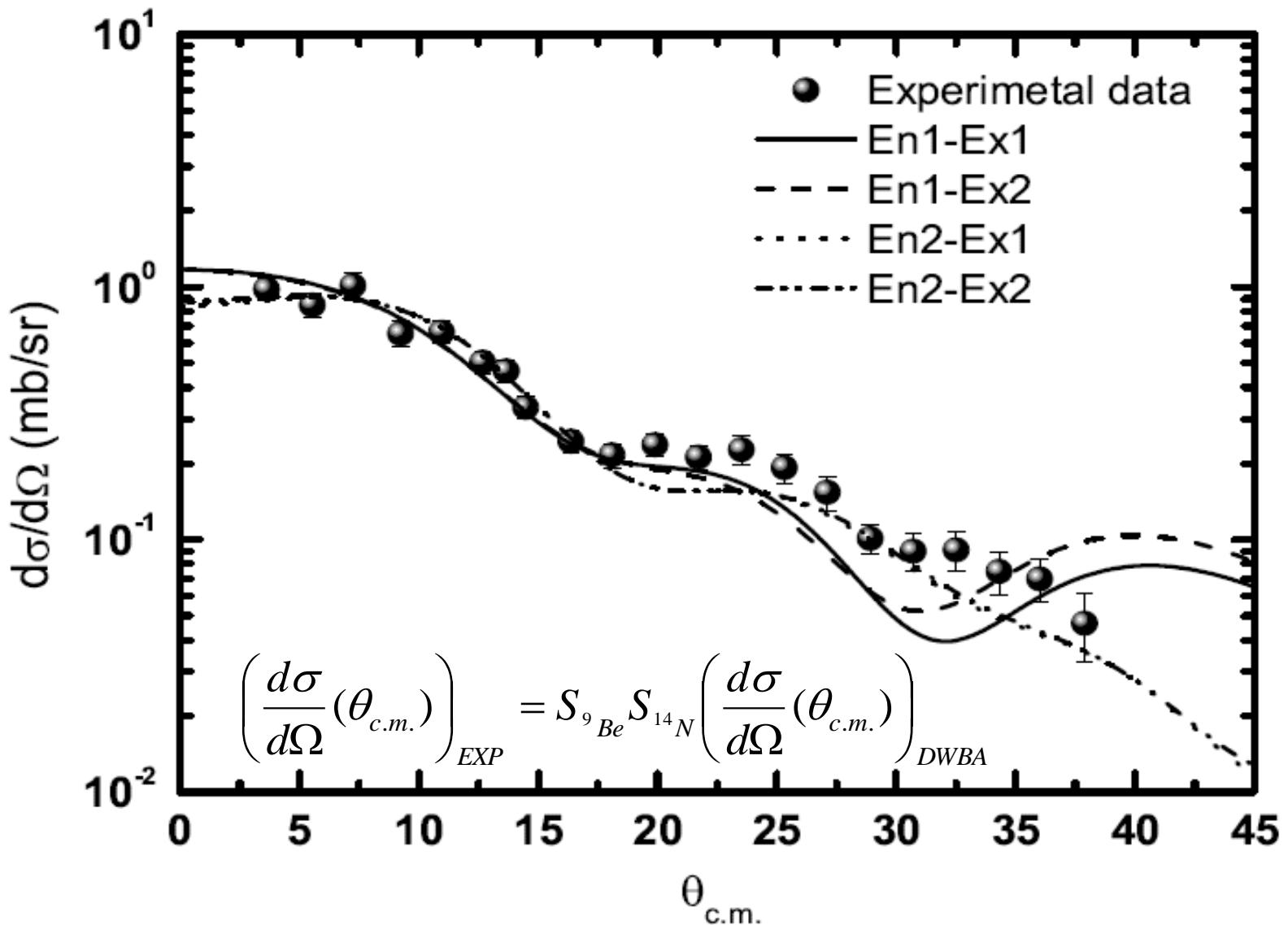
${}^9\text{Be} + {}^{13}\text{C}$ 弹性散射角分布



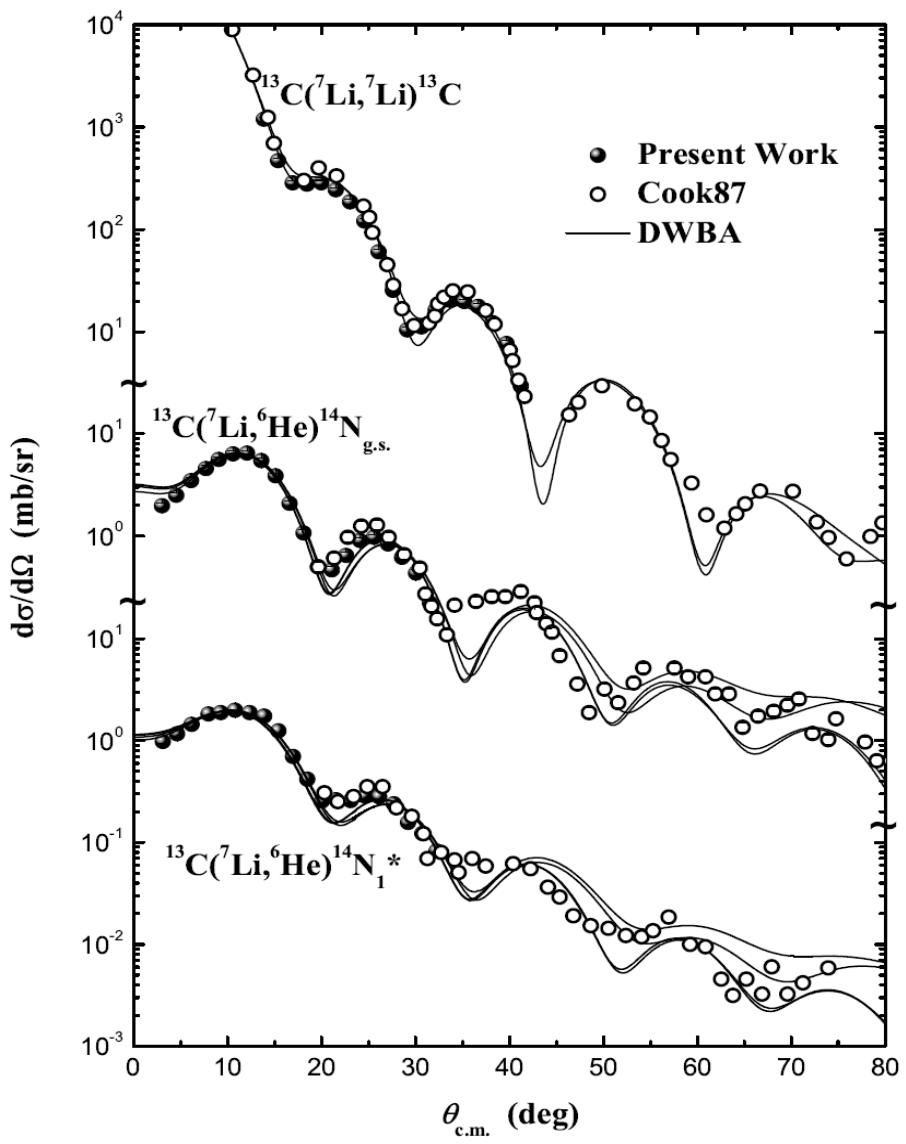
$^{7}\text{Li} + ^{14}\text{N}$ 弹性散射角分布



$^{13}\text{C}(^{9}\text{Be},^{8}\text{Li})^{14}\text{N}$ 转移反应的角分布



^{14}N 基态的质子谱因子



^{14}N 基态的质子谱因子: 0.67 ± 0.09

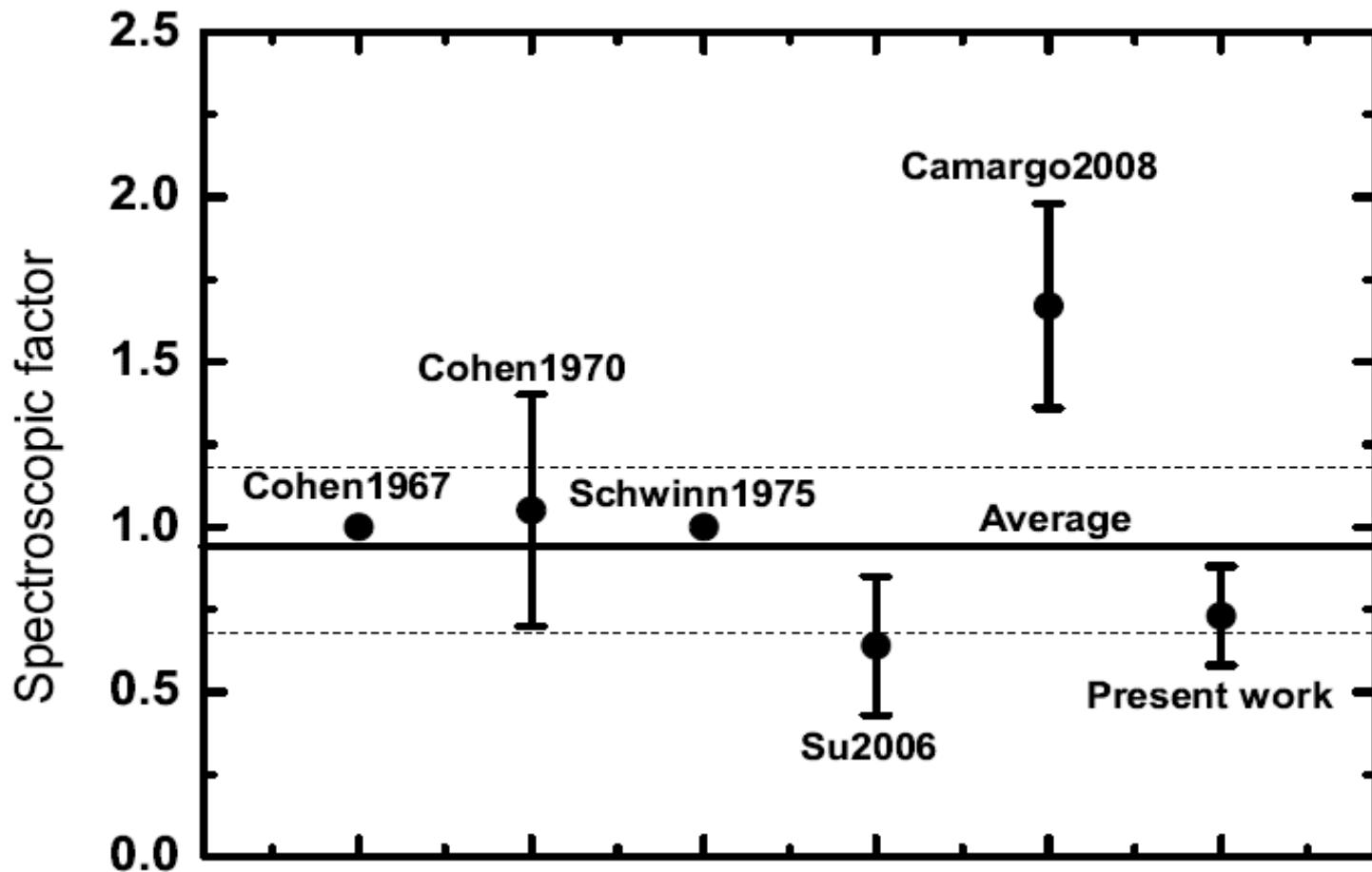
文章将在EPJA上发表，评委意见如下：

Quality of the experimental data is good. The first peak of the $^{13}\text{C}(^{7}\text{Li}, ^{6}\text{He})^{14}\text{N}$ angular distribution was identified for the first time. The manuscript is well written and mostly comprehensive.

This paper describes a new determination of the S factor and thermonuclear rate of the $^{13}\text{C}(p,\gamma)$ reaction. This is a nice work that is accepted for publication after consideration of the minor revisions noted below.

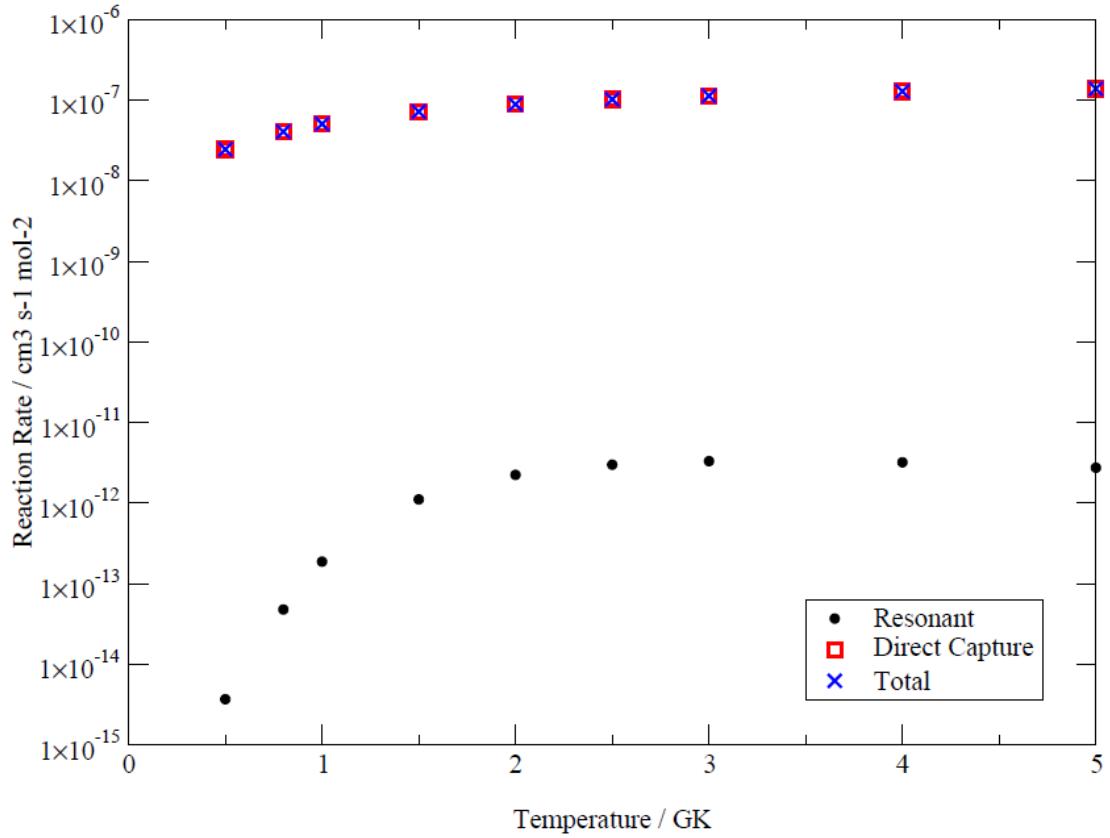
Y. J. Li et al., EPJA, 48 (2012) 13

${}^9\text{Be}$ 基态的质子谱因子

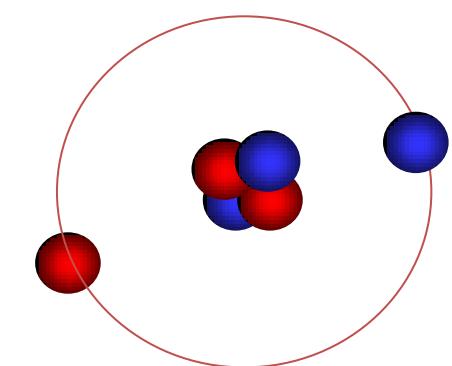
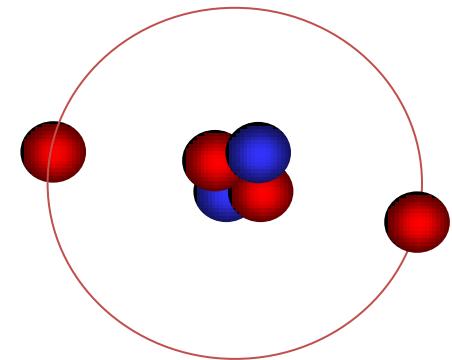


证明我们2006年发表的结果是正确的!

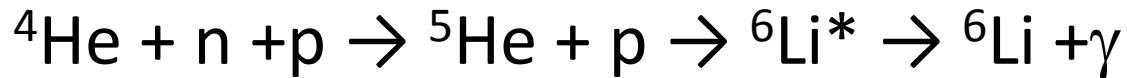
$^4\text{He}(np,\gamma)^6\text{Li}$ 辐射俘获反应



$^4\text{He}(2n,\gamma)^6\text{He}$ astrophysical reaction rate



TWO-STEP CAPTURE THEORY

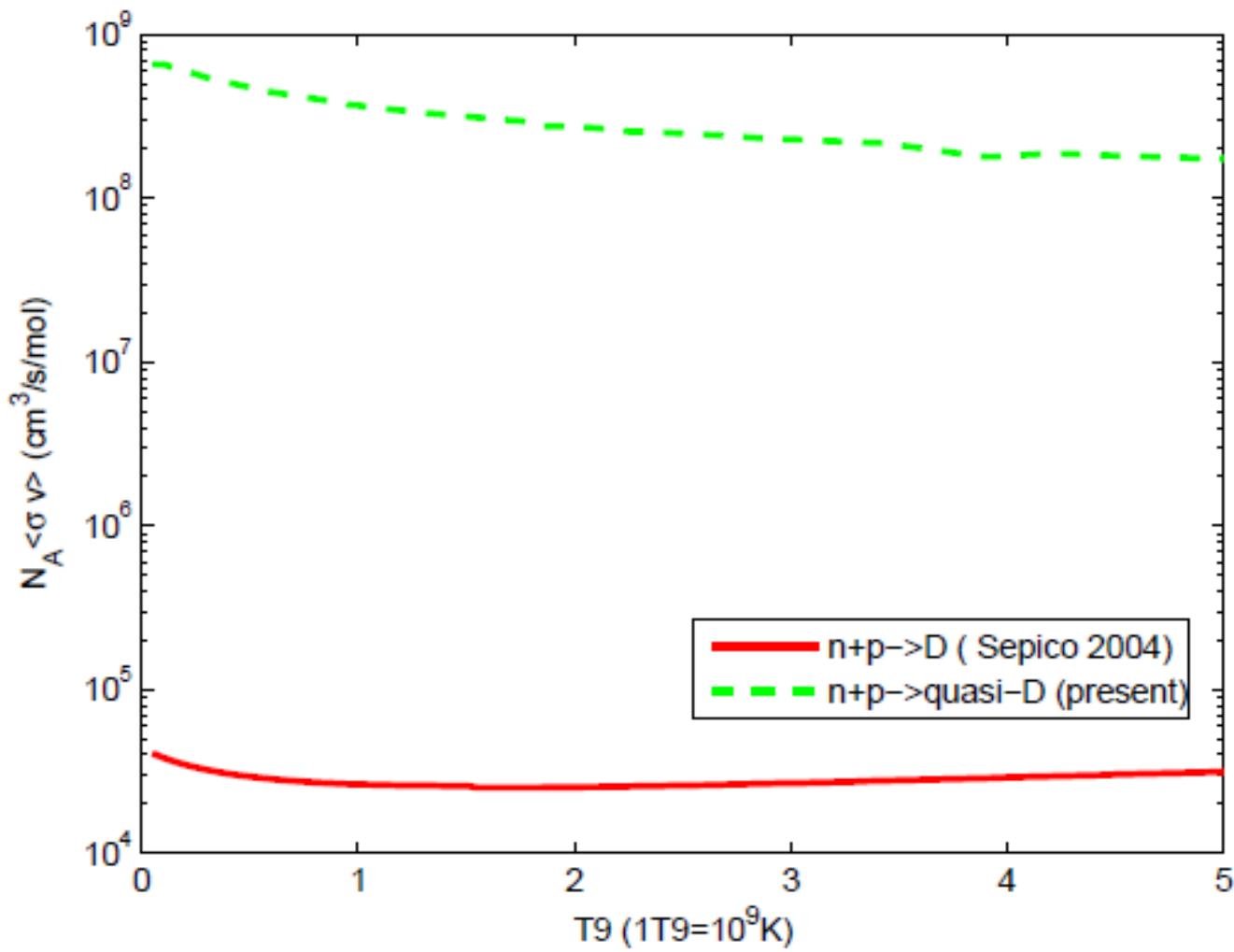


$$N_A^2 <1pp> = N_A^2 \int_{E_1} \frac{d <(p,p)> (E_1)}{dE_1} \frac{2\hbar}{\Gamma(E_1)} \left[\int_{E_2} \frac{d <p,\gamma> (E_1, E_2)}{dE_2} dE_2 \right] dE_1$$

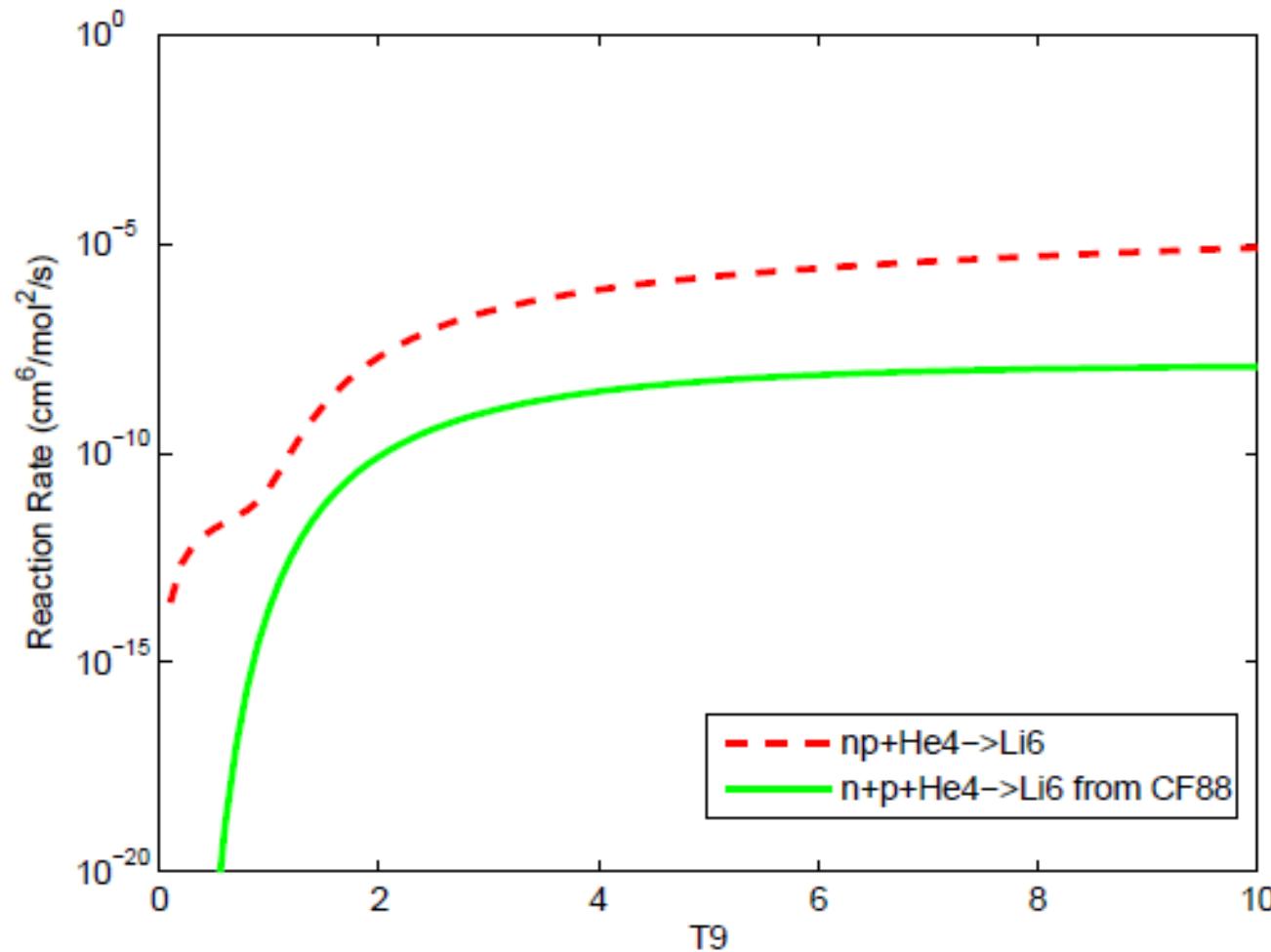
$$\frac{d <\sigma v>}{dE} = \sqrt{\frac{8}{\pi\mu}} \frac{1}{(kT)^{\frac{3}{2}}} \sigma(E) \exp\left(-\frac{E}{kT}\right),$$

$$f = \exp(c_0 + c_1 T_9 + c_2 T_9^2 + c_3 T_9^3 + c_4 T_9^4 + c_5 T_9^5 + c_6 T_9^6 + c_7 T_9^7)$$

Forming the quasi-deuteron



$^4\text{He}(\text{np},\gamma)^6\text{Li}$ 天体物理反应率



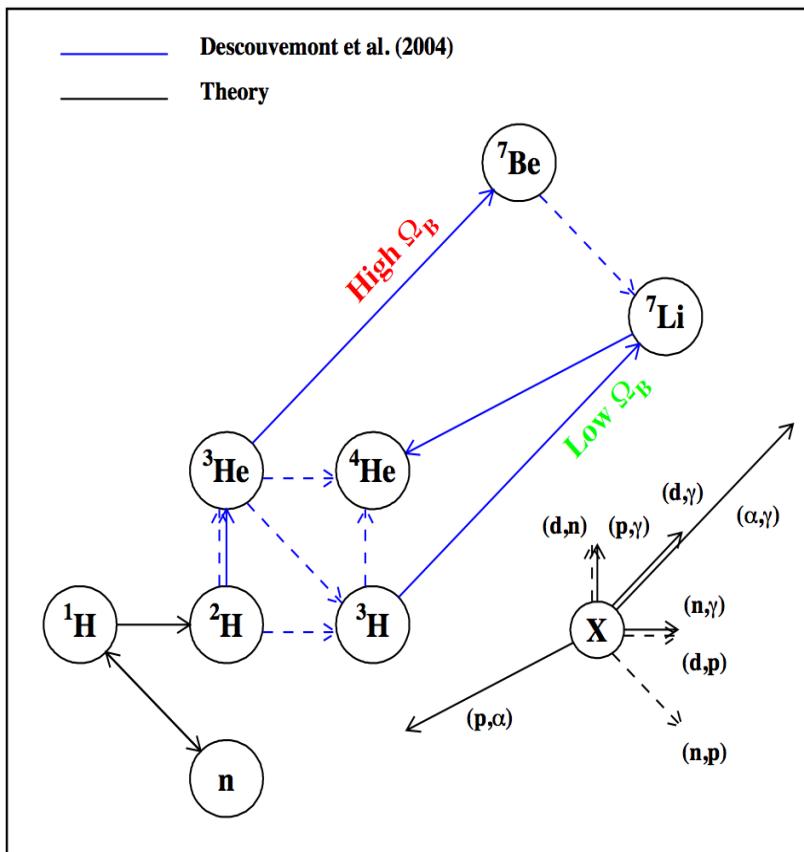
The astrophysical $^4\text{He}(\text{np},\gamma)^6\text{Li}$ reaction rates deduced with a novel quasi-deuteron capture Mechanism.

总 结

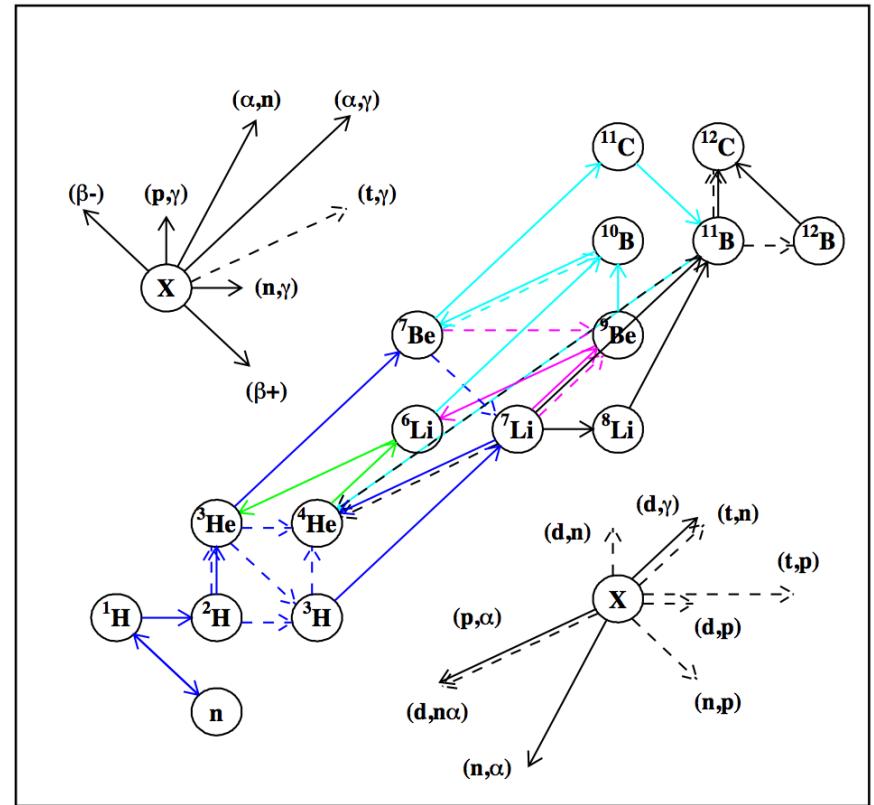
- 为解决“锂难题”，研究了5个相关的核反应。
- 由 ${}^6\text{He}(\text{d},\text{n}){}^7\text{Li}$ 反应角分布导出了 ${}^6\text{He}(\text{p},\gamma){}^7\text{Li}$ 反应的天体物理S因子。
- 从 ${}^{13}\text{C}({}^7\text{Li}, {}^8\text{Li}){}^{12}\text{C}$ 反应角分布导出了原初 ${}^7\text{Li}$ $(\text{n},\gamma){}^8\text{Li}$ 反应的激发函数。
- 测量了两个能点的 ${}^2\text{H}({}^7\text{Be}, {}^6\text{Li}){}^3\text{He}$ 反应角分布，计算了该反应的激发函数。
- 测量了 ${}^{13}\text{C}({}^9\text{Be}, {}^8\text{Li}){}^{14}\text{N}$ 转移反应的角分布，导出了 ${}^9\text{Be}$ 的质子谱因子。
- 利用两步法计算了 ${}^4\text{He}(\text{np},\gamma){}^6\text{Li}$ 天体物理反应率。
- 这些反应对原初锂丰度的影响需要进行评估。

BBN extended network up to CNO

Alain Coc et al.

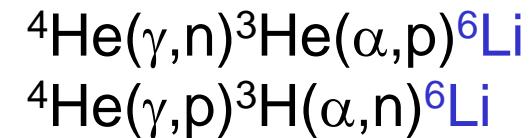
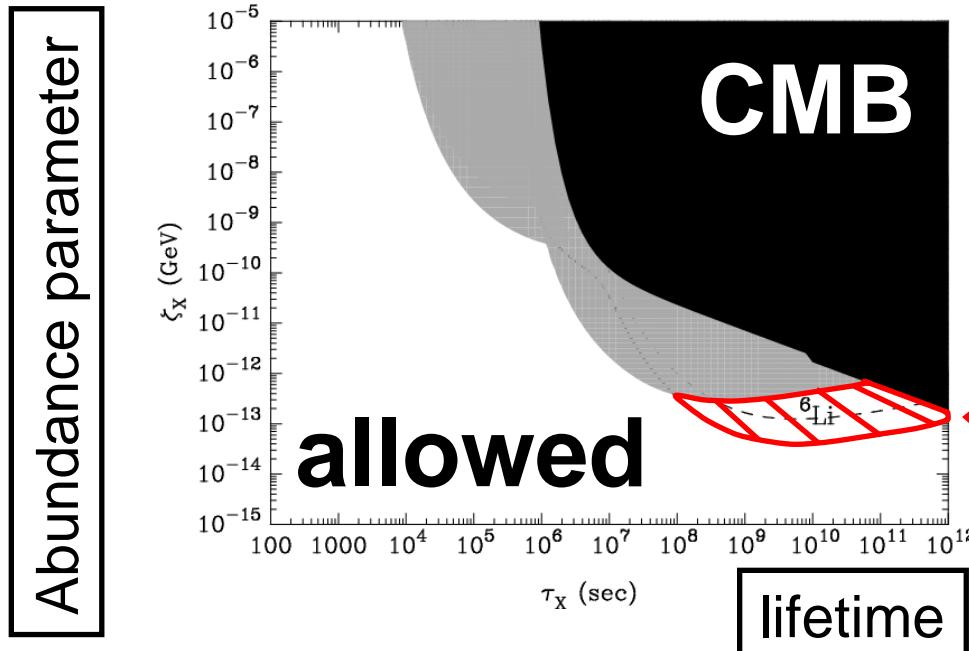


The 12 reactions of standard BBN



Main path for: H , D , ^3He , ^4He , ^7Li , ^6Li , ^9Be , $^{10,11}\text{B}$ and CNO (^{12}C), out of the >400 reactions

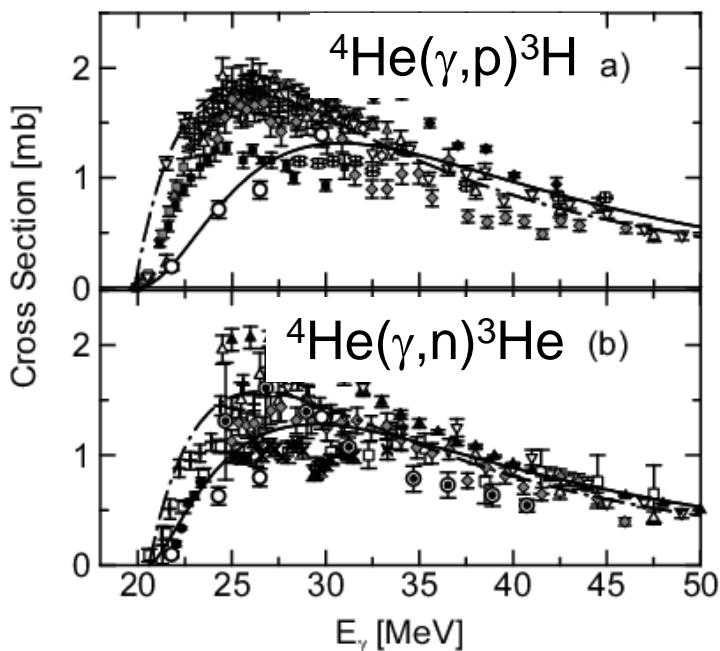
1. ${}^6\text{Li}$ production by the radiative particle decay



$\lesssim 10 \times$ MPHSS ${}^6\text{Li}$

${}^6\text{Li}$ production!

MK, Kajino, Mathews,
PRD 74, 023526 (2006)



Cross sections are measured
→ smaller values than previous ones

O: data of Laser Compton experiment
(Shima et al. 2005)

— functions fitted
(only Odata in $E_\gamma \leq 30\text{MeV}$)
- - - - fitted to old data

The small Magellanic Cloud

Howk et al. Nature, 489 (2012) 121



The ^7Li abundance is nearly equal to the BBN predictions

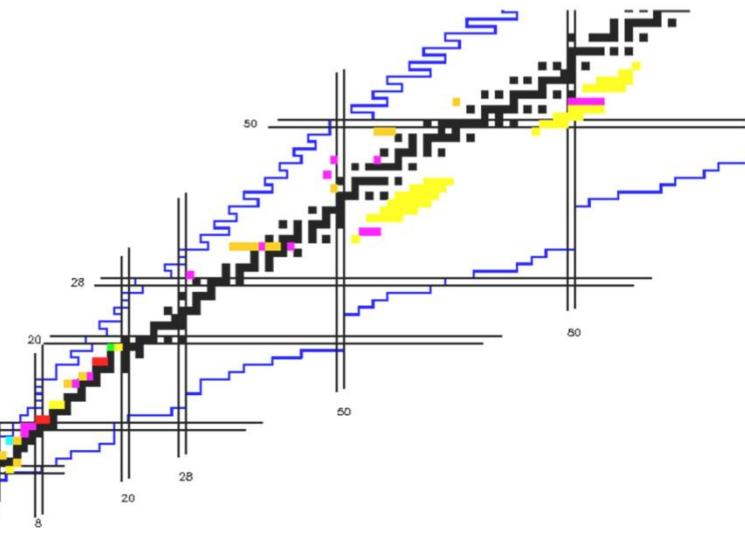
谢谢!

ESIC

Annual Report 2011

欢迎光临：核天体物理创新群体网站

<http://esic.ciae.ac.cn>



Elements Synthesis in Cosmos

创新研究群体

esic.ciae.ac.cn