宇宙中第一代恒星演化的研究进展

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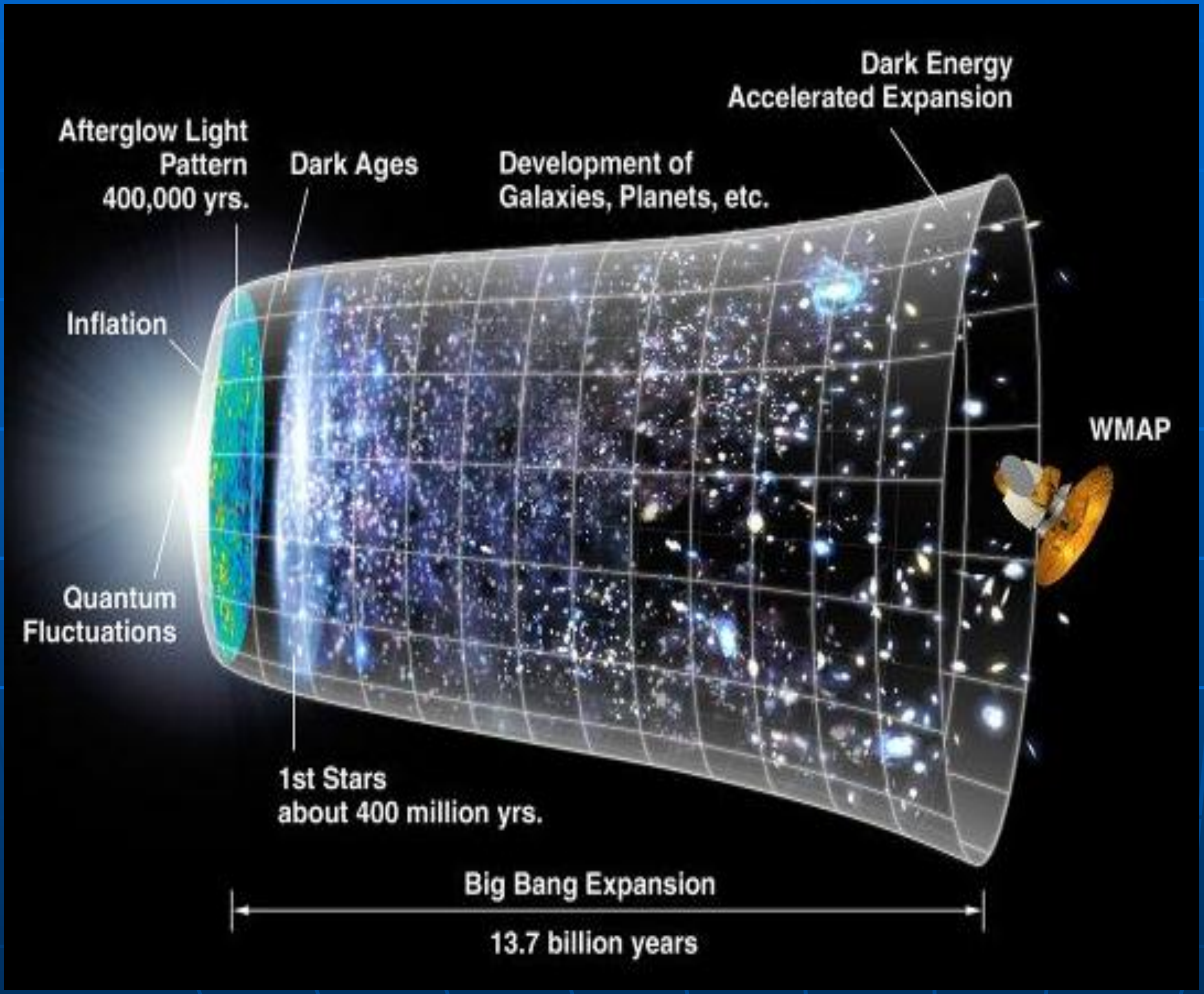
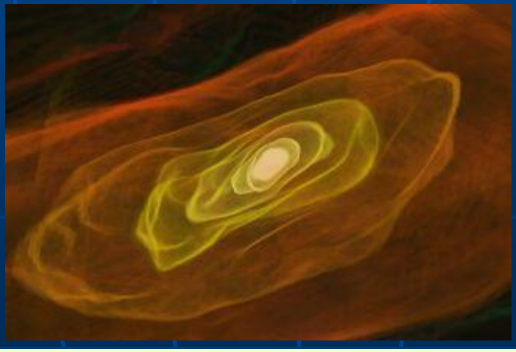
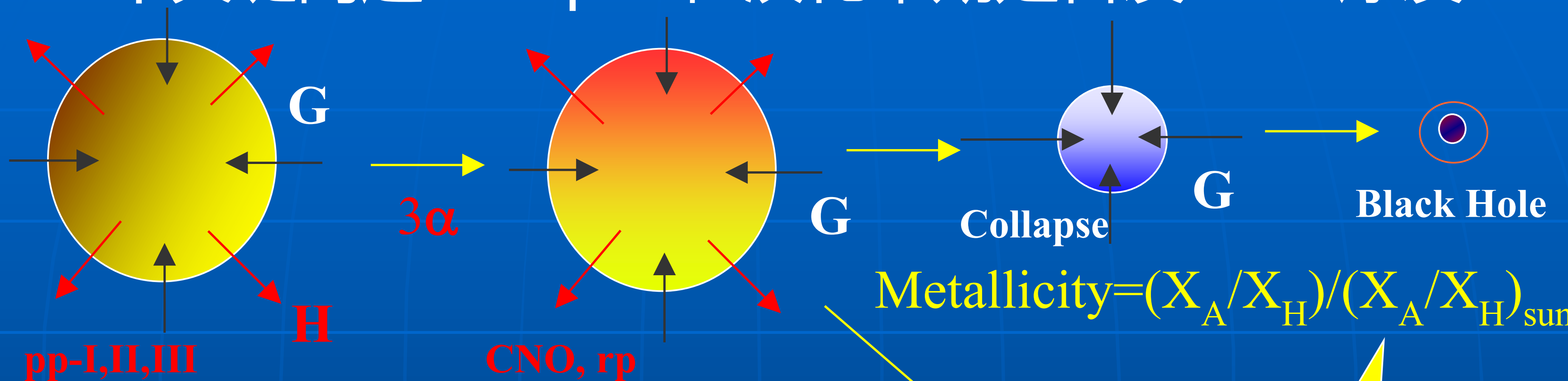


- 第一代恒星形成于大爆炸后几百万年 (at the end of dark ages)
- 由H/He气体形成
- 一种关键转变：homogeneous and simple universe to highly structured and complex one
- Pop III: zero metallicity

- Population I stars - new stars that contain numerous heavy metals in their atmosphere
- Population II stars - old stars that contain little heavy metals in their atmosphere
- Population III stars – the first stars, metal free, very massive ~ 100 - 1000 M_{sun}
- 第一代恒星是天文学与核天体物理研究的热点：
- Nature 326, 829 (1987); Science 295, 93 (2002); rmp 74, 1015 (2002); Nature 472, 454 (2011); Science 338, 1190 (2012)...



一个关键问题：Pop III在演化末期是否发生SN爆发？



$$\text{Metallicity}=(X_A/X_H)/(X_A/X_H)_{sun}$$

- SN爆发将会给星际介质提供重元素，并对随后的星系演化产生重要影响
- 演化后期，Pop III星主要通过CNO循环和rp过程产生能量，其能量产生率决定了它是否会发生超新星爆发
- 能量产生率的大小取决于恒星核合成过程产生的CNO核的数量，因此研究CNO核的合成反应非常重要

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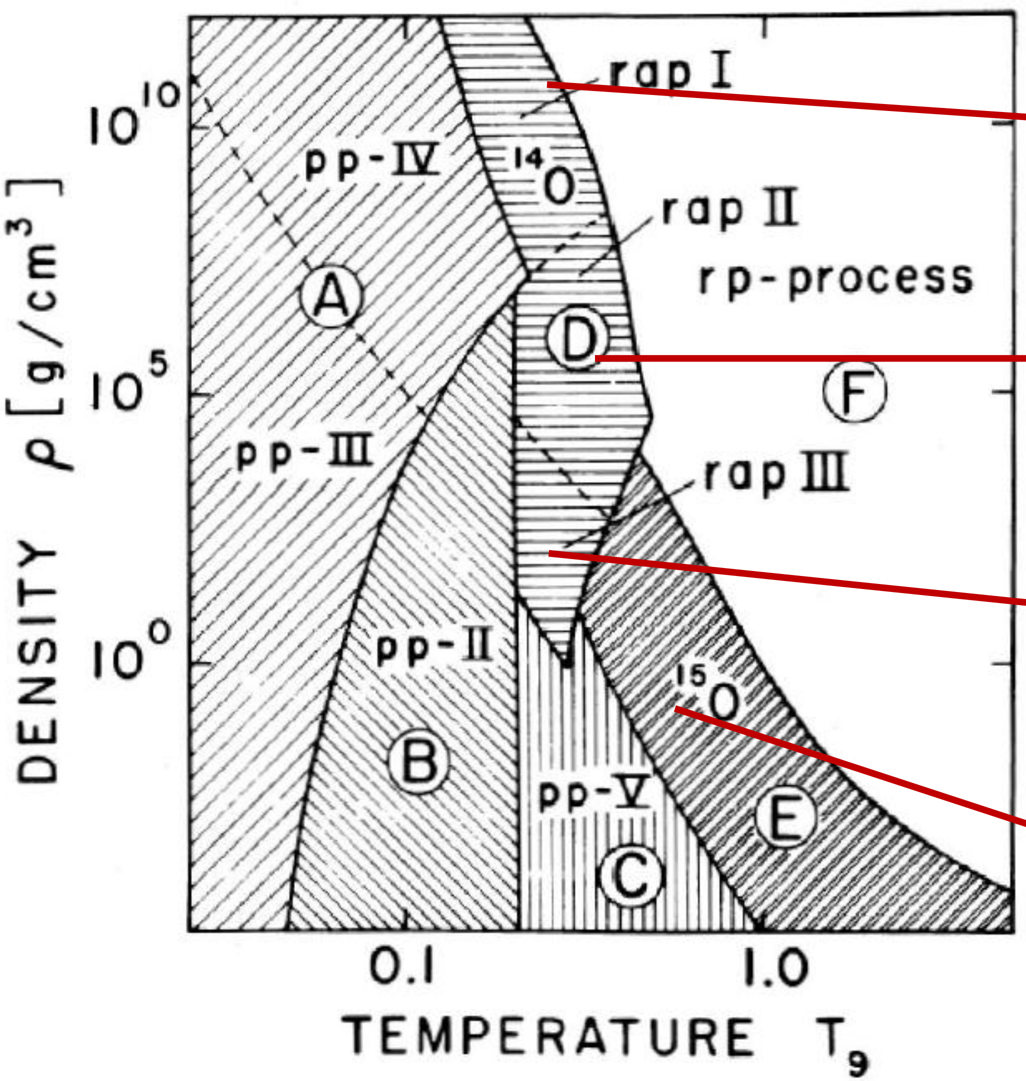
CNO核合成反应

- 3α过程：加利福尼亚大学，Fuller et al. studied the evolution of supermassive stars and concluded that these stars will collapse into BH without a supernova explosion because 3α-process does not produce sufficient amounts of CNO material.

  Fuller et al., ApJ 307, 675 (1986).

- 其它机制：圣母大学、多伦多大学、哈佛大学联合研究，Wiescher et al. suggested the rap-processes as alternative paths which would permit these stars to bypass 3α-process and yield the CNO nuclides

  Wiescher et al., ApJ 343, 352 (1989).



Wiescher et al., ApJ 343, 352 (1989).

^{7}Be(p,γ)^{8}B(p,γ)^{9}C(α,p)^{12}N(p,γ)^{13}O(β$^+$υ)^{13}N(p,γ)^{14}O, **rap-I**

^{7}Be(α,γ)^{11}C(p,γ)^{12}N(p,γ)^{13}O(β$^+$υ)^{13}N(p,γ)^{14}O, **rap-II**

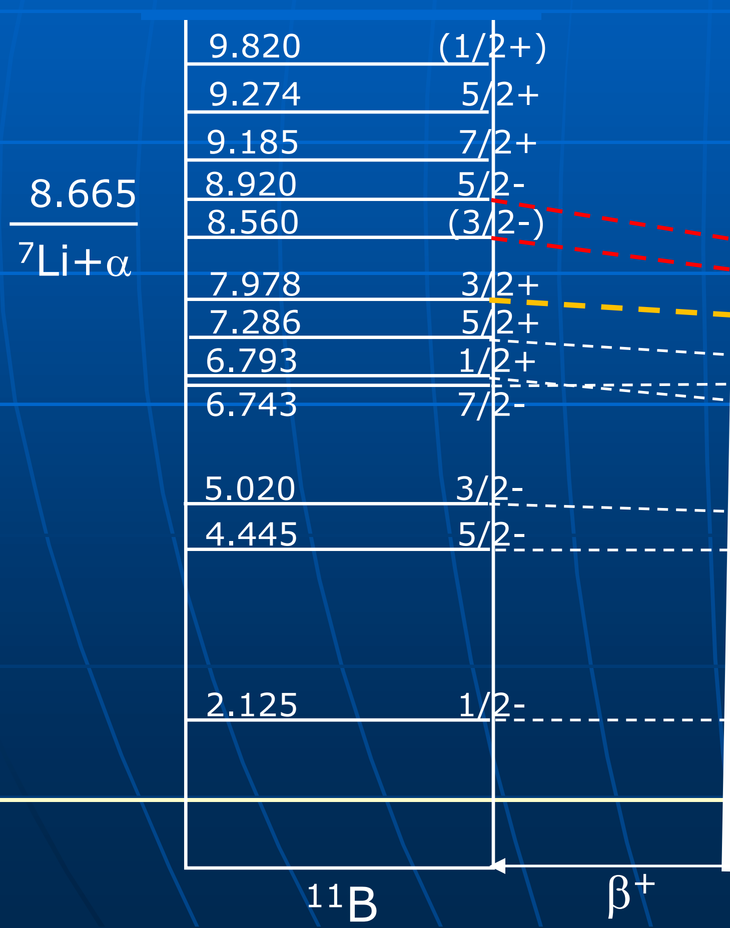
^{7}Be(α,γ)^{11}C(p,γ)^{12}N(β$^+$υ)^{12}C(p,γ)^{13}N(p,γ)^{14}O, **rap-III**

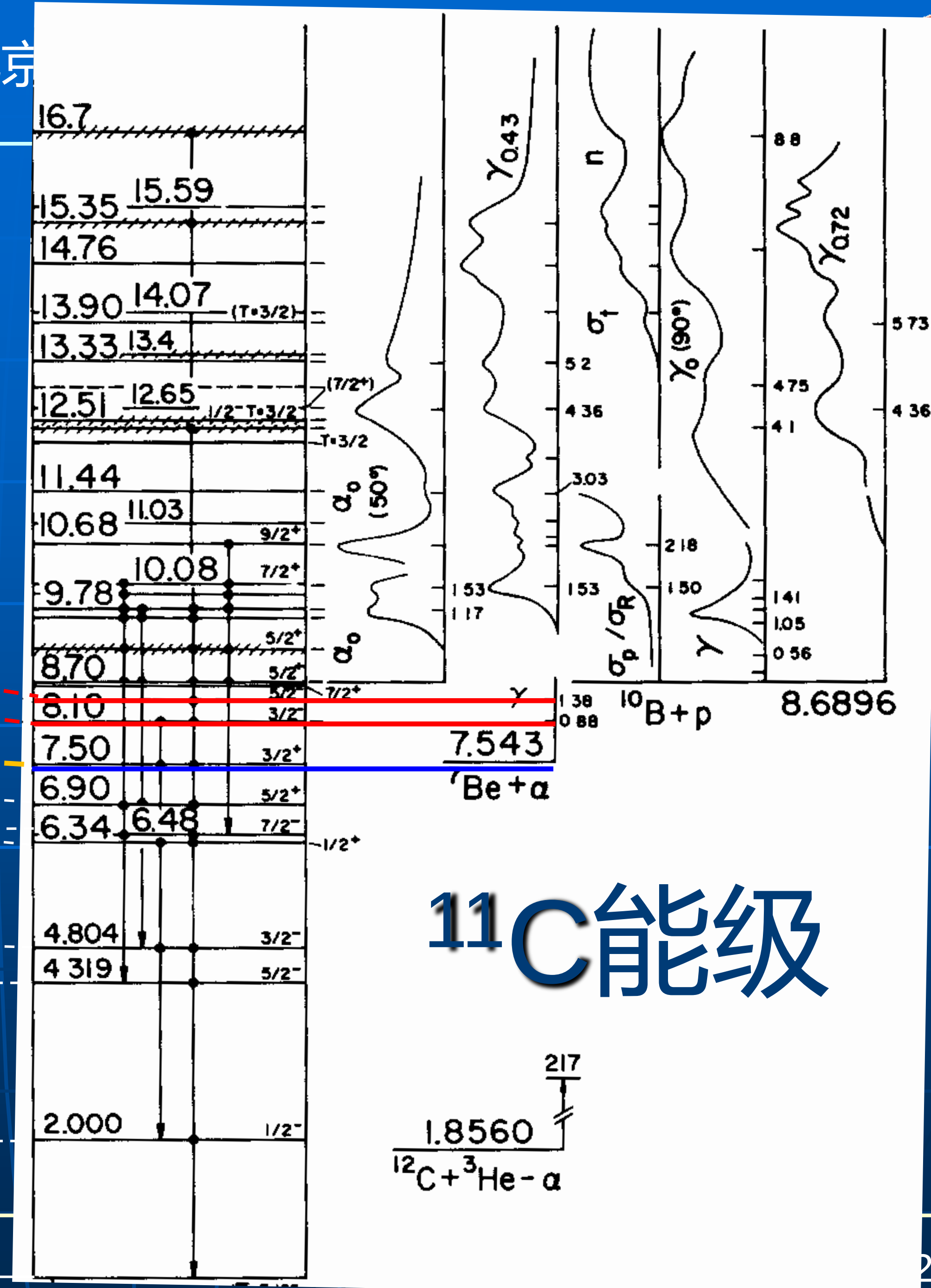
^{7}Be(α,γ)^{11}C(α,p)^{14}N(p,γ)^{15}O, **rap-IV**

需要对这些反应进行系统地测量

^{7}Be(α, γ)^{11}C反应率的实验研究

3条共振影响较大：2条阈上共振（E_R= 0.562, 0.877MeV），1条阈下共振（E_R = -0.043MeV）





研究现状

- 两条阈上共振（E_R=0.877MeV, 0.562MeV）

  α轰击^{7}Be靶，通过测量γ来得到共振强度ωγ；结合其它工作给出的Γ_γ/Γ，导出了Γ_γ和Γ_α

  西密西根大学，阿贡，PRC 29, 1199 (1984).

Nucleus	E_x (keV)	J^π	Γ_γ (eV)	Γ_α (eV) Experimental	Γ_α (eV) Calculated
^{11}B	9274	$\frac{5}{2}^+$	1.15 ± 0.16	4×10^3	
^{11}B	9185	$\frac{7}{2}^+$	$0.17^{+0.06}_{-0.03}$	$1.6^{+1.5}_{-1.1}$	
^{11}B	8920	$\frac{5}{2}^-$	4.368 ± 0.021[a]	0.0059 ± 0.0009	0.0072
^{11}C	8421	$\frac{5}{2}^-$	3.1 ± 1.3	12.6 ± 3.8	11
^{11}C	8105	$\frac{3}{2}^-$	0.350 ± 0.056	$4\to18$	53

- 阈下共振：理论预言其非常重要，目前为止无实验数据

(α,γ)反应的实验研究方法

- 直接测量：和(p,γ)相比，(α,γ)涉及的库伦势垒更高，天体物理低能区截面也更小，直接测量难度更大
- 厚靶方法：可以测量离发射阈较远的阈上共振，CNS近年开始了这方面的工作
- (^{3}He,t)反应：可以研究发射阈附近的阈上共振，圣母大学W.P. Tan等
- 电荷对称性方法：适合于研究发射阈附近的共振（包括阈下共振），这种情况下α宽度更加重要

电荷对称性方法

^{7}Li(^{6}Li,d)^{11}B反应角分布

↓ DWBA分析

虚衰变 $^{11}B \rightarrow {}^{7}Li + \alpha$的ANC

↓ 镜像核电荷对称性

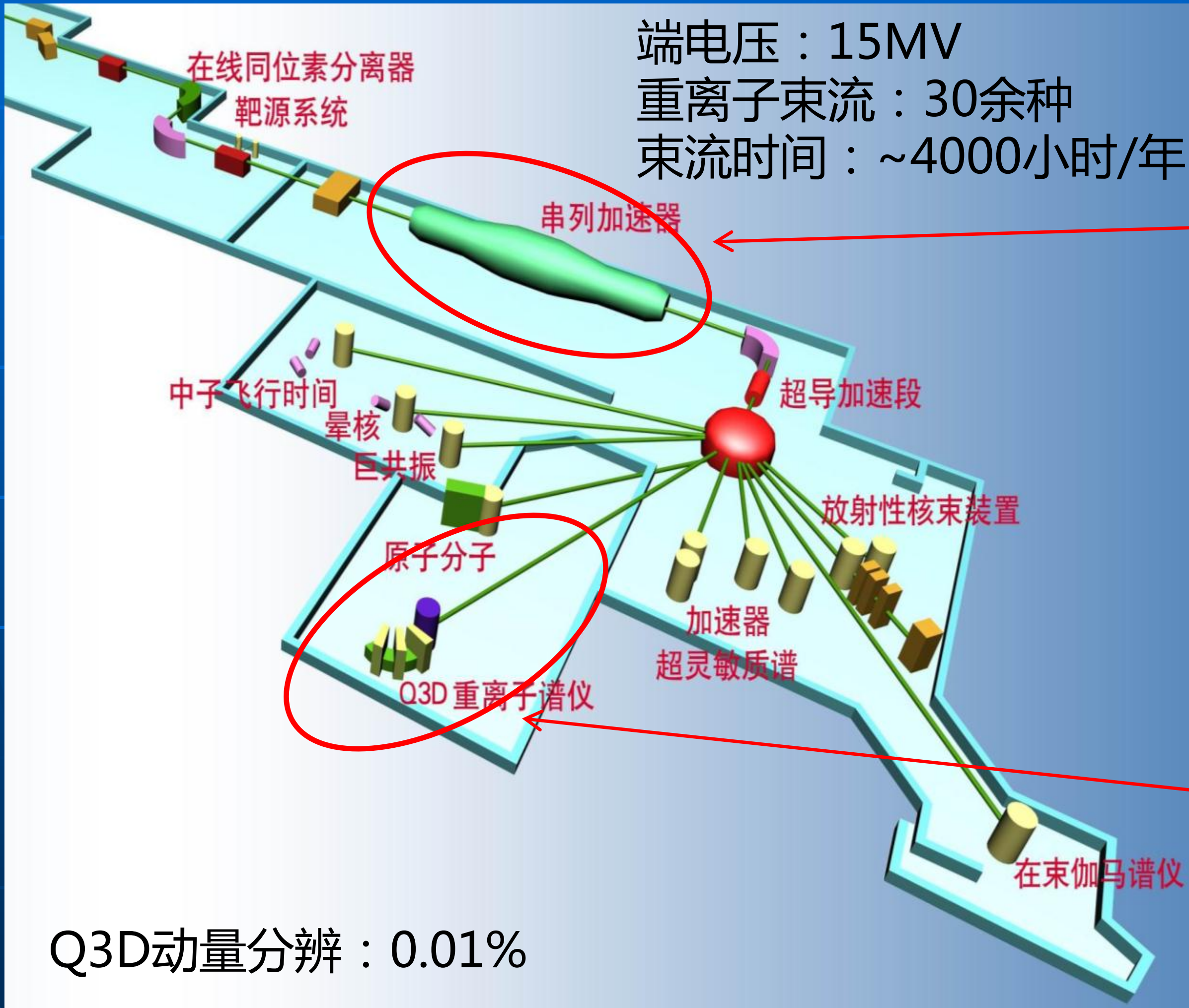
^{11}C阈下共振态的α宽度

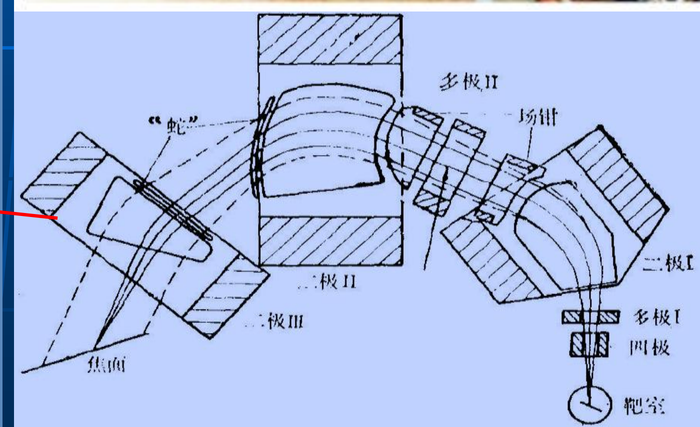
↓ Breit-Wigner公式

$^{7}Be(\alpha,\gamma)^{11}C$天体物理S因子和反应率

北京HI-13串列加速器和Q3D磁谱仪

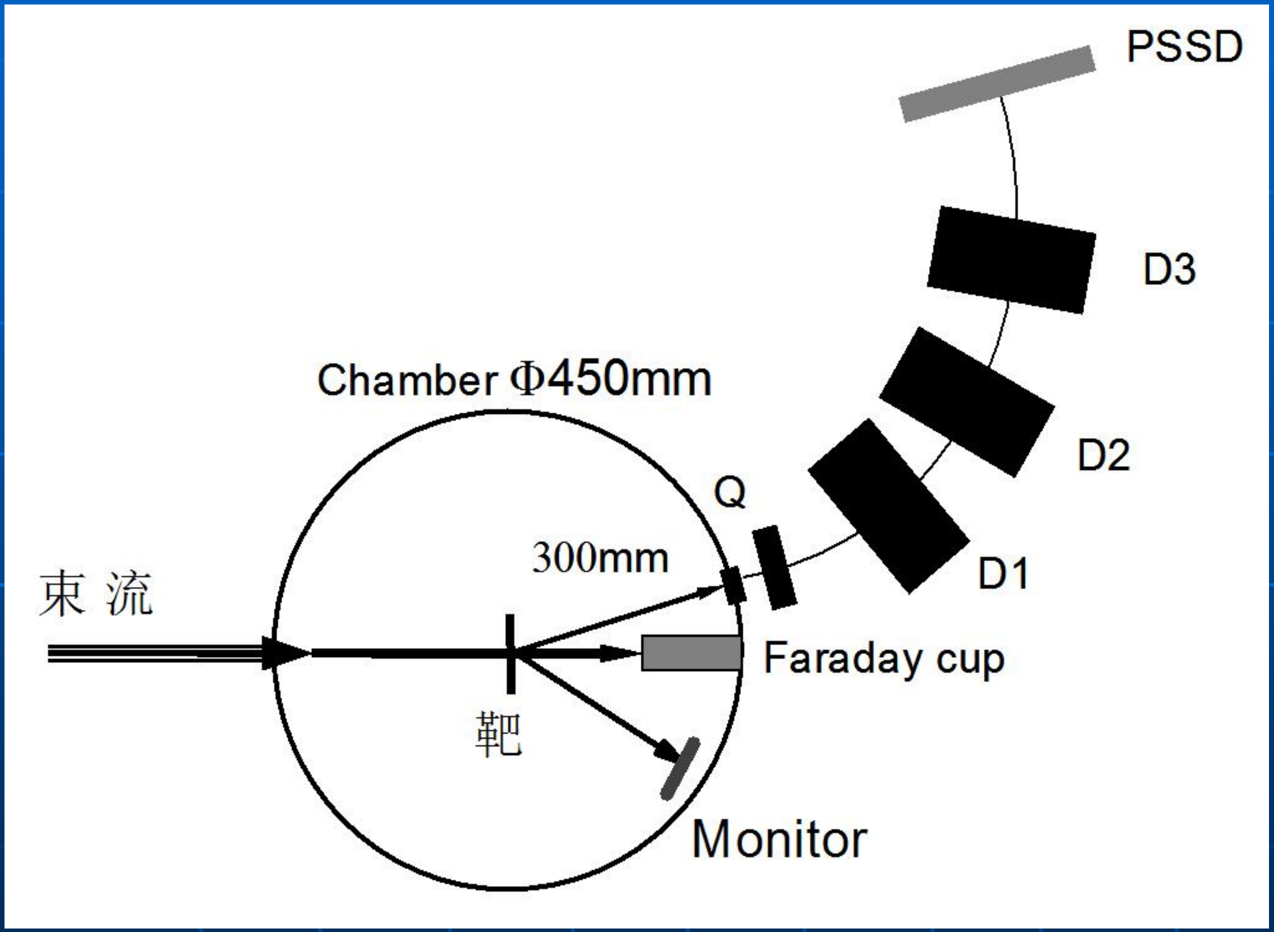
端电压：15MV
重离子束流：30余种
束流时间：~4000小时/年



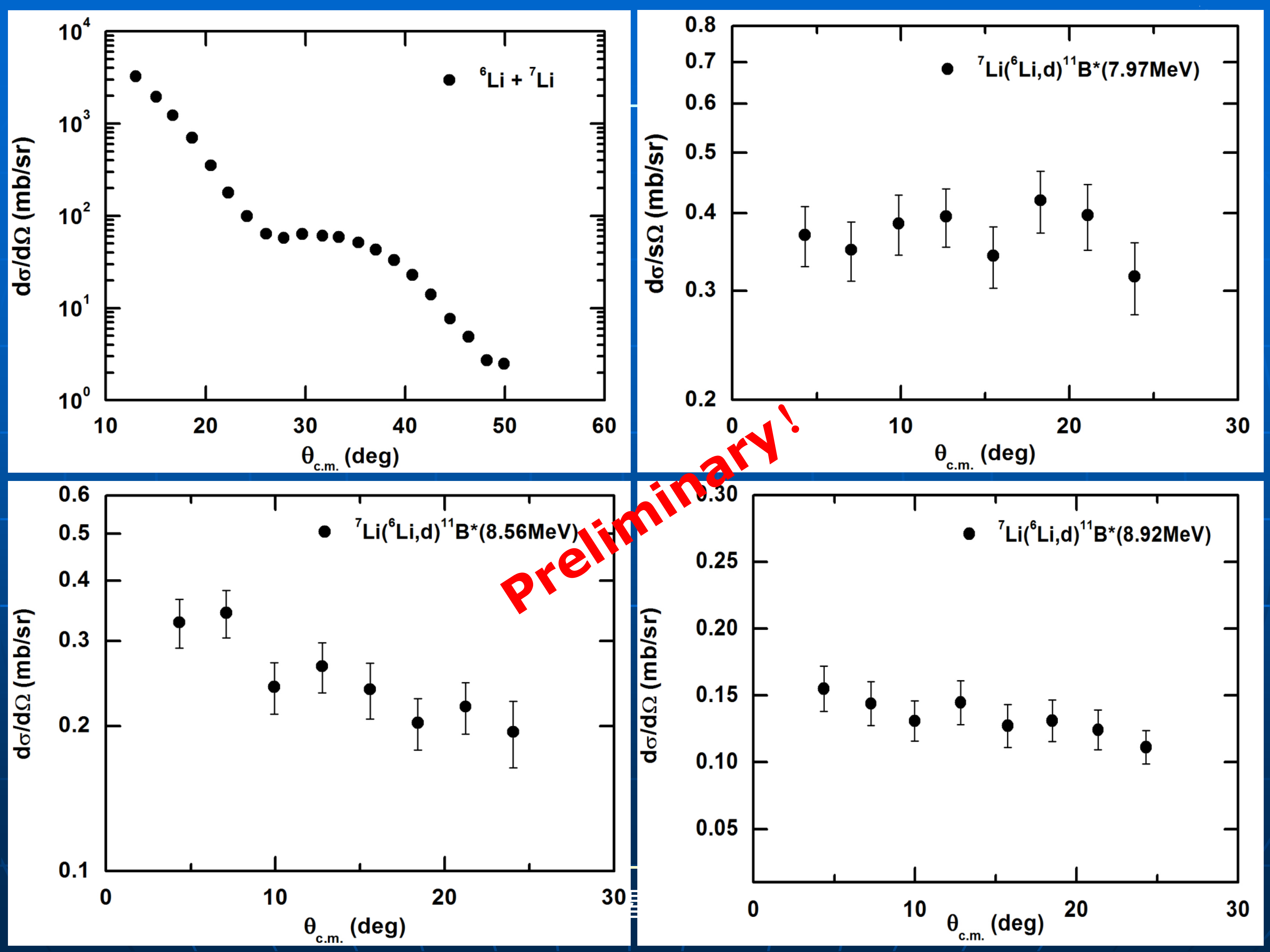


Q3D动量分辨：0.01%

实验设置 —— ^{7}Li(^{6}Li,d)^{11}B角分布测量

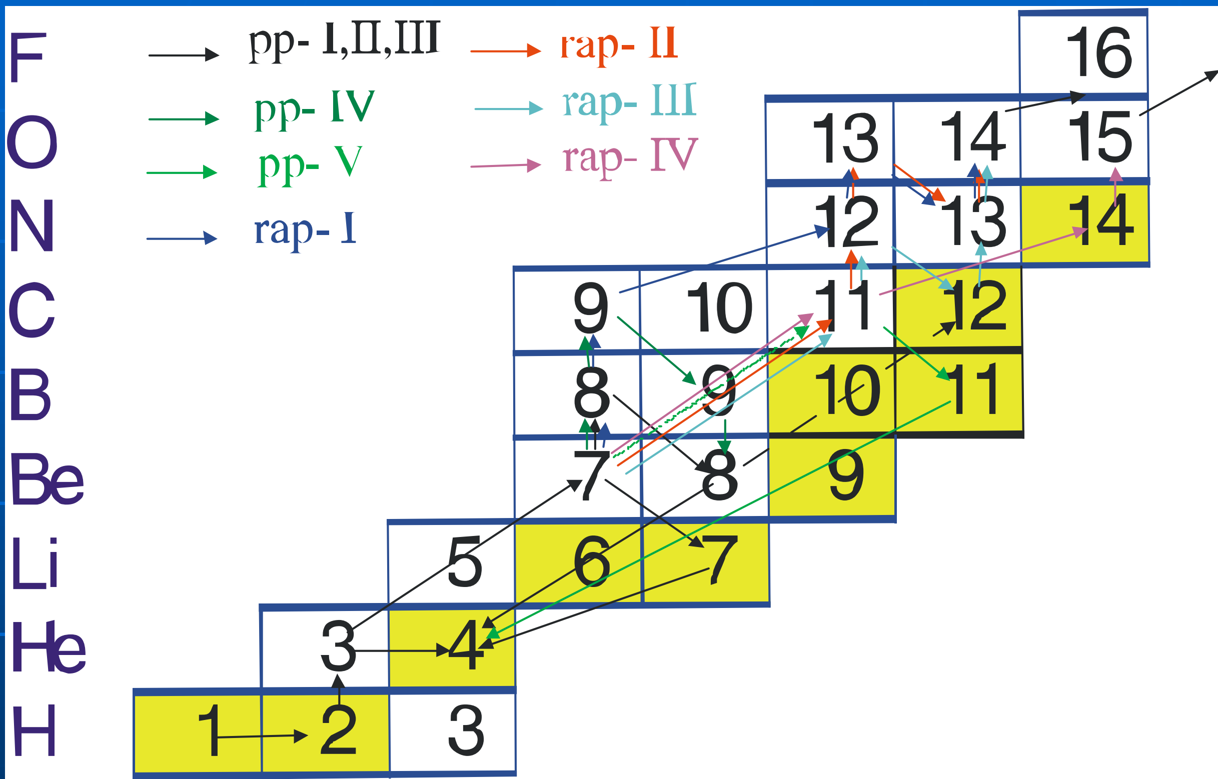


- ^{6}Li束流：50 MeV
- 法拉第筒：束流绝对归一
- ΔE-E望远镜：相对归一
- PSSD：二维位置、能量



6Li + 7Li
dσ/dΩ (mb/sr)
θc.m. (deg)
7Li(6Li,d)11B*(7.97MeV)
dσ/sΩ (mb/sr)
θc.m. (deg)
7Li(6Li,d)11B*(8.56MeV)
dσ/dΩ (mb/sr)
θc.m. (deg)
7Li(6Li,d)11B*(8.92MeV)
dσ/dΩ (mb/sr)
θc.m. (deg)
Preliminary!

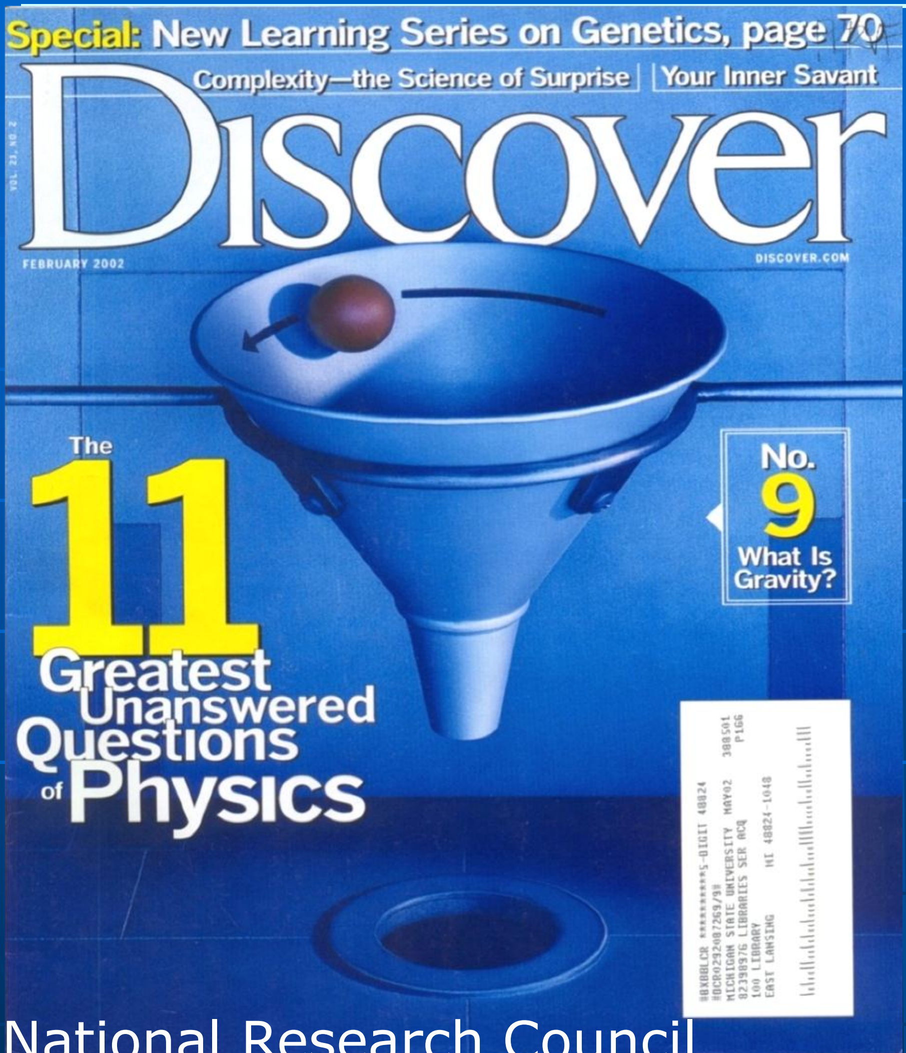
rap过程涉及8个关键核反应



- $^{7}Be(p,\gamma)^{8}B$, W. Liu et al., PRL 77, 611 (1996).
- $^{8}B(p,\gamma)^{9}C$, B. Guo et al., NPA 761, 162 (2005).
- $^{11}C(p,\gamma)^{12}N$, W. Liu et al., NPA 728, 275 (2003).
- $^{12}N(p,\gamma)^{13}O$, B. Guo et al., PRC, submitted (2012).
- $^{13}N(p,\gamma)^{14}O$, Z. H. Li et al., PRC 74, 035801 (2006).
- $^{7}Be(\alpha,\gamma)^{11}C$, 阈下共振的首次实验，data analysis.
- $^{9}C(\alpha,p)^{12}N$
- $^{11}C(\alpha,p)^{14}N$

- 自1996年以来，我们研究了其中的6个核反应
- 下一步计划：网络计算研究新反应率对第一代恒星演化的影响

s过程核合成主中子源反应$^{13}C(\alpha, n)^{16}O$的研究



National Research Council

3. 质量数大于铁的核素如何产生？

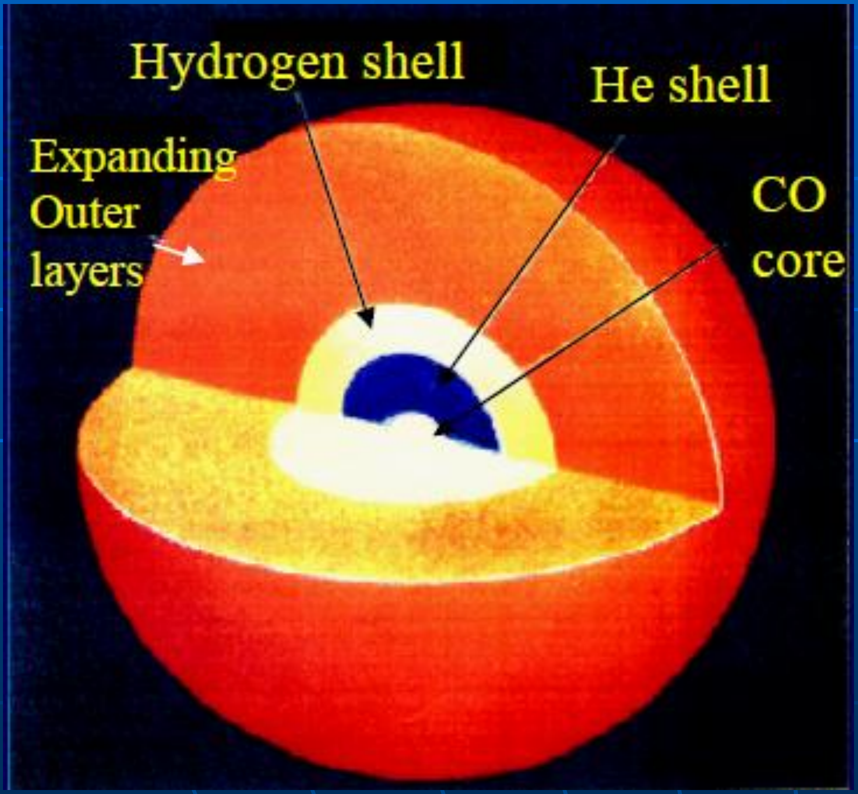
物理学11个未解之谜

1. What is dark matter?
2. What is dark energy?
3. **How were the heavy elements from iron to uranium made?**
4. Do neutrinos have mass?
5. Where do ultrahigh-energy particles come from?
6. Is a new theory of light and matter needed to explain what happens at very high energies and temperatures?
7. Are there new states of matter at ultrahigh temperatures and densities?
8. Are protons unstable?
9. What is gravity?
10. Are there additional dimensions?
11. How did the universe begin?

慢速中子俘获（s）过程

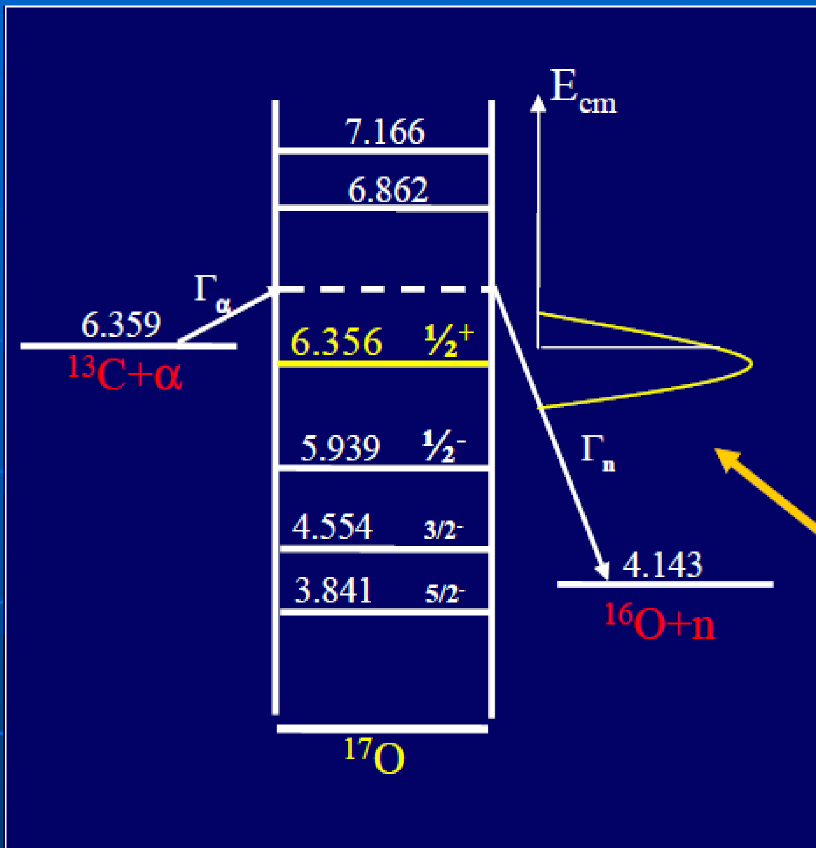
- s过程由在铁种子核上发生的一系列中子俘获反应构成，并伴随不稳定核的β衰变，使得反应流通向更重核区
- 质量数大于铁的核素大约一半是通过s过程合成的
- 自由中子的半衰期仅有大约10分钟，宇宙早期通过大爆炸产生的自由中子早已衰变殆尽
- s过程核合成需要的大量中子从哪里来？

- 大爆炸产生的部分中子“躲”入原子核中成为稳定粒子（^{4}He等），而得以“保存”下来
- s过程需要的大量中子只能当场通过核反应产生



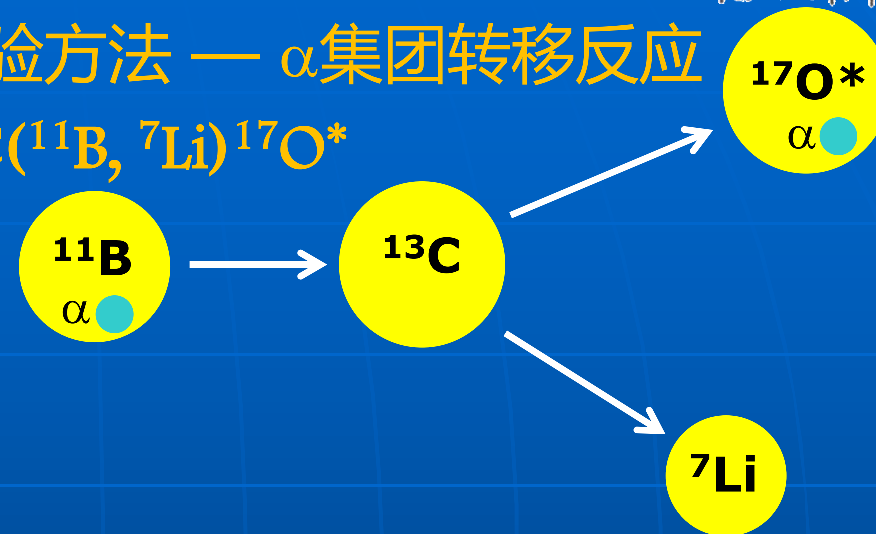
AGB星， 1~3M_{sun}， 温度~10^8 K

中子源：$^{13}C(\alpha, n)^{16}O$



实验方法 — α集团转移反应

$^{13}C(^{11}B,\ ^{7}Li)\,^{17}O^*$



$$(d\sigma/d\Omega)_{exp} = S_\alpha^*(d\sigma/d\Omega)_{DWBA}$$

↓

约化α宽度γ^2

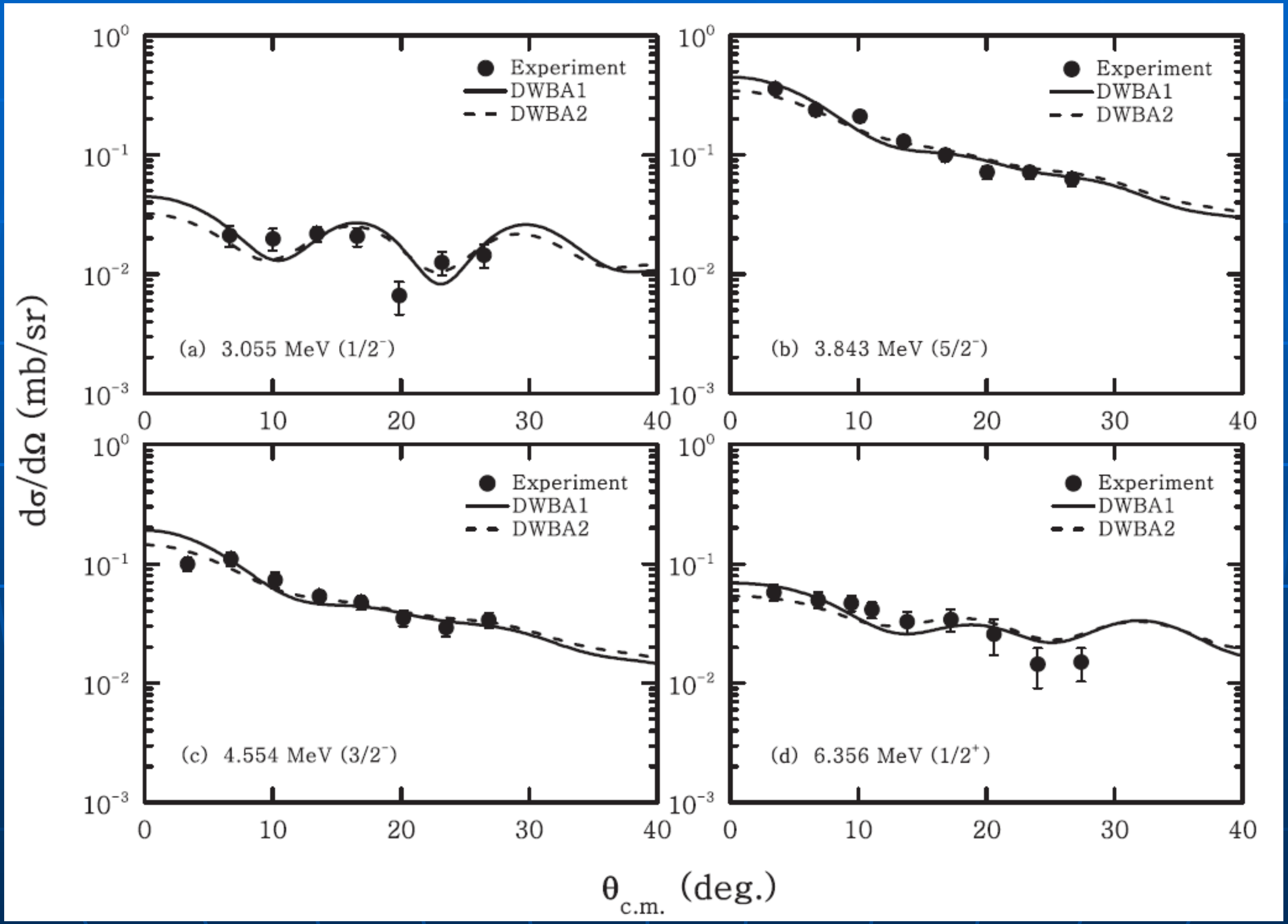
↓

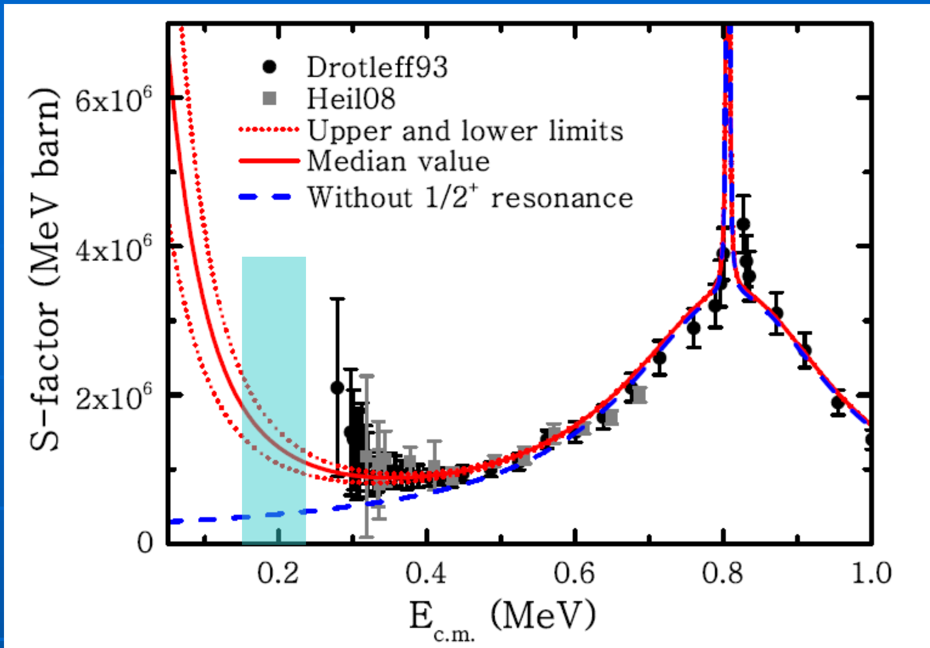
$^{13}C(\alpha,\ n)\,^{16}O$的S因子与反应率

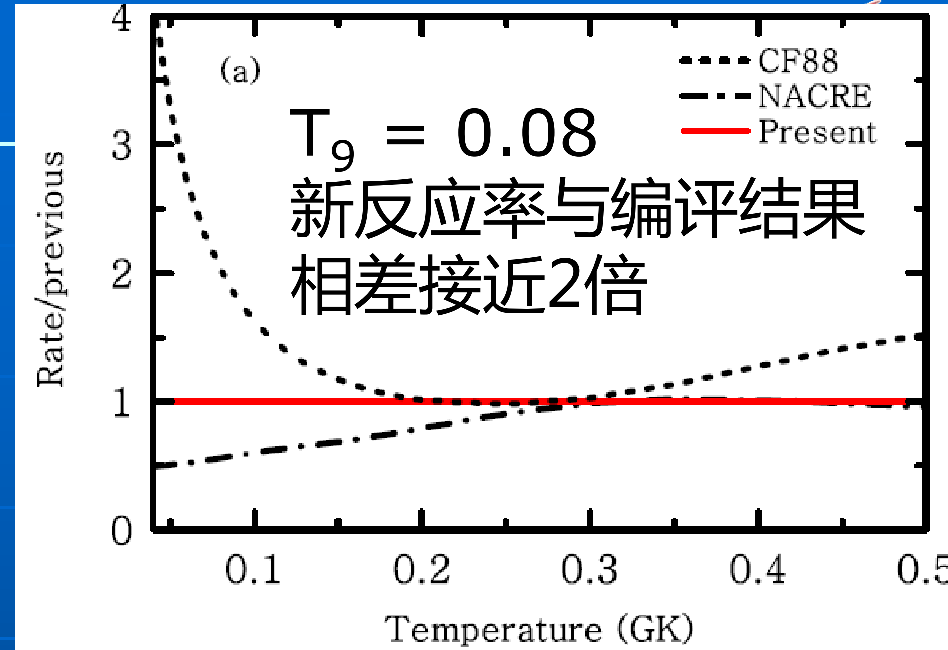
关键：研究阈下共振，仅比α发射阈低**0.003MeV**，其高能尾巴影响Gamow窗口截面

克服直接测量的困难：用截面较大(mb~μb)的转移反应替代截面小(nb~pb)的(α, n)反应

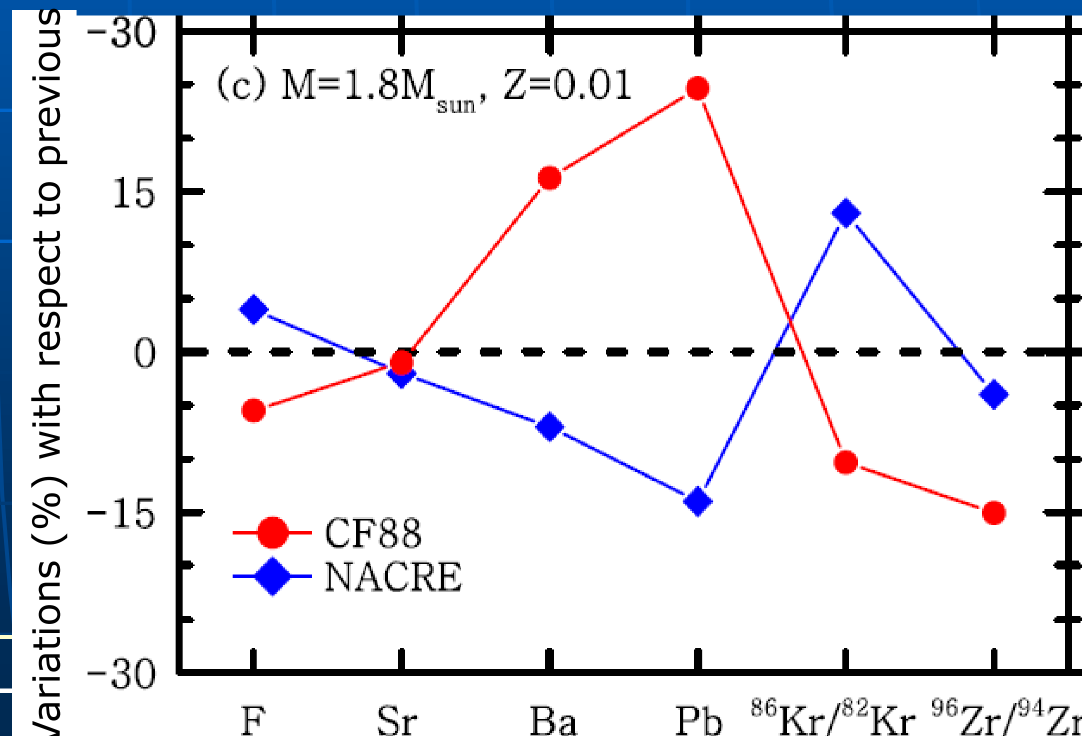
$^{13}C(^{11}B, {^7}Li)^{17}O^*$反应角分布







结果：对F和Sr影响较小（<5%），Ba丰度变化16%，Pb丰度变化达到25%，同位素比例变化与丰度变化趋势相反



一些评价

亚洲核物理学会理事Dao T. Khoa教授： “I have seen the preprint on your exp. on $^{13}C(a,n)^{16}O$... Experiment in Beijing is indeed a milestone in this dispute.”

日本国立天文台的Toshitaka Kajino教授：”It is interesting and very important paper. I, Grant Mathews and Wako Aoki also will study the s-process by using your new $^{13}C(a,n)$ rates!! ”

12月4日发表的卡塔尼亚大学与佛罗里达州立大学的联合实验结果与我们的结果一致，PRL 109, 232701 (2012)

The Astrophysical Journal, 756:193 (10pp), 2012 September 10 doi:10.1088/0004-637X/756/2/193

NEW DETERMINATION OF THE $^{13}C(\alpha, n)^{16}O$ REACTION RATE AND ITS INFLUENCE ON THE s-PROCESS NUCLEOSYNTHESIS IN AGB STARS

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ABSTRACT

We present a new measurement of the α-spectroscopic factor (S_α) and the asymptotic normalization coefficient for the 6.356 MeV $1/2^+$ subthreshold state of ^{17}O through the $^{13}C(^{11}B, ^{7}Li)^{17}O$ transfer reaction and we determine the α-width of this state. This is believed to have a strong effect on the rate of the $^{13}C(\alpha, n)^{16}O$ reaction, the main neutron source for *slow* neutron captures (the *s*-process) in asymptotic giant branch (AGB) stars. Based on the new width we derive the astrophysical *S*-factor and the stellar rate of the $^{13}C(\alpha, n)^{16}O$ reaction. At a temperature of 100 MK, our rate is roughly two times larger than that by Caughlan & Fowler and two times smaller than that recommended by the NACRE compilation. We use the new rate and different rates available in the literature as input in simulations of AGB stars to study their influence on the abundances of selected *s*-process elements and isotopic ratios. There are no changes in the final results using the different rates for the $^{13}C(\alpha, n)^{16}O$ reaction when the ^{13}C burns completely in radiative conditions. When the ^{13}C burns in convective conditions, as in stars of initial mass lower than $\sim 2\,M_\odot$ and in post-AGB stars, some changes are to be expected, e.g., of up to 25% for Pb in our models. These variations will have to be carefully analyzed when more accurate stellar mixing models and more precise observational constraints are available.

Key words: nuclear reactions, nucleosynthesis, abundances – stars: AGB and post-AGB

Online-only material: color figures

ApJ 756, 193 (2012). September 10

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群体基金资助下完成的工作

$^{13}C(\alpha, n)^{16}O$, ApJ 756, 193 (2012).

$^{12}N(p, \gamma)^{13}O$, PRC, submitted (2012).

$^{15}N(n, \gamma)^{16}N$, PRC, to be submitted (2013).

$^{7}Be(\alpha, \gamma)^{11}C$, data analysis.

Thanks!