核天体物理相关共振态的实验研究

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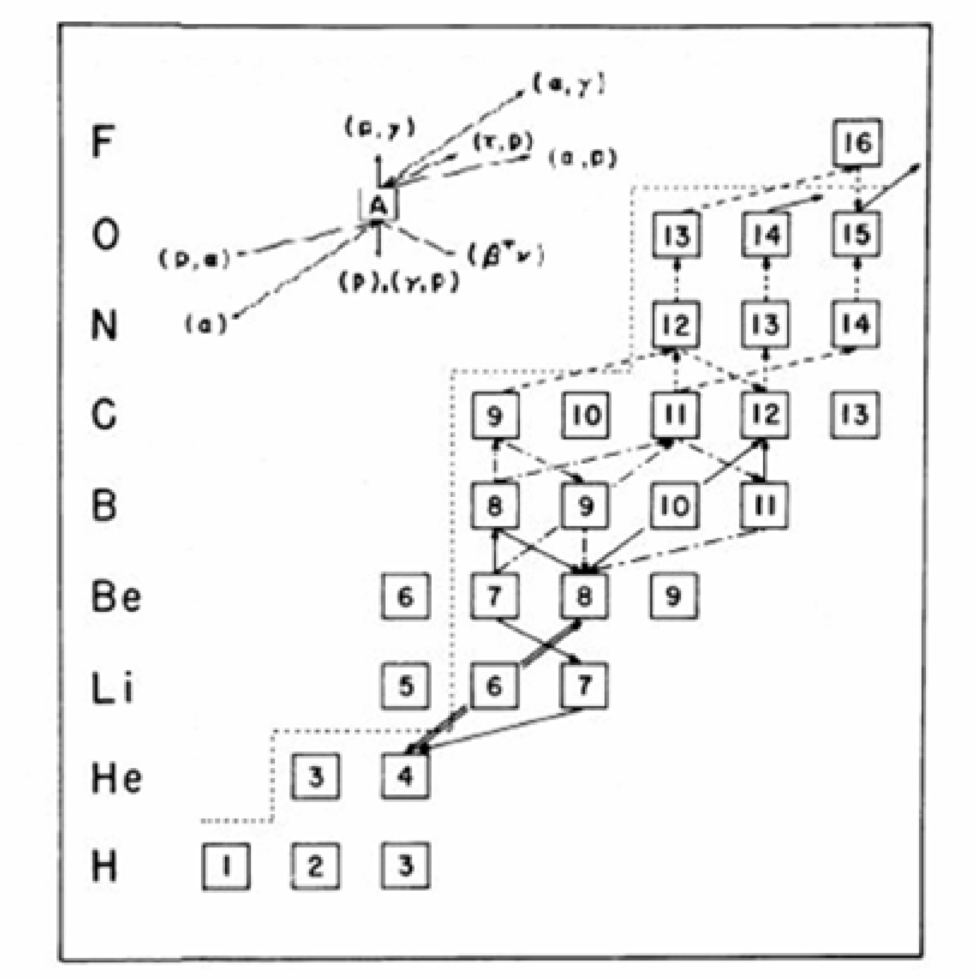
核天体物理创新研究群体科学基金项目进展报告会

2011年10月

内　容

- $^{3}He + ^{12}C$反应体系的实验测量
- CRIB ^{22}Na+p厚靶实验

高温p-p反应链上$^{8}B(\alpha,p)^{11}C$反应

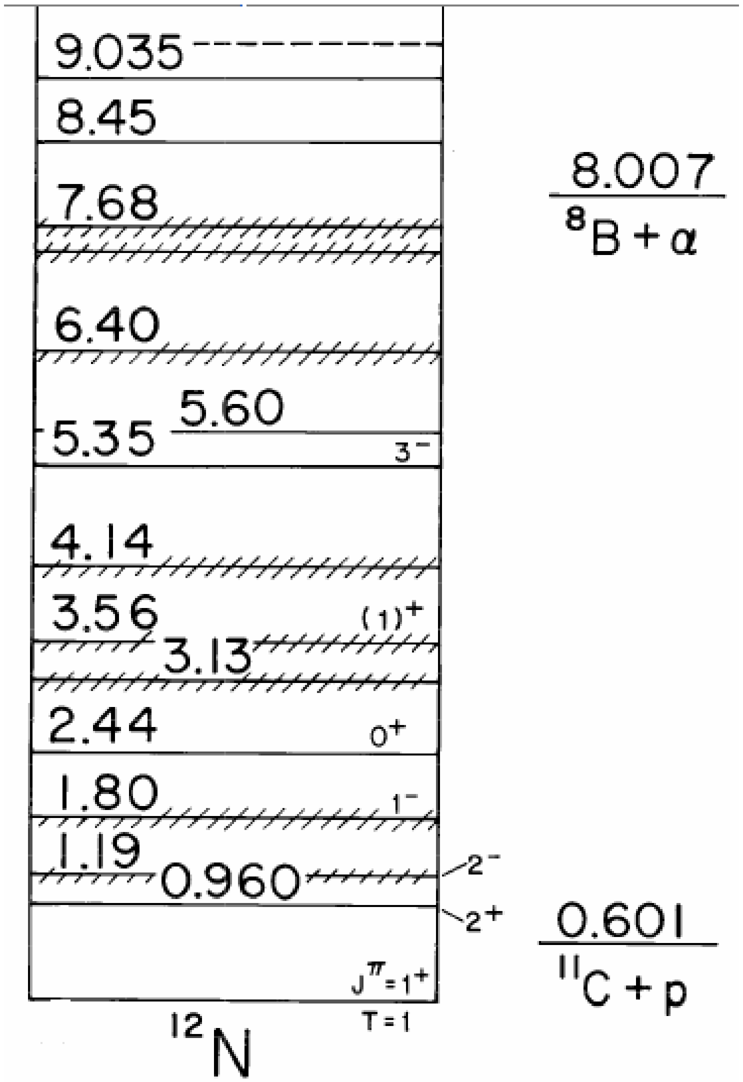


$^{8}B(p,\gamma)^{9}C$,
$^{9}C(\alpha,p)^{12}N$,
$^{8}B(\alpha,p)^{11}C$,
$^{11}C(p,\gamma)^{12}N$,
$^{11}C(\alpha,p)^{14}N$,
$^{12}N(p,\gamma)^{13}O$,
$^{13}O(\alpha,p)^{16}F$

连接到高温CNO循环。高温p-p反应链可能是$3\alpha \rightarrow {}^{12}C$过程以外合成CNO核的另一种途径

高温p-p反应链(M.Wiescher et al.,Astrophys.J.,343:352(1989)

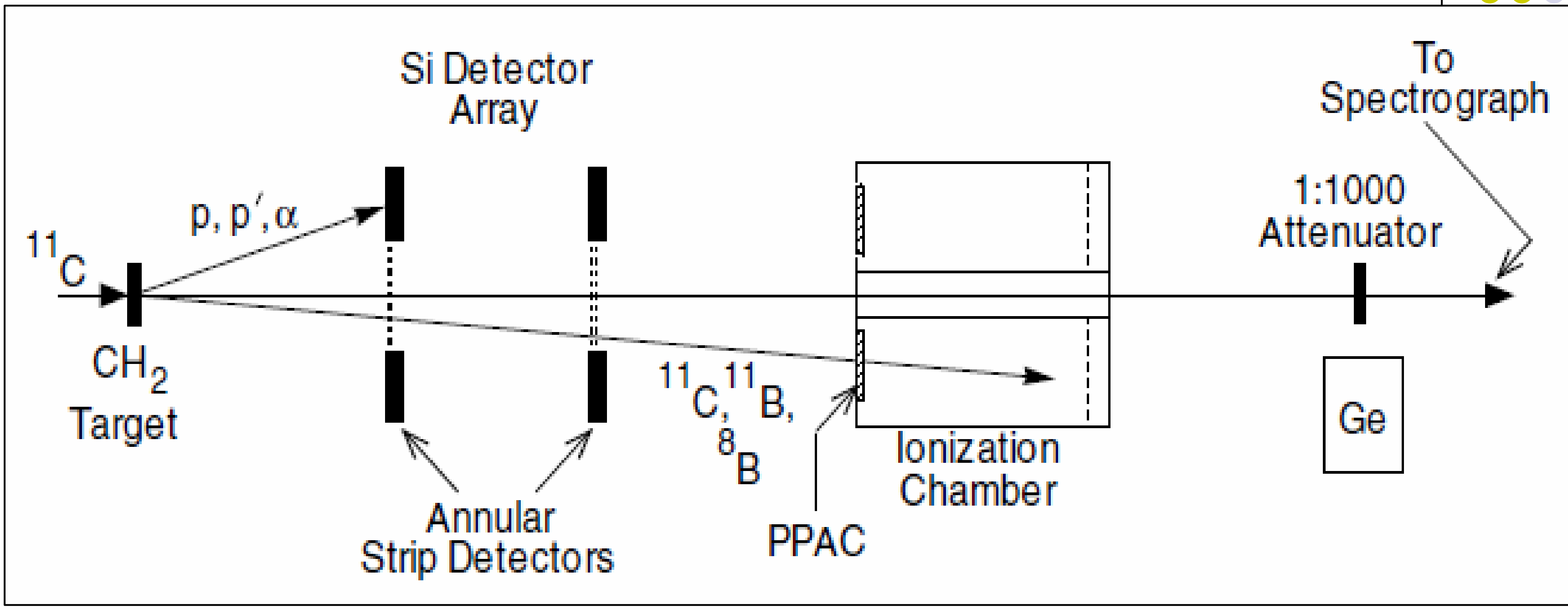
$^{8}B(\alpha,p)^{11}C$反应研究现状



- 迄今尚没有编评数据
- 没有直接测量
- α 阈上能级位置、性质以及贡 献均不清楚
- 只有一家实验数据，非常粗糙

K.E. Rehm, NPA746, 354c(2004)

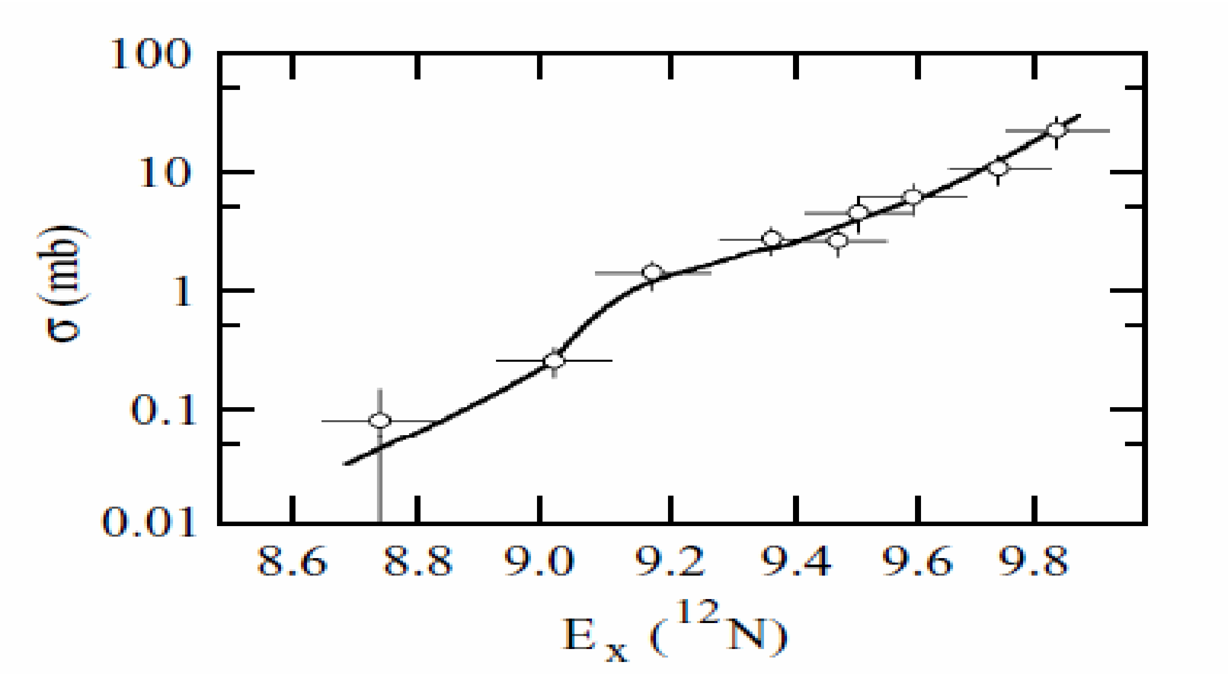
$^{8}B(\alpha,p)^{11}C$逆反应直接测量



- ^{11}C: 2×10^{5} pps, 98-110 MeV, 9个能量点。$(CH_2)_n$: 720 μg/cm^{2}
- 能量分辨：质心系125 keV， ^{11}C纯度 50-70%
- ^{8}B和α符合测量， 探测效率约 70%.
- θ_{cm}=30-160°，角分布积分得总截面。

K.E. Rehm, NPA746, 354c(2004)

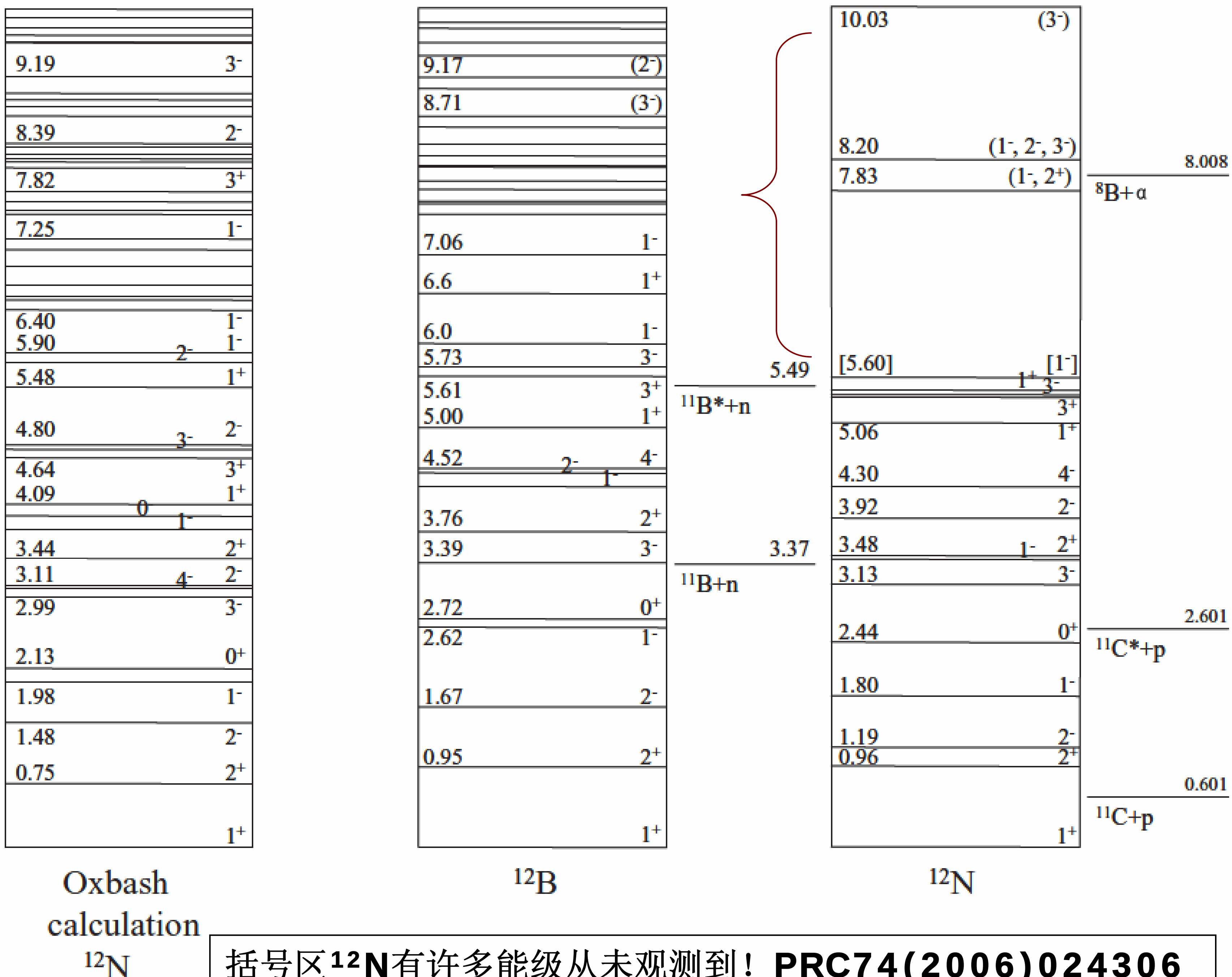
$^{8}B(\alpha,p)^{11}C$反应截面



误差来源：束流归一约**25%**，另外角分布积分等。

不足： 电离室粒子鉴别差，能量分辨差；逆反应测量，^{11}C的激发态贡献无法评估等。

结果：没有共振



括号区^{12}N有许多能级从未观测到！PRC74(2006)024306

$^{12}C(^{3}He,t)^{12}N$多能级角分布测量

- 测量从基态到α分离阈上多条能级的角分布
- 寻找^{12}N的新激发态
- 研究新激发态以及α分离阈上能级的共振能量及可能的自旋、宇称
- α分离阈上能级发射α的分支比

$^{12}C(^{3}He,t)^{12}N$研究现状

- Nuclear Physics A405 (1983) 109-125

  Groningen AVF cyclotron.

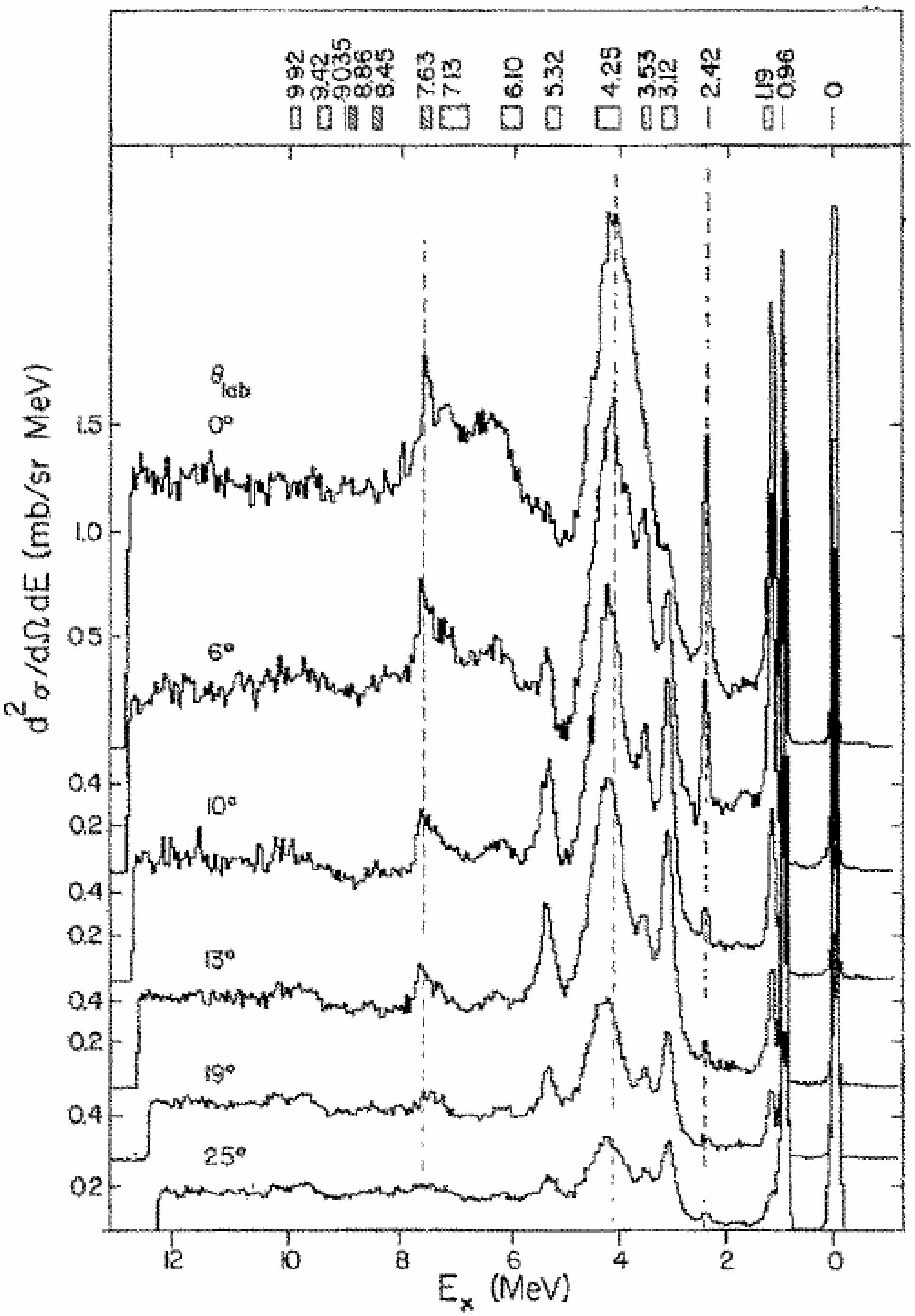
  QMG/2 磁谱仪，两个 52 cm 长位置灵敏计数器

  $E(^{3}He)$=75,81 MeV, I=20-30 nA，纯碳靶：460 $\mu g/cm^2$

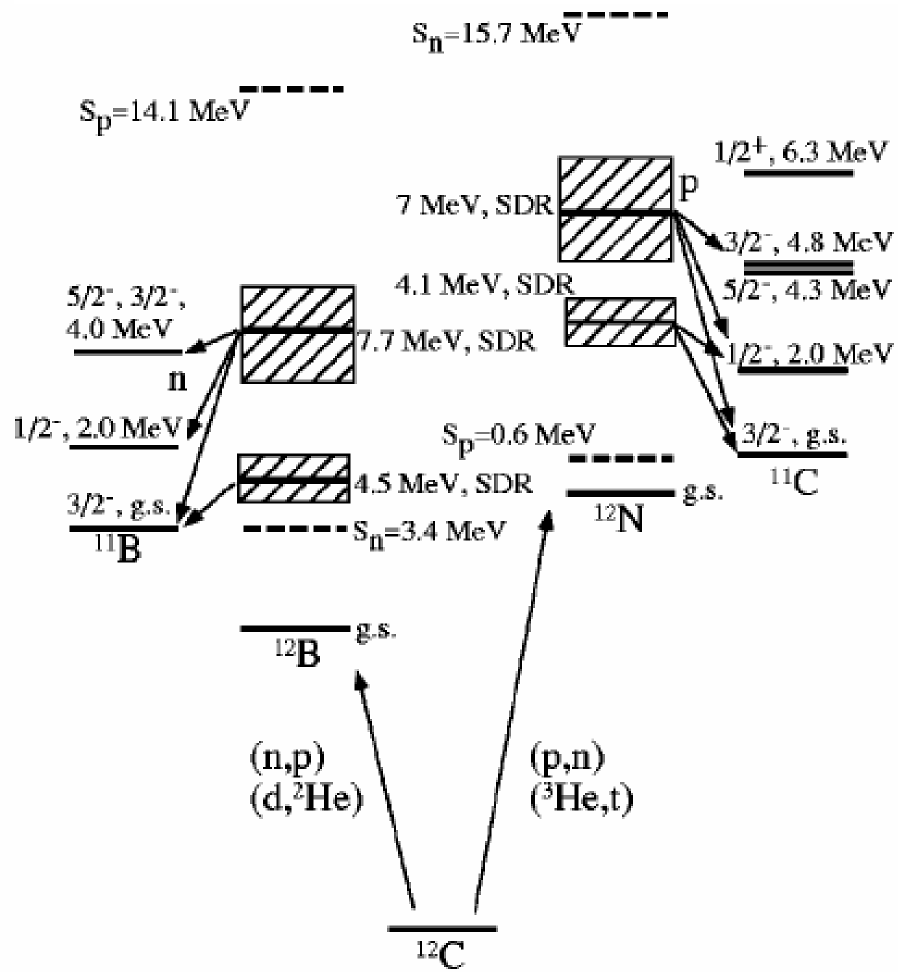
  实验室系 0-28° 角分布
- 能量分辨 70 keV(FWHM)
- 这是迄今最系统的测量工作，其它实验主要是中能0°测量

  B(GT), 如： PRC 57(98)3153; NPA422 (1984) 12-44; NPA469 (1987) 648-668; 以及NPA394 (1983)39 -59

不同角度出射的氚能谱

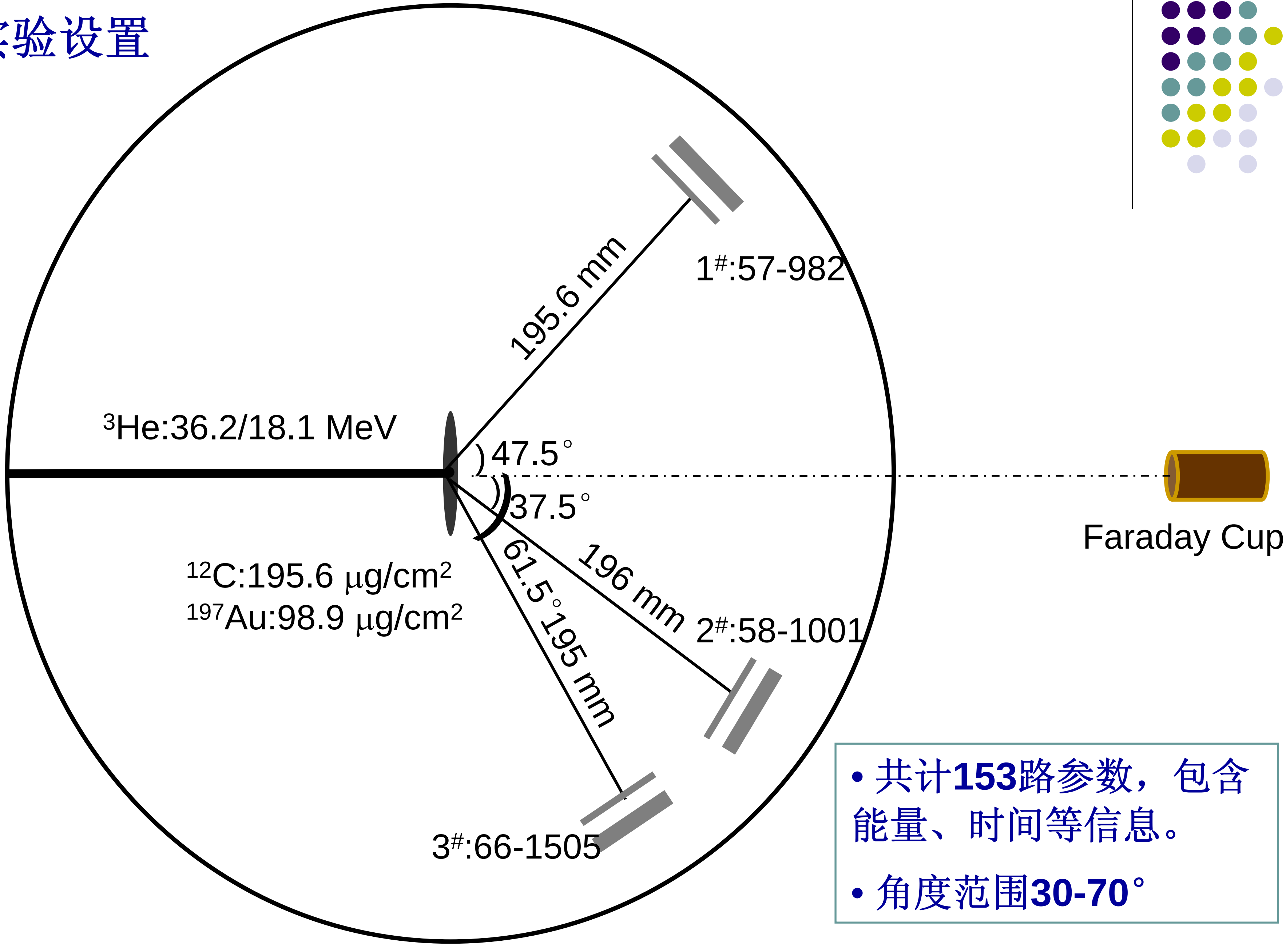


9.92
9.42
9.035
8.86
8.45
7.63
7.13
6.10
5.32
4.25
3.53
3.12
2.42
1.19
0.96
0
θ_{lab}
0°
6°
10°
13°
19°
25°
$d^2\sigma/d\Omega dE$ (mb/sr MeV)
1.5
1.0
0.5
0.4
0.2
12
10
8
6
4
2
0
E_x (MeV)



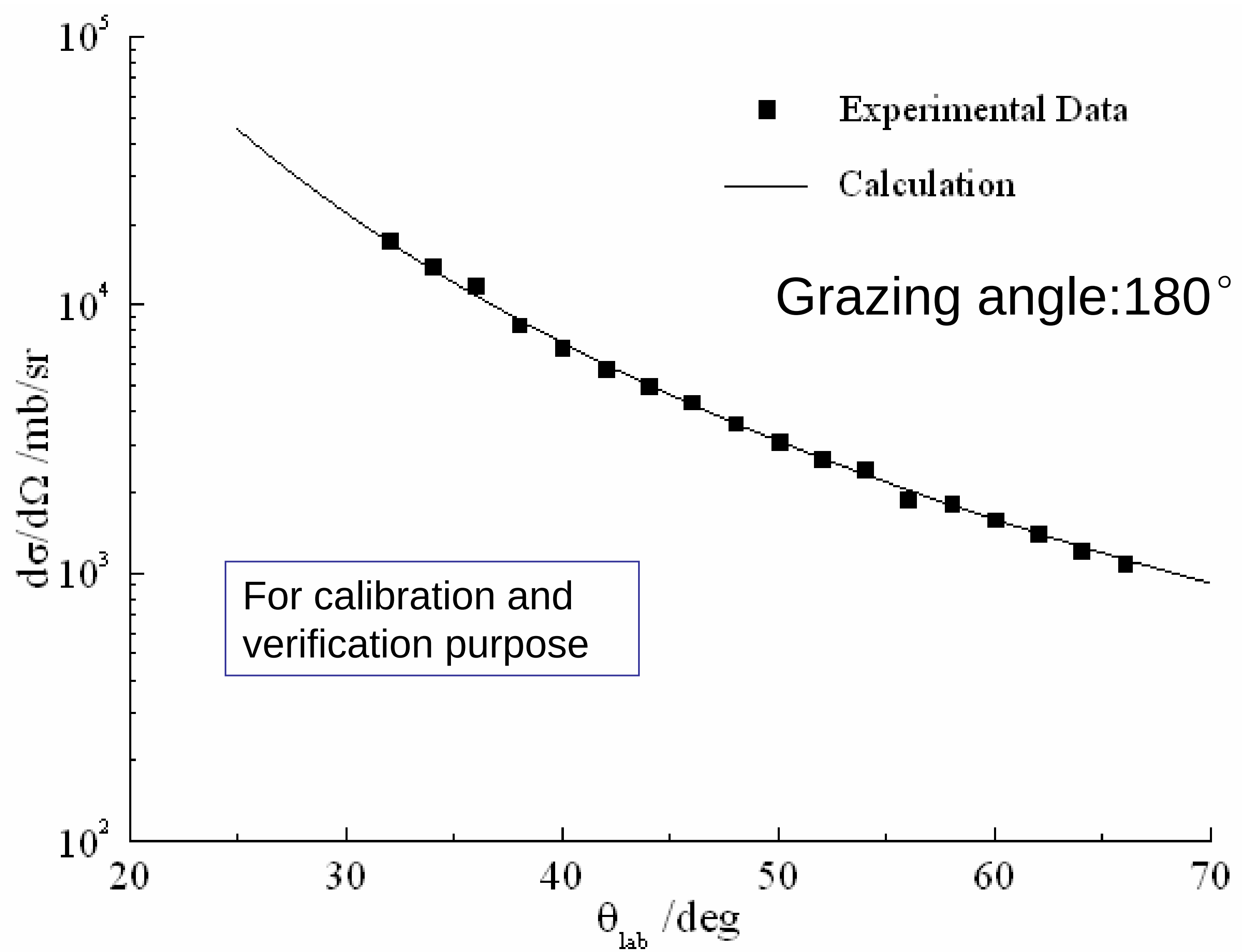
S_n=15.7 MeV
S_p=14.1 MeV
1/2$^+$, 6.3 MeV
7 MeV, SDR
p
3/2$^-$, 4.8 MeV
5/2$^-$, 4.3 MeV
4.1 MeV, SDR
5/2$^-$, 3/2$^-$,
4.0 MeV
7.7 MeV, SDR
1/2$^-$, 2.0 MeV
n
1/2$^-$, 2.0 MeV
3/2$^-$, g.s.
S_p=0.6 MeV
4.5 MeV, SDR
g.s.
^{11}C
3/2$^-$, g.s.
S_n=3.4 MeV
^{12}N
^{11}B
g.s.
^{12}B
(n,p)
(d,^{2}He)
(p,n)
(^{3}He,t)
^{12}C

实验设置

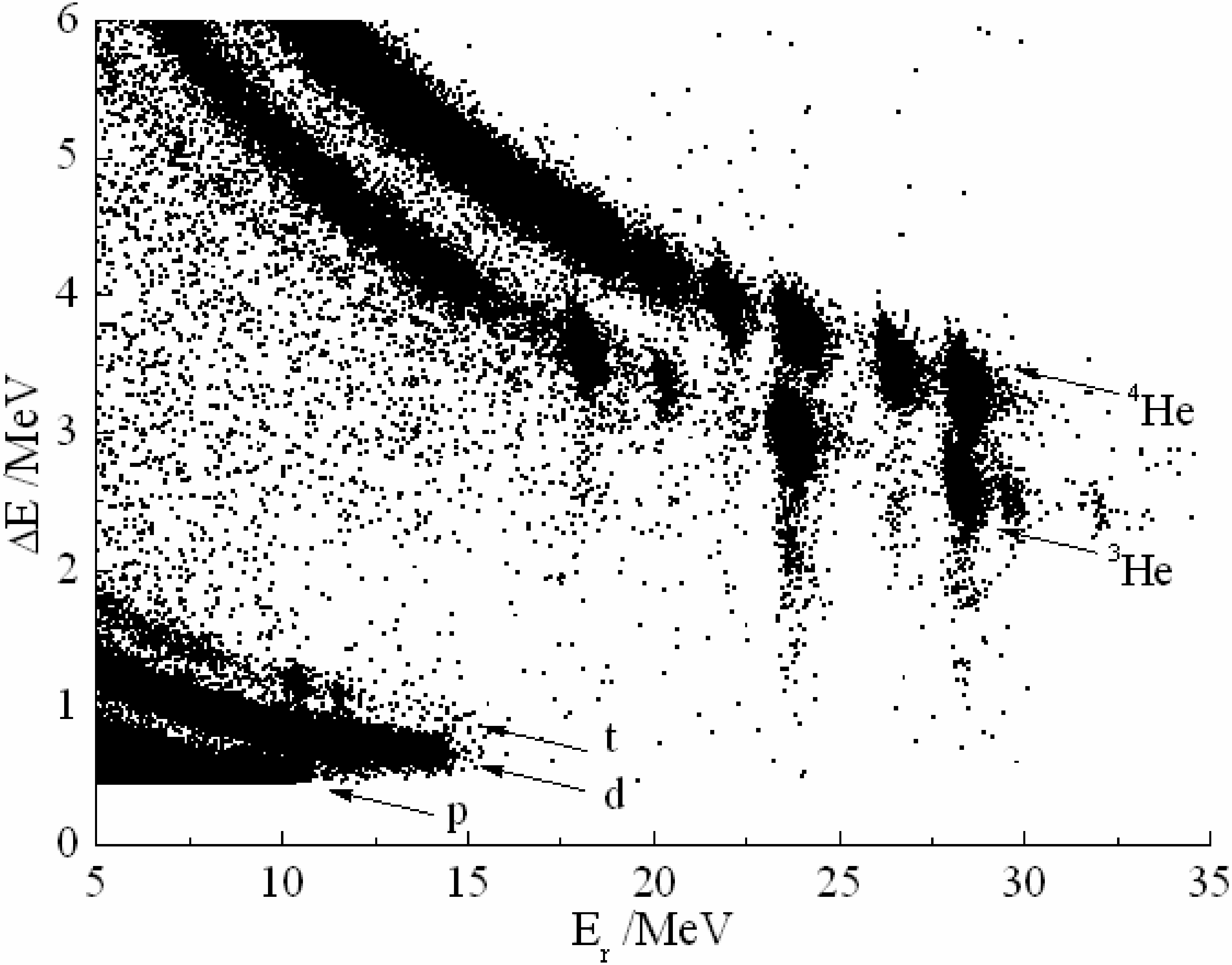


- 共计**153**路参数，包含能量、时间等信息。
- 角度范围**30-70°**

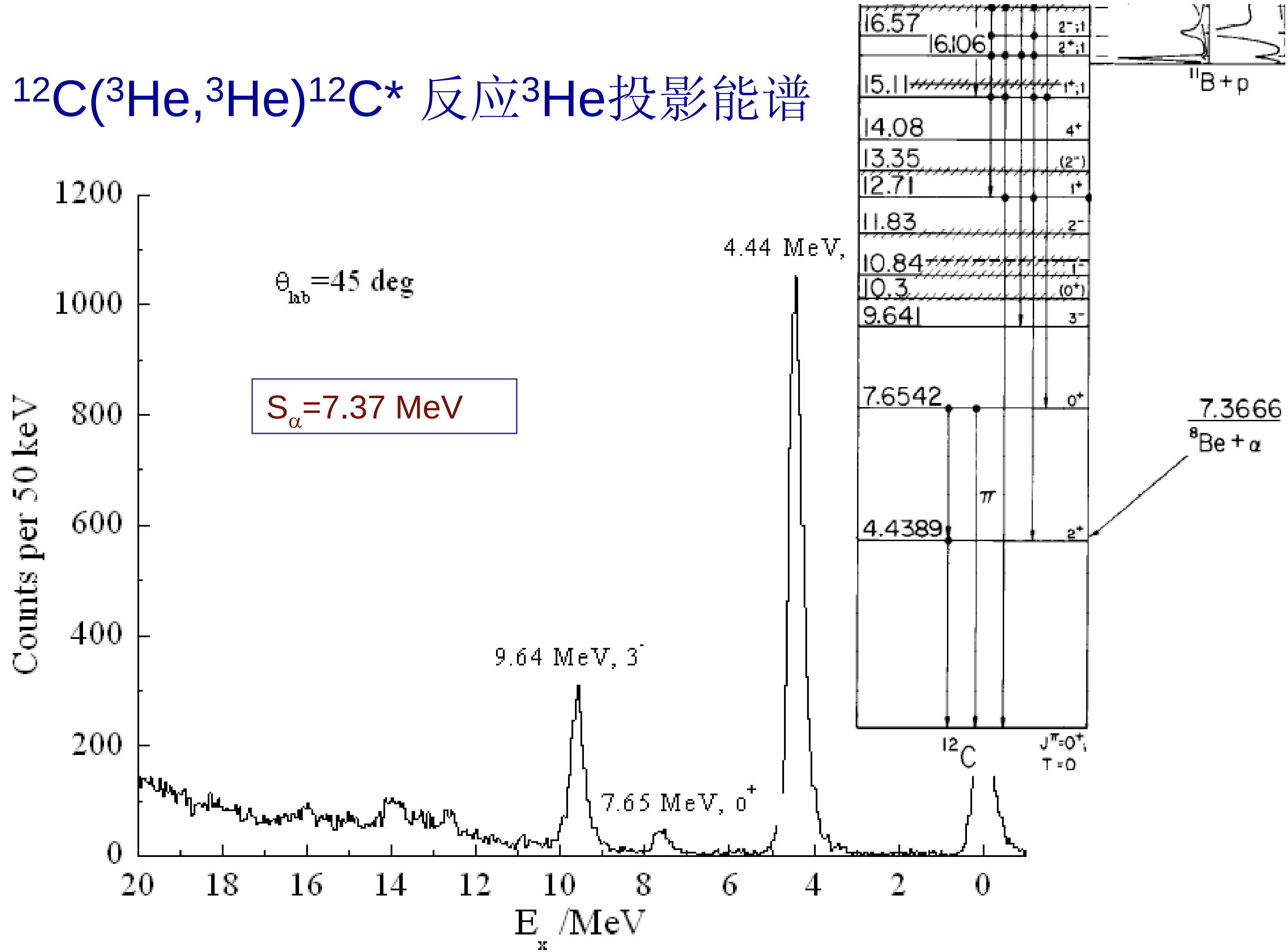
$^{3}He+^{197}Au$弹散@18.1 MeV



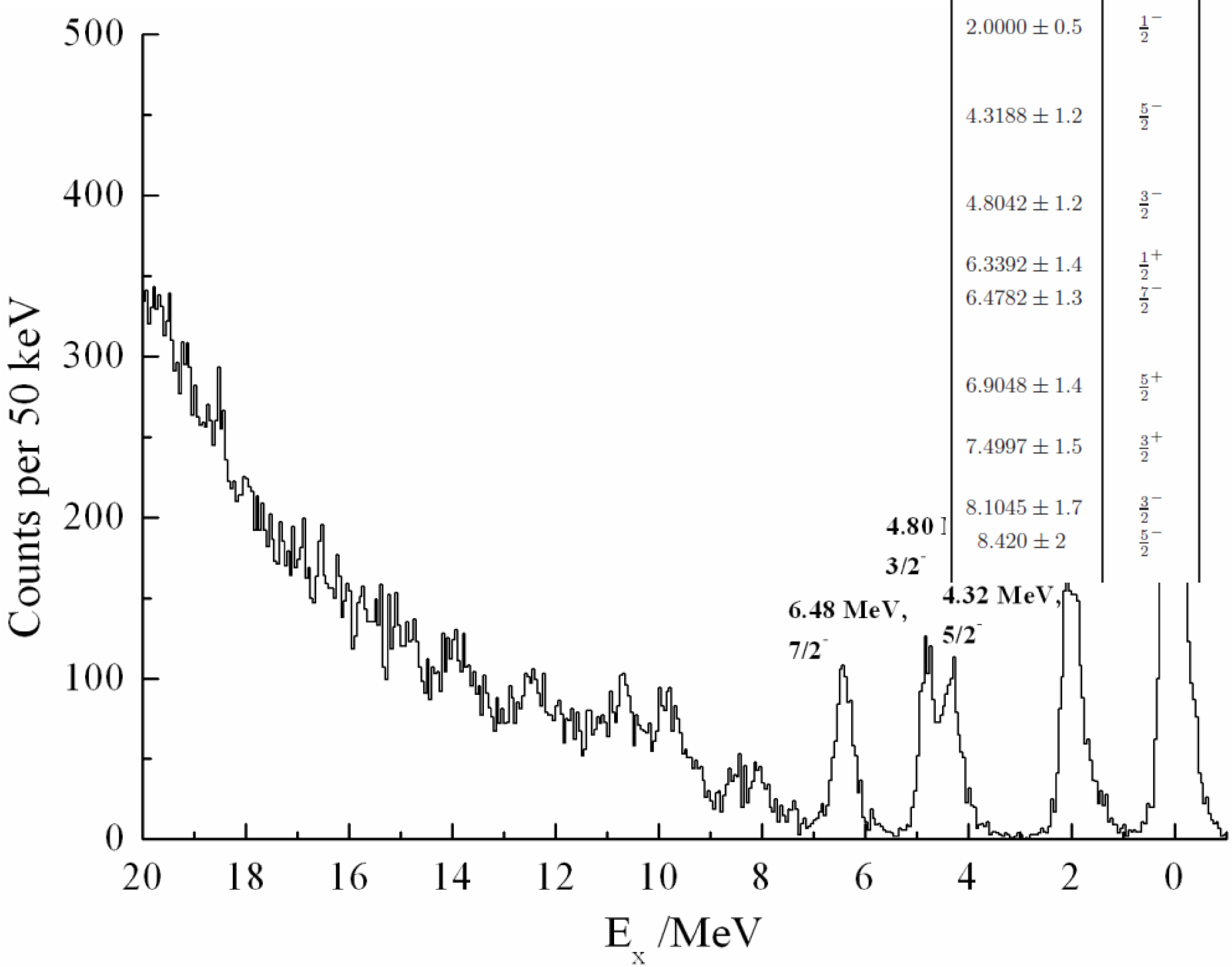
ΔE-E粒子鉴别



$^{12}C(^3He,^3He)^{12}C^*$ 反应^3He投影能谱

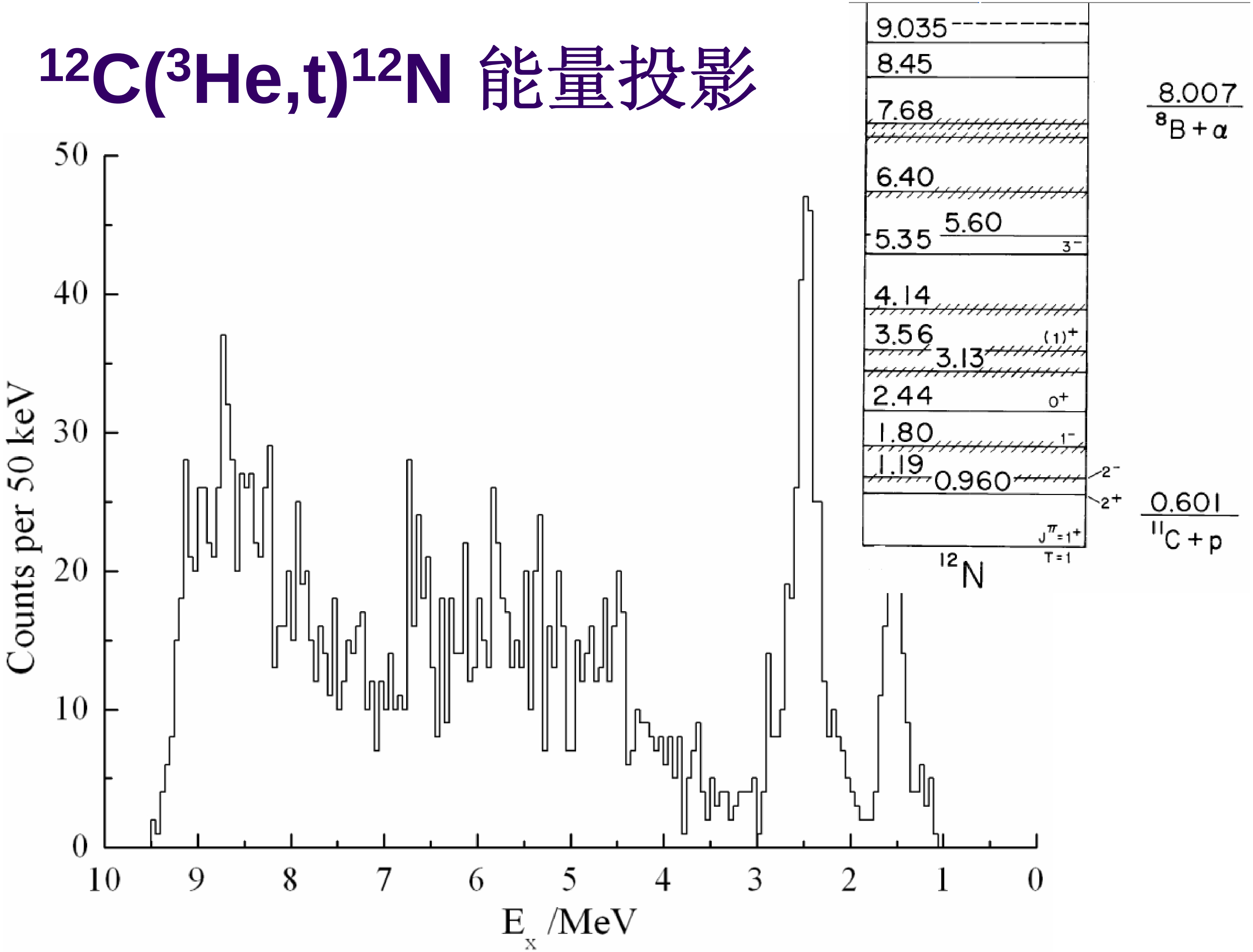


$^{12}C(^3He,^4He)$ 能量投影谱

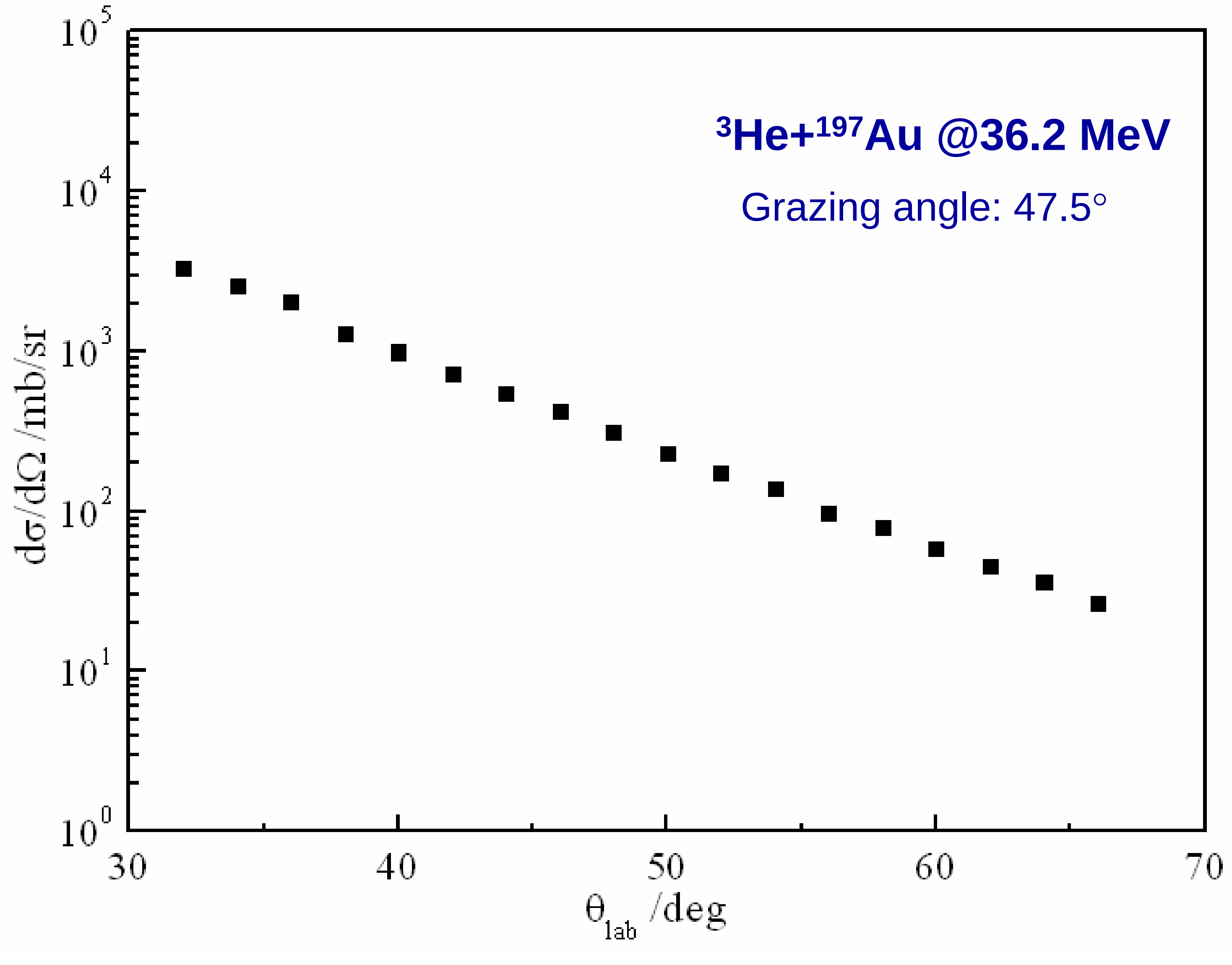


E_x in ^{11}C (MeV ± keV)	$J^\pi; T$	τ or $\Gamma_{c.m.}$	Decay
0	$\frac{3}{2}^-; \frac{1}{2}$	$\tau_{1/2} = 20.39 \pm 0.02$ min	β^+
2.0000 ± 0.5	$\frac{1}{2}^-$	$\tau_m = 10.3 \pm 0.7$ fs	γ
4.3188 ± 1.2	$\frac{5}{2}^-$	< 12 fs	γ
4.8042 ± 1.2	$\frac{3}{2}^-$	< 11 fs	γ
6.3392 ± 1.4	$\frac{1}{2}^+$	< 110 fs	γ
6.4782 ± 1.3	$\frac{7}{2}^-$	< 8 fs	γ
6.9048 ± 1.4	$\frac{5}{2}^+$	< 69 fs	γ
7.4997 ± 1.5	$\frac{3}{2}^+$	< 91 fs	γ
8.1045 ± 1.7	$\frac{3}{2}^-$	0.06 ± 0.04 fs[b]	γ, α
8.420 ± 2	$\frac{5}{2}^-$	0.043 ± 0.011 fs[b]	γ, α

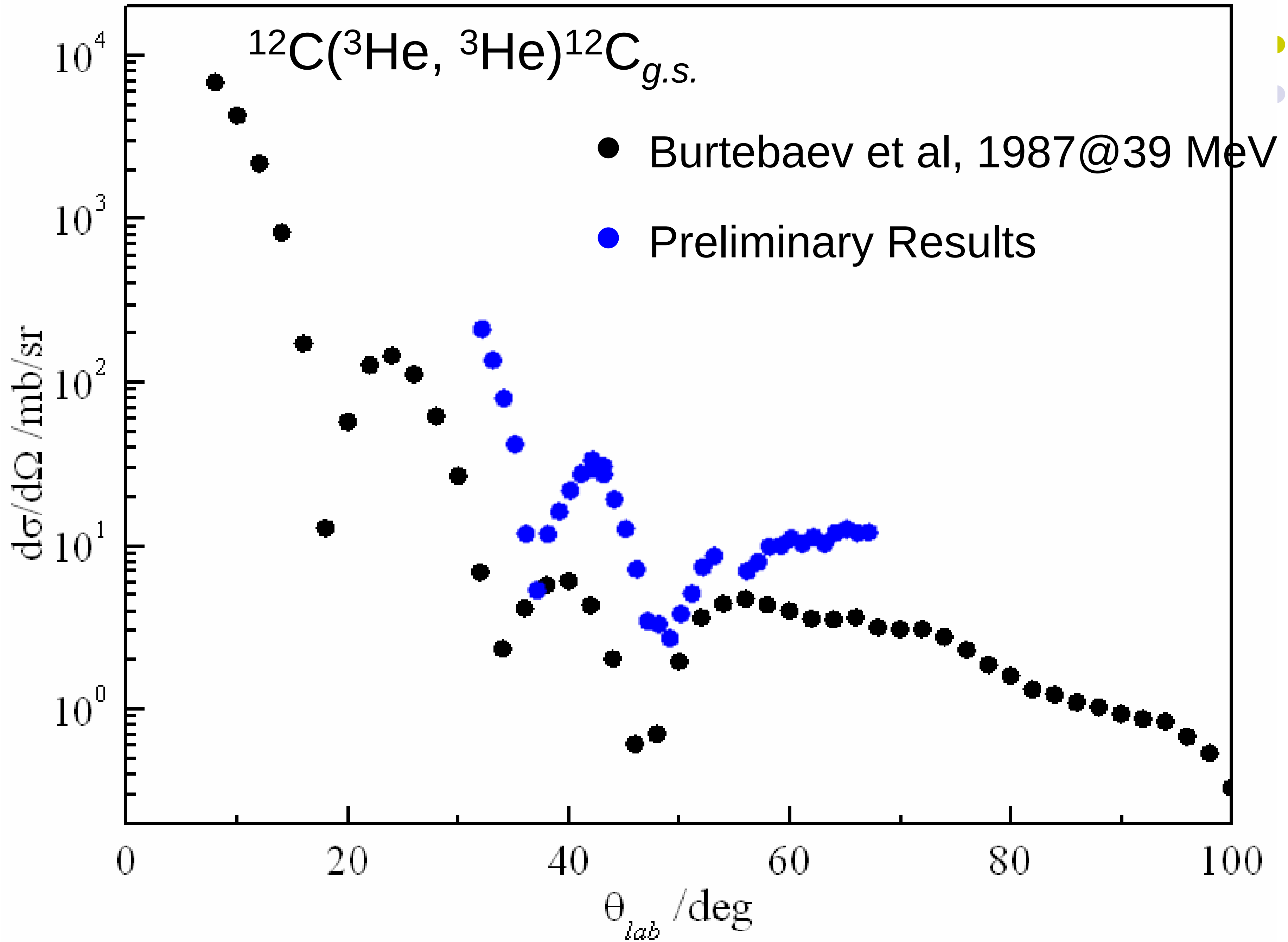
$^{12}C(^{3}He,t)^{12}N$ 能量投影



其它反应道初步结果

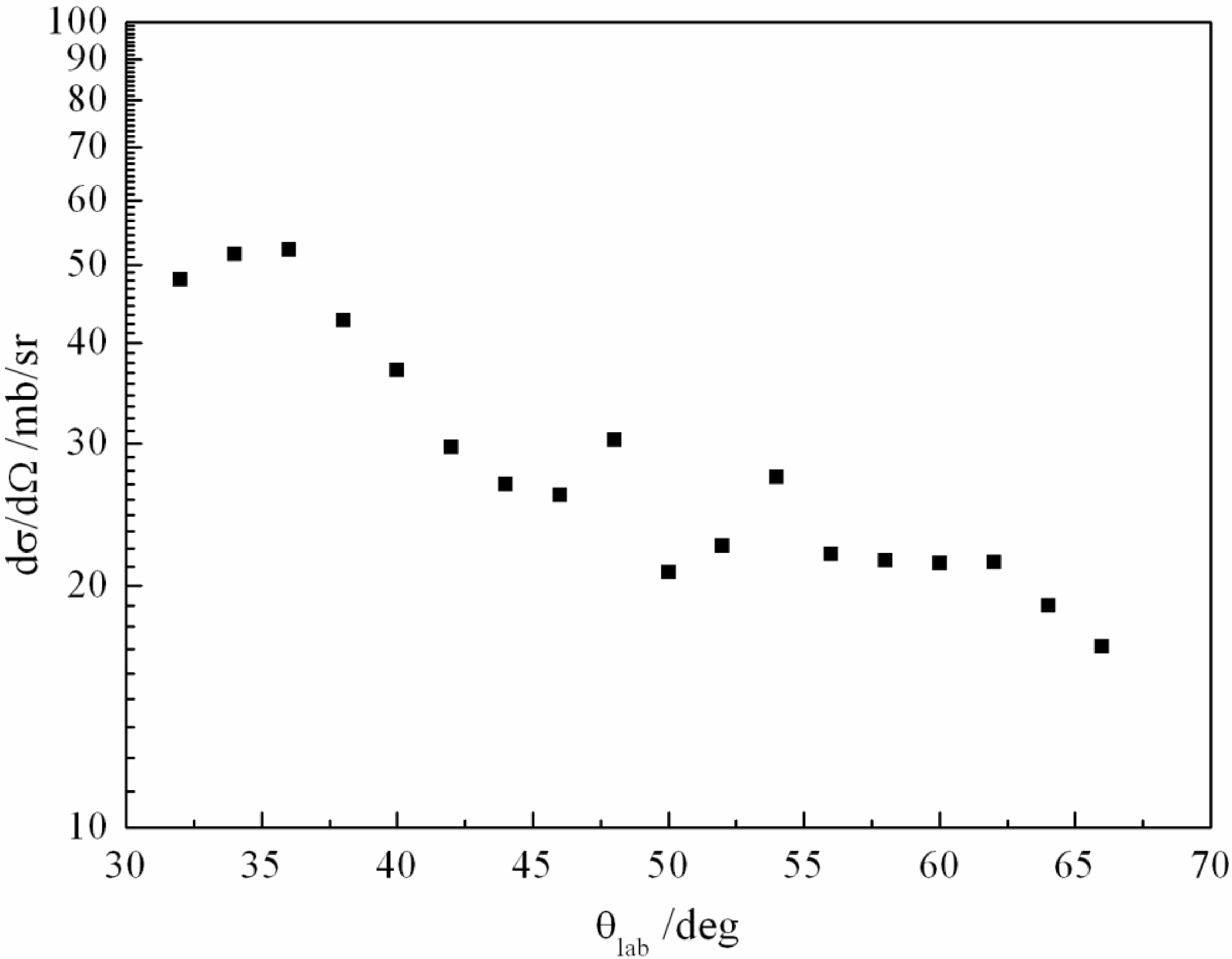


$^{3}He+^{197}Au$ @36.2 MeV
Grazing angle: 47.5°
$d\sigma/d\Omega$ /mb/sr
θ_{lab} /deg
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
30
40
50
60
70

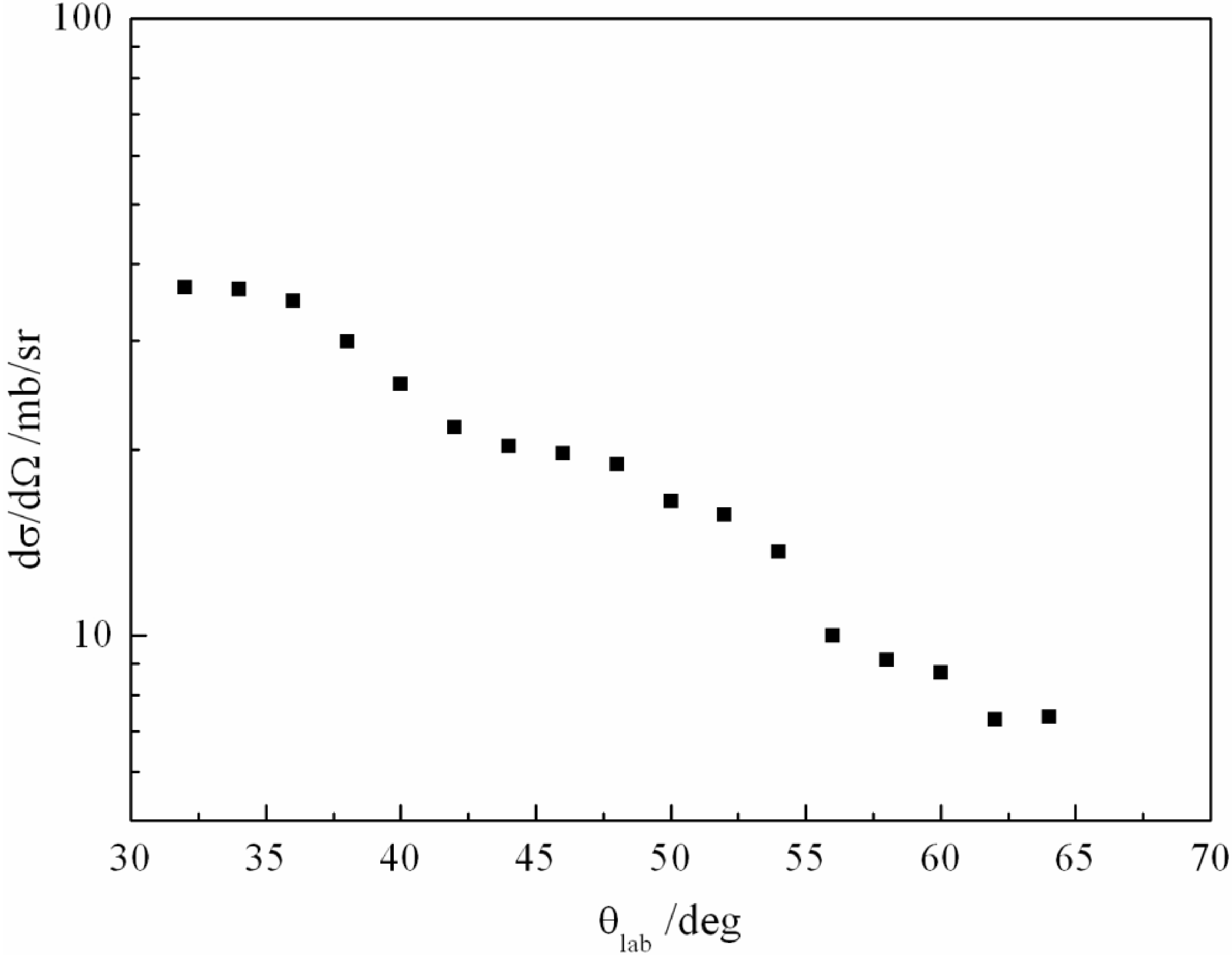


$^{12}C(^{3}He, ^{3}He)^{12}C_{g.s.}$
Burtebaev et al, 1987@39 MeV
Preliminary Results
$d\sigma/d\Omega$ /mb/sr
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
0
20
40
60
80
100
θ_{lab} /deg

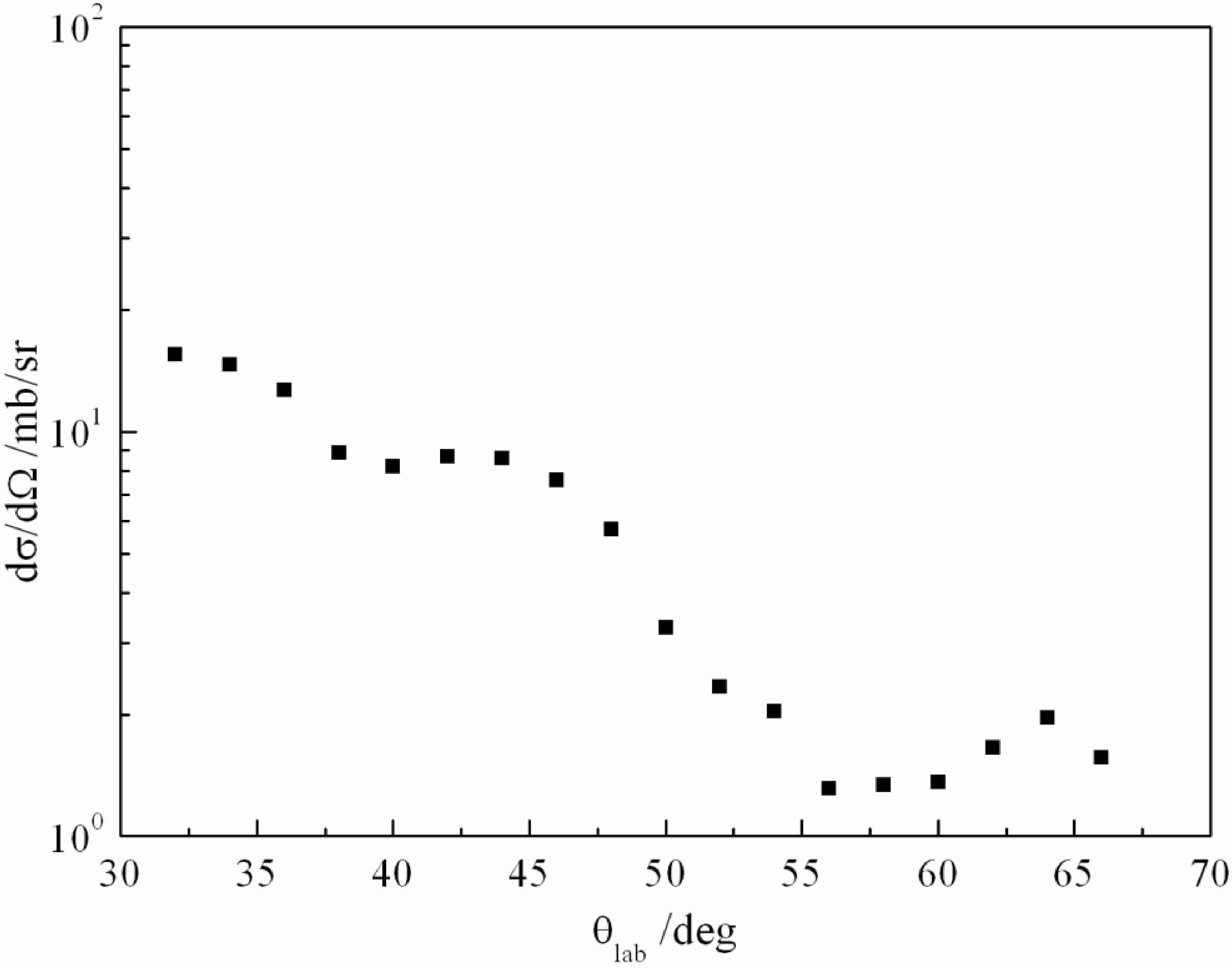
$^{12}C(^3He, ^3He)^{12}C_{ex1}$ 角分布



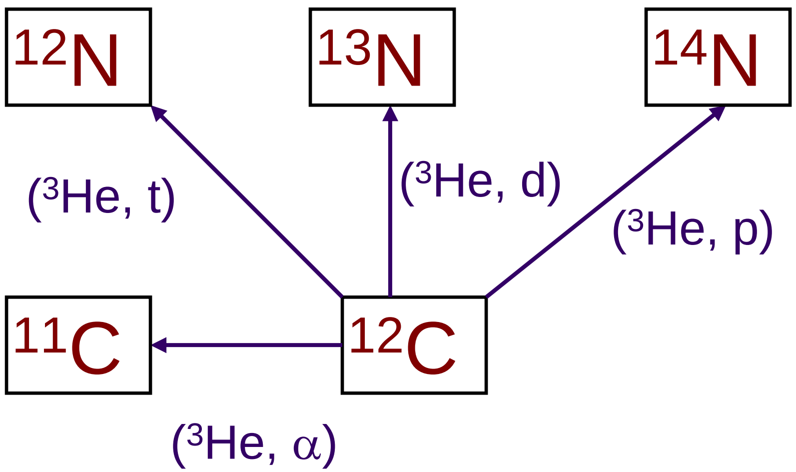
$^{12}C(^3He, \alpha)^{11}C_{g.s.}$ 角分布



$^{12}C(^{3}He, \alpha)^{11}C_{ex1}$ 角分布



$^{3}He+^{12}C$主要反应道



- $^{12}C(^{3}He,^{3}He)^{12}C$, ^{12}C激发态， 3α过程
- $^{12}C(^{3}He,\alpha)^{11}C$, ^{11}C激发态, $^{7}Be(\alpha,\gamma)$, $^{7}Be(\alpha,p)$
- $^{12}C(^{3}He,t)^{12}N$, ^{12}N激发态， $^{8}B(\alpha,\gamma)$, $^{8}B(\alpha,p)$

下一步的工作

- CRIB ^{22}Na+p厚靶实验

<u>此前厚靶实验的一些技术积累：</u>

[1] Y.B. Wang, S.J. Jin, B.X. Wang et al., "Study of elastic resonance scattering at CIAE" The 13th National Conference on Nuclear Structure, Chifeng, July 25-30, 2010, to be published in the World Scientific conference series.

[2] JIN Sun-Jun, WANG You-Bao, WANG Bao-Xiang et al., "Excited states in ^{18}Ne studied via ^{17}F+p" **Chin. Phys. Lett. 27(3), 032102(2010)**

[3] Y.B. Wang, B.X. Wang, S.J. Jin et al., "Elastic resonance scattering of ^{13}N+p and ^{17}F+p" **Nucl. Phys. A834**, **100c-102c(2010)**

[4] WANG You-Bao, QIN Xing, WANG Bao-Xiang et al., "Simulation and analysis of ^{13}N+p elastic resonance scattering" **Chin. Phys. C33(3), 181-186 (2009)**

[5] Y.B. Wang, B.X. Wang, X. Qin et al., "^{13}N+p elastic resonance scattering via a thick-target method" **Phys. Rev. C 77, 044304(2008)**

[6] QIN Xing, WANG You-Bao, BAI Xi-Xiang et al., "Levels in ^{13}N examined by ^{12}C+p elastic resonance scattering with thick target" **Chin. Phys. C32(12), 957-961(2008)**

Study of resonant elastic/inelastic scattering of ^{22}Na+p relevant to the astrophysical ^{22}Na(p, γ)^{23}Mg reaction

Main collaborators from:

China Institute of Atomic Energy (CIAE, Beijing)

CNS, University of Tokyo

Institute of Modern Physics (IMP, Lanzhou)

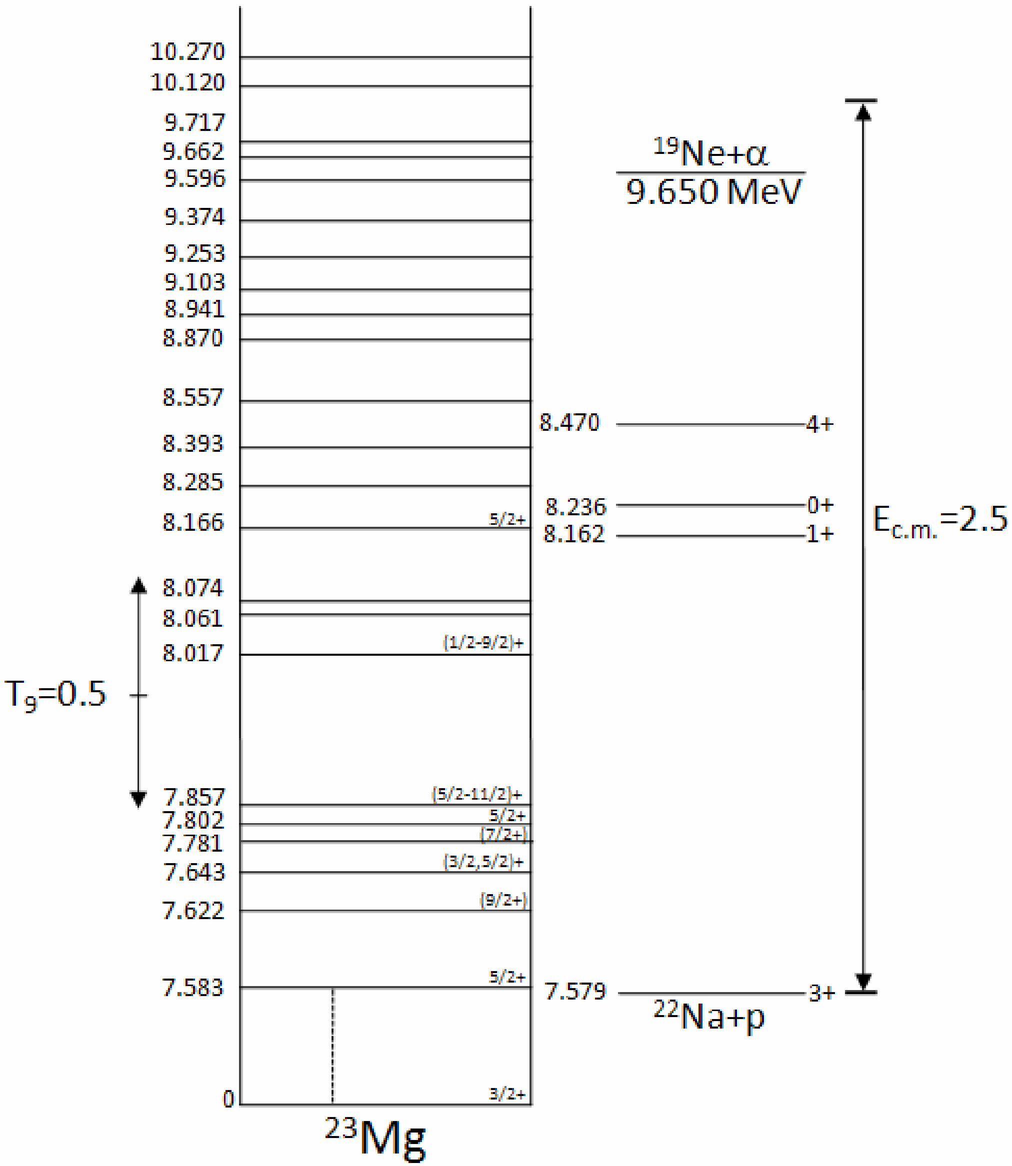
Kyushu University

Tohoku University

Tsukuba University

Yamagata University

Goals of the measurement



- To map the relevant resonances in ^{23}Mg over larger excitation energy region using ^{22}Na+p channel with a well-developed thick target method
- To deduce the resonance parameters including energy、spin/parity and proton width for ^{22}Na(p,γ)^{23}Mg reaction and for level systematics
- To touch ^{22}Na(p,α)^{19}Ne reaction
- To develop ^{22}Na secondary beam for future studies of ^{22}Na(α,α) and ^{22}Na(α,p)

Nearly 30 energy levels are missing up to 9.7MeV comparing with ^{23}Na

Recommendation from 8th NP-PAC meeting

NP1012-AVF11

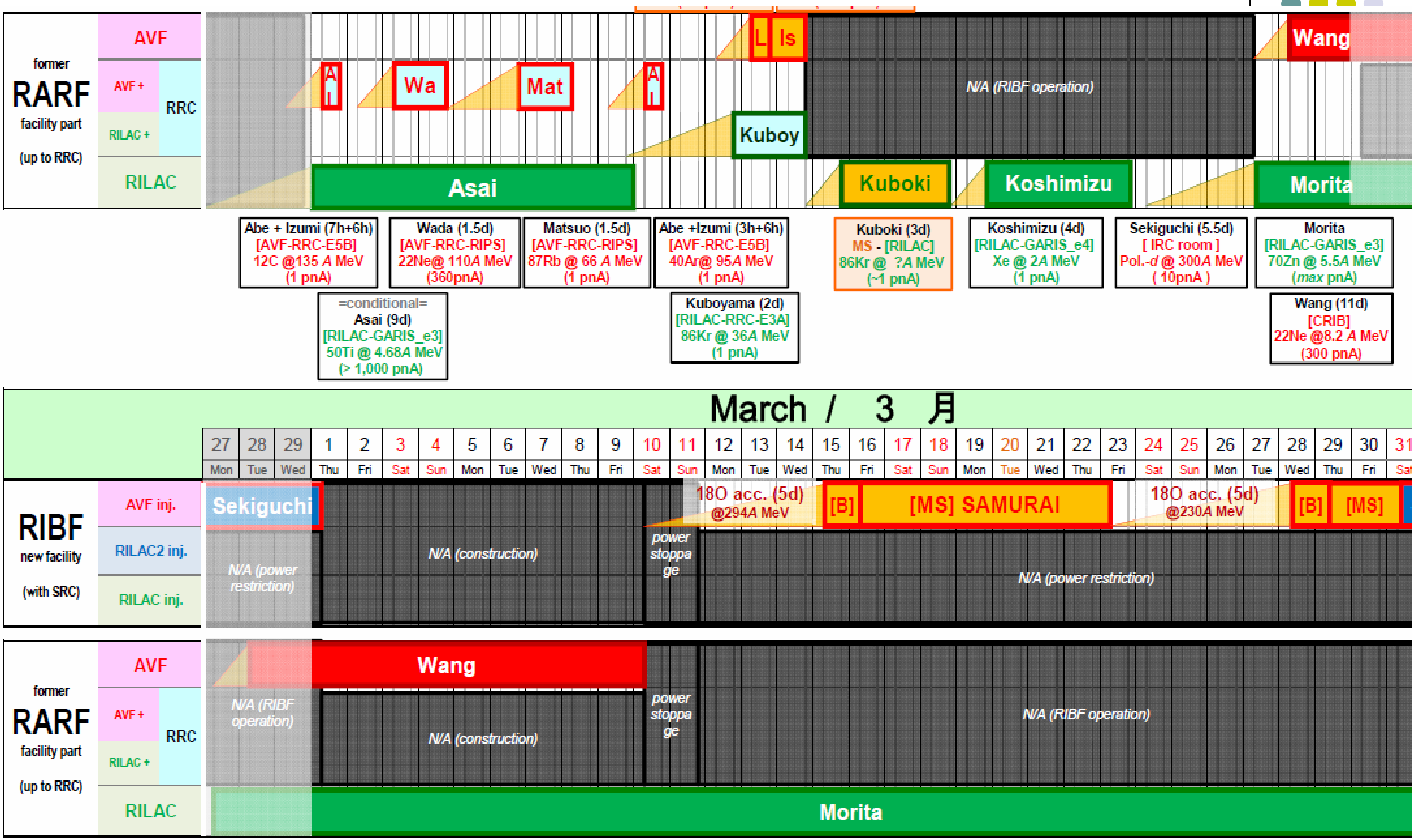
Spokesperson: Youbao Wang

Study of resonant elastic/inelastic scattering of ^{22}Na+p relevant to the astrophysical ^{22}Na(p, γ)^{23}Mg reaction

Approved — Grade A/B

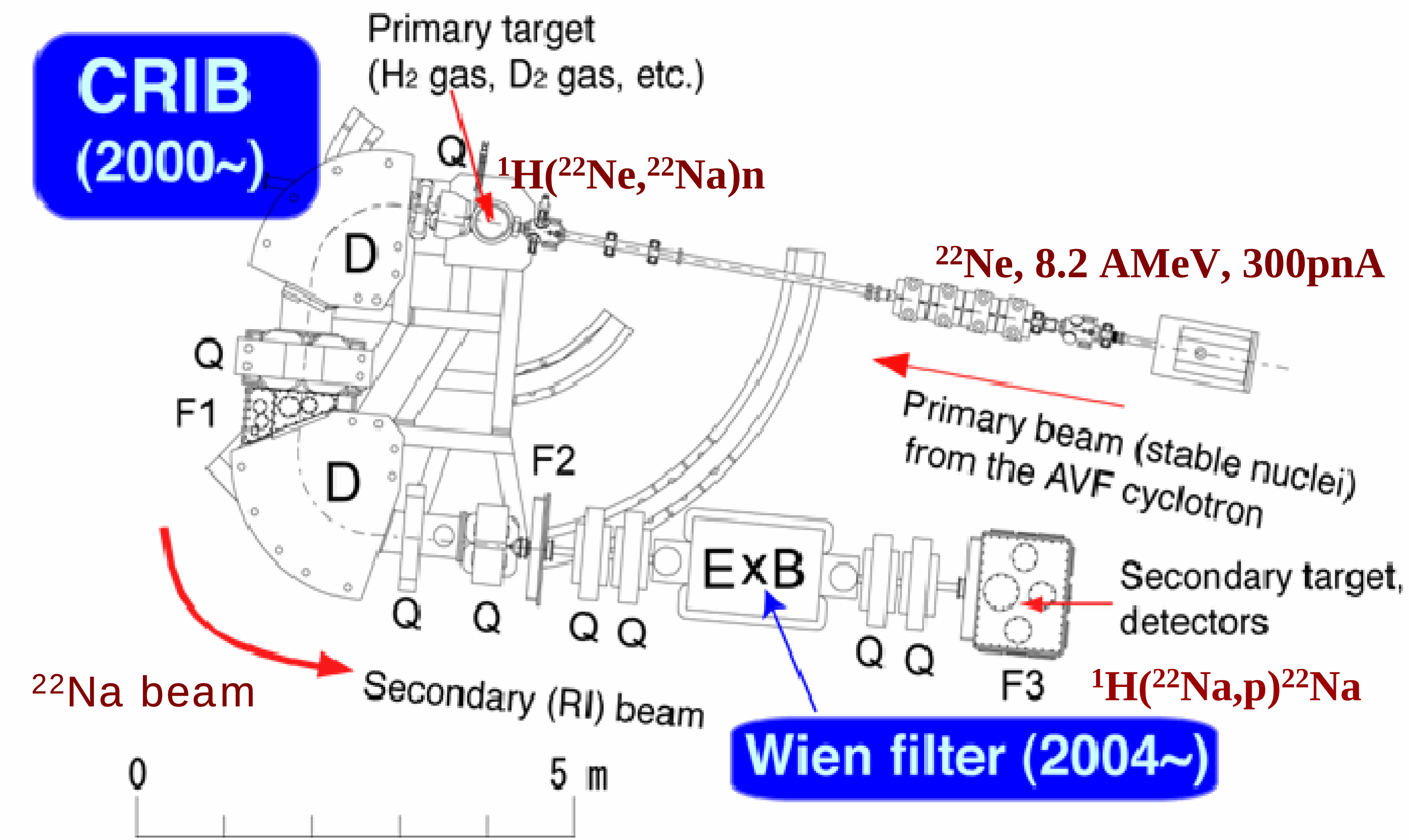
It is proposed to study elastic and inelastic proton scattering on ^{22}Na in the novae energy region by the inverse kinematics, thick target method. The aim is to determine the parameters of the resonances dominating the ^{22}Na(p,γ) rate at nova conditions. Additionally it is proposed to study the (p,α) reaction on ^{22}Na. The PAC considers the physics motivation for this experiment as high. The proposed experiment is expected to provide new information which, together with a recent direct (p,γ) measurement and a measurement of the beta-delayed protons and gammas from ^{23}Al, will help to constrain the reaction rate that depletes ^{22}Na in novae.

Beam-time allocation

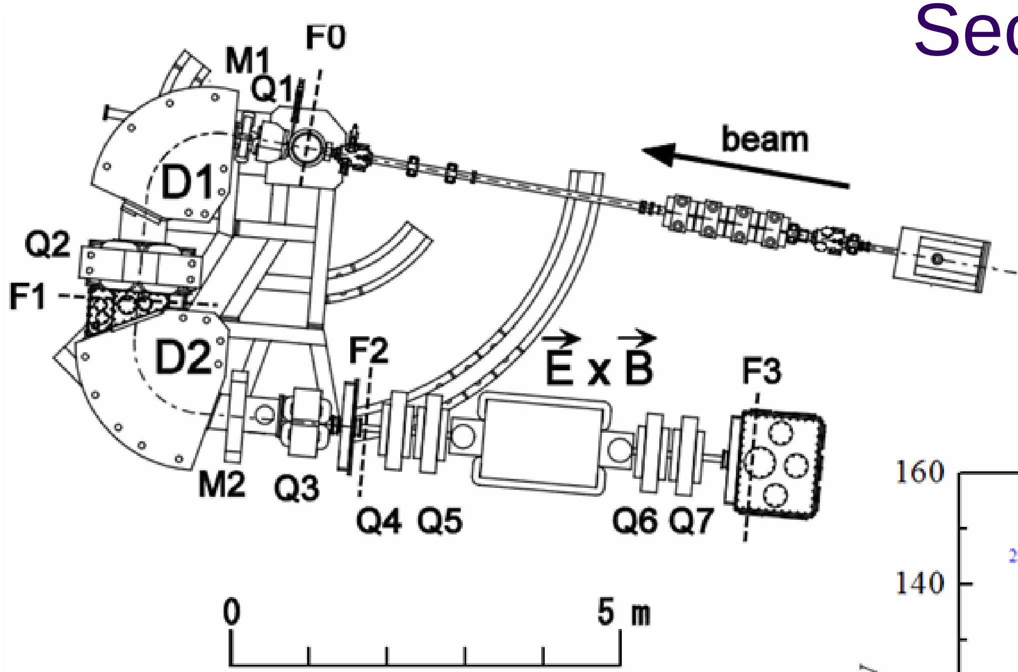


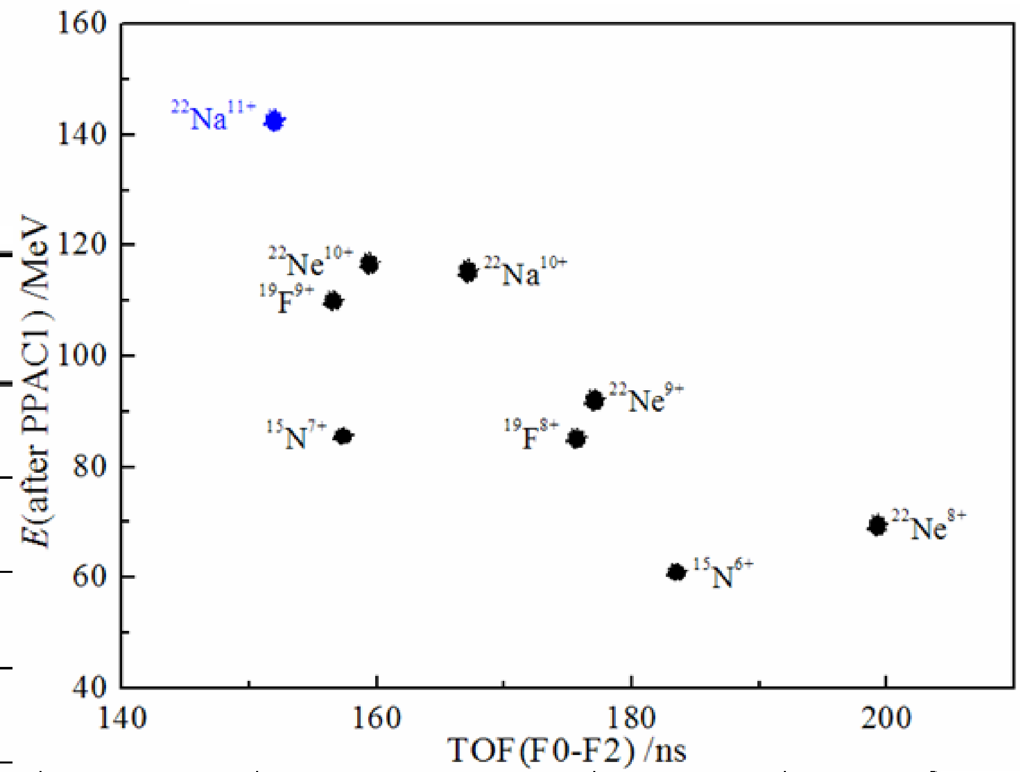
束流时间：2012年2月28日-3月10日

CRIB次级束装置


CRIB
(2000~)
Primary target
(H2 gas, D2 gas, etc.)
Q
1H(22Ne,22Na)n
D
22Ne, 8.2 AMeV, 300pnA
Q
F1
Primary beam (stable nuclei)
from the AVF cyclotron
D
F2
ExB
Secondary target,
detectors
Q Q Q Q
Q Q
F3
1H(22Na,p)22Na
22Na beam
Secondary (RI) beam
Wien filter (2004~)
0
5 m

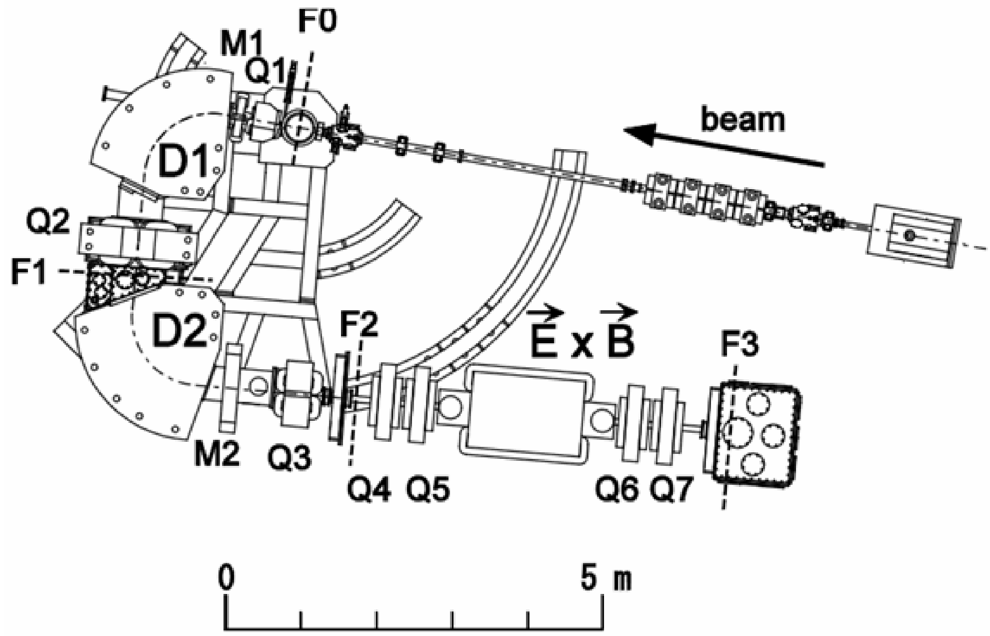
Secondary beams via (p,n) production reaction at CRIB





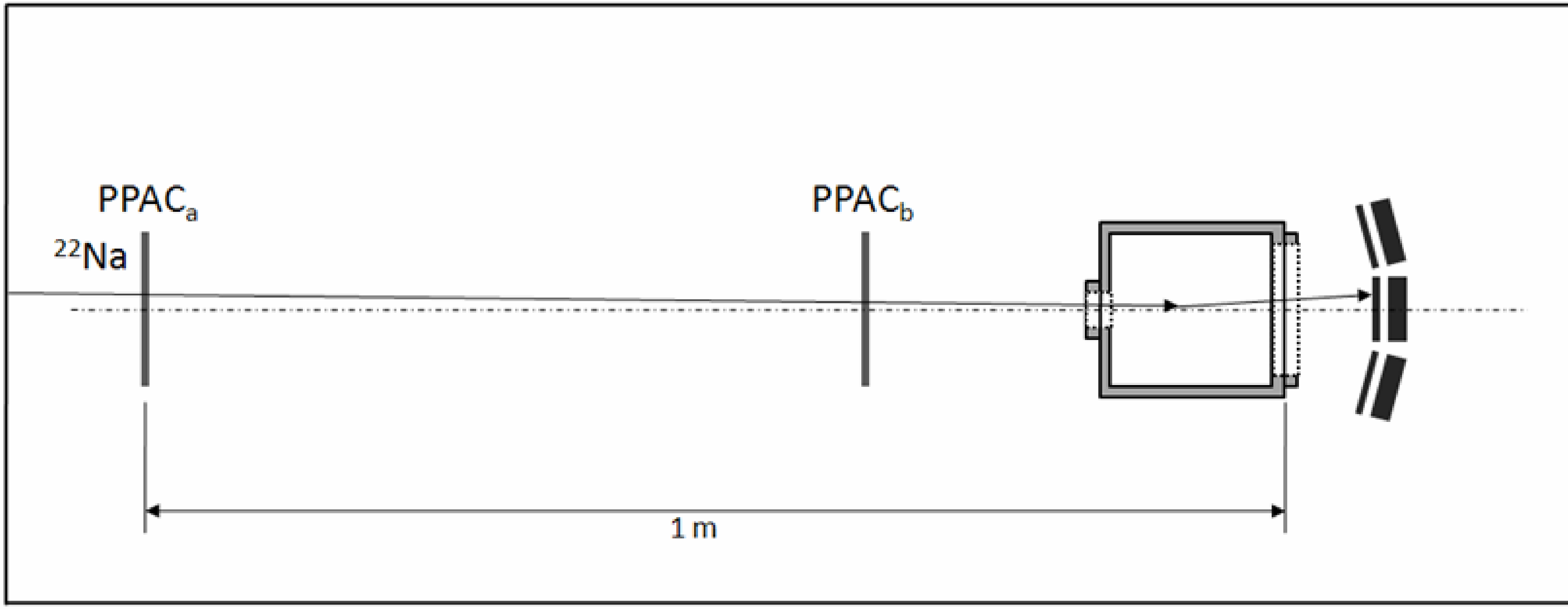
Secondary Beam		Primary Beam				
$^{7}Be^{4+}$	8.1 *A* MeV	$^{7}Li^{3+}$ 150 pnA				
$^{10}C^{6+}$	6.1 *A* MeV	$^{10}B^{4+}$ 200 pnA				
$^{13}N^{7+}$	6.5 *A* MeV	$^{13}C^{5+}$ 500 pnA				
$^{14}O^{8+}$	6.7 *A* MeV	$^{14}N^{6+}$ 500 pnA				
$^{18}F^{9+}$	2.7 *A* MeV	$^{18}O^{4+}$ 500 pnA	(p,n)	H_2 gas (0.67)	**1.5×10^5**	**98%**

^{22}Na beam production conditions



Primary beam	$^{22}Ne^{8+}$
Energy	8.2 MeV/A
Intensity	300 pnA
Production reaction	$^{22}Ne(p, n)^{22}Na$
Production target	^{1}H gas, 1.15 mg/cm^2 (LN$_2$-cooled, 400 Torr, 90K, 80 mm in length
Degrader after F0 target	16 and 12 μm Havar foil

Experimental setup

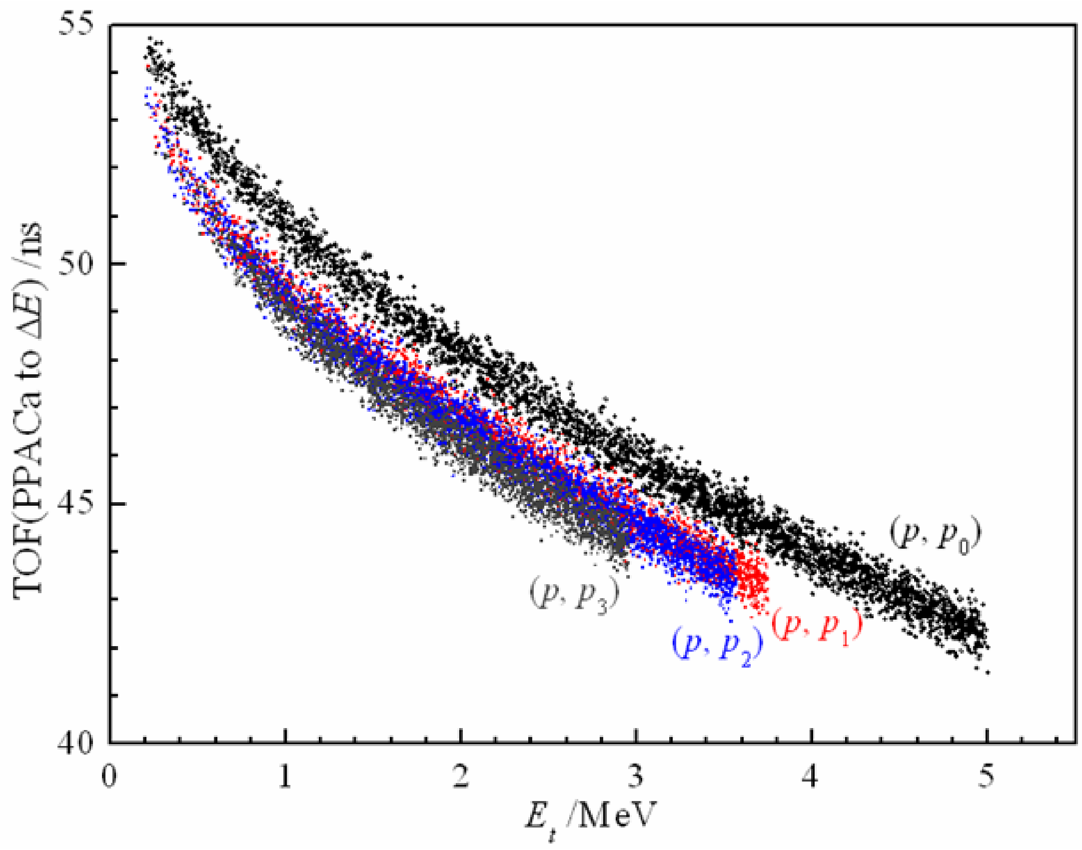


$^{22}Na^{11+}$ on entrance window
Energy: 2.2 MeV/A, 3.2 MeV/A
Intensity: ~1.0×10^5 pps

$^1H_2$ gas target
Length: 200 mm
Pressure: 400 Torr
Entrance: ϕ 30 mm
Exit: 40×150 mm^2
Windows: 2.5 μm Havar foil

Detector Telesopes
50×50 mm^2
ΔE: 75 μm PSD
E: 1.0 mm SSD

Identification of elastic/inelastic channels



<u>Energy resolution in cm:</u>

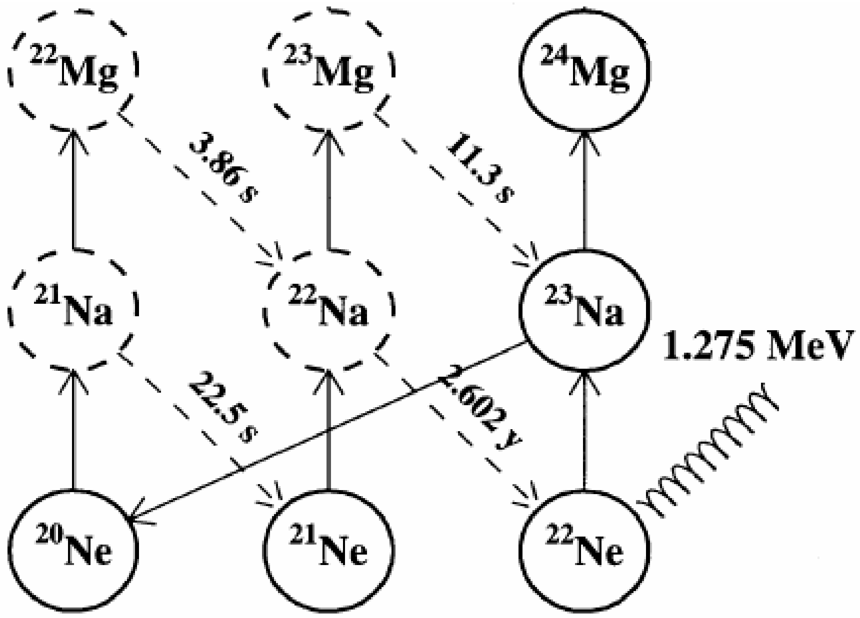
20-50 keV (FWHM)

总 结

- 这两个实验，我们尽可能地扩大实验规模。
- 在技术手段上，同时测量能量和时间，因此可以利用ΔE-E和TOF来鉴别反应产物，并且提供了更多的符合手段。
- 作为回报，实验可以提供的信息更加丰富。
- 与国际上带电粒子探测器阵列相比，仍有相当大的差距，但不失为一个很好的锻炼。

谢谢大家！

^{22}Na+p弹性共振散射的物理意义

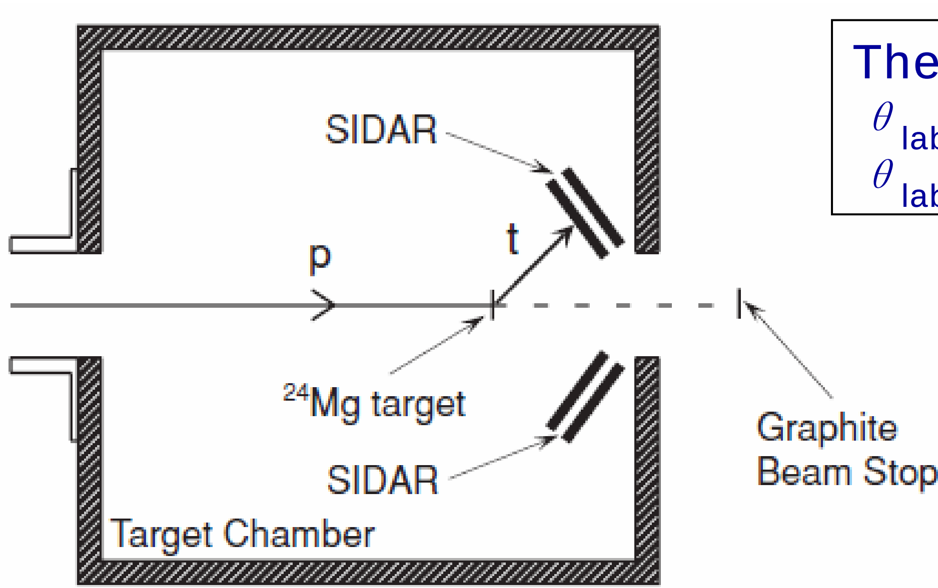


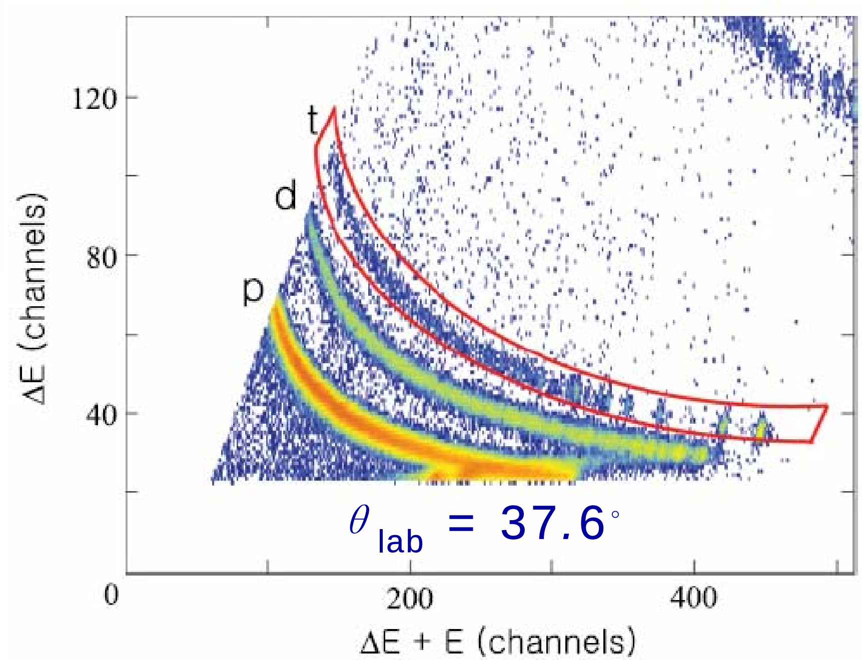
新星演化过程中涉及^{22}Na的反应网络

- 1972年发现Orgueuil陨石中^{22}Ne丰度异常高，表明新星等爆发事件可产生^{22}Na
- 因为半衰期适中，并伴随可测量的伽马射线，^{22}Na 是重要的宇宙伽马射线发射体
- 但是星载探测器测量的^{22}Na非常少
- $T \geqslant 5\times10^7$k，^{21}Ne(p,γ)^{22}Na是循环中最主要的反应
- $T \geqslant 7\times10^7$k，^{22}Na(p,γ)^{23}Mg开始起作用，目前这个反应还有许多的未知因素。

ORNL $^{24}Mg(p,t)^{22}Mg$ 例子

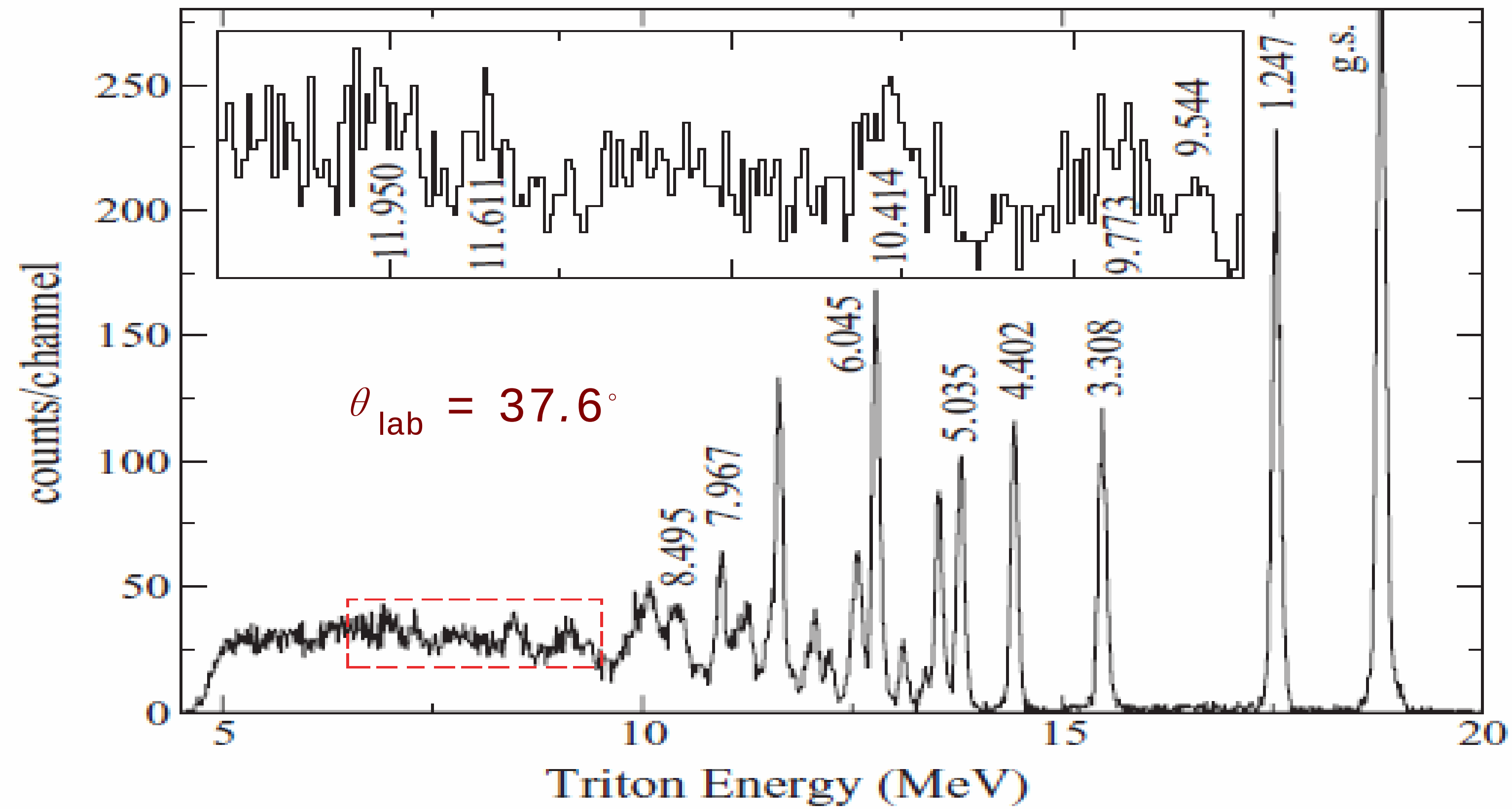
The angles covered by SIDAR were
θ_{lab} = 18°- 48° for E_p = 41 MeV
θ_{lab} = 27°- 69° for E_p = 41.5 MeV



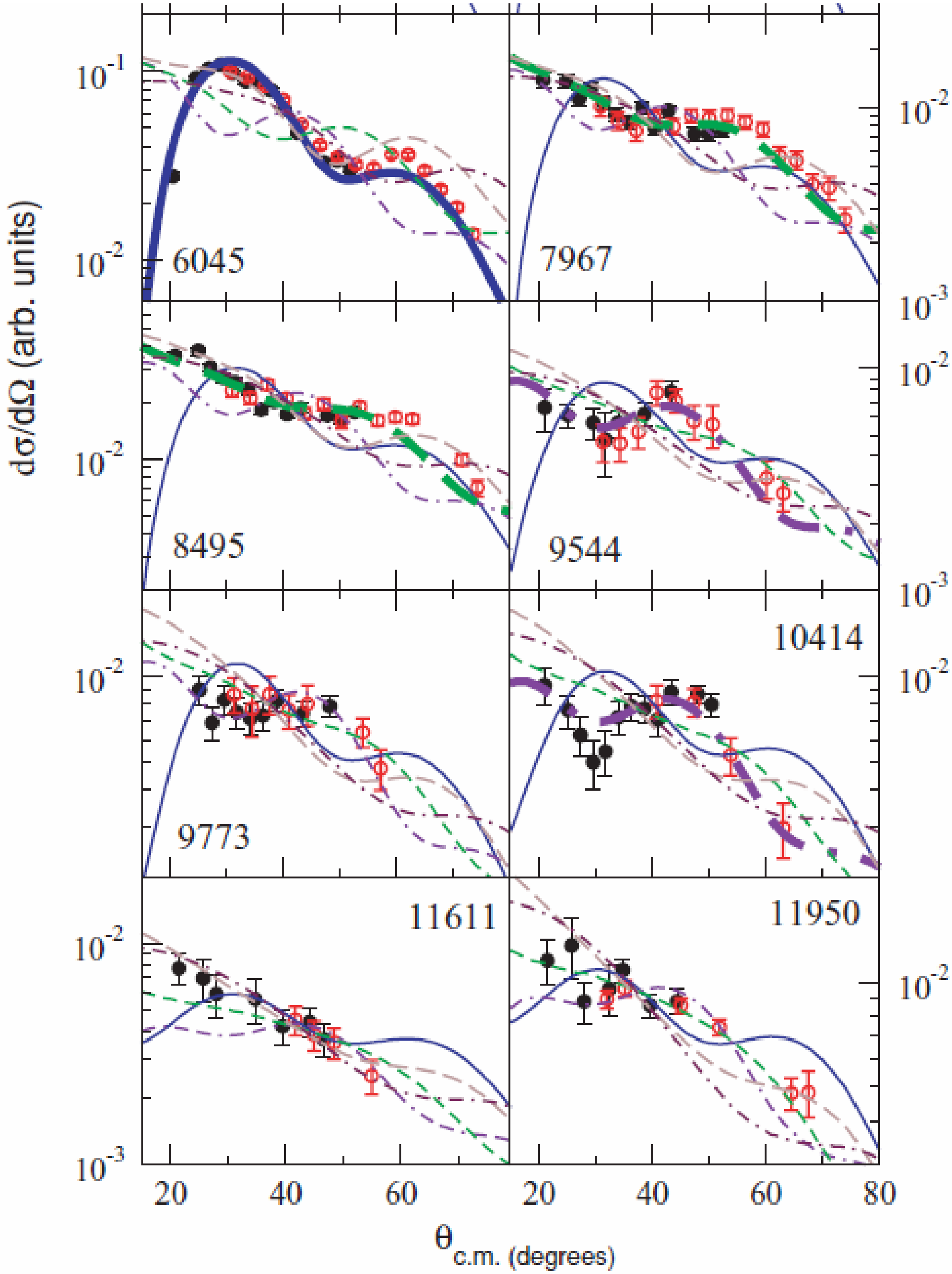


PRC**79**, 055804 (2009)

氚的能谱



Twenty ^{22}Mg levels were observed including six above the α threshold. S_p=5502 keV, S_α=7345 keV



角分布分析

实验贡献：

共振能级的能量

共振能级可能的自旋

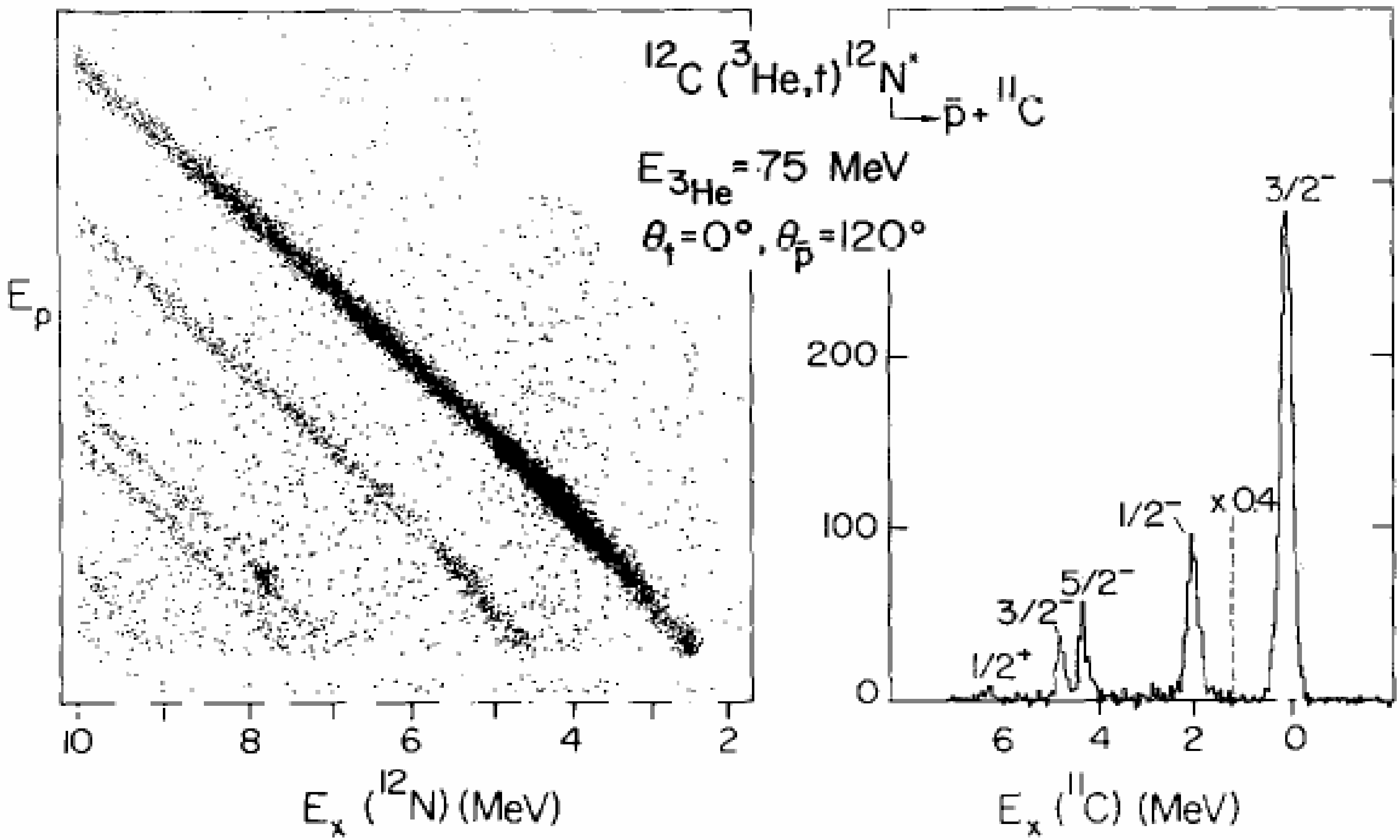
Reaction Q-values for $^{12}C + {}^{3}He(E_{lab}=37.5\ MeV)$

Reaction Products	Q-value (keV)	Threshold (keV)
$^{15}O+\gamma$	12075.6 *5*	0.0 *0*
$^{14}N+p$	4778.8311 *25*	0.0 *0*
$^{11}C+\alpha$	1856.0 *10*	0.0 *0*
$^{12}C+{}^{3}He$	0.0 *0*	0.0 *0*
$^{14}O+n$	-1147.45 *11*	1435.82 *14*
$^{13}C+2p$	-2771.738 *3*	3468.313 *3*
$^{13}N+d$	-3550.0 *3*	4442.1 *3*
$^{7}Be+2\alpha$	-5688.65 *11*	7118.28 *13*
$^{13}N+n+p$	-5774.6 *3*	7225.8 *3*
$^{10}B+p+\alpha$	-6833.4 *4*	8550.7 *5*
$^{3}He+3\alpha$	-7274.747 *3*	9102.987 *4*
$^{4}He+{}^{3}He+2\alpha$	-7274.748 *3*	9102.989 *4*
$^{8}Be+{}^{3}He+\alpha$	-7366.59 *4*	9217.91 *4*
$^{10}C+n+\alpha$	-11263.7 *4*	14094.4 *5*
$^{6}Li+p+2\alpha$	-11294.381 *15*	14132.809 *19*
$^{4}He+p+d+2\alpha$	-12768.2256 *24*	15977.050 *3*
$^{8}Be+p+d+\alpha$	-12860.07 *4*	16091.97 *4*
$^{9}B+d+\alpha$	-13045.1 *10*	16323.5 *12*
$^{9}Be+2p+\alpha$	-13419.3 *4*	16791.7 *5*
$^{5}Li+d+2\alpha$	-1.473E+4 *5*	1.844E+4 *6*
$^{4}He+n+2p+2\alpha$	-14992.7910 *25*	18760.678 *3*
$^{8}Be+n+2p+\alpha$	-15084.63 *4*	18875.60 *4*
$^{9}B+n+p+\alpha$	-15269.7 *10*	19107.1 *12*
$^{5}He+2p+2\alpha$	-1.588E+4 *5*	1.987E+4 *6*
$^{11}B+p+{}^{3}He$	-15956.9 *4*	19967.1 *5*
$^{6}Be+n+2\alpha$	-16365 *5*	20478 *7*
$^{5}Li+n+p+2\alpha$	-1.696E+4 *5*	2.122E+4 *6*
$^{12}N+t$	-17356.7 *10*	21718.6 *13*

Interesting decay channels

- $^{11}C+\alpha$
- $^{13}N+d$

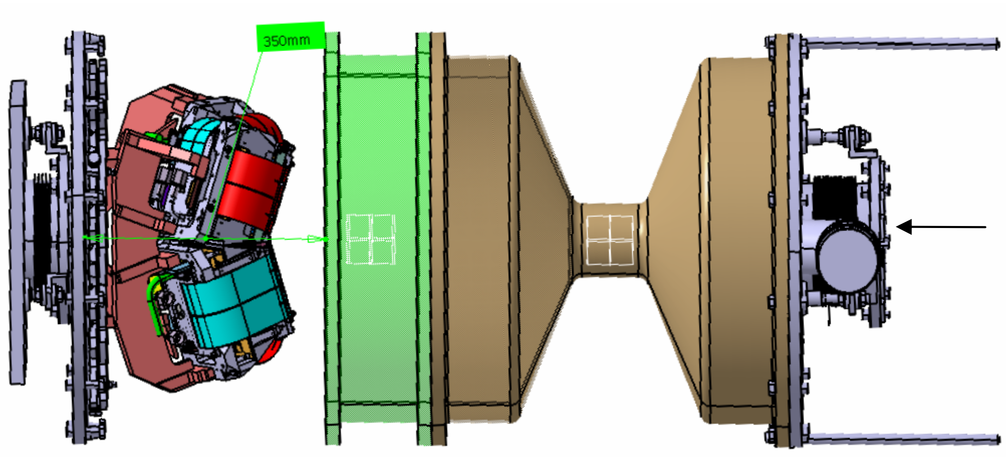
t—p 符合测量



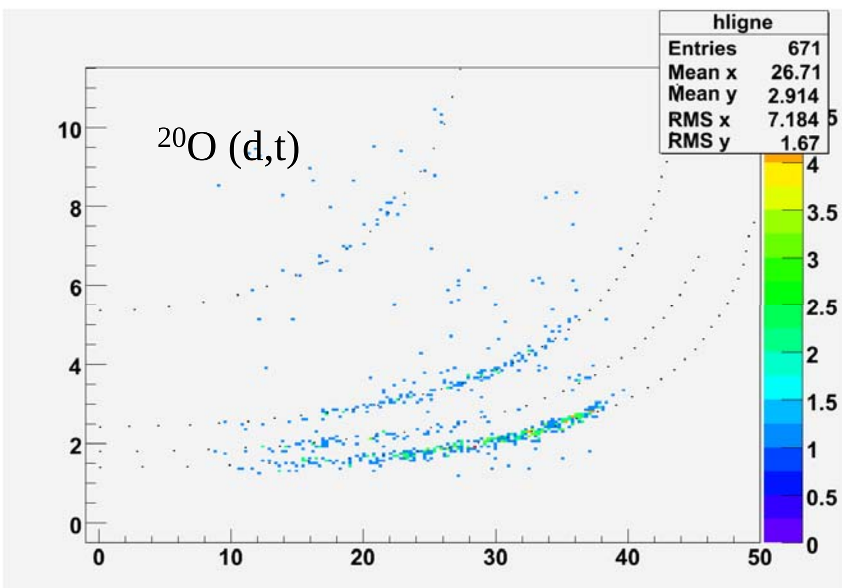
$^{12}C(^{3}He,t)^{12}N^{*} \to \bar{p} + ^{11}C$
$E_{^3He}$=75 MeV
θ_t=0°, $\theta_{\bar{p}}$=120°
E_p
10
8
6
4
2
E_x (^{12}N) (MeV)
200
100
0
3/2⁻
1/2⁻
x 0.4
5/2⁻
3/2⁻
1/2⁺
6
4
2
0
E_x (^{11}C) (MeV)

Transfer reactions (d,p), (p,t), (d,t), (d,^{3}He)

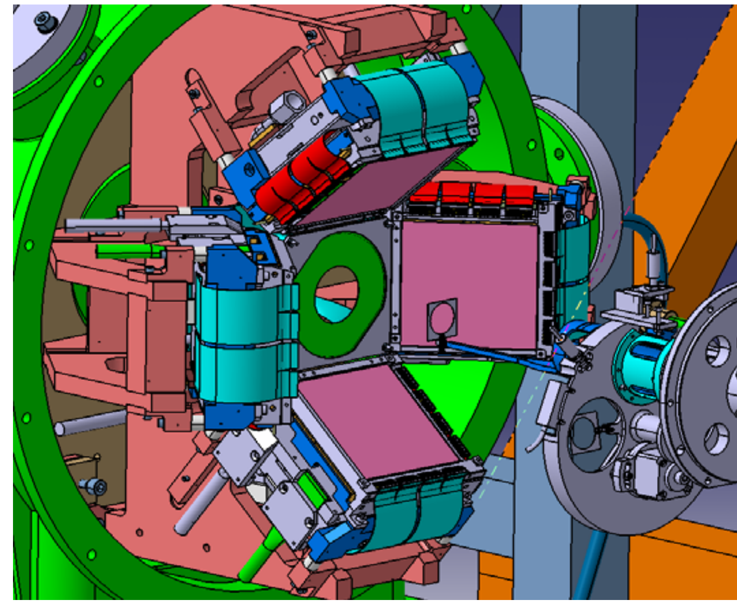
SPIRAL1 beams :
^{20}O (d,p), (d,t); ^{26}Ne (d,p) (d,t)



MUST2 + TIARA + EXOGAM

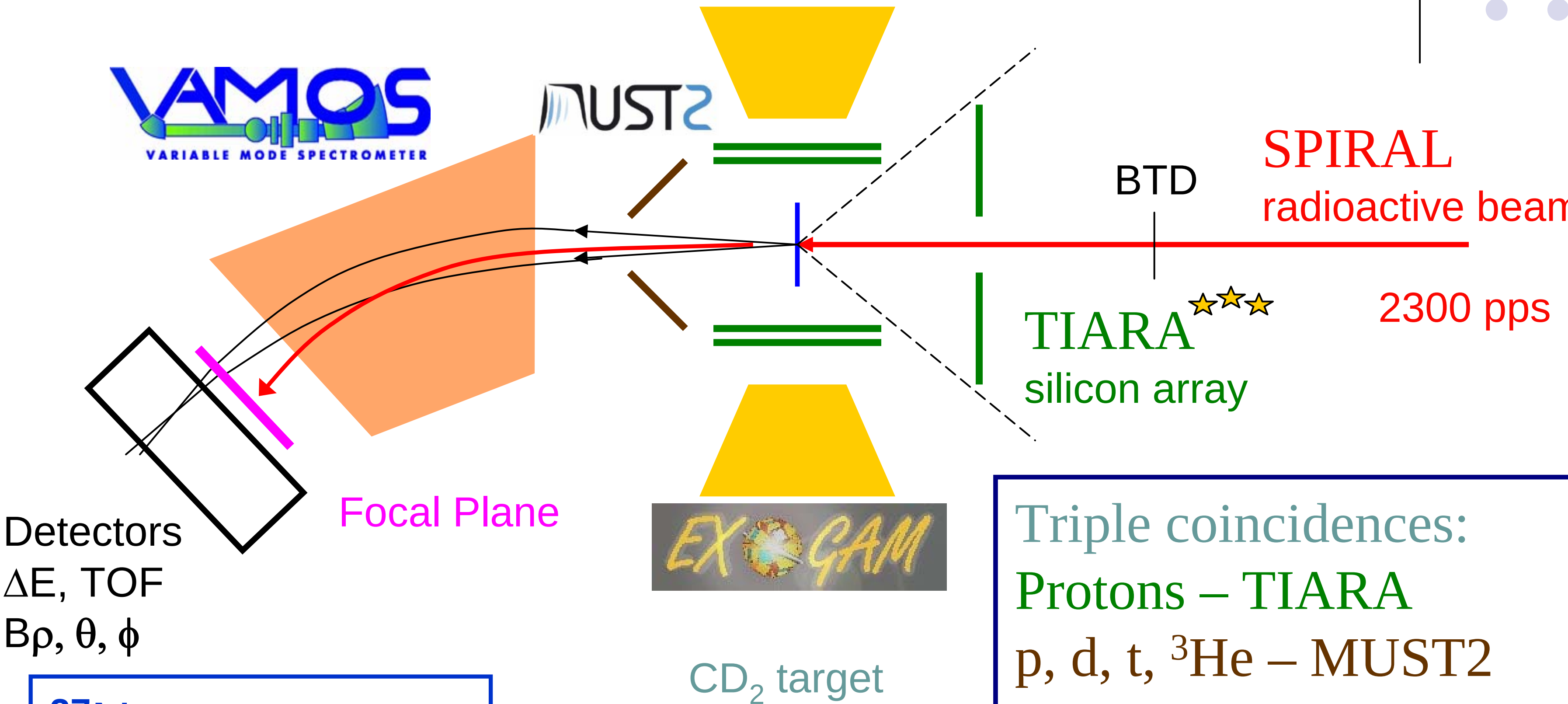


-(d,p) for (n,γ) in ^{60}Fe ;
-size of N=50 gap in ^{68}Ni ;



MUST2 + annular Si + EXOGAM

^{26}Ne (d,p γ) ^{27}Ne at 9.8 MeV/A

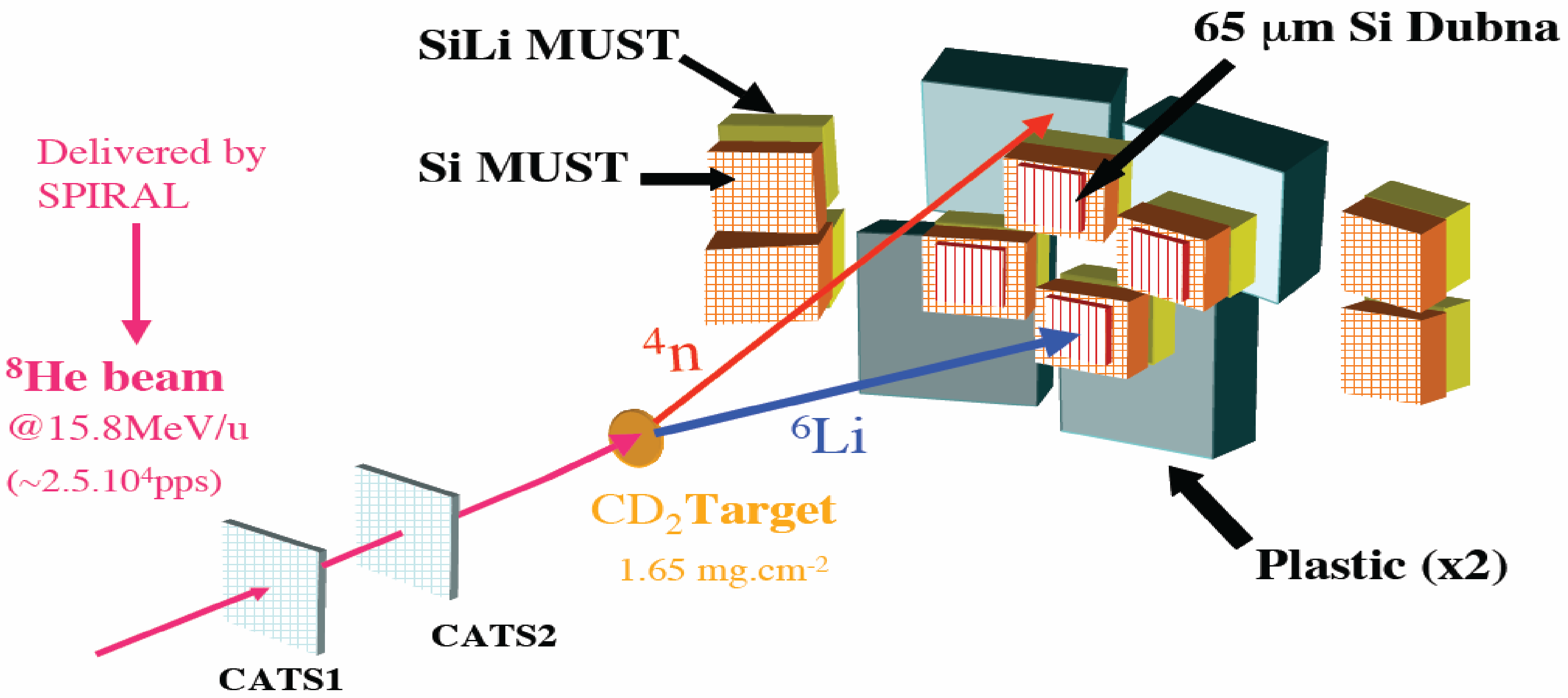


^{27}Ne

$^{27}Ne \rightarrow {}^{26}Ne + n$

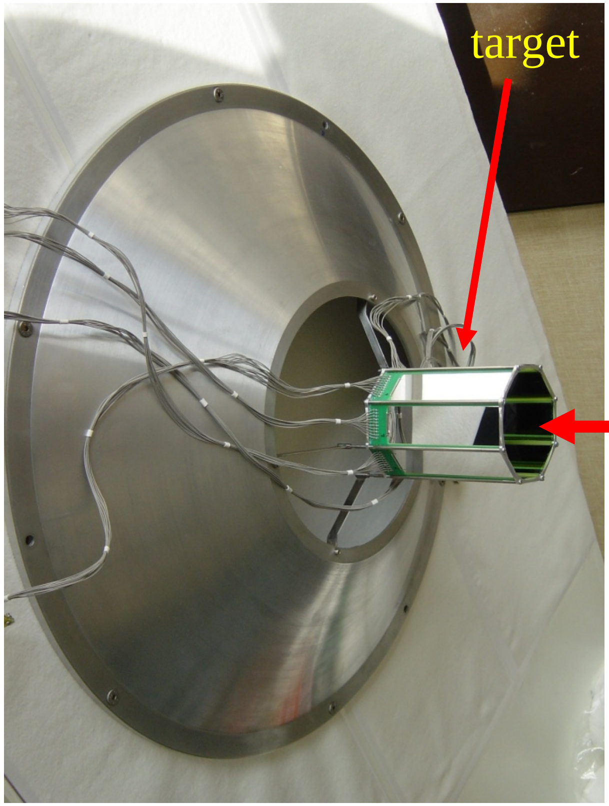
Triple coincidences:
Protons – TIARA
p, d, t, ^{3}He – MUST2
Neons - VAMOS
Gammas - EXOGAM
Trigger: hit in TIARA .OR. MUST2

Setup of E465s at G3-SPEG
d(^{8}He,^{6}Li)

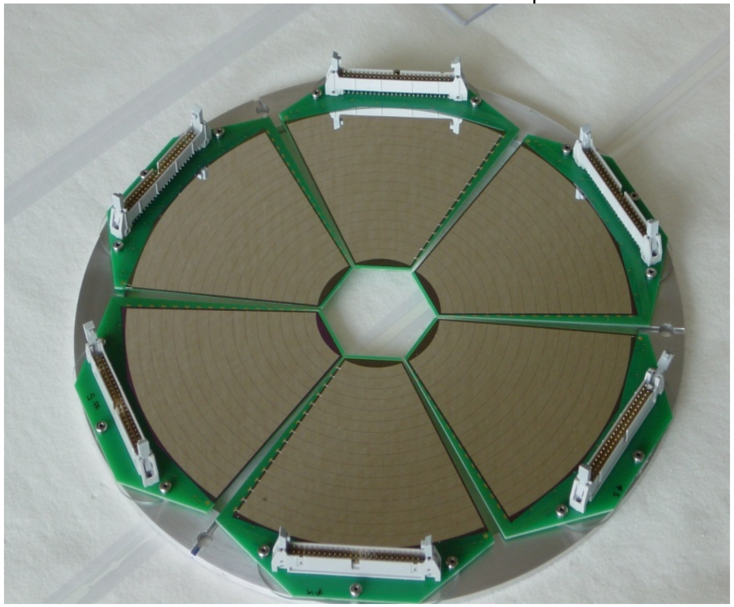


Detection technique

TIARA☆☆☆



annulus angles near 180°

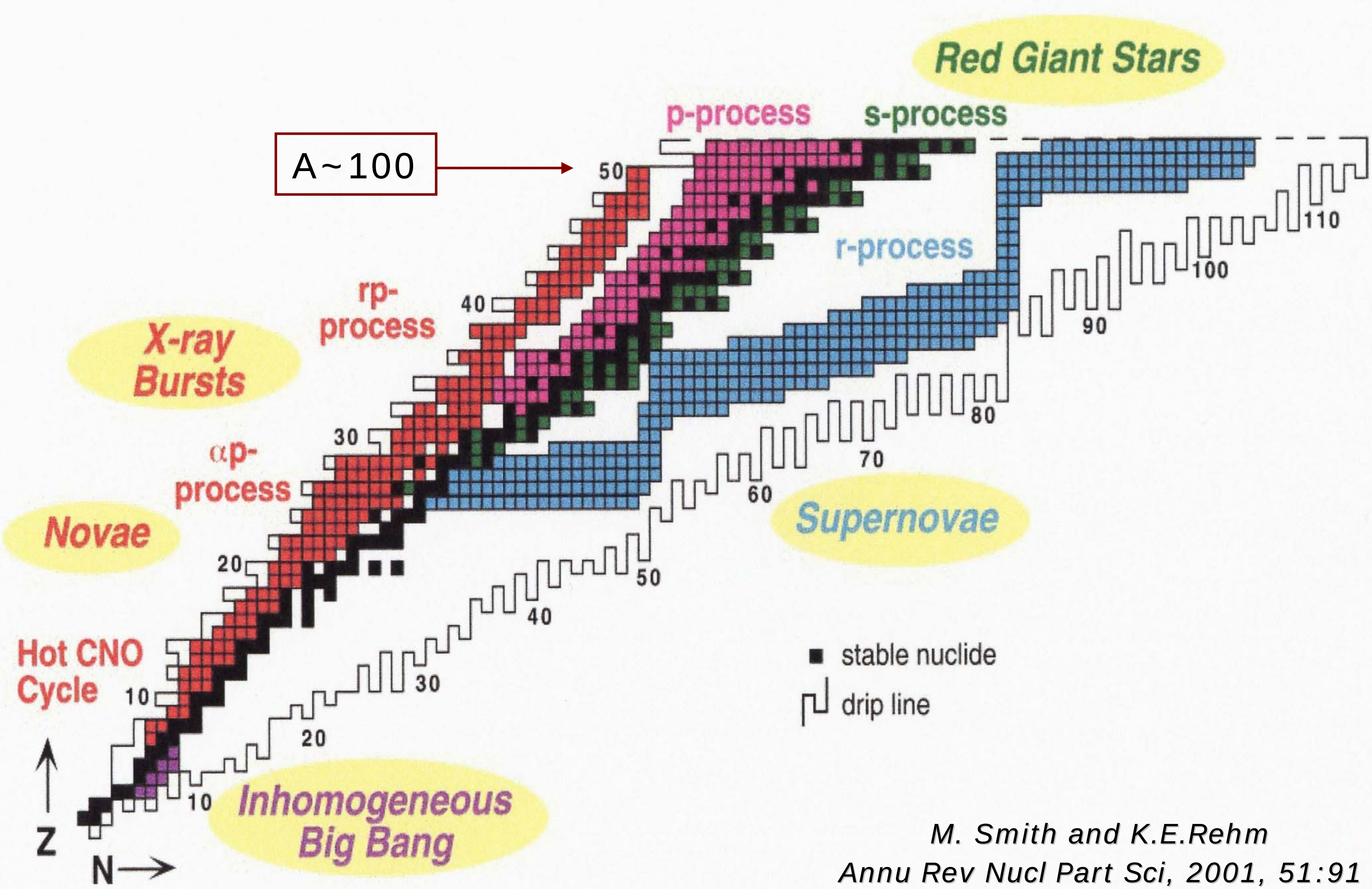


- Overall geometric coverage of TIARA is ~ 80% of 4 π .
- Excellent angular coverage is key in TIARA design philosophy.
- Compact design allows for 4 segmented Ge clover detectors to be positioned close to the target to maximise gamma-ray efficiency.

国际公认的核天体物理关键科学问题

1. 恒星平稳演化阶段最重要的热核反应在天体物理能区的直接测量
2. 高能区带电粒子反应截面向天体物理能区的合理外推
3. 若干关键的平稳核燃烧阶段和爆发性rp及r过程核反应截面的间接测量
4. **rp和r过程涉及核素衰变性质、质量、反应和共振态性质的测量**
5. 核天体物理反应和衰变性质的理论研究、数据库和网络方程的建立
6. 通过关键数据输入网络计算，结合元素丰度的观测

主要的核天体过程及天体环境



M. Smith and K.E.Rehm
Annu Rev Nucl Part Sci, 2001, 51:91