中国原子能科学研究院
中核集团 CHINA INSTITUTE OF ATOMIC ENERGY

丰质子核奇异衰变和近垒奇特核反应

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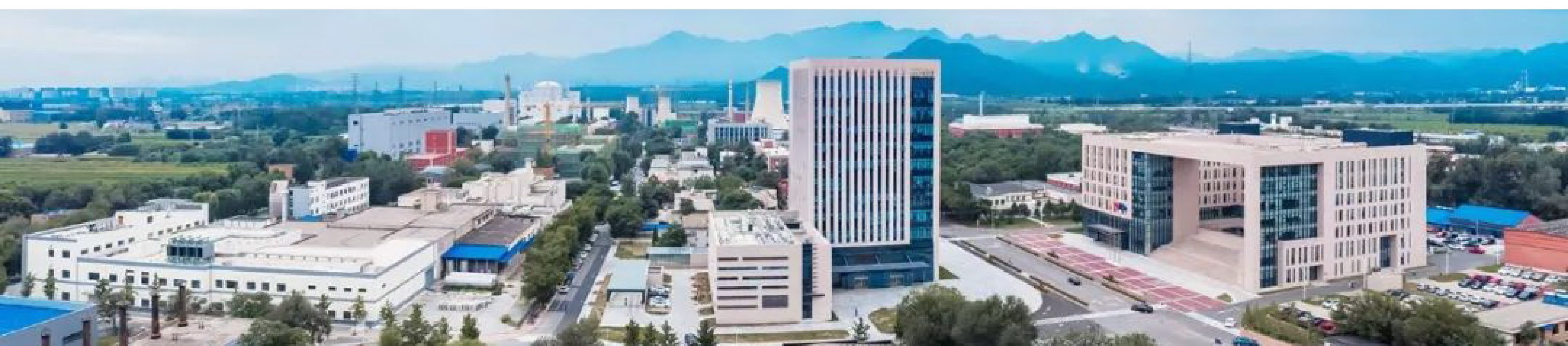


报告内容

一、前言

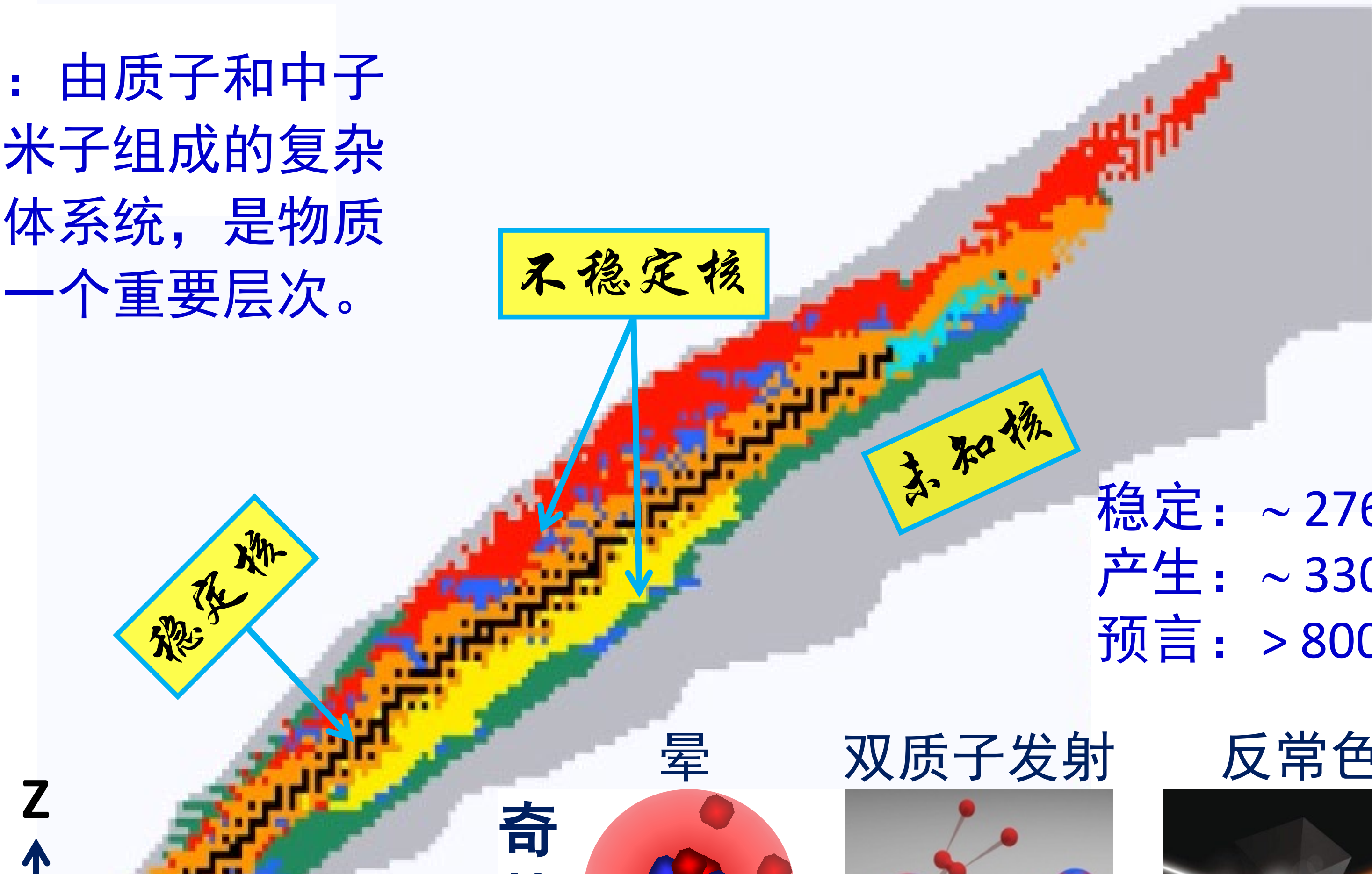
二、极丰质子核的奇异衰变

三、奇特核的近垒反应机制

四、小结

放射性核束(RIB)物理

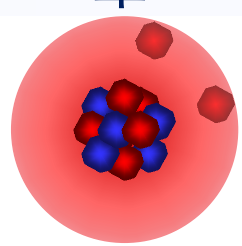
原子核：由质子和中子两种费米子组成的复杂量子多体系统，是物质结构的一个重要层次。



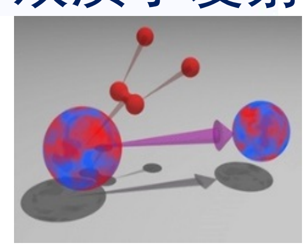
稳定：～276
产生：～3300
预言：＞8000

奇特核

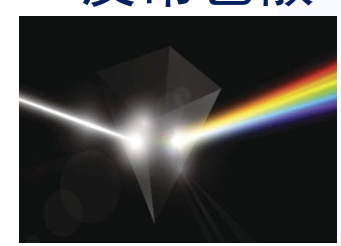
晕



双质子发射



反常色散



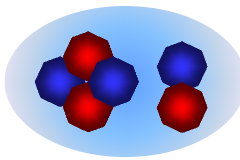
新结构、新衰变、新有效相互作用

奇特核

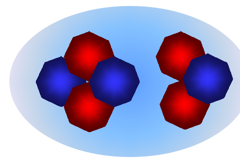
★ **Exotic nuclei:**

weakly-bound & <u>having unusual structure</u> (cluster, halo/skin …) → Beyond the Mean Field

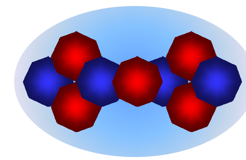
cluster



^{6}Li (α+d)
S_α = 1.47 MeV

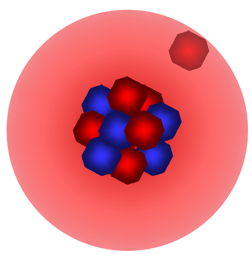


^{7}Li (α+t)
S_α = 2.47 MeV

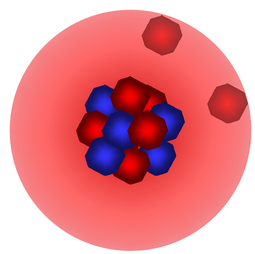


^{9}Be (α+n+α)
S_n = 1.66 MeV

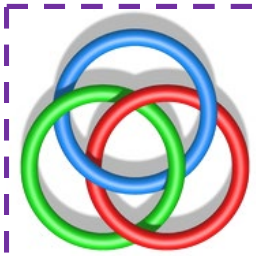
halo



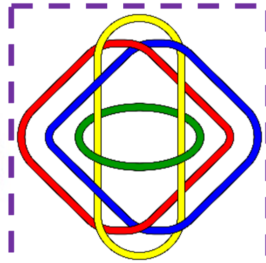
^{11}Be (^{10}Be+n)
S_n = 0.50 MeV



^{6}He (α+2n)
S_{2n} = 0.98 MeV



Borromean



4b-Brunnian

…

^{10}C (α+α+p+p)

奇特核产生是一种近阈(接近分离阈)行为，弱束缚是产生奇特结构的首要条件。

我国核物理实验基地

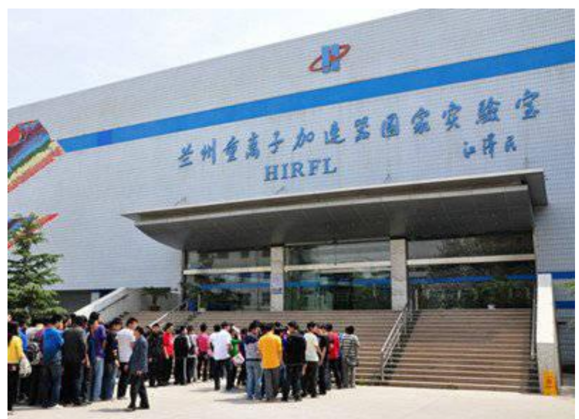
低能

HI-13串列加速器 (87)
(1+*q*)×13 MeV, H-U

北京串列加速器
国家实验室(BTANL)

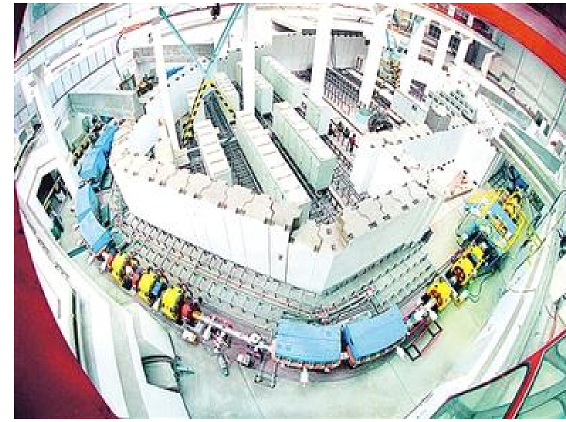
中能

SSC回旋加速器 (88)
100 MeV/u, C-U



兰州重离子加速器
国家实验室(HIRFL)

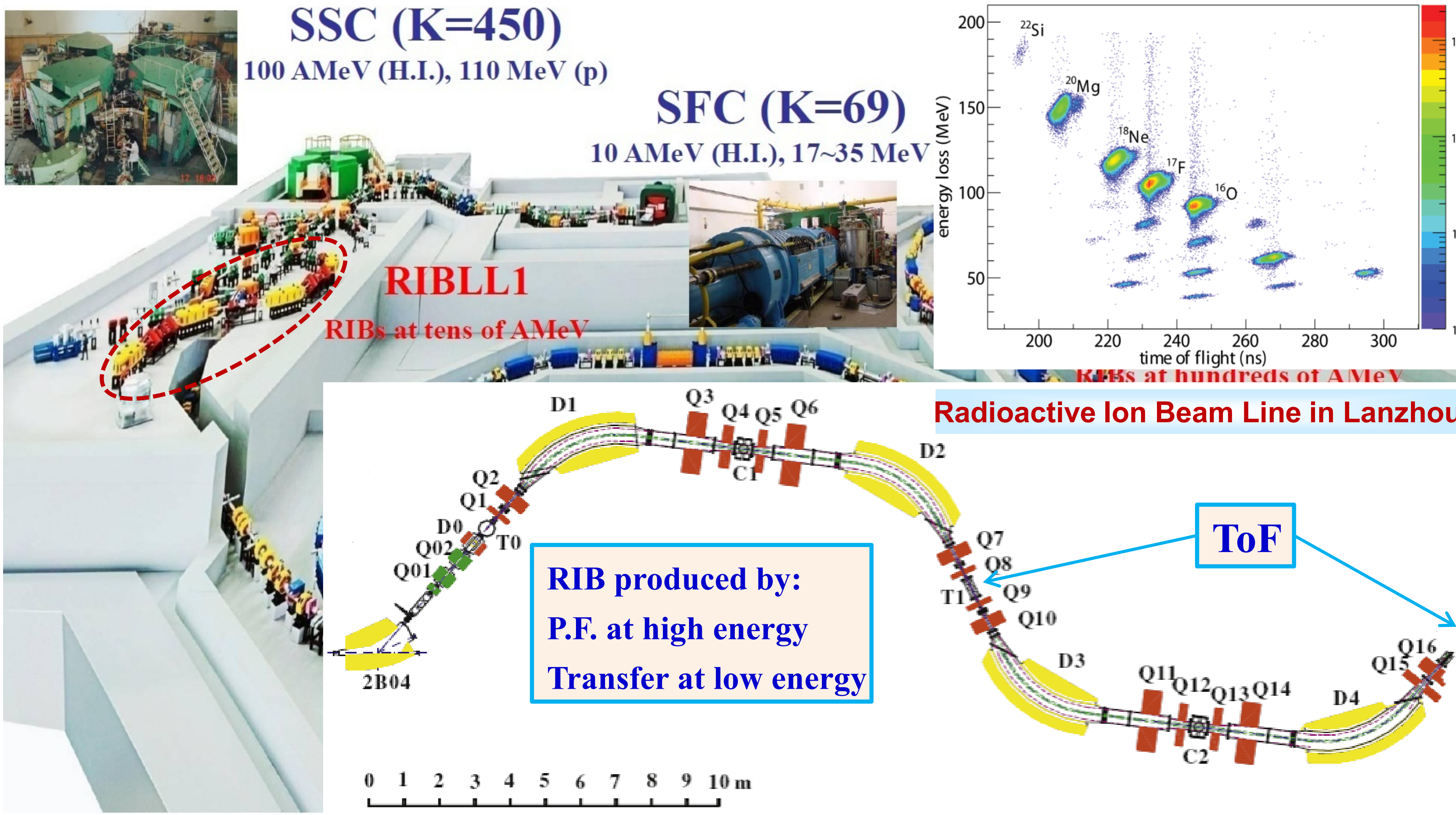
高能



正负电子对撞机 (88)
5 GeV, e^+e^-

北京正负电子对撞机
国家实验室(BEPC)

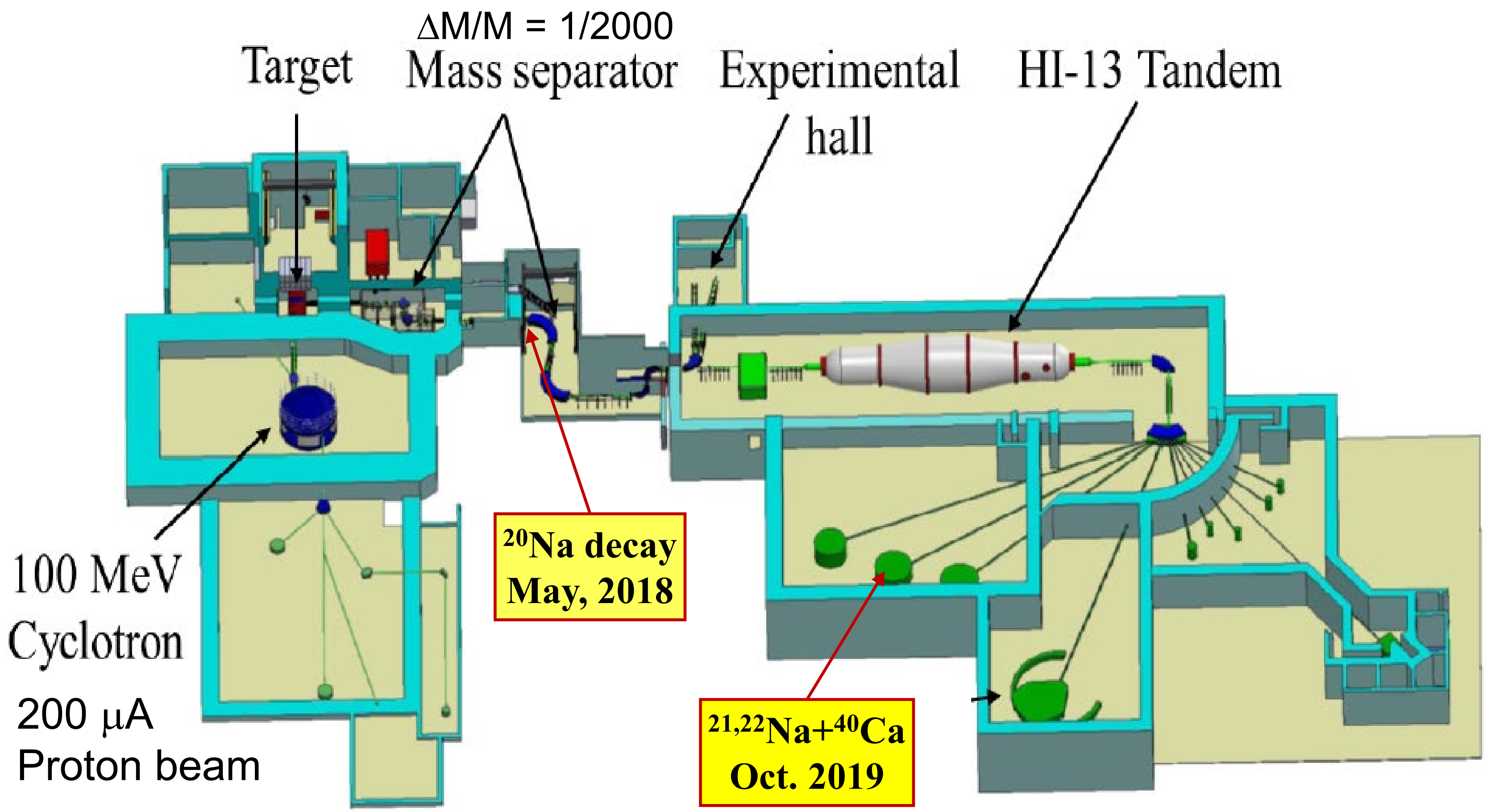
放射性核束的产生：PF法



Heavy Ion Research Facility in Lanzhou (HIRFL)

放射性核束的产生：ISOL法

Beijing Radioactive Ion-beam Facility (BRIF)



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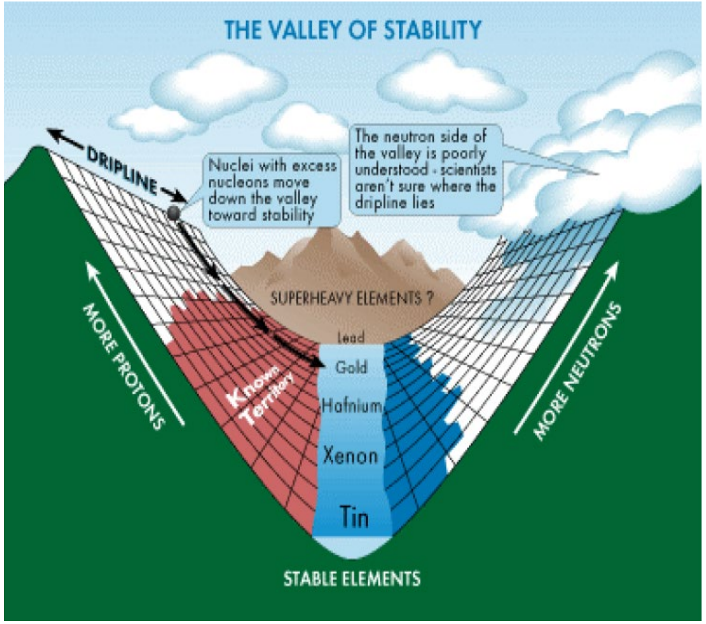
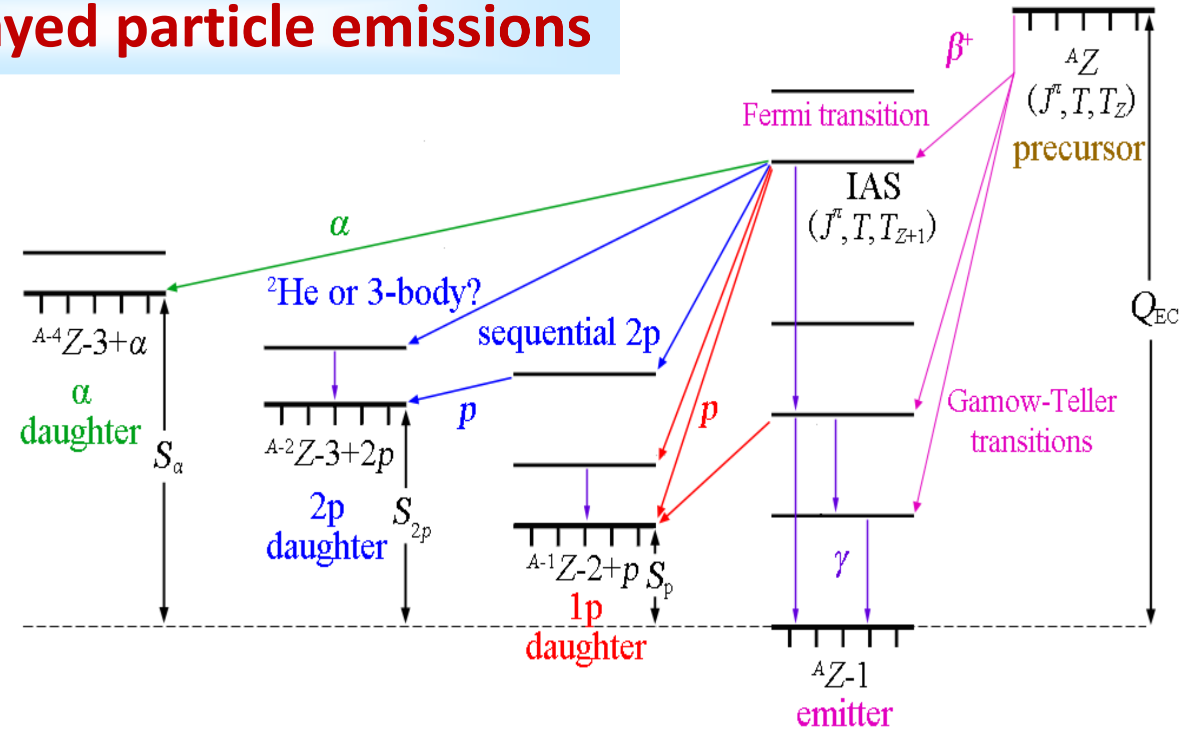
极丰质子核的奇异衰变

Beta-delayed particle emissions





βp，$\beta 2p$，$\beta 3p$，$\beta p\gamma$，$\beta\gamma p$，$\beta\alpha$，$\beta 2\alpha$，$\beta\alpha p$，$\beta p\alpha$，$\beta p2\alpha$，βn，$\beta 2n$，$\beta 3n$，βd，βt，βF…

- **Structures of *p*-rich nuclei close to/beyond the drip-line**
- **Effective interaction – pairing, isospin non-conserving (INC), three-body force**
- **Initial state interaction (ISI), final state interaction (FSI), quantum entanglement**
- **Nuclear astrophysics – (*p*,*γ*), (2*p*,*γ*), (*α*,*γ*) … processes**

sd壳层丰质子核的衰变

β-decay spectroscopy of nuclei close to the proton drip line

^{36,37}Ca: CPL **32**, 012301 (2015);

^{28}S: NPR **38**, 117 (2021);

^{27}S: PRC **99**, 064312 (2019);
PLB **802**, 135213 (2020);
PRC **103**, L061301 (2021);

^{26}P: PRC **101**, 024305 (2020);
Sym. **13**, 2278 (2021);

^{23}Al, ^{24}Si: NIMA **804**, 1 (2015);

^{22}Si : PLB **766**, 321 (2017);
PRL **125**, 192503 (2020);

^{20}Mg: PRC **95**, 014314 (2017);

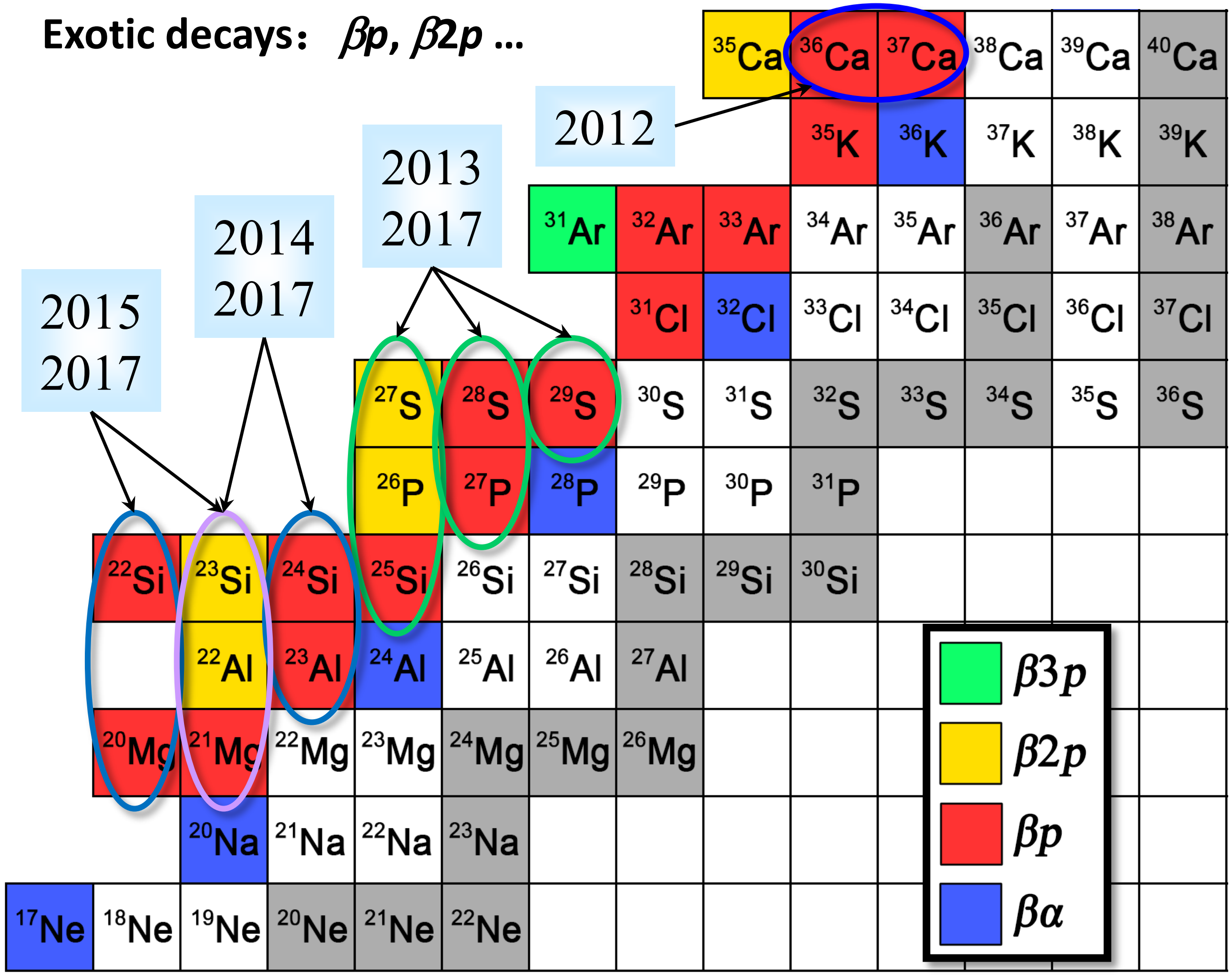
^{23}Si: IJMPE **27**, 1850014 (2018);

^{22}Al : NST **29**, 98 (2018);
PLB **784**, 12 (2018);
PRC **104**, 044311 (2021);

^{21}Mg: EPJA **54**, 107 (2018);

…

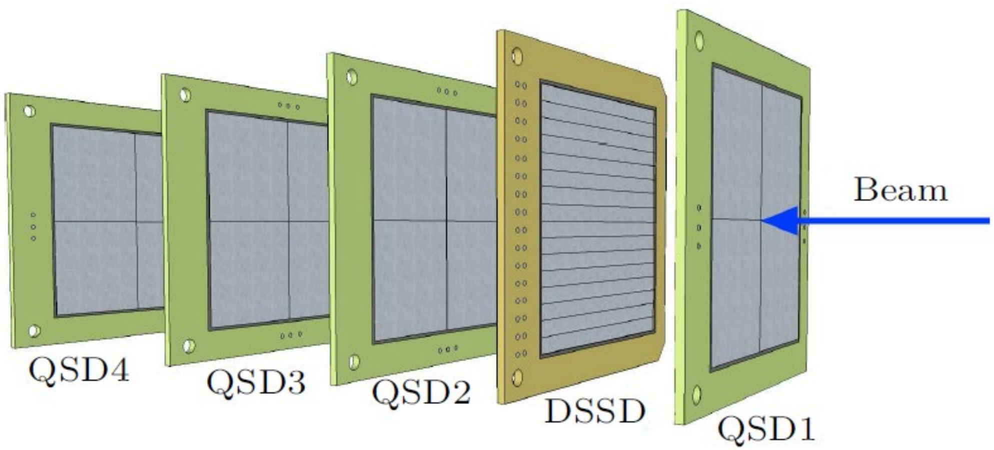
Exotic decays: *βp*, *β2p* …



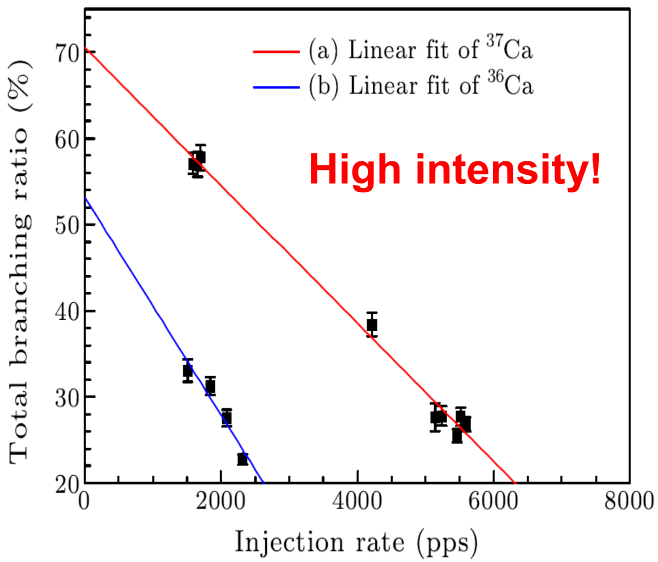
Detection Method

Test of the continuous-beam mode

- Beam on/off: implant (0.1 ms) - decay measure (> 1000 ms)
  low efficiency ☹, low background ☺;
- Continuous beam: implant & decay, time & position correlated measure
  high efficiency ☺, high background ☹ → coincident measurement ☺



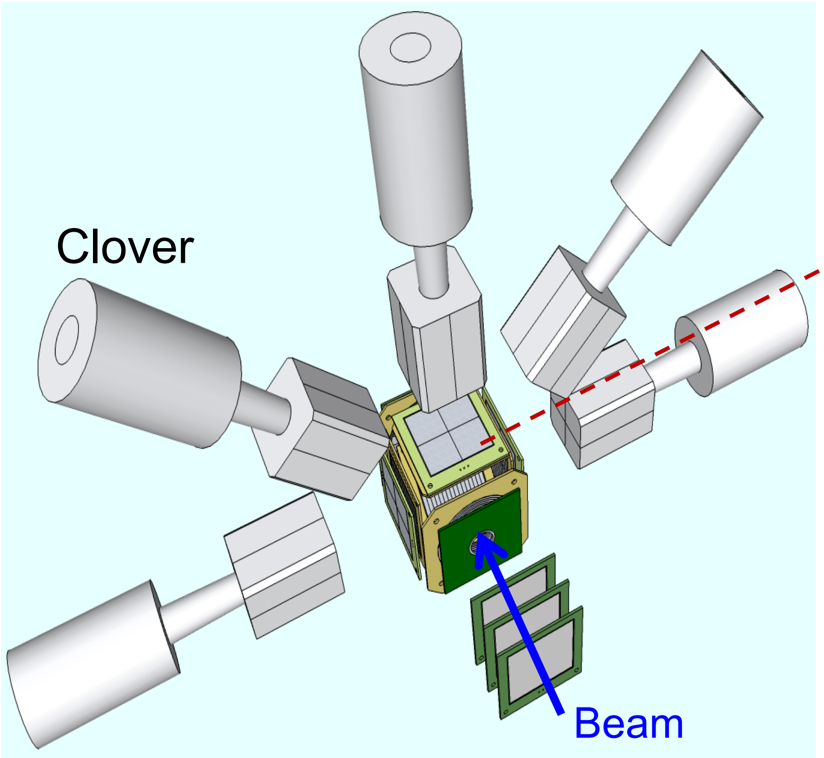
Layout of the detection setup

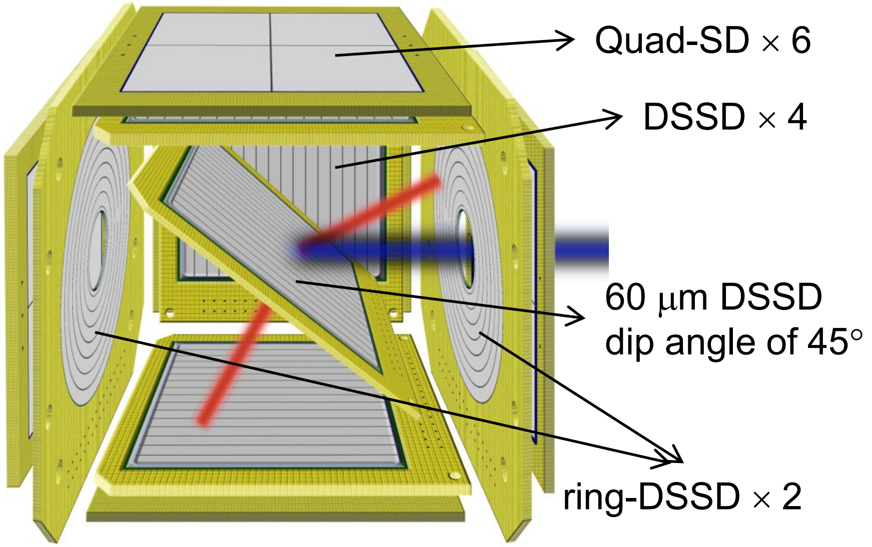


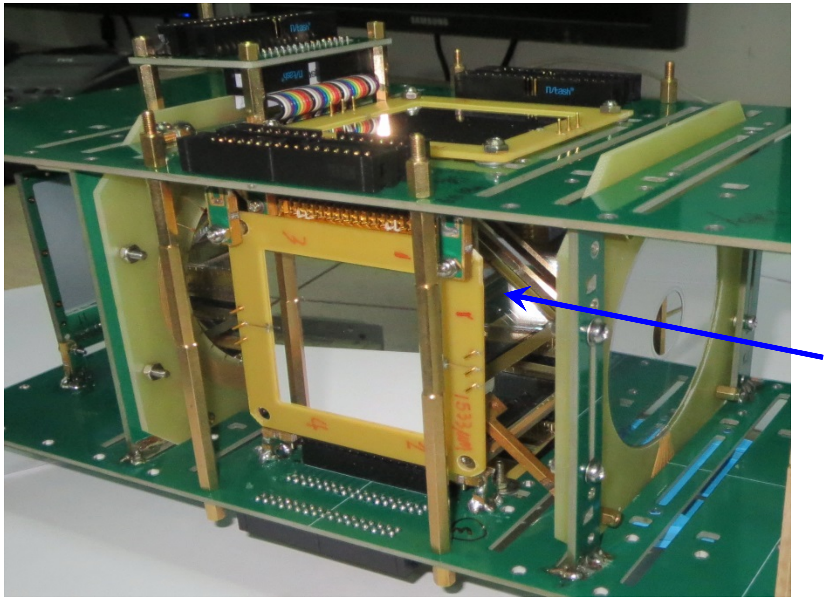
^{36,37}Ca βp decay energies, half-lives and branching-ratios have been confirmed.

Sun Li-Jie, LIN Cheng-Jian*, Xu Xin-Xing *et al*., Chin. Phys. Lett. **32**, 012301 (2015).

Detector Array – G1





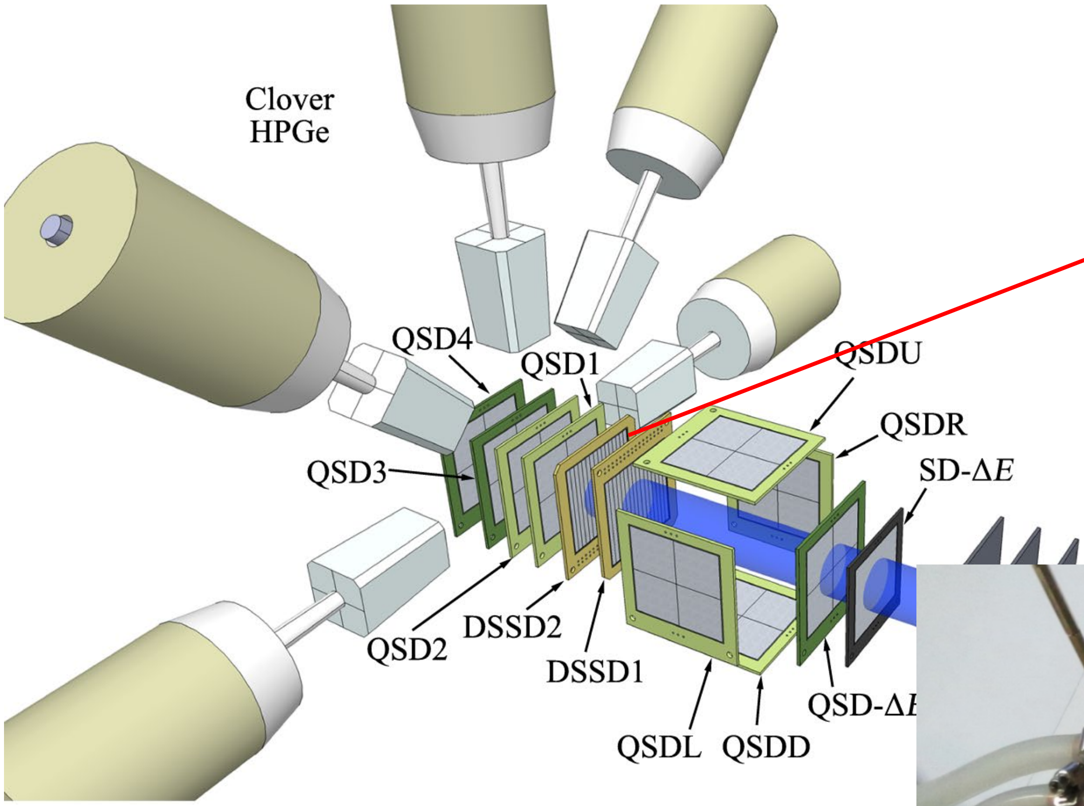


A detector array for 2*p*-decay study by **implantation** method

for lifetime > 10 μs

1p efficiency: ~65%; 2p efficiency: ~20%

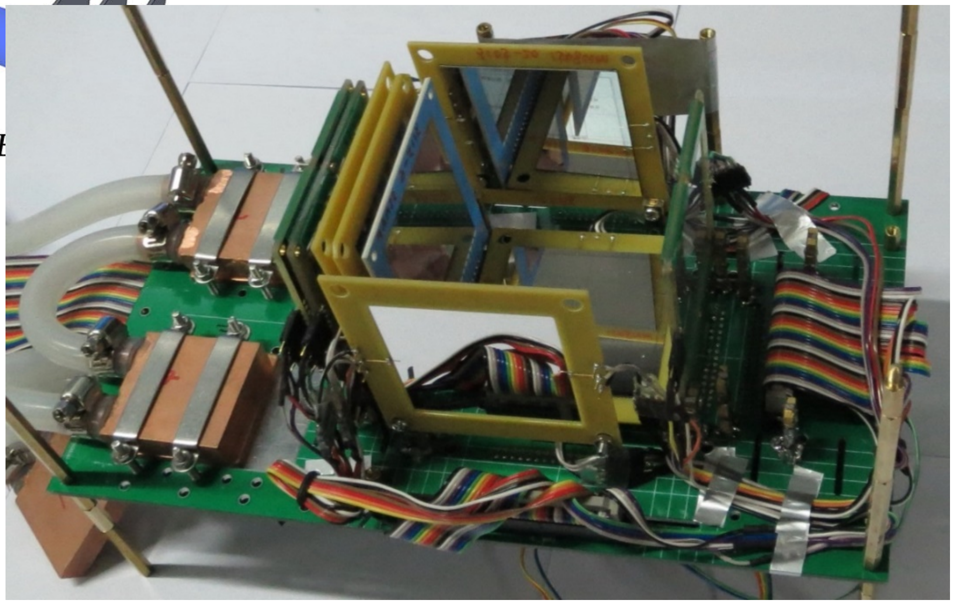
Detector Array – G2



- 150 um + 60 um DSSDs for ion implantations and *p*/2*p*-decay measurements.
- Others for β-decay measu. and background rejection.

L.J. Sun *et al.*, NIMA **804**, 1 (2015).

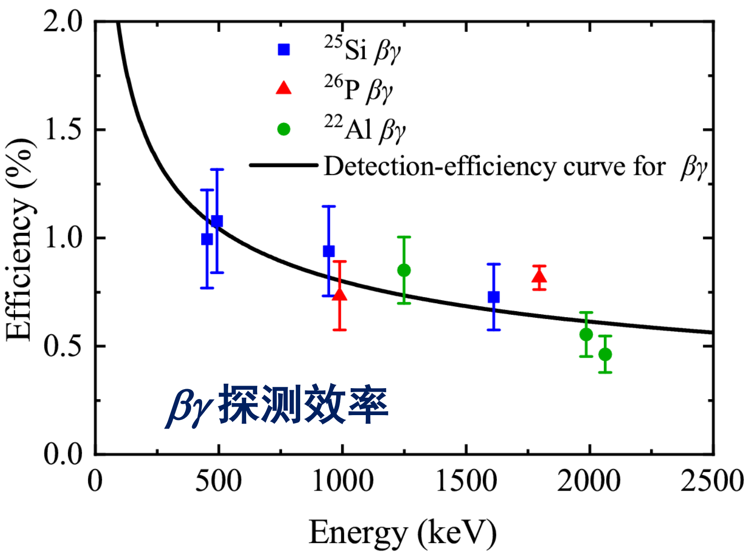
- ♣ Implanted close to the back edge of the 150 um DSSD.
- ♣ 1*p* efficiency: ~70%;
  2p efficiency: ~20%

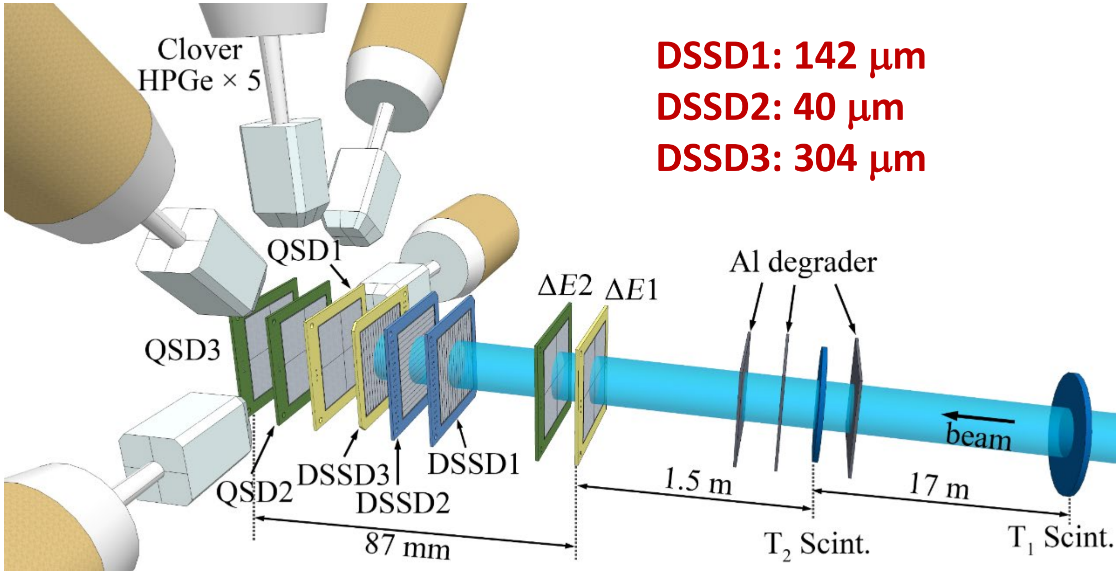


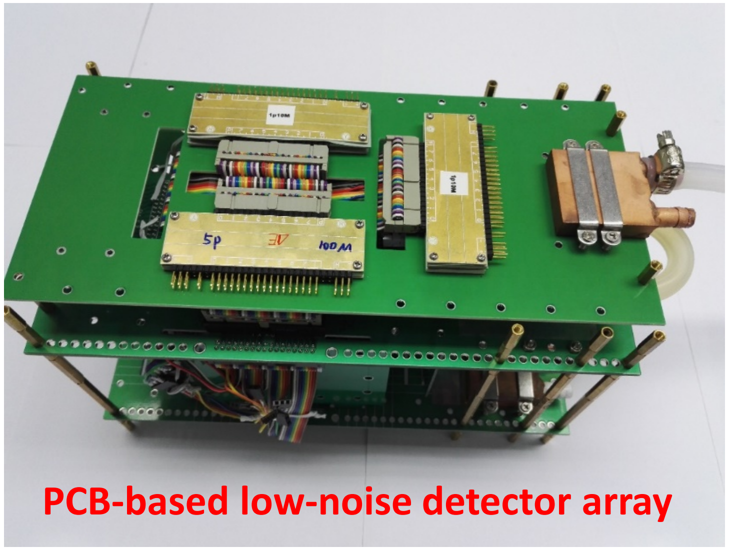
Detector Array – G3

阻停-衰变探测器阵列：

- **连续束注入-衰变探测**方法，**高精度β延迟**质子/双质子衰变谱学与衰变机制研究。
- 厚薄DSSD组合，兼顾能量分辨和探测效率。
- 高探测效率：～50% (1p)；～15% (2p)
  低探测阈值：～200 keV；～100 keV (数字化)
  高能量分辨：< 35 keV；～20 keV (数字化)

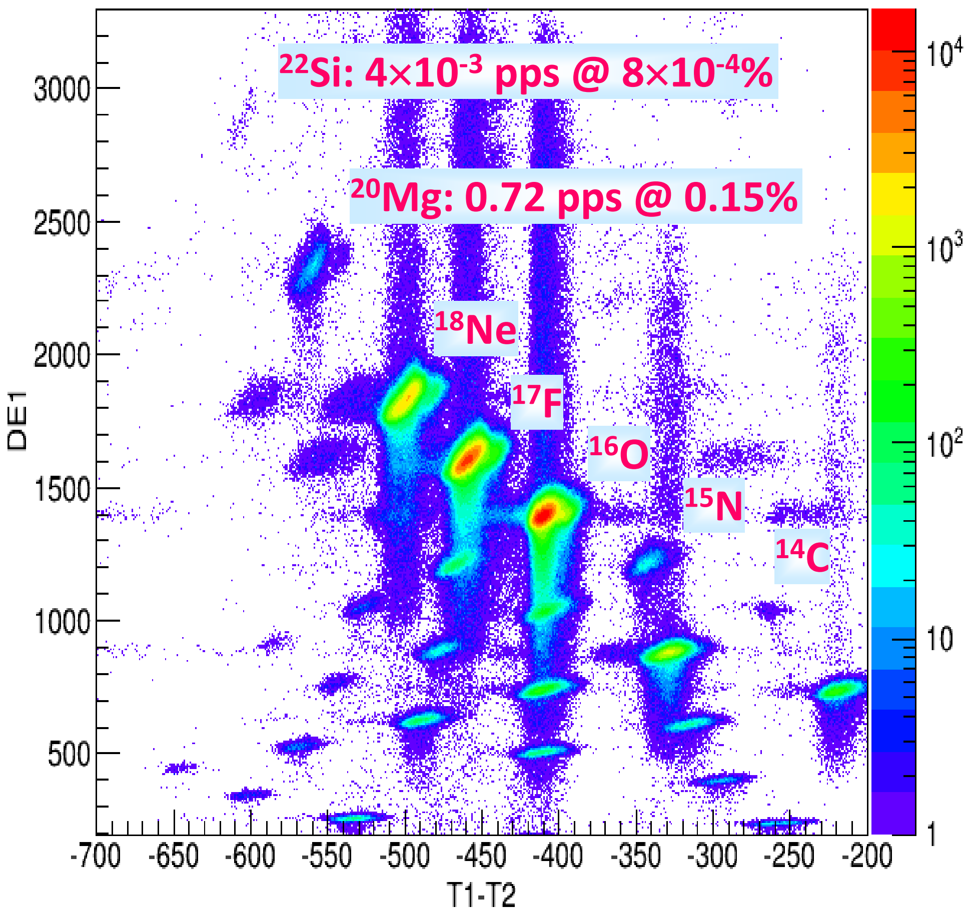




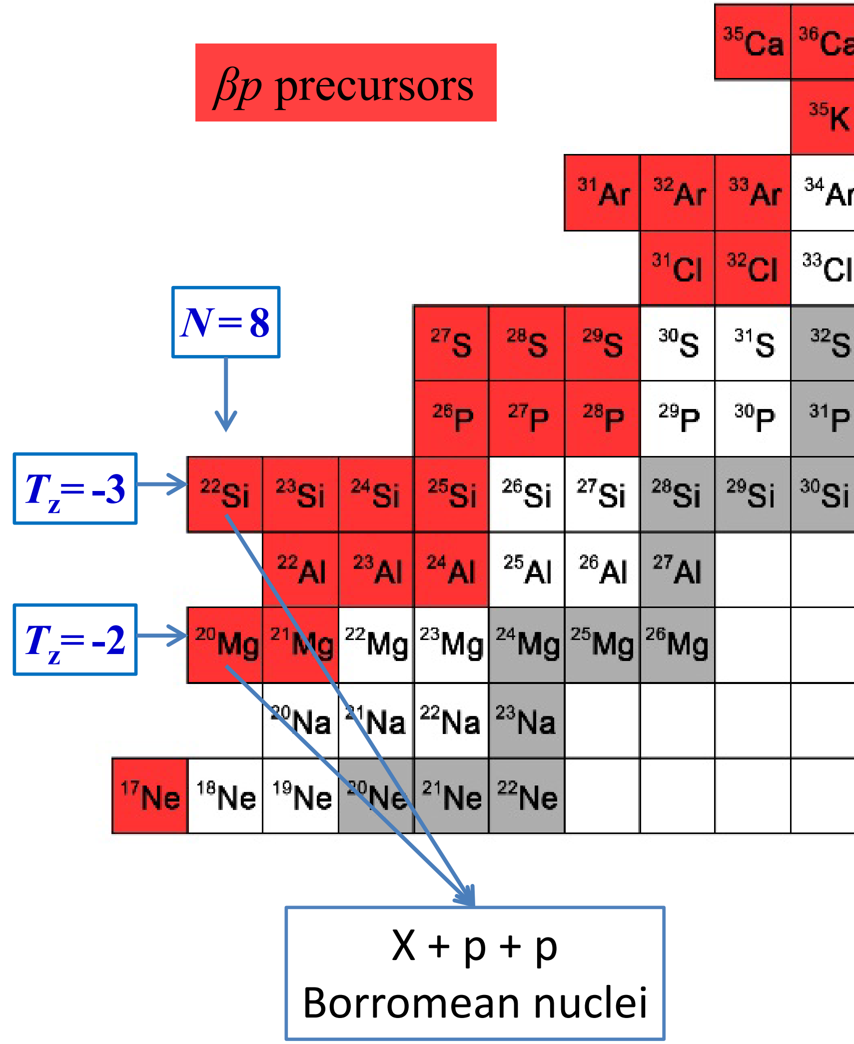


Results1: ^{22}Si/^{20}Mg Cases

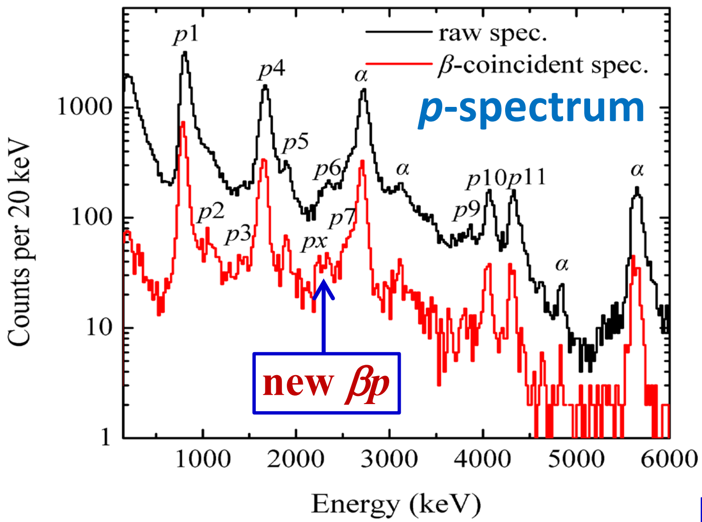
Primary beam: ^{28}Si, 75.3 MeV/u @ 40 enA.

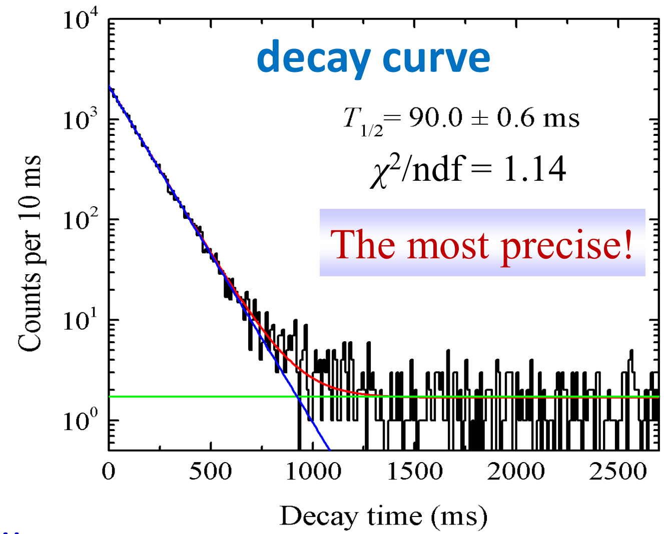


PID of the secondary beam

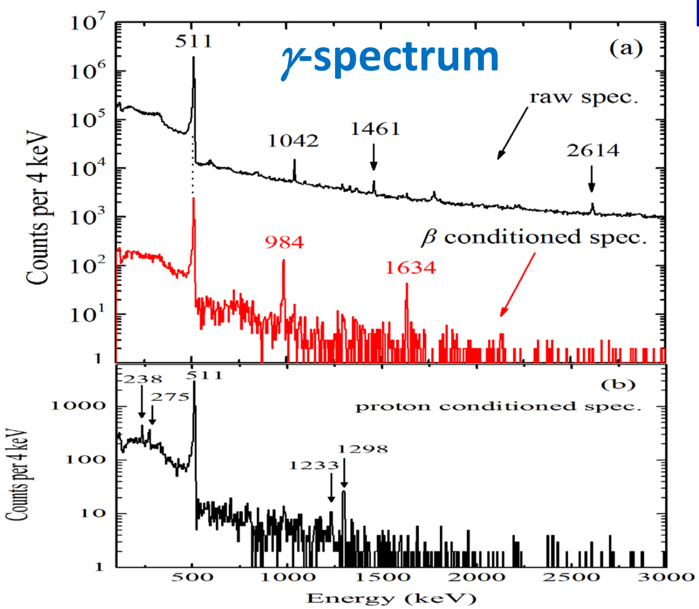


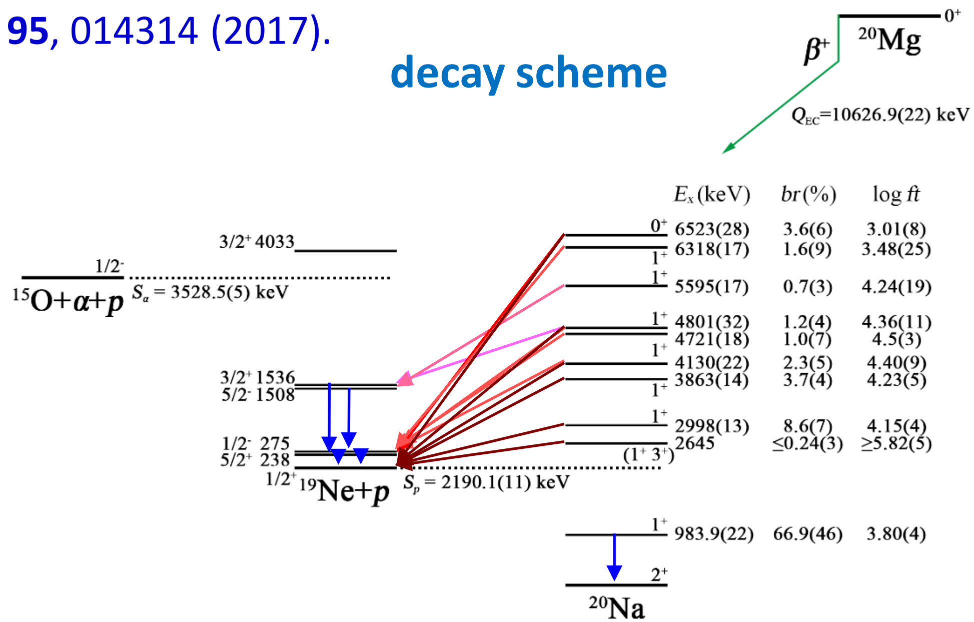
^{20}Mg Decays



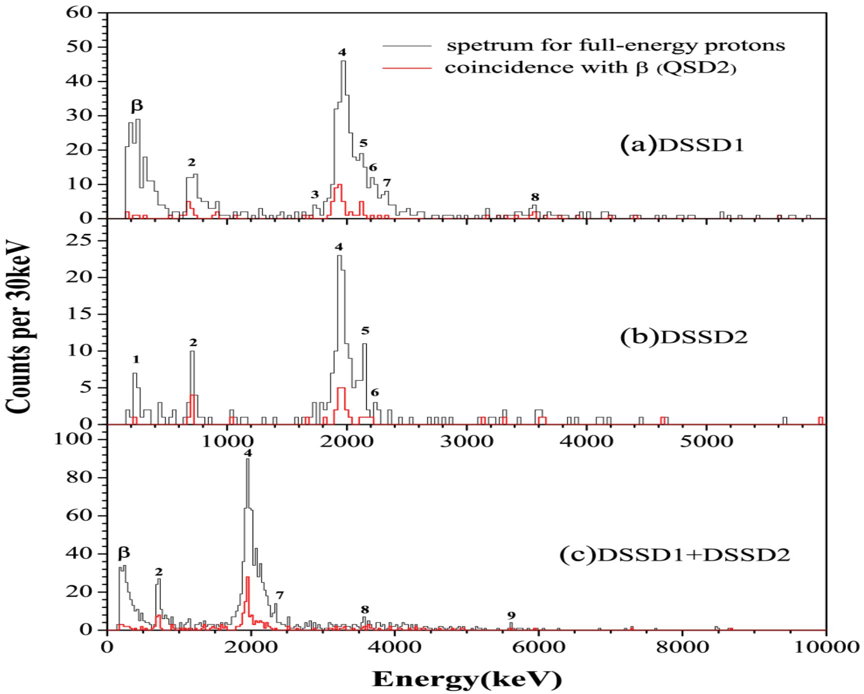


L. J. Sun et al.,
PRC **95**, 014314 (2017).

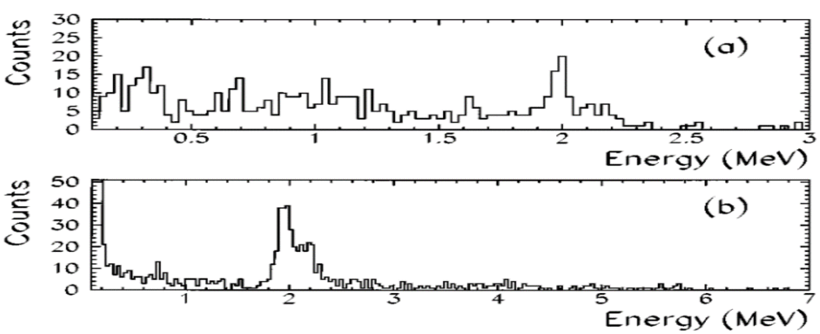




^{22}Si Decays



CIAE - Phys. Lett. B **766**, 312 (2017).



GANIL - Phys. Rev. Lett. 59, 33 (1987).
Phys. Rev. C 54, 572 (1996).

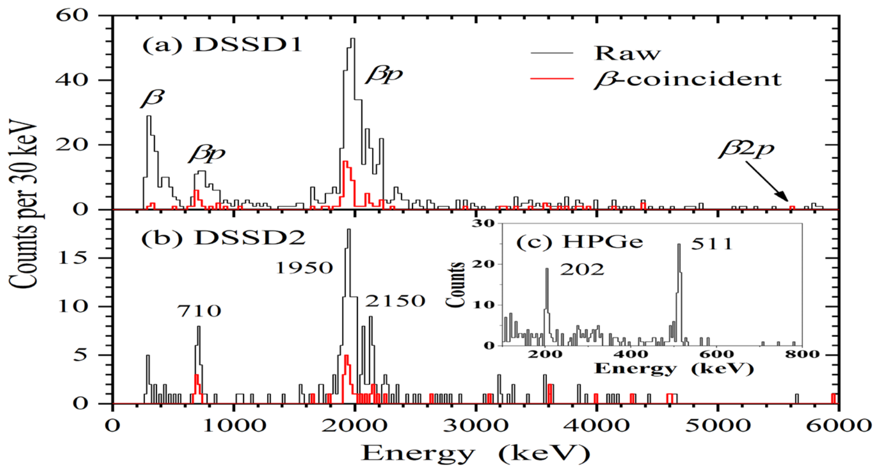
Peak	Energy (keV)	BR (%)	Decay Mode
1	**230(50)**	**2.9(10)**	***2p* ?**
2	680(50)	6.8(14)	*βp*
3	1710(50)	1.9(7)	*βp*
4	1950(50)	52.0(74)	*βp*
5	2110(50)	10.9(21)	*βp*
6	2180(50)	6.5(15)	*βp*
7	2330(50)	5.1(13)	*βp*
8	3550(50)	2.5(9)	*βp*
9	**5600(70)**	**0.7(3)**	***β2p***

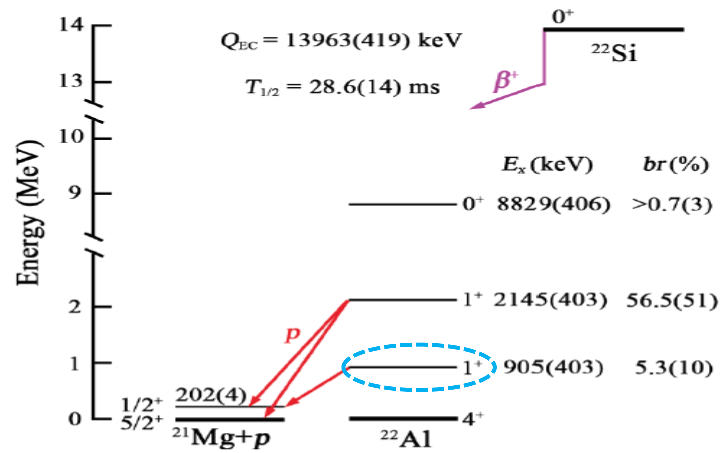
★ **^{22}Si is a precursor of *β2p* decay.**

★ **Mass of ^{22}Si**

- $\Delta(^{22}\mathrm{Si}) = \Delta(^{22}\mathrm{Al\ IAS}) + \Delta E_C - \Delta_{nH}$
  → **S_{2p} = -108 ± 125 keV;**
- $\Delta(^{22}\mathrm{Si}) = \Delta(^{22}\mathrm{O}) - 2b(A,T)T_Z$
  → **S_{2p} = -15 keV**

Exotic Decays of ^{22}Si





★ 首次发现^{22}Si存在$\beta 2p$衰变模式，由此给出其实验质量，表明它是一个非常边缘的核，三体力扮演了重要作用。

X.X. Xu *et al*., PLB **766**, 312 (2017).

表：^{22}Si/^{22}O衰变的比较

	^{22}Si → ^{22}Al Q_{EC} = 13963 keV					^{22}O → ^{22}F Q_{β^-} = 6490 keV					$\delta = \frac{ft^+}{ft^-} - 1$ δ (%)	
	Experiment			Calculations		Experiment			Calculations			
I_i^π	E_x (MeV)	br%	log(ft^+)	E_x (MeV)	log(ft^+)	E_x (MeV)	br%	log(ft^-)	E_x (MeV)	log(ft^-)	Experiment	Calculations
1_1^+	0.905	5.3 (10)	5.09 (9)	1.12 [1.69]	4.81 [4.52]	1.625	29 (4)	4.6 (1)	1.98 [1.56]	4.32 [4.56]	209 (96)	212 [−7]
1_2^+	2.145	56.5 (51)	3.83 (5)	2.43 [2.55]	3.71 [3.72]	2.572	68 (6)	3.8 (1)	2.58 [2.51]	3.72 [3.68]	7 (28)	−3.4 [10]

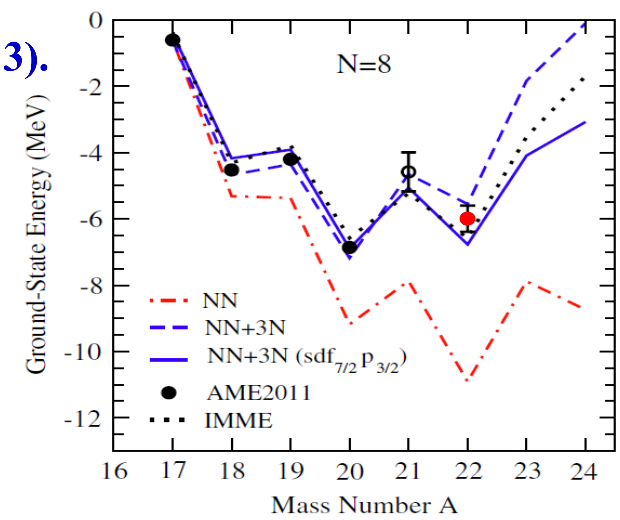
★ 在镜像核^{22}Si/^{22}O衰变中发现一个极大的同位旋不对称性(δ~209%)，包含同位旋不守恒力的壳模型计算重现了实验结果，指出这个大的不对称性来源于^{22}Al $s_{1/2}$轨道的晕结构。

J. Lee *et al*., PRL **125**, 192503 (2020).

Discussions on ^{22}Si/^{20}Mg

☞ **Mass → Three-Body Force** **PRL110,022502(2013).**

Nucleus $N=8$	S_p Expt. [IMME]	S_p $NN+3N$ sd	S_p $NN+3N$ $sdf_{7/2}p_{3/2}$	S_{2p} Expt. [IMME]	S_{2p} $NN+3N$ sd	S_{2p} $NN+3N$ $sdf_{7/2}p_{3/2}$
^{18}Ne	3.92	4.05	3.76	4.52	4.67	4.17
^{19}Na	−0.32	−0.32	−0.26	3.60	3.73	3.50
^{20}Mg	2.66	2.83	2.98	2.34	2.51	2.72
^{21}Al	[−1.34]	−2.52	−1.83	[1.45]	0.30	1.15
^{22}Si	[1.35]	0.90	1.71	[0.01]	−1.63	−0.12



(Isospin Non-Conservation)

☞ **Mirror asymmetry → INC interaction** asymmetry parameter: $\delta = \frac{ft^+}{ft^-} - 1$

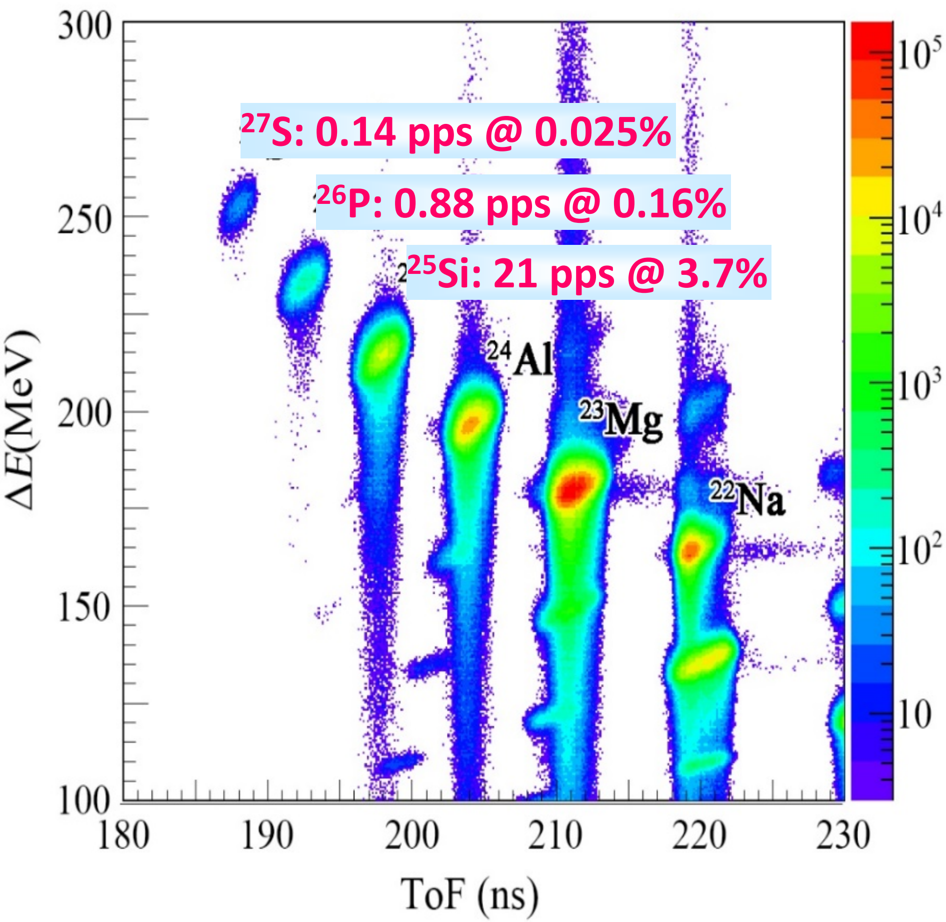
^{20}Mg→^{20}Na				^{20}O→^{20}F			
^{20}Na E^* (keV)	br (%)	log ft	J^π	^{20}F E^* (keV)	br (%)	log ft	δ
983.9(22)	66.9(46)	3.80(4)	1^+	1056.848(4)	99.973(3)	3.740(6)	**0.148(107)**
2998(13)	8.6(7)	4.15(4)	1^+	3488.54(10)	0.027(3)	3.65(6)	**2.16(53)**
^{22}Si→^{22}Al				**^{22}O→^{22}F**			
^{22}Al E^* (keV)	br (%)	log ft	J^π	^{22}F E^* (keV)	br (%)	log ft	δ
1170(50)	5.1(3)	5.10(5)	1^+	1625	29(4)	4.6(1)	**2.16(82)**
2400(50)	60.6(65)	3.79(7)	1^+	2572	68(6)	3.8(1)	**-0.02(28)**

PRC **95**, 014314 (2017).

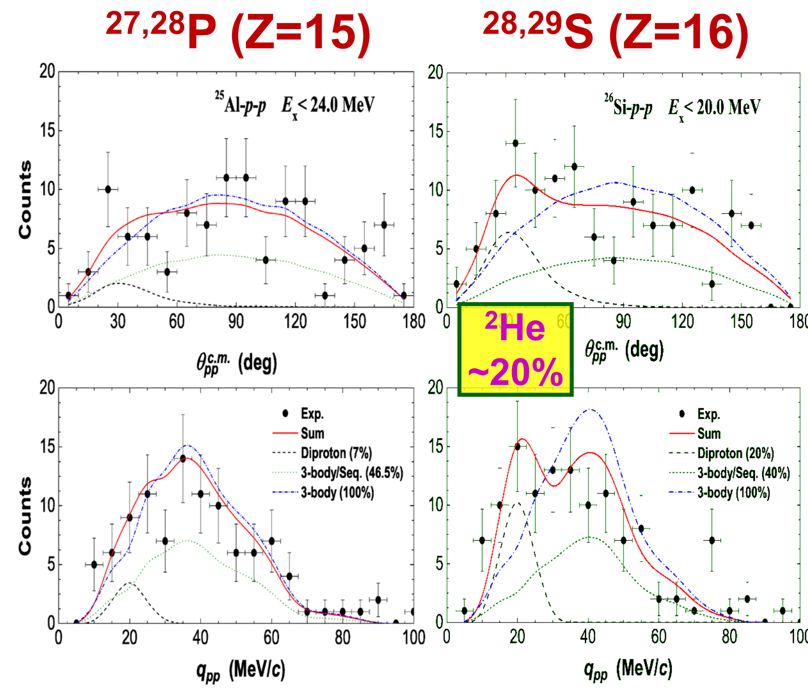
PRL **125**, 192503 (2020).

Results2: $^{27}S/^{26}P$ Cases

Primary beam: ^{32}S, 80.6 MeV/u @ 90 enA.



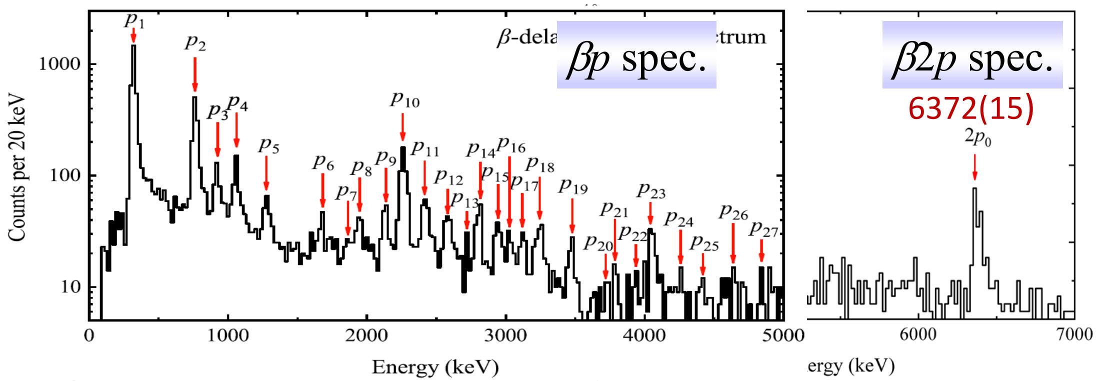
PID of the secondary beam



★ Diproton emissions from the excited states of $^{28,29}S$, but none for $^{27,28}P$.

$^{28}S/^{27}P$: Phys. Lett. B **727**, 126 (2013).
^{29}S: Phys. Rev. C **80**, 014310 (2009);
^{28}P: PRC **81**, 054317 (2010).

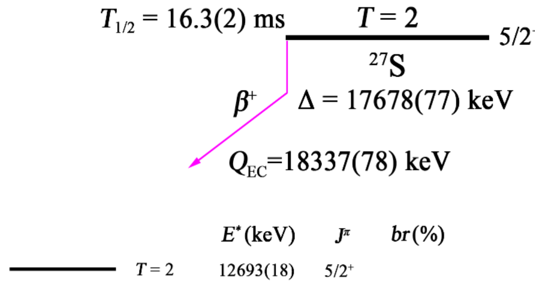
^{27}S Decays



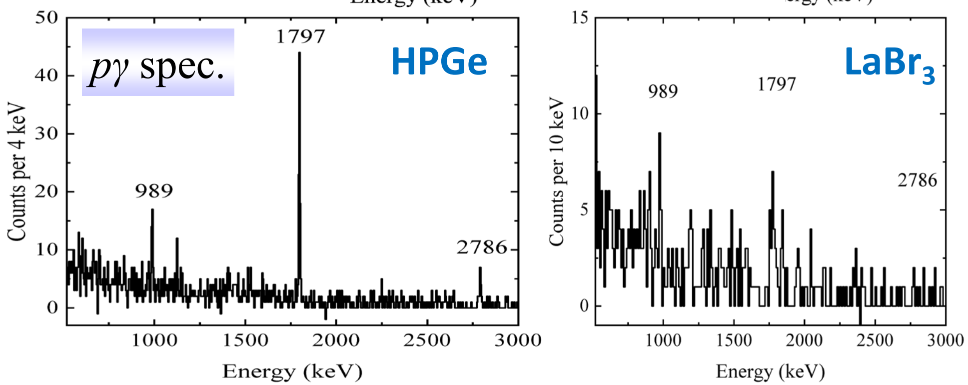
27 βp & 1 $\beta 2p$ decays

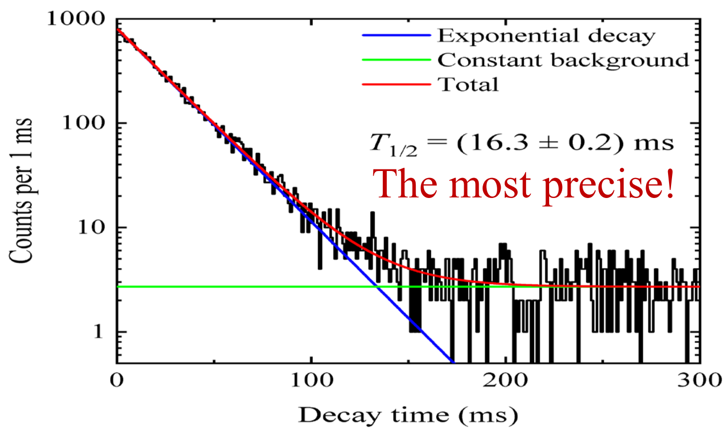
Old: p_1, p_2, p_{10} (BR>5.7%)

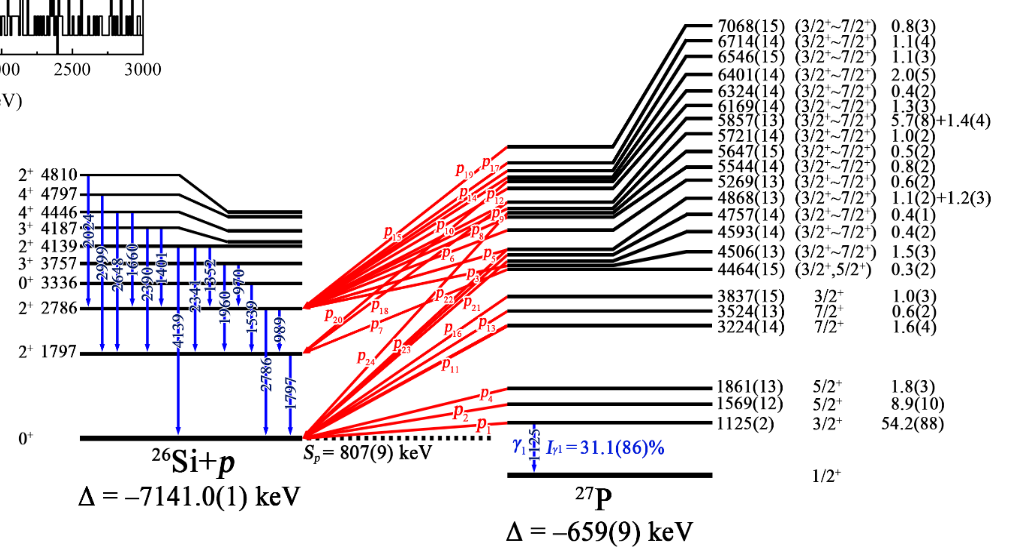
New: 24 βp (BR>0.3%) & 1 $\beta 2p$



L.J. Sun *et al.*,
PRC **99**, 064312 (2019).

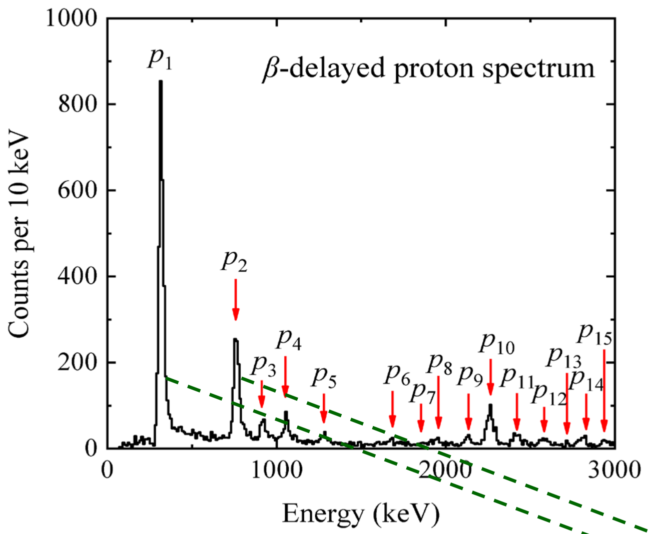


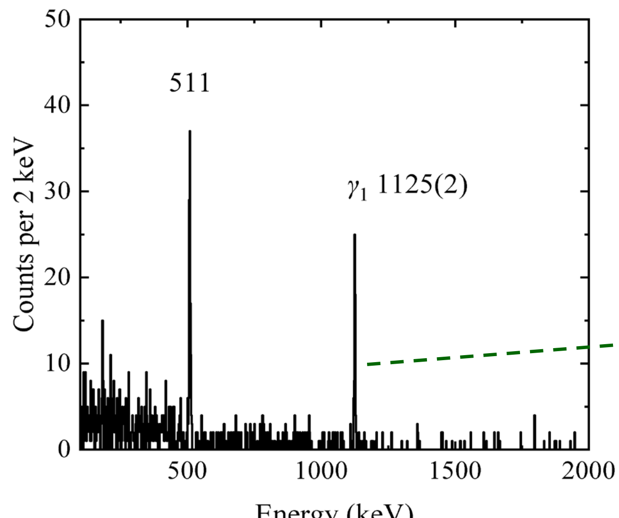




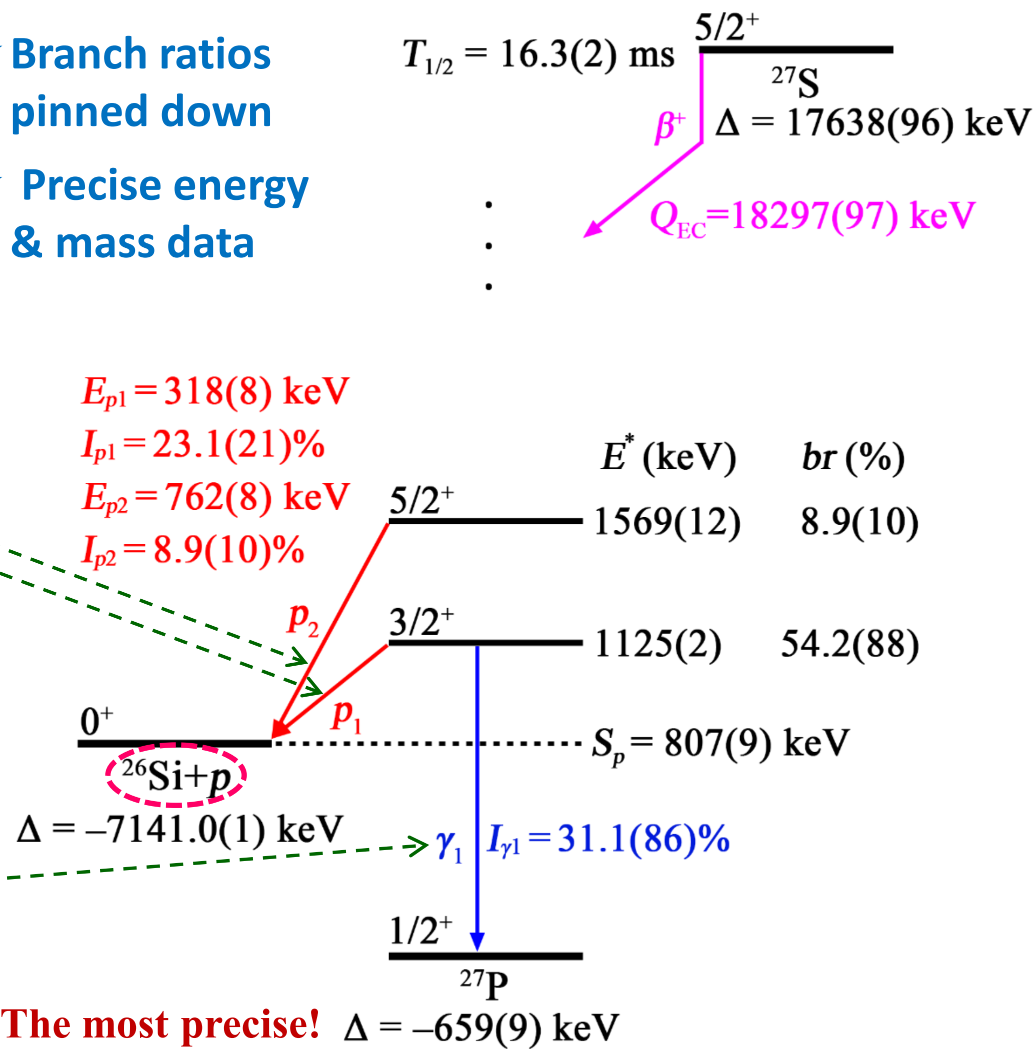
Daughters: $^{27}P/^{26}Si$

βp & $\beta\gamma$ were measured simultaneously for the first time.

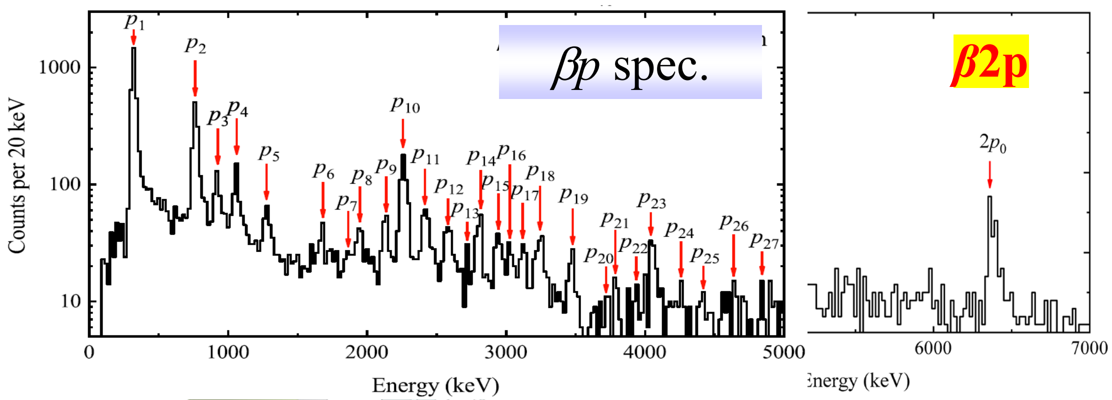


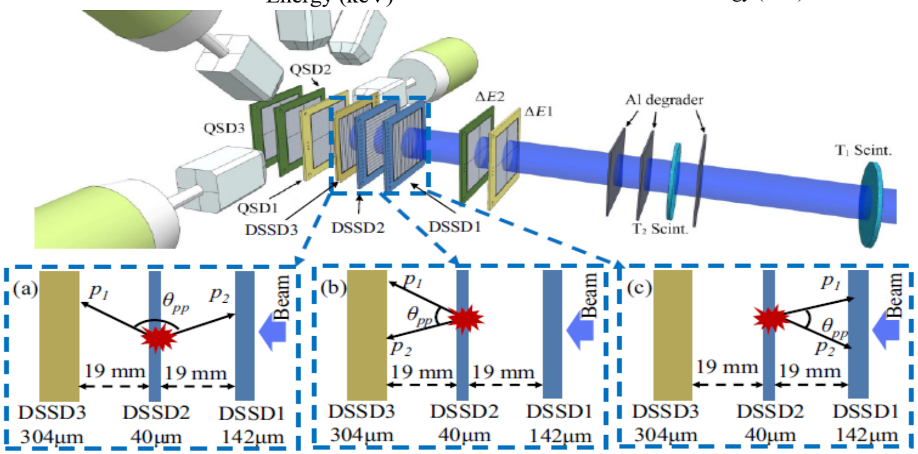


- ★ Branch ratios pinned down
- ★ Precise energy & mass data



β2p Decay of ^{27}S



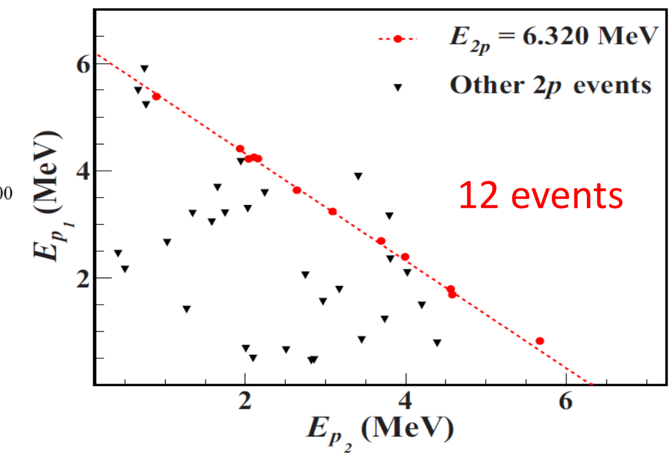


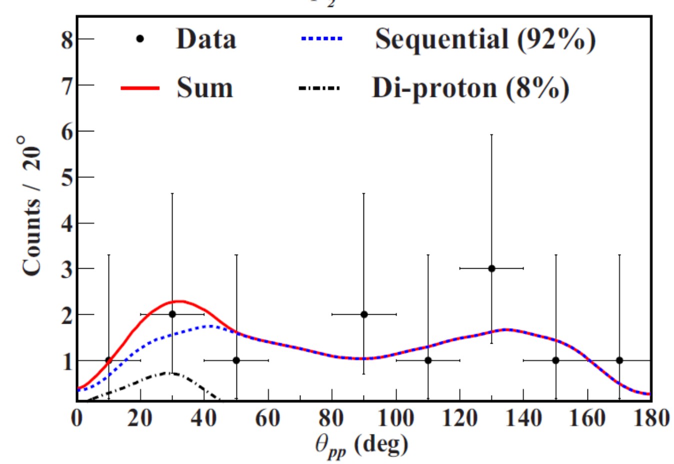
图：2p关联事件的判选

- ^{27}S β缓发双质子发射主要是级联衰变过程。
- Referee: “such measurements are pioneering.”

G.Z. Shi *et al.*, Phys. Rev. C **103**, L061301(2021).

27 *βp* & 1 *β2p* decays

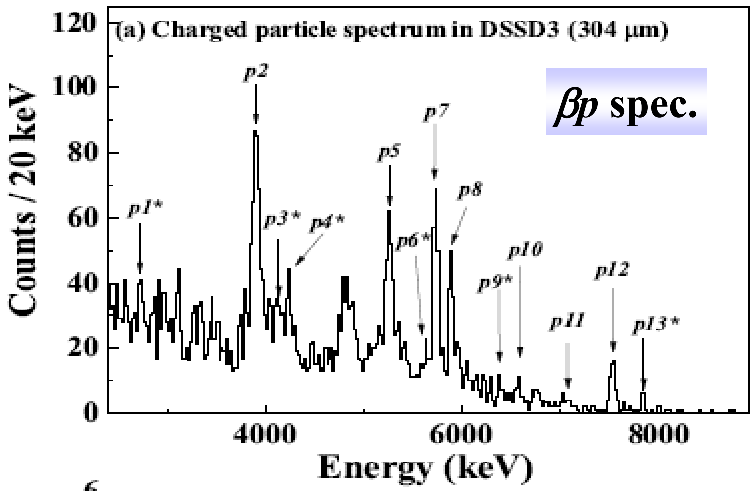


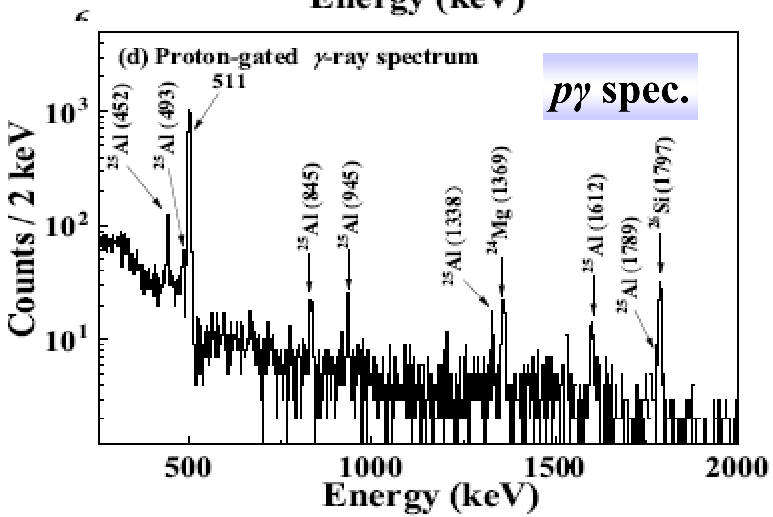


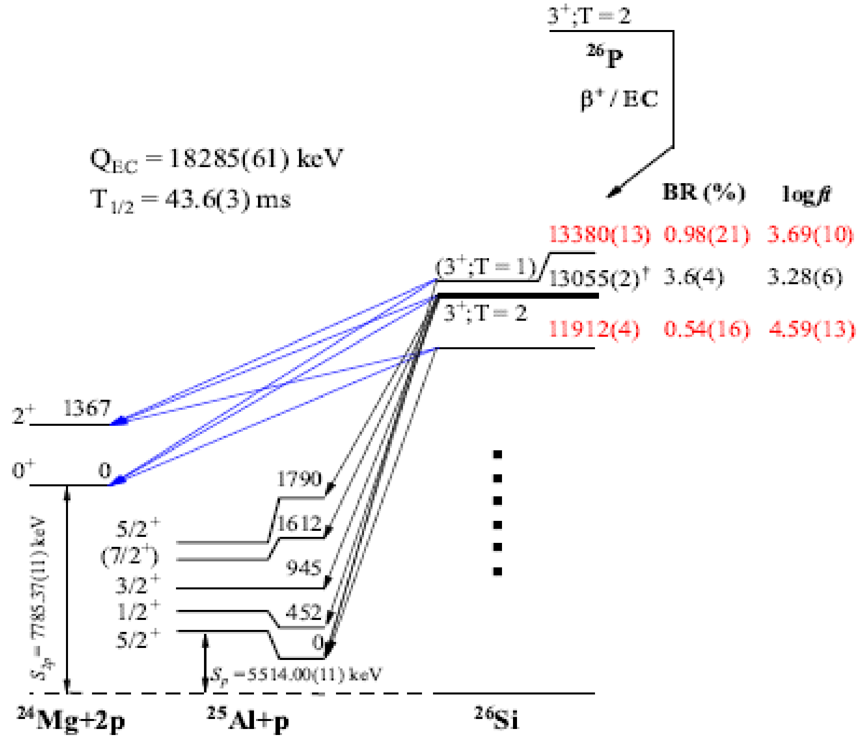
^{27}S β2p的能量和角关联

^{26}P Decays

★ 极强的同位旋混合态







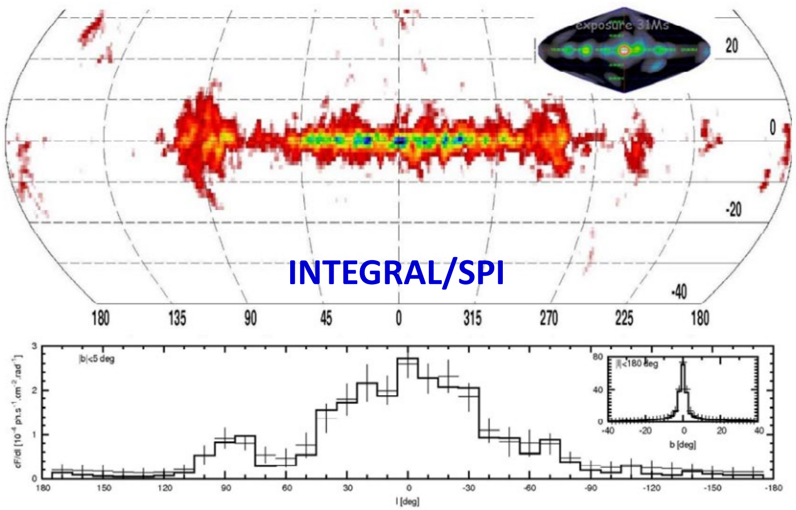
E (keV)	I_β (%)	log ft	B(F)	B(GT)
13380(13)	0.98(21)	3.69(10)	0.8(4)	0.29(13)
13055(2)^{IAS}	3.6(4)	3.28(6)	3.2(4)	
11912(4)	0.54(16)	4.59(13)		0.099(30)

mixing angle: $\theta = 27(6)°$

mixing matrix element: $v = 130(21)$ keV

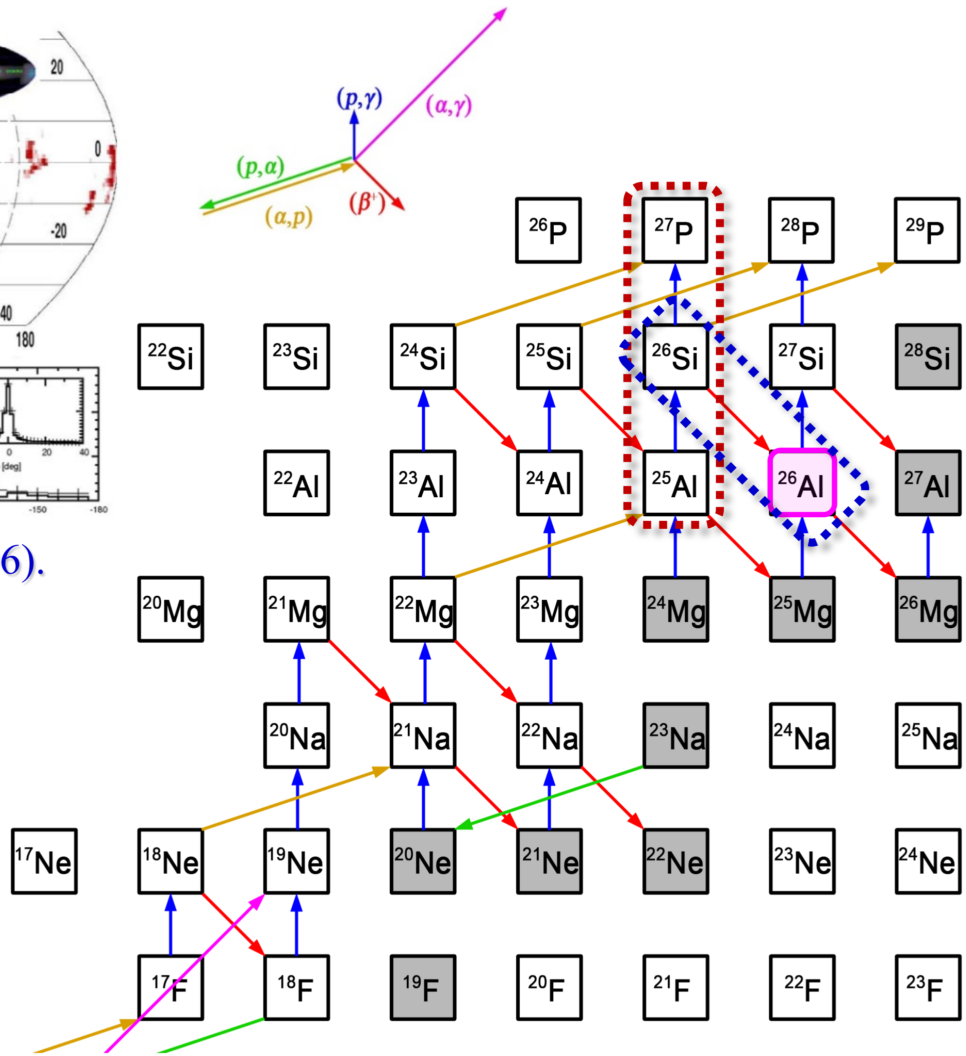
J.J. Liu *et al.*, Submitted to Phys. Rev. Lett.

The Galactic ^{26}Al Puzzle



R. Diehl *et al*., Nature **439**, 45 (2006).

The ^{26}Si$(p,\gamma)^{27}$P reaction competes with the β decay of ^{26}Si to ^{26}Al^m, and the latter can produces ^{26}Al^g via thermal excitations. Thus, the production and destruction of ^{26}Si by proton capture should be influential in determining the amount of the ^{26}Al^m and ^{26}Al^g produced by the equilibrium.



Explosive hydrogen burning scenarios

***βp* decays of ^{27}S/^{26}P**

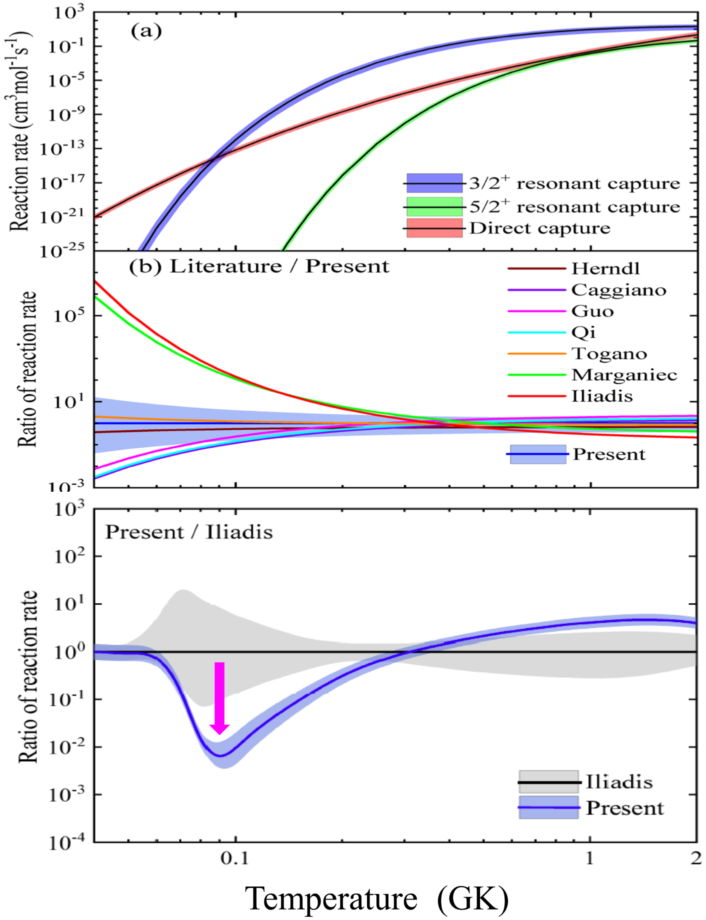
^{26}Si$(p,\gamma)^{27}$P

^{26}Si$(\beta^+)^{26}$Al^m

^{25}Al$(p,\gamma)^{26}$Si

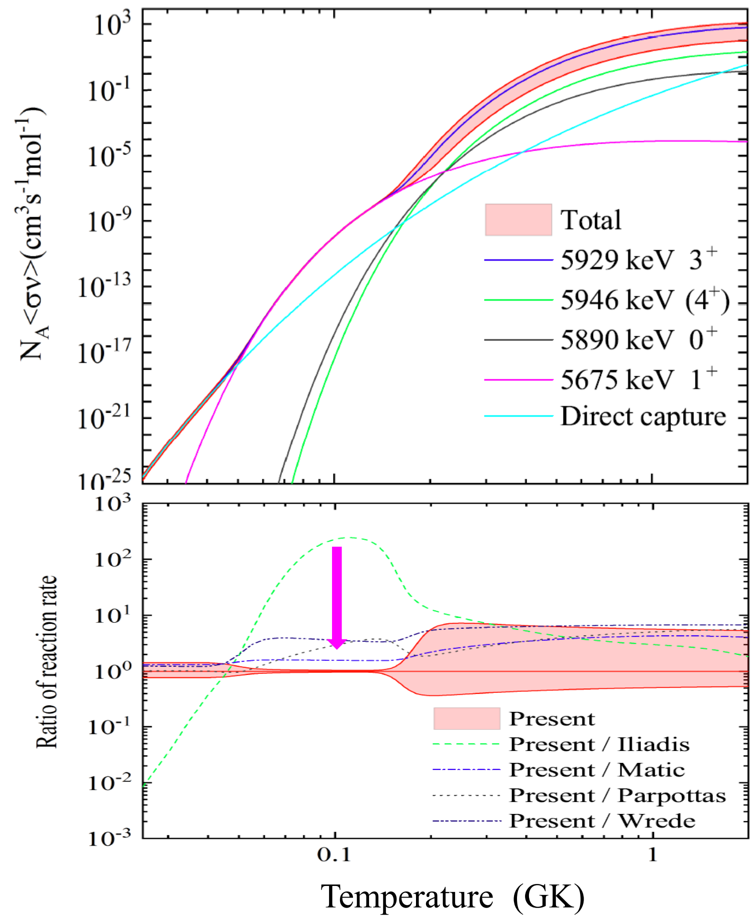
Thermonuclear Reaction Rates

^{26}Si(*p*,*γ*)^{27}P



L.J. Sun *et al.*,
Phys. Lett. B **802**, 135213 (2020).

^{25}Al(*p*,*γ*)^{26}Si



P.F. Liang *et al.*,
Phys. Rev. C **101**, 024305 (2020).

报告内容

一、前言

二、极丰质子核的奇异衰变

三、奇特核的近垒反应机制

四、小结

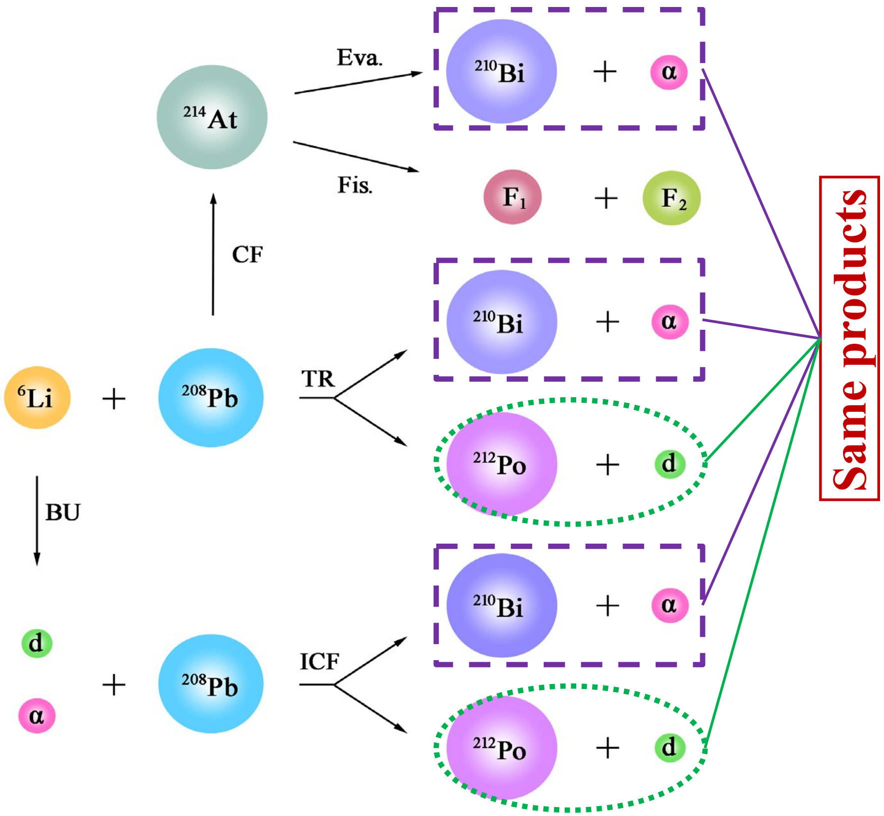
奇特核反应

奇特核：弱束缚的、具有奇特结构（晕、集团）的核。奇特核反应机制研究是核物理学科一个新兴的热点方向，**破裂机制**和**连续态强耦合机制**是研究中的两个核心问题，**运动学完全测量**是关键。

♠ **弹性/准弹性散射（较多数据）**
- 库仑虹抑制 ✔
- 3-body, 4-body CDCC

♠ **熔合（少量数据）**
- 总熔合 (TF = ICF+CF) ✔
- 不完全熔合 (ICF) ✘
- 全熔合 (CF) ✘

♠ **破裂/转移（极少数据）**
- 单举测量 ✔
- 符合测量 ✘



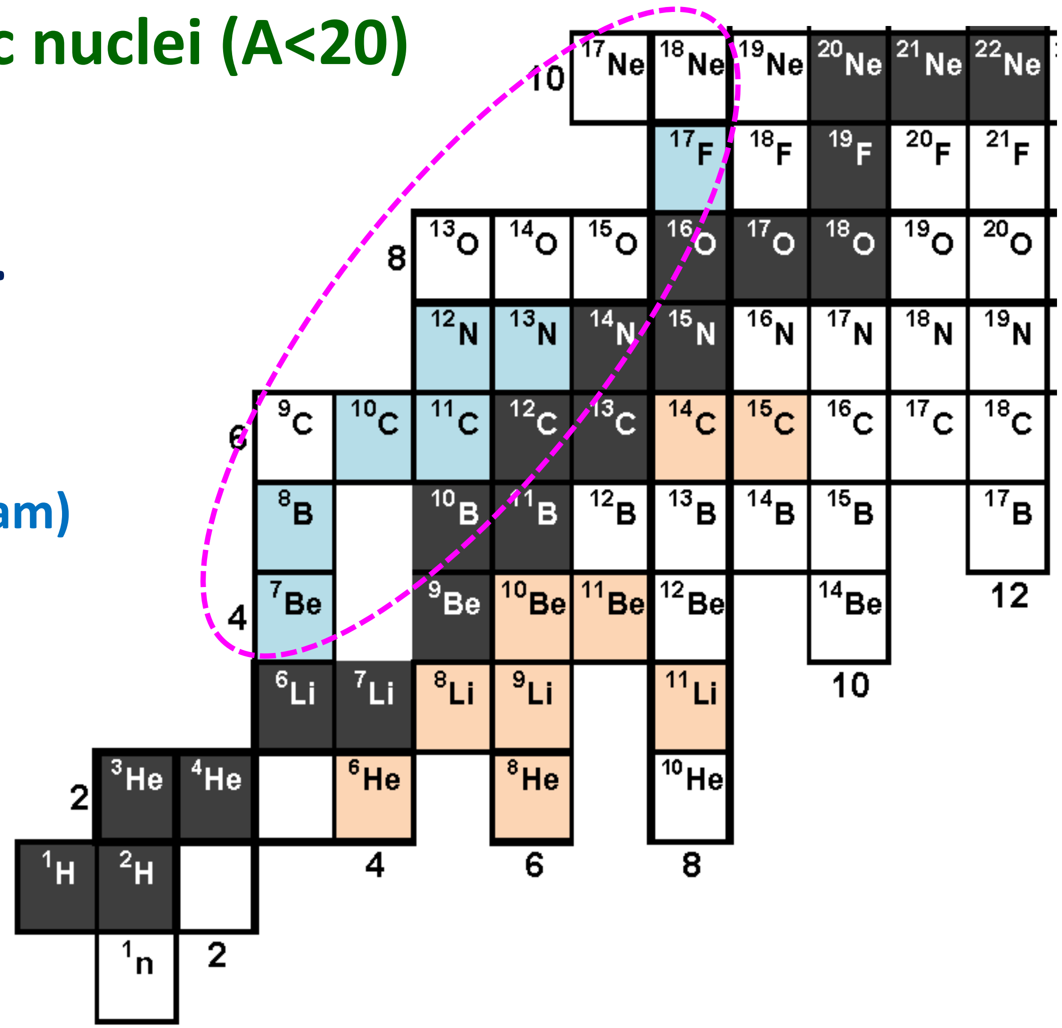
丰质子核的反应

Reactions with light exotic nuclei (A<20)

- Elastic, fusion, breakup …
- Proton-rich nuclei
- ^{7}Be, ^{8}B, ^{17}F (Key R&D Program)

  ^{12}N, ^{17,18}Ne …
- Complete-kinematics measurement

  (particle identification & large solid-angle covered)

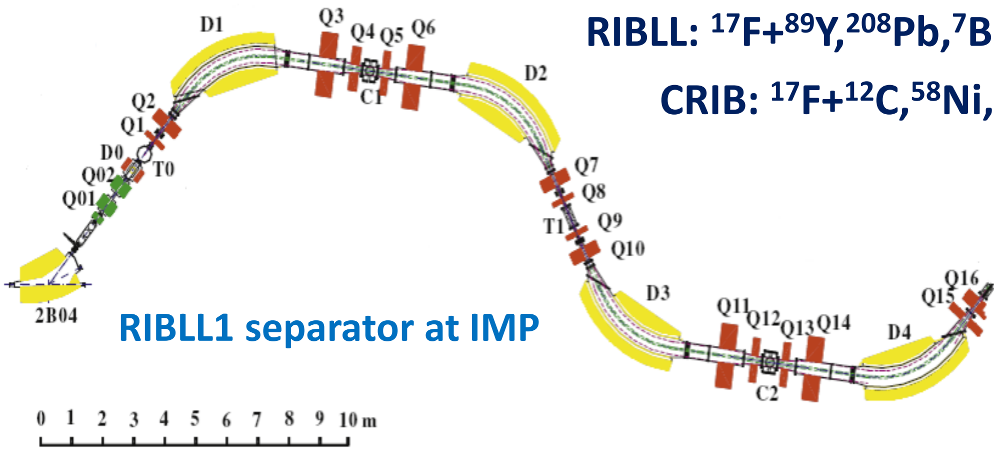


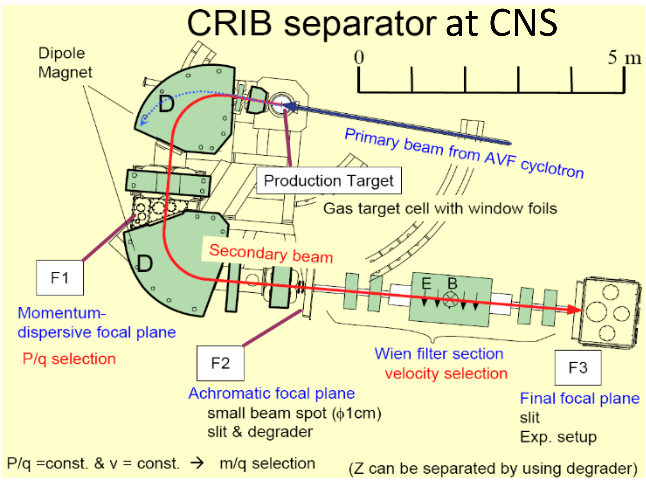
Experiments

★ Complete-kinematics measurement ; ★ Reactions induced by ^{7}Be, ^{8}B, ^{17}F …

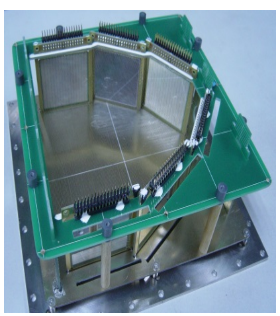
RIBLL: ^{17}F+^{89}Y,^{208}Pb,^{7}Be+^{209}Bi,^{120}Sn

CRIB: ^{17}F+^{12}C,^{58}Ni, ^{8}B+^{120}Sn

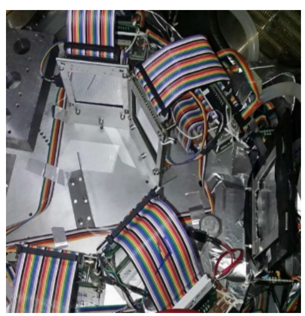




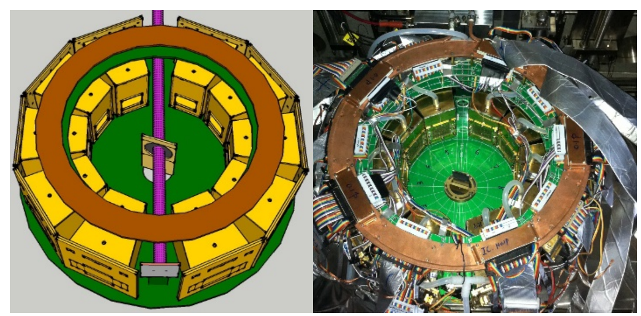
^{17}F+^{12}C
2007@CRIB



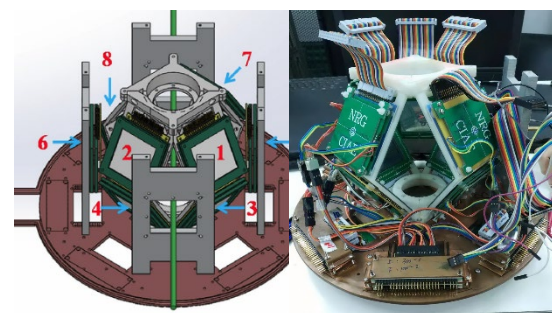
^{17}F+^{89}Y
2015@RIBLL1



^{17}F+^{208}Pb, 2015@RIBLL1
^{17}F+^{58}Pb, 2015@CRIB

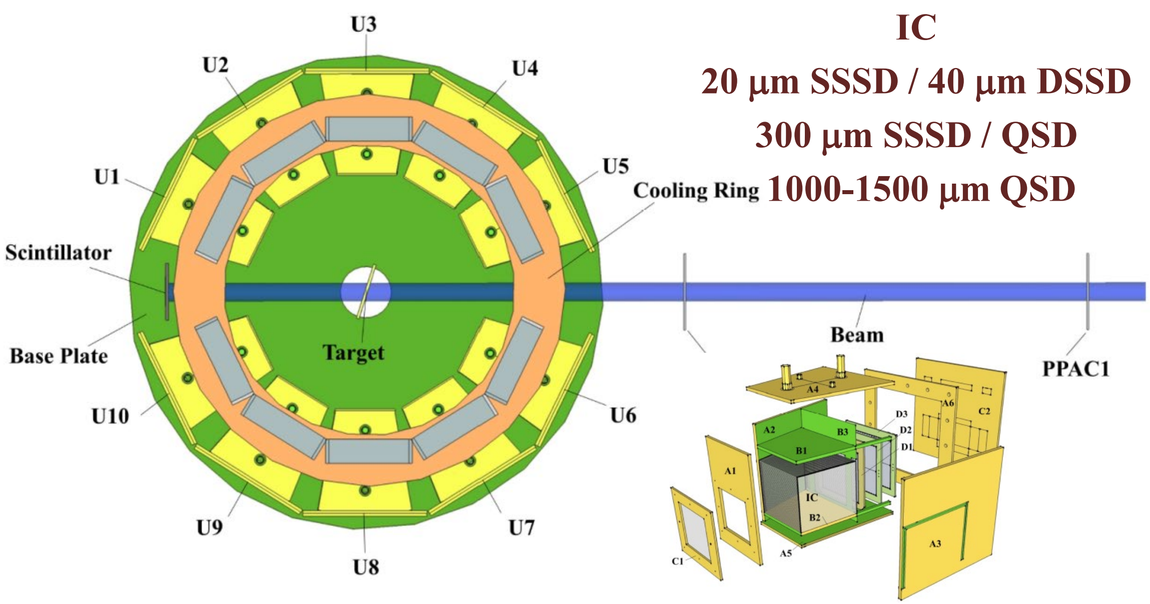


^{7}Be+^{209}Bi, 2018@RIBLL1
^{8}B+^{120}Sn, 2019@CRIB
^{7}Be+^{120}Sn, 2021@RIBLL1

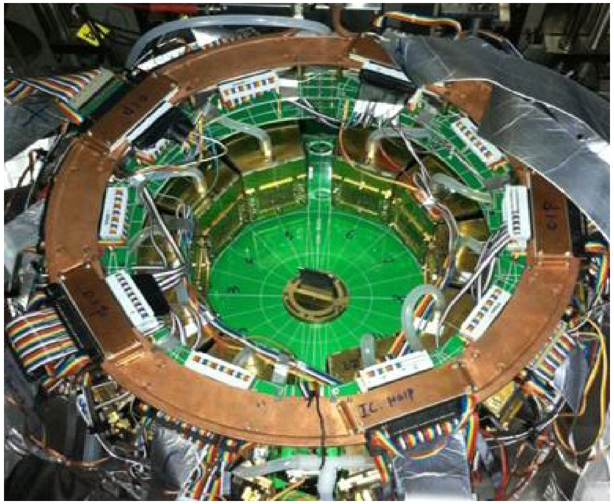


EPJA **48**, 65 (2012); PRC **97**, 044618 (2018); EPJA **57**, 143 (2021); PLB **813**, 136045 (2021) …

电离室多重望远镜阵列



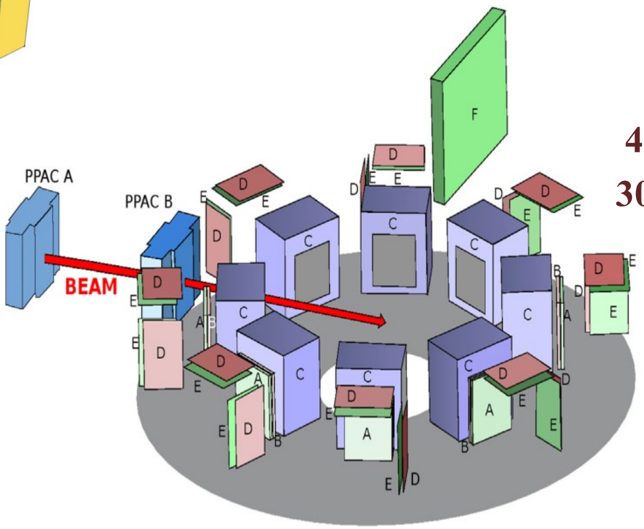
IC
20 μm SSSD / 40 μm DSSD
300 μm SSSD / QSD
1000-1500 μm QSD



CIAE-MITA阵列，10组4重，8% 4π

N.R. Ma et al., EPJA **55**, 87 (2019). 【封面文章】

- **运动学完全测量**方法，开展**较重**奇特核（^{17}F）的**反应机制**研究。
- 多层探测器组合，兼顾轻重离子鉴别。
- PCB架构，轻便易携带，方便合作。

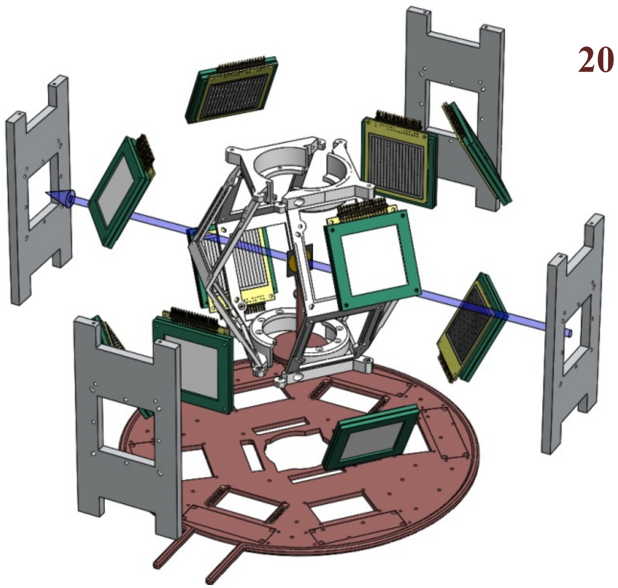


IC
40 μm DSSD
300 μm DSSD

NIMA 834, 46 (2016).

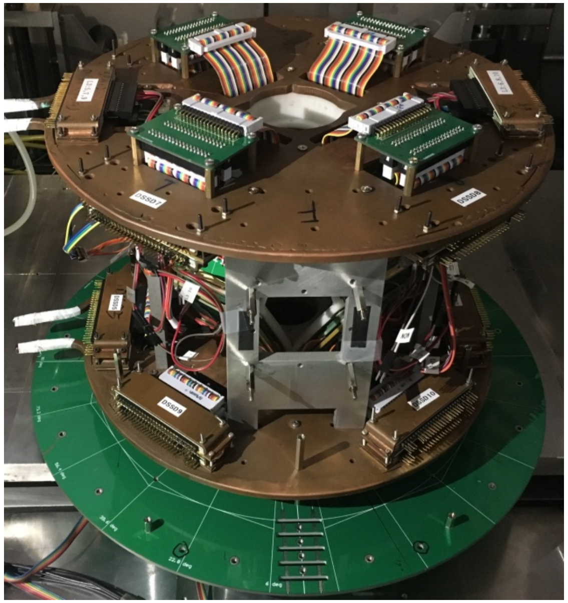
意大利EXPADES阵列，8组3重，5% 4π

大立体角硅条望远镜阵列



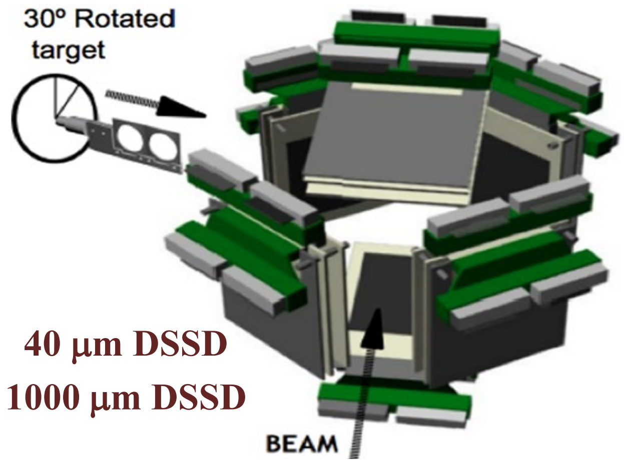
20 μm SSSD / 40 μm DSSD
300 μm SSSD / QSD
1000-1500 μm QSD

3D打印中心骨架



CIAE阵列，10组3重， 40% 4π

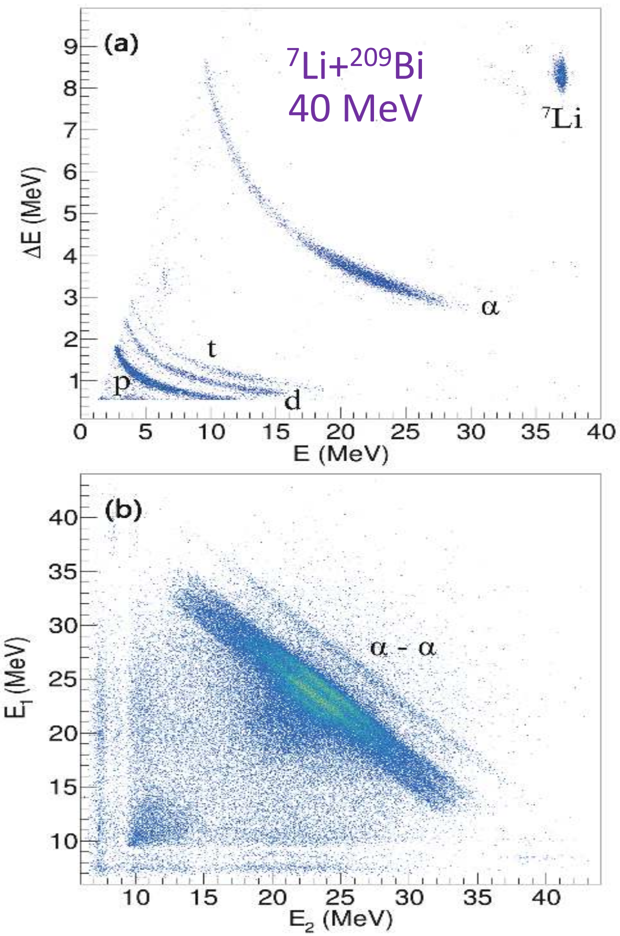
- **运动学完全测量**方法，开展**较轻**奇特核（^{7}Be, ^{8}B）的**反应机制**研究。
- 大立体角覆盖，16×16 ×10 = 2560点阵。
- 多层探测器组合，离子鉴别性能优秀。



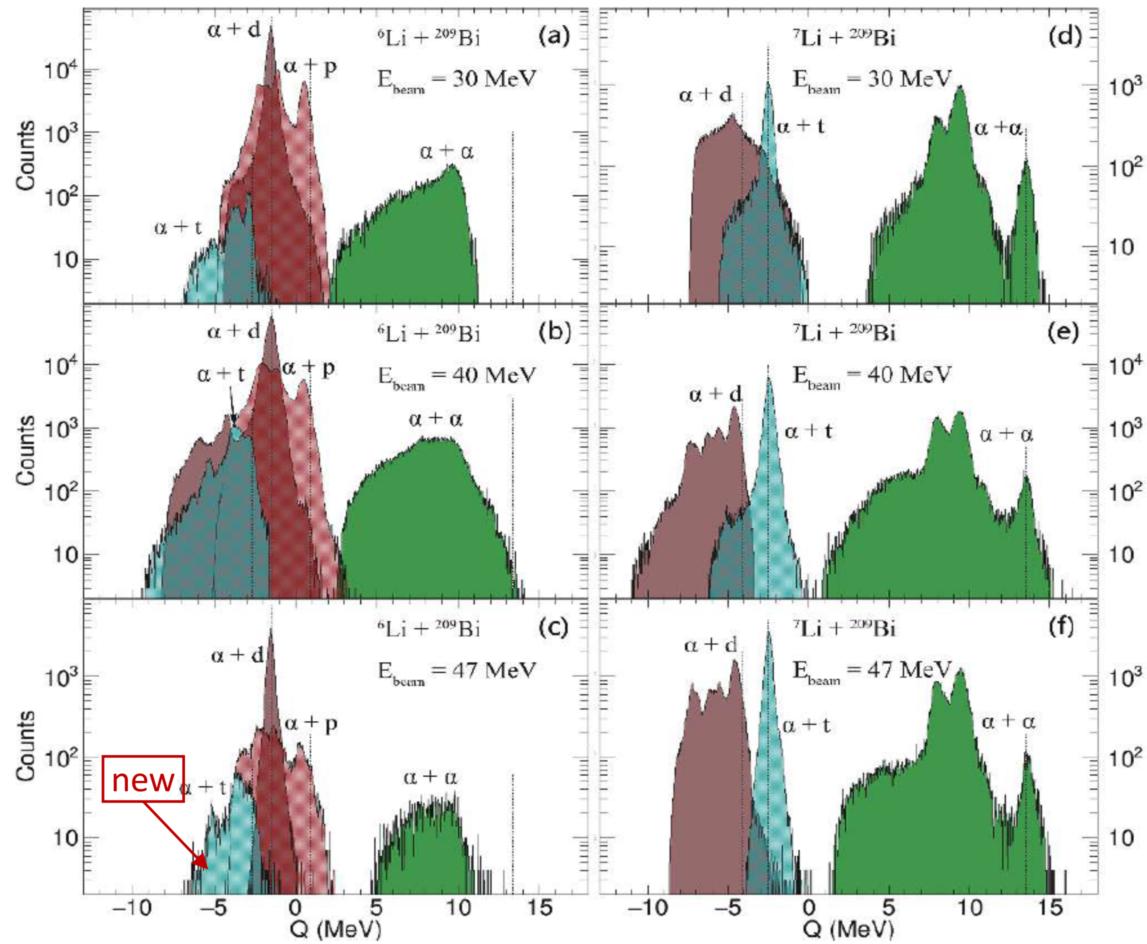
欧洲GLORIA阵列，6组2重，30% 4π

Results1: $^{6,7}Li+^{209}Bi$ - 1

利用运动学完全测量详细研究了$^{6,7}Li+^{209}Bi$在30, 40, and 47 MeV的反应机制。



探测器粒子鉴别图和关联图

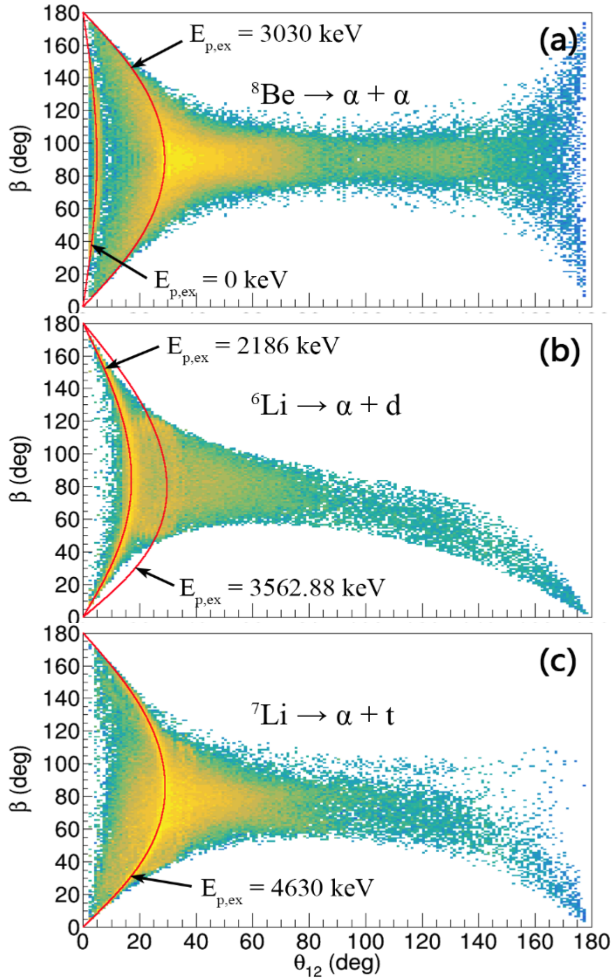


不同破裂道Q值谱

Y.J. Yao *et al.*, Nucl. Sci. Tech. 32, 14 (2021); Chin. Phys. C **45**, 054104 (2021).

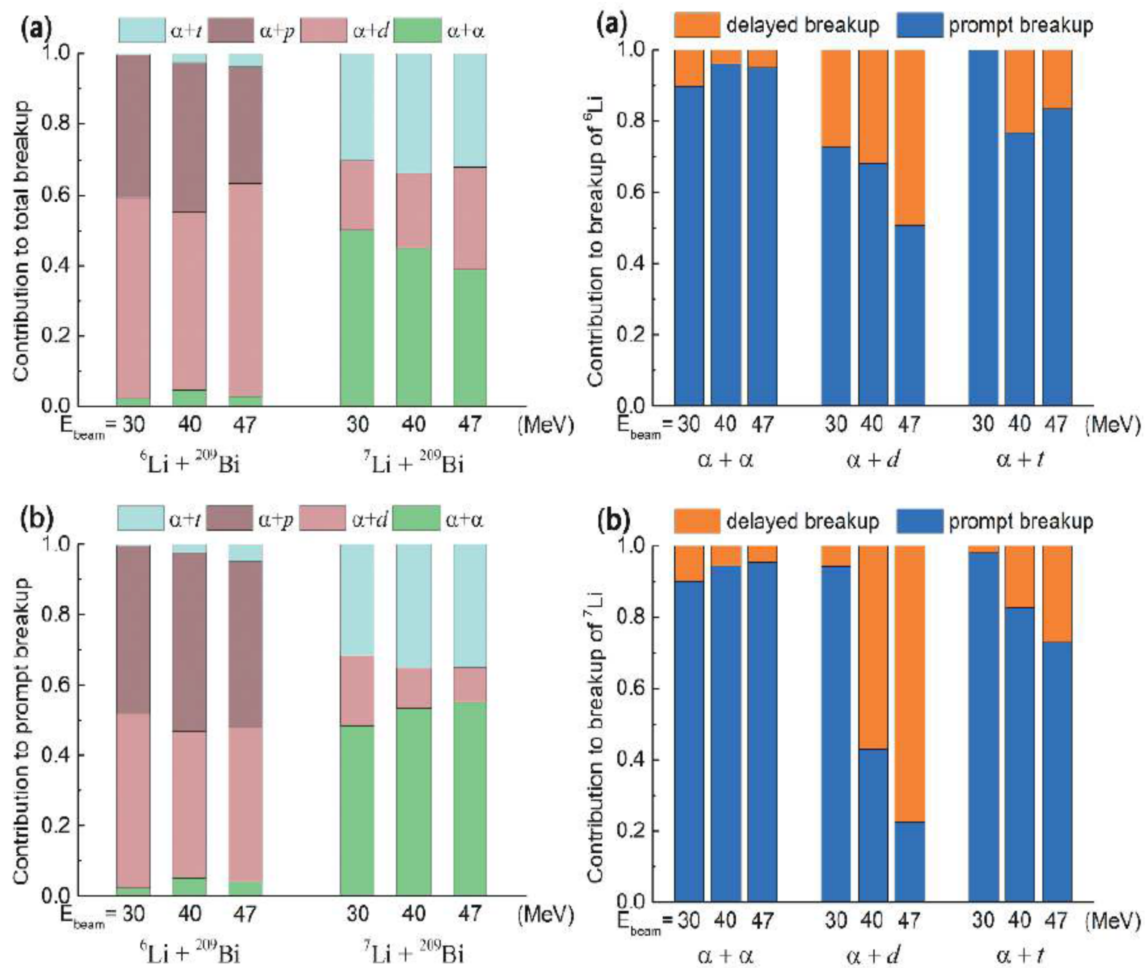
Results1: ^{6,7}Li+^{209}Bi - 2

^{7}Li+^{209}Bi @ 40 MeV



破裂子体角关联

^{6,7}Li+^{209}Bi @ 30,40,47 MeV

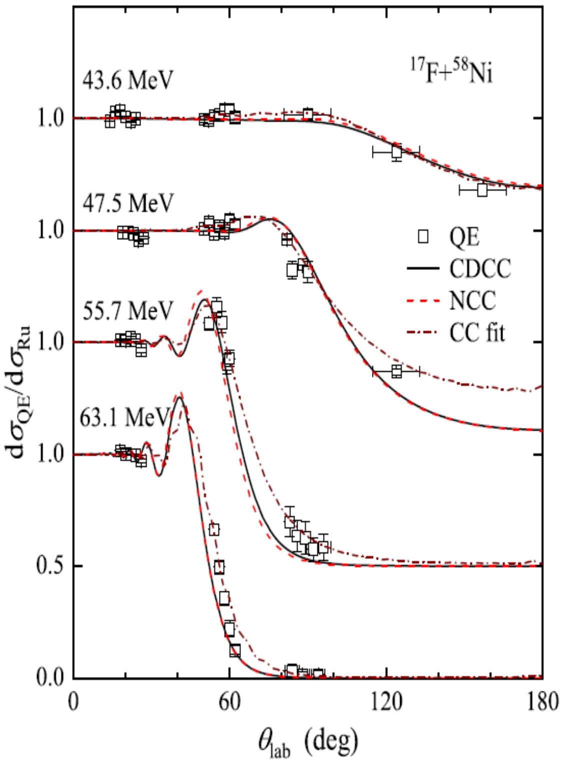


不同破裂道、不同破裂时标的分支比

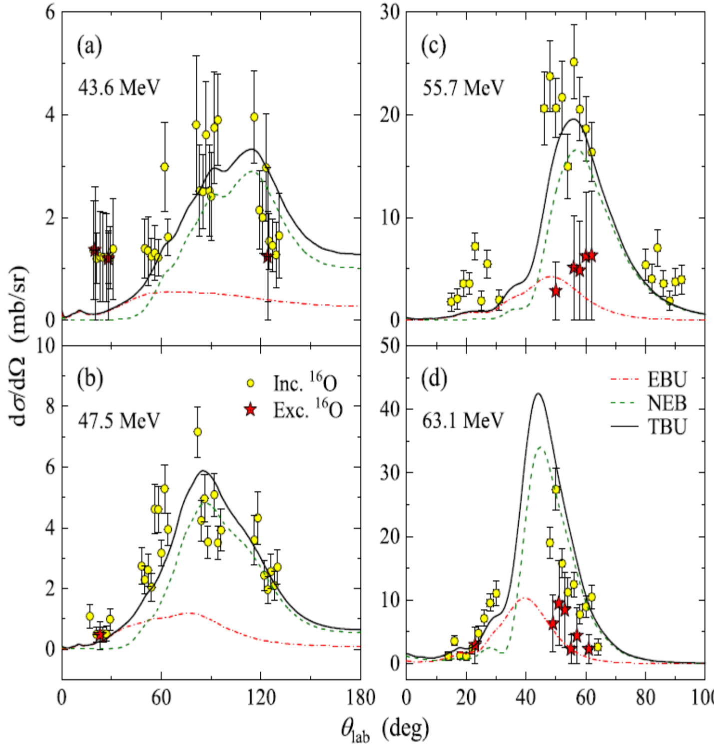
Y.J. Yao *et al.*, Nucl. Sci. Tech. 32, 14 (2021); Chin. Phys. C **45**, 054104 (2021).

Results2: $^{17}F+^{58}Ni$

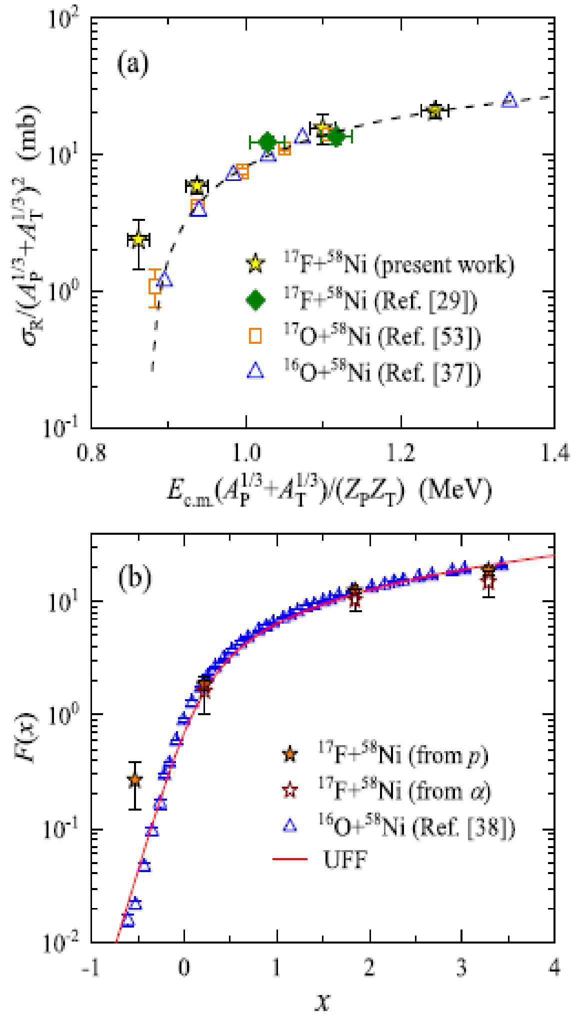
★ 运动学完全测量，首次在近垒能区获得带电粒子的全反应道的数据。



准弹性散射角分布



破裂/转移角分布



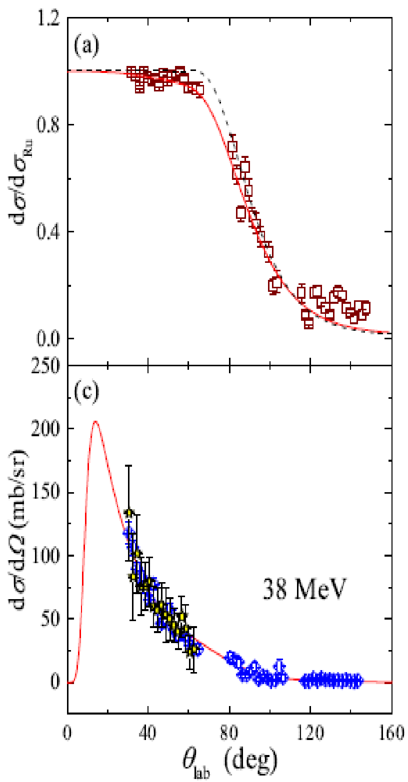
- 采用CC、CDCC、IAV、PLATYPUS等模型分析；
- 非弹性破裂为主；垒下反应截面和全熔合截面增强。

L. Yang *et al.*, Phys. Lett. B 813, 136045 (2021).

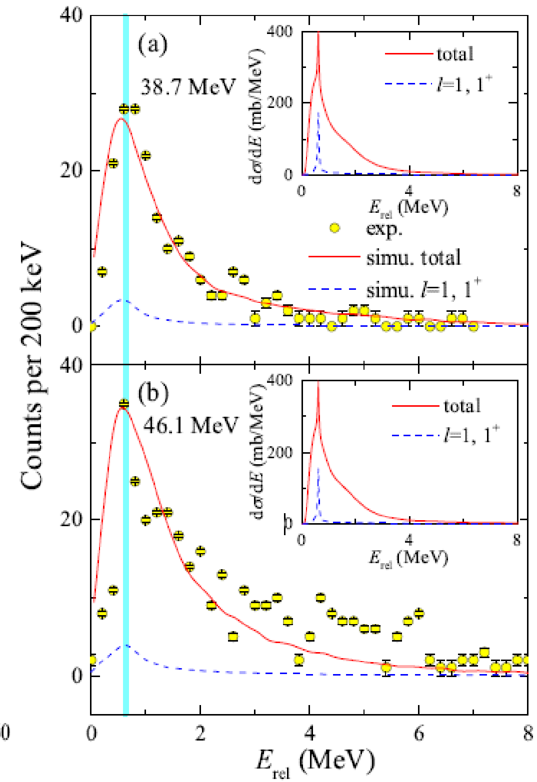
反应（上）和全熔合（下）激发函数

Results3: $^{8}B+^{120}Sn$

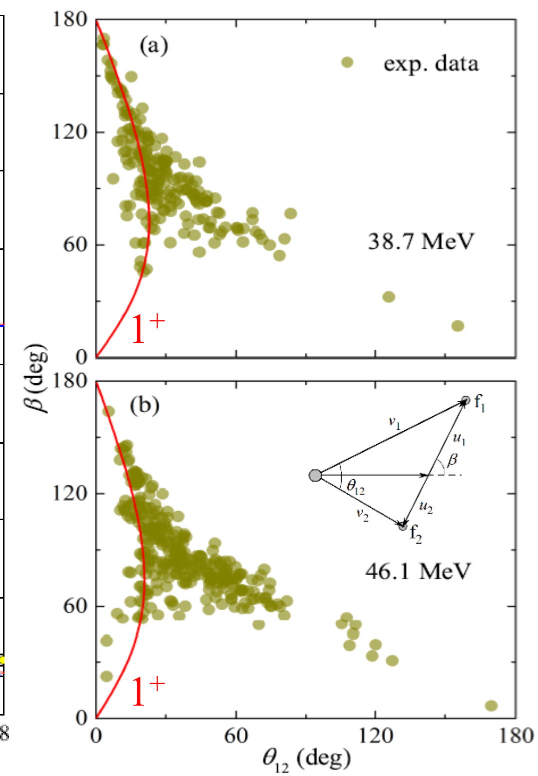
★ 运动学完全测量，首次在近垒能区获得^{8}B破裂子体(^{7}Be+p)的关联数据。



准弹、Inc和Exc破裂角分布



^{7}Be-p相对能量分布

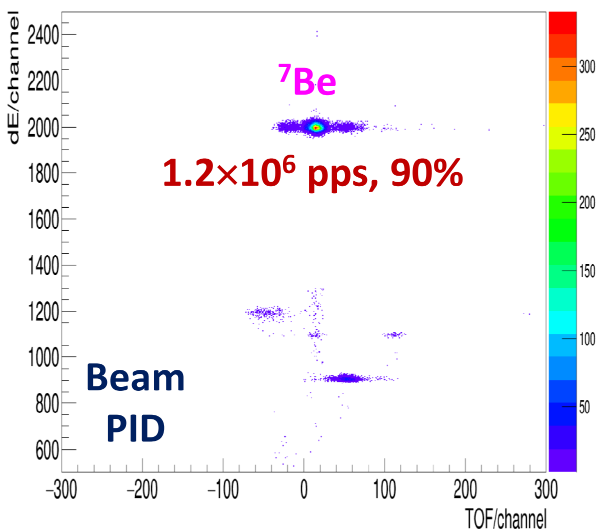


^{7}Be-p角关联

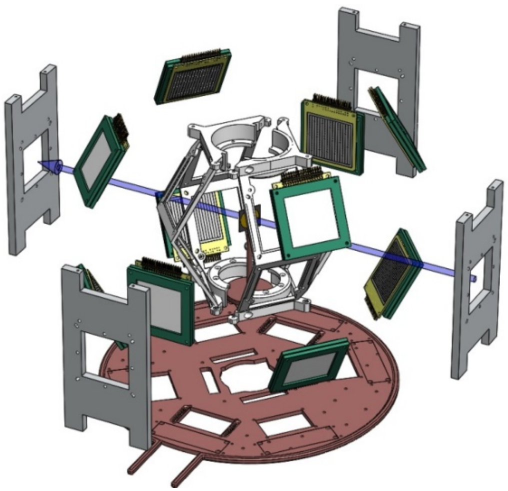
- Exc破裂截面几乎等于Inc破裂截面，弹性破裂为主；
- CDCC计算，1^{+}共振态贡献仅占4%；
- 出射道瞬时破裂破裂为主。

L. Yang *et al.*, submitted to Nature Communications.

In Progress: $^{7}Be+^{209}Bi,^{120}Sn$

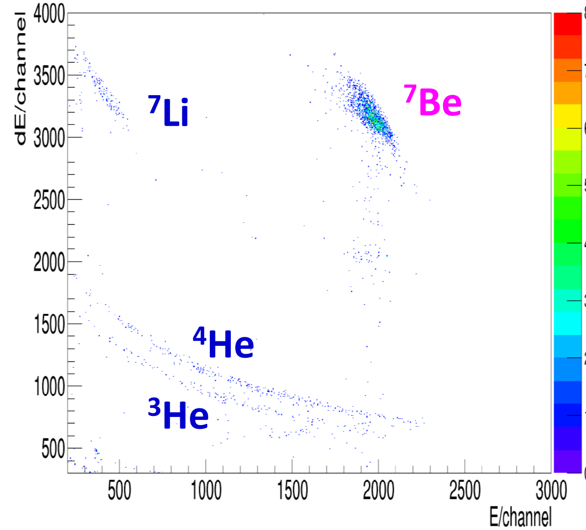


p(^{7}Li, ^{7}Be)n
^{7}Li: 8.8 MeV/u, 1.5 euA
H_2 gas: 1000 mbar, 8 cm, 90 K



20/40μm SSD + 300μm QSD + 1.5mm QSD

10 group of ΔE-ΔE-E telescopes
40% of 4π



ΔE-ΔE spectrum
by 40μm DSSD & 300μm QSD
(1 strip, 1 run, 2 hours)

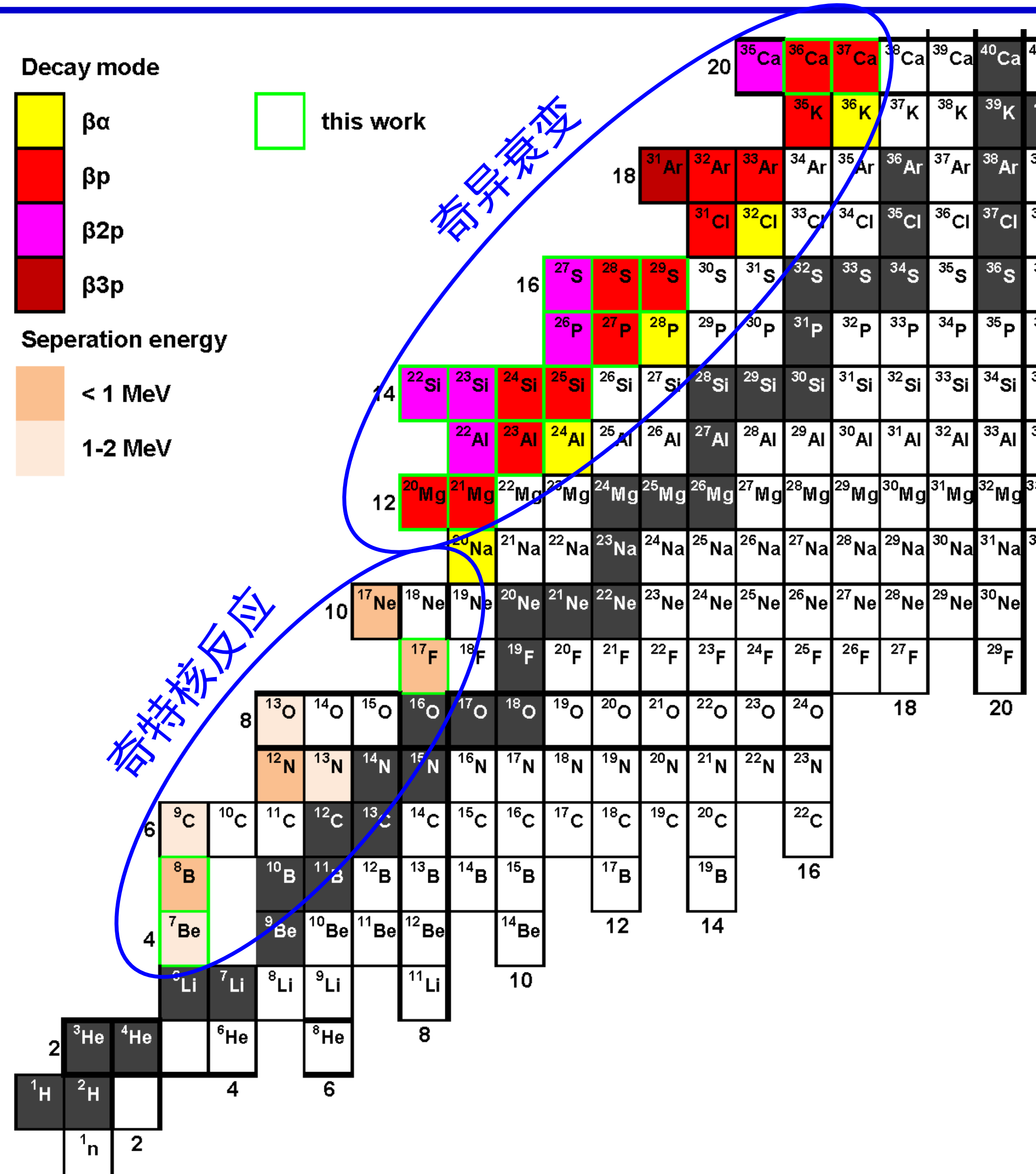
1. Exclusive breakup: ^{7}Be → ^{3}He+^{4}He (coin. Eff. ~10% by MC simulations);
2. ^{4}He stripping: ^{7}Be+^{209}Bi → ^{3}He+^{213}At;
3. ^{3}He stripping: ^{7}Be+^{209}Bi → ^{4}He+^{212}At;
4. 1*n* stripping: ^{7}Be+^{209}Bi → ^{6}Be(→^{4}He+*p*+*p*)+^{210}Bi;
5. 1*n* pickup: ^{7}Be+^{209}Bi → ^{8}Be(→^{4}He+^{4}He)+^{208}Bi;
6. 1*p* striping: ^{7}Be+^{209}Bi → ^{6}Li(→^{4}He+*d*)+^{210}Po;
8. 1*p* pickup: ^{7}Be+^{209}Bi → ^{8}B(→???)+^{208}Pb;
9. Fusion: ^{7}Be+^{209}Bi → ^{216}Fr → *α*, *p*, *n* eva. & decay (energy & angular distri.)

(Items 2–8: **ICF** (Ene-Ang corr.))

小结

1) **奇异衰变**：高精度测量了sd壳层15个丰质子核的β延迟衰变，获得了丰富的谱学信息，深入理解了核结构性质及其有效相互作用。

2) **奇特核反应**：运动学完全测量了^{7}Be、^{8}B和^{17}F与不同靶核的反应，获得了带电粒子全反应道的信息，深入理解了破裂机制及其连续态耦合机制。



Thanks to all the collaborators!

for example

PHYSICAL REVIEW C 99, 064312 (2019)

β-decay spectroscopy of ^{27}S

L. J. Sun (孙立杰),[1,2,3] X. X. Xu (徐新星),[1,2,*] C. J. Lin (林承键),[1,4,†] J. Lee (李晓菁),[2,‡] S. Q. Hou (侯素青),[5]
C. X. Yuan (袁岑溪),[6] Z. H. Li (李智焕),[7] J. José,[8,9,§] J. J. He (何建军),[10,11] J. S. Wang (王建松),[5] D. X. Wang (王东玺),[1]
H. Y. Wu (吴鸿毅),[7] P. F. Liang (梁鹏飞),[2] Y. Y. Yang (杨彦云),[5] Y. H. Lam (蓝乙华),[5] P. Ma (马朋),[5]
F. F. Duan (段芳芳),[12,5] Z. H. Gao (高志浩),[5,12] Q. Hu (胡强),[5] Z. Bai (白真),[5] J. B. Ma (马军兵),[5] J. G. Wang (王建国),[5]
F. P. Zhong (钟福鹏),[4,1] C. G. Wu (武晨光),[7] D. W. Luo (罗迪雯),[7] Y. Jiang (蒋颖),[7] Y. Liu (刘洋),[7] D. S. Hou (侯东升),[5,11]
R. Li (李忍),[5,11] N. R. Ma (马南茹),[1] W. H. Ma (马维虎),[5,13] G. Z. Shi (石国柱),[5] G. M. Yu (余功明),[5] D. Patel,[5]
S. Y. Jin (金树亚),[5,11] Y. F. Wang (王煜峰),[14,5] Y. C. Yu (余悦超),[14,5] Q. W. Zhou (周清武),[15,5] P. Wang (王鹏),[15,5]
L. Y. Hu (胡力元),[16] X. Wang (王翔),[7] H. L. Zang (臧宏亮),[7] P. J. Li (李朋杰),[2] Q. Q. Zhao (赵青青),[2] L. Yang (杨磊),[1]
P. W. Wen (温培威),[1] F. Yang (杨峰),[1] H. M. Jia (贾会明),[1] G. L. Zhang (张高龙),[17] M. Pan (潘敏),[17,1]
X. Y. Wang (汪小雨),[17] H. H. Sun (孙浩瀚),[1] Z. G. Hu (胡正国),[5] R. F. Chen (陈若富),[5] M. L. Liu (柳敏良),[5]
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Insight into the reaction dynamics of proton drip-line nuclear system $^{17}F+^{58}Ni$ at near-barrier energies

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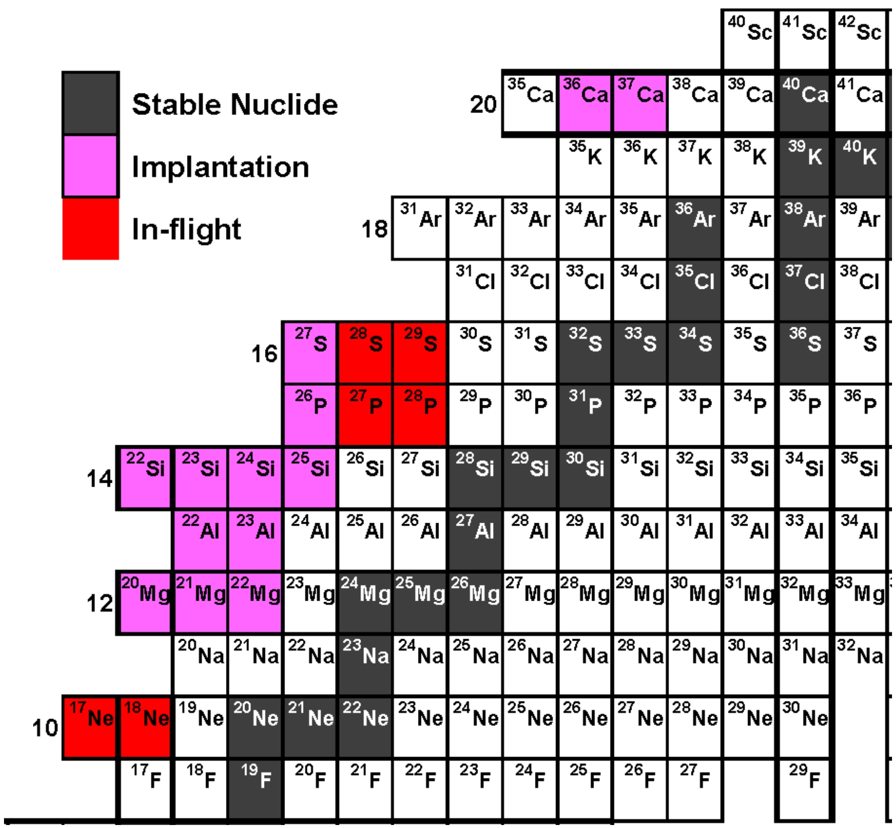
谢谢关注！

Appendix:

Optical Potential of Exotic Nuclear System

丰质子核的奇异衰变

奇异衰变：滴线附近原子核的奇异衰变模式，如*p*, 2*p*, *βp*, *β*2*p*等。奇特衰变的研究是核物理学科一个新兴的热点方向，**衰变机制**和**初态构形**是其中的两个重要问题。



- **RIBLL@HIRFL, from 2004**
- **In-flight** measurement

  ^{28,29}S/^{27,28}P;
  ^{17,18}Ne.

- **Implantation** method

  ^{36,37}Ca;
  ^{27}S/^{26}P/^{25}Si;
  ^{22}Si/^{20}Mg;
  ^{23}Si/^{22}Al/^{21}Mg;
  ^{24}Si/^{23}Al.

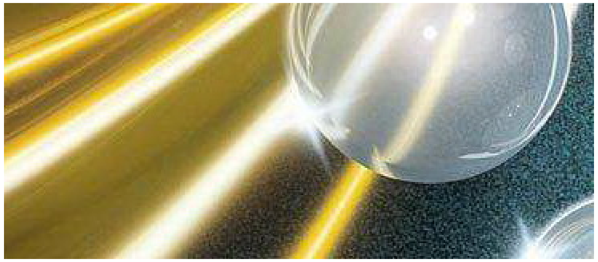
Optical Model Potential

♠ Optical Model is a successful model to explain the nuclear scattering and reaction, which resembles the case of light scattered by an opaque glass sphere.

Optical Model Potential (OMP):

$$U = V(r) + iW(r)$$

attractive (for $V(r)$) **absorptive** (for $iW(r)$)



★phenomenological potential, independent on energy.

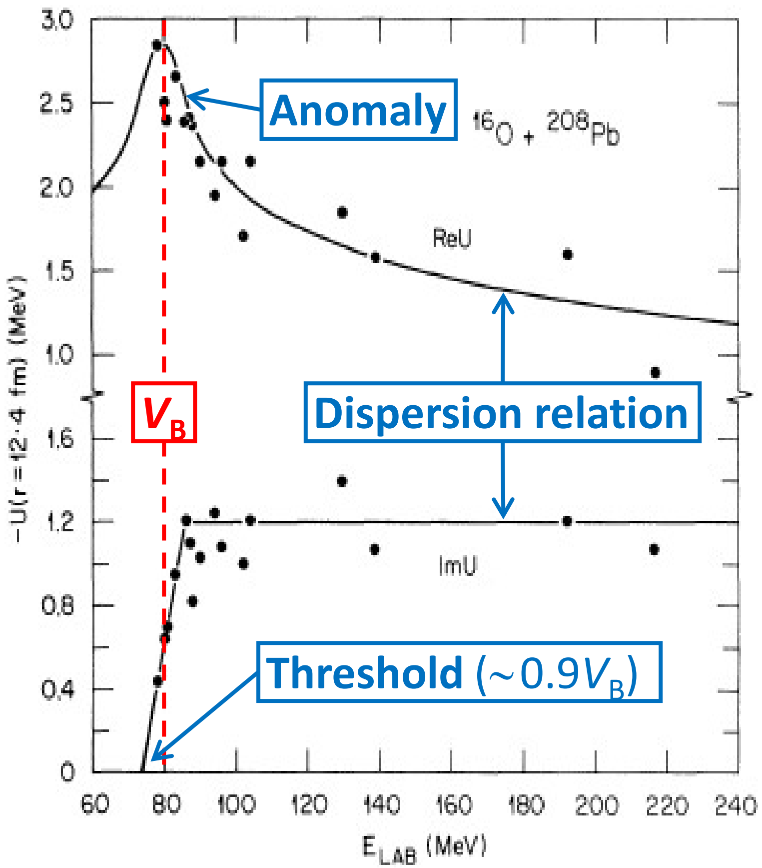
♠ A basic task in nuclear reaction study is to understand the nucleus-nucleus interaction.

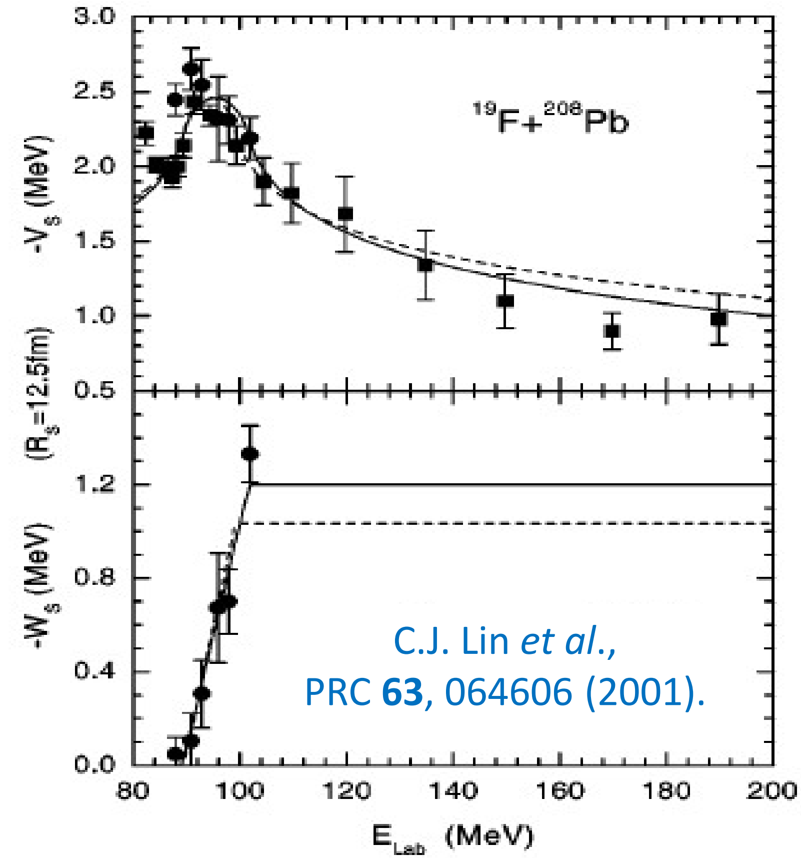
Cf: 1) S. Fernbach, R. Serber, and T. B. Taylor, Phys. Rev. **73**, 1352 (1949).
2) H. Feshbach, “The optical model and its justification”, Ann. Rev. Nucl. Sci. **8**, 49 (1958).

Tightly-bound-nuclei Systems

Threshold Anomaly

A universal phenomenon within the Coulomb barrier energy region

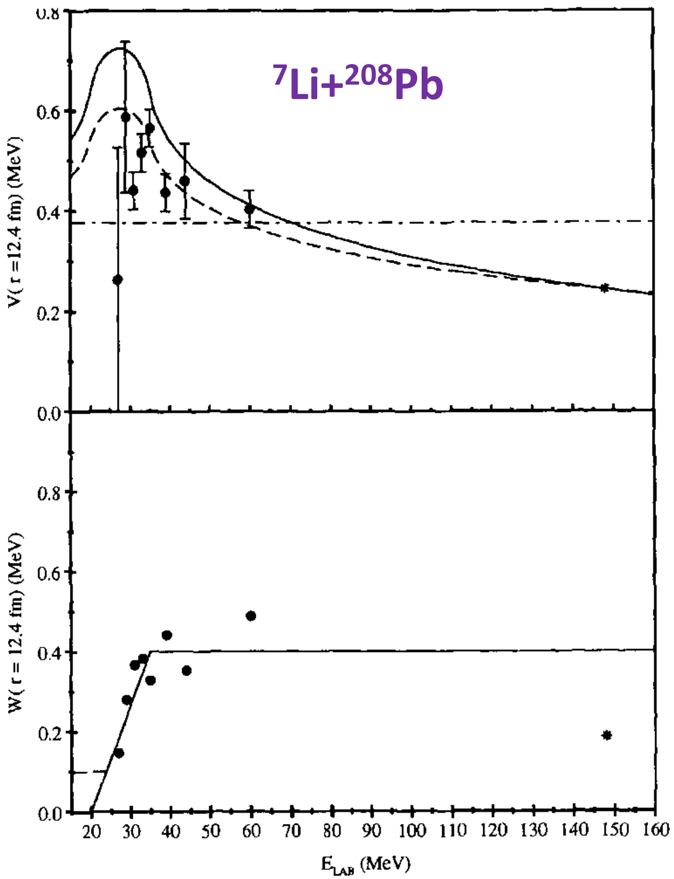




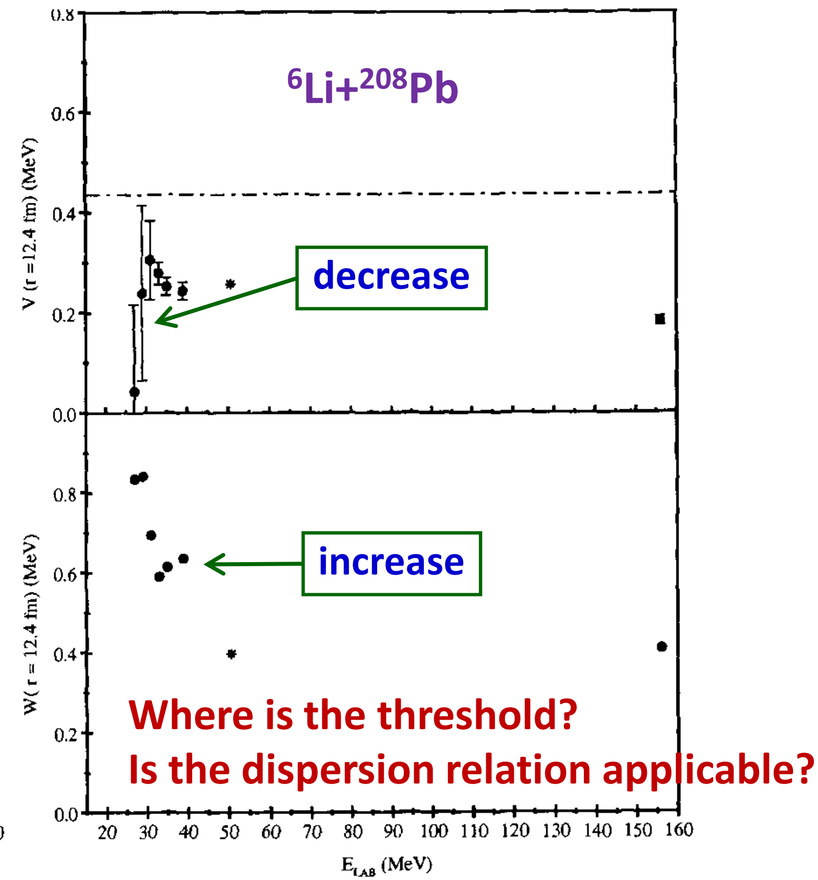
Cf: 1) M. A. Nagarajan, C. C. Mahaux, and G. R. Satchler, Phys. Rev. Lett. **54**, 1136 (1985).
2) C. Mahaux, H. Ngo, and G. R. Satchler, Nucl. Phys. **A449**, 354 (1986).
3) G. R. Satchler, Phys. Rep. **199**, 147 (1991).

Weakly-bound-nuclei Systems

Threshold Anomaly



Abnormal Threshold Anomaly

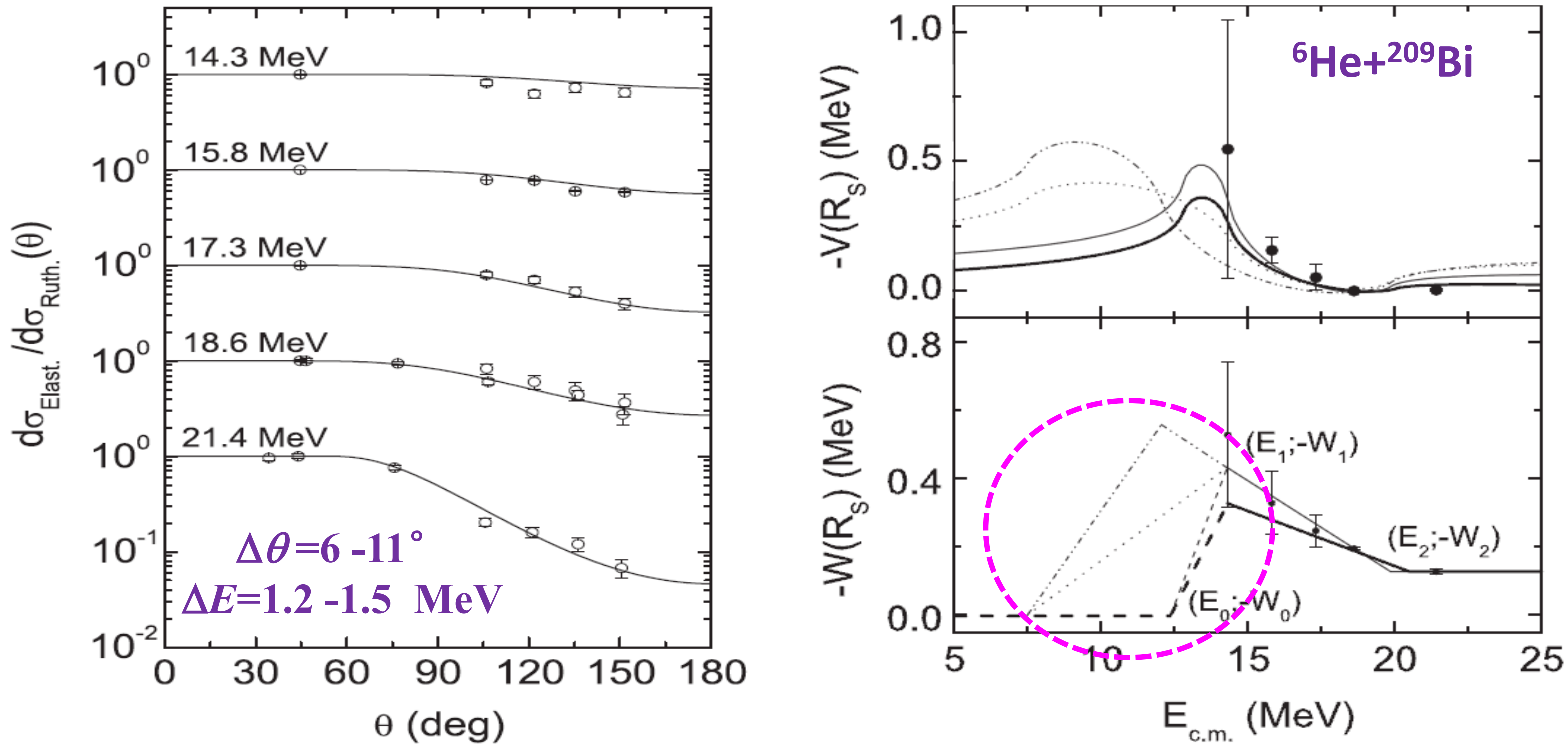


N. Keeley et al., Nucl. Phys. A **571**, 326 (1994).

Halo-nuclei Systems

Abnormal Threshold Anomaly

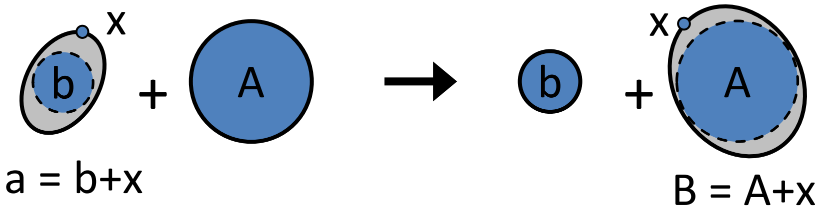
OMPs are usually extracted from elastic scattering.



★ Almost Impossible to extract effective OMPs at energy far below the barrier.

Cf: 1) E.F. Aguilera *et al.*, PRL **84**, 5058 (2000); PRC **63**, 061603R (2001).
2) A. R. Garcia *et al.*, Phys. Rev. C **76**, 067603 (2007).

Transfer Method



$$\left(\frac{d\sigma}{d\Omega}\right)_{if} = P_{if}\left(\left(\frac{d\sigma}{d\Omega}\right)_{ii} \cdot \left(\frac{d\sigma}{d\Omega}\right)_{ff}\right)^{1/2}$$

Transfer reaction A(a,b)B

elastic scatting cross sections

Transition amplitude: $T = J\int d^3r_b \int d^3r_a \chi^{(-)}(\vec{k}_f, \vec{r}_b)^* \langle bB|V|aA\rangle \chi^{(+)}(\vec{k}_i, \vec{r}_a),$

4 wave functions are needed,

♣ two bound states: b+x & A+x (single-particle potential model)

♣ two scattering states: incoming & outgoing (optical potentials)

Proposed: C. J. Lin et al., AIP Conf. Proc. **853**, 81 (2006), presented at the FUSION06.

^{16}O(^{14}N,^{13}C)^{17}F: Chin. Phys. Lett. **25**, 4237 (2008).

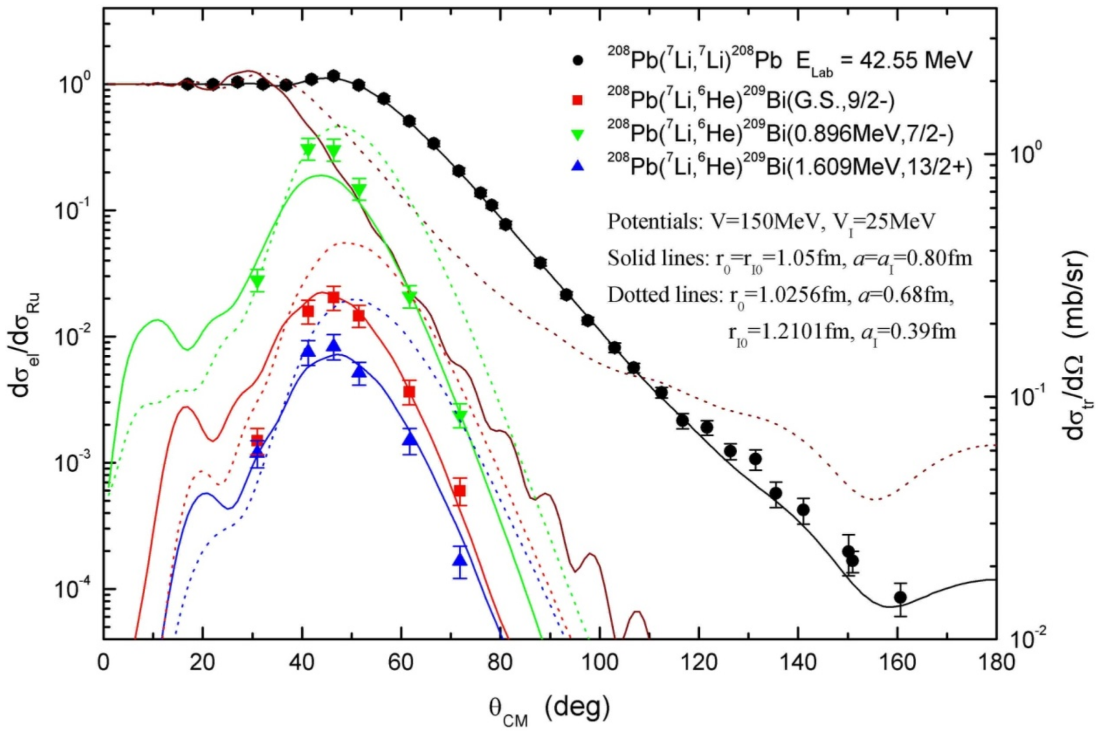
^{11}B(^{7}Li,^{6}He)^{12}C: Chin. Phys. Lett. **26**, 022503 (2009). Phys. Rev. C **87**, 047601 (2013).

^{208}Pb(^{7}Li,^{6}He)^{209}Bi: Phys. Rev. C **89**, 044615 (2014), Il Nuovo Cimento C **39**, 367 (2016), Chin. Phys. Lett. **31**, 092401 (2014), Phys. Rev. C **96**, 044615 (2017), Phys. Rev. Lett. **119**, 042503 (2017).

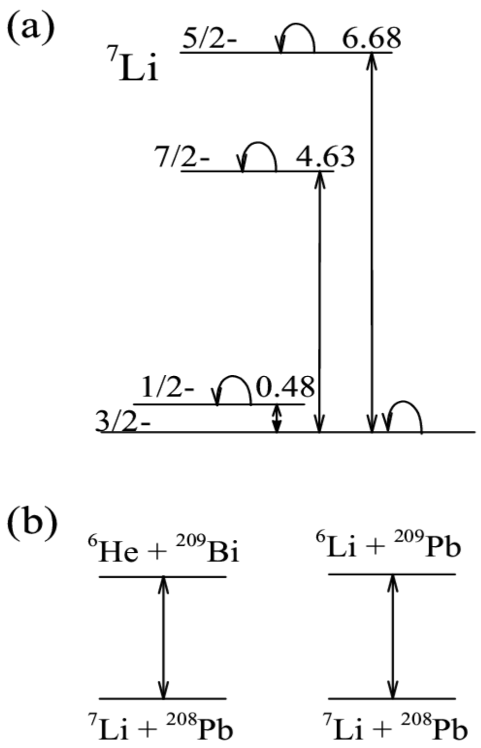
^{63}Cu(^{7}Li,^{6}He)^{64}Zn: Phys. Rev. C **95**, 034616 (2017).

Data Analysis: $^{208}Pb(^{7}Li,^{6}He)^{209}Bi$

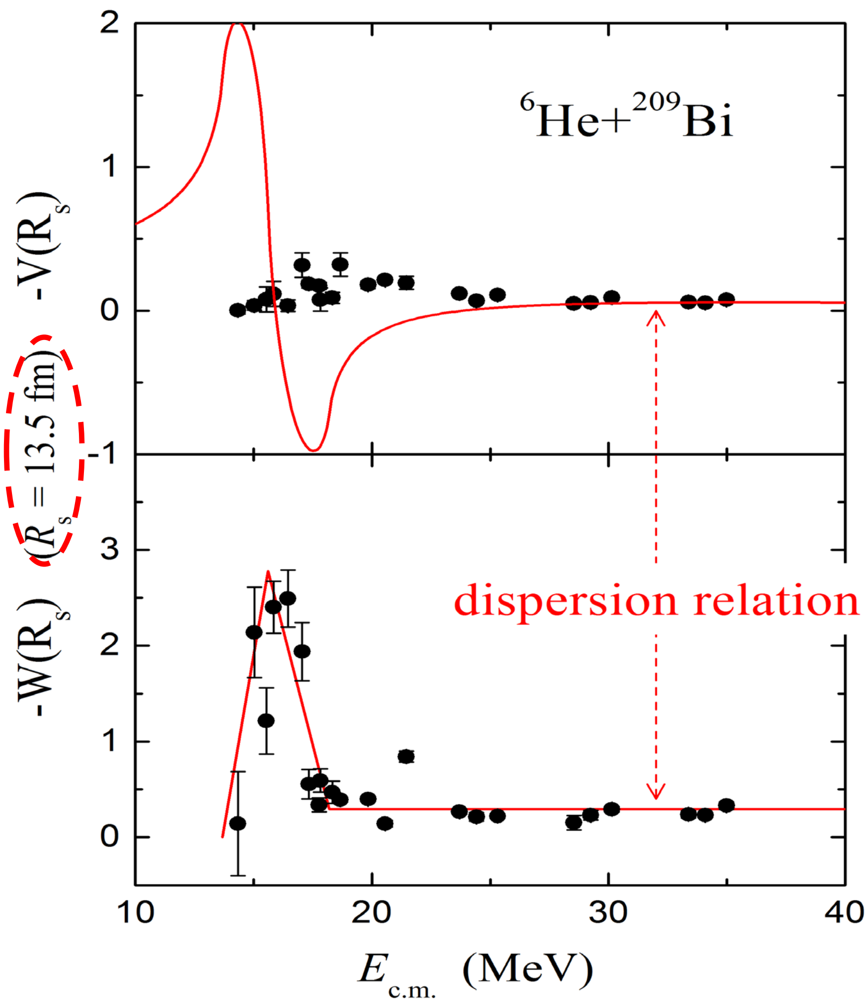
- Fit the elastic scattering to get the OP of $^{7}Li+^{208}Pb$
- Fit the transfer reactions to extract the OP of $^{6}He+^{209}Bi$
- By DWBA and CRC methods.



CRC scheme



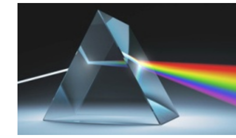
Results: $^{208}Pb(^{7}Li,^{6}He)^{209}Bi$



- ★ OMPs of the $^{6}He+^{209}Bi$ system are determined precisely for the first time;
- ★ The **decreasing trend** in the imaginary part is observed, and the **threshold energy** is about 13.73 MeV (**~0.7V_B**);
- ★ The behavior of real part looks normal, i.e. like a bell shape around the barrier;
- ★ The dispersion relation **does NOT hold** in this system.

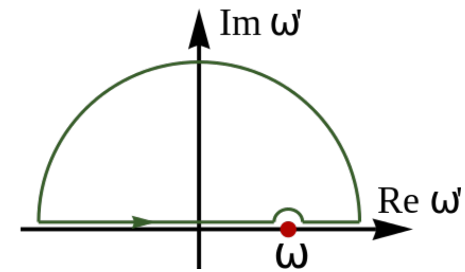
L. Yang, C.J. Lin, H.M. Jia et al., Phys. Rev. Lett. **119**, 042503 (2017);
Phys. Rev. C **96**, 044615 (2017).

Discussions



★ Dispersion relation results from causality, connecting real and imaginary part;
★ Any wave/particle should follow this rule when it passes through a media;
★ The classical dispersion relation is not applicable for exotic nuclear systems.

Possible reasons:



Cauchy's residue theorem

- **Causality → dispersion relation**

  stable systems: causality ↔ analyticity

  [Phys. Rev. **104**, 1760 (1956).]

- **Cauchy integration**

  infinity poles (breakup) & off-axis (multi-process)

  [Nucl. Phys. A **449**, 354 (1986).]

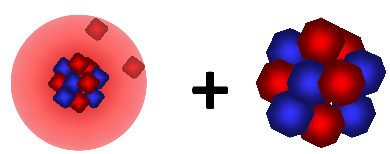
- **Negative Index of Refraction**

  causality based criteria must be used with care

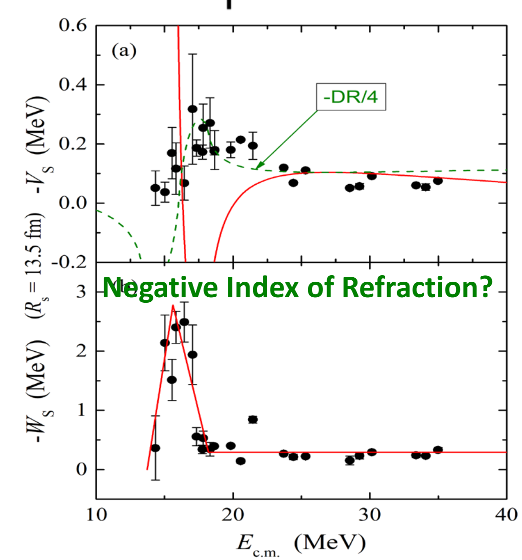
  [Phys. Rev. Lett. **101**, 167401 (2008).]

- **Locality vs. non-locality**

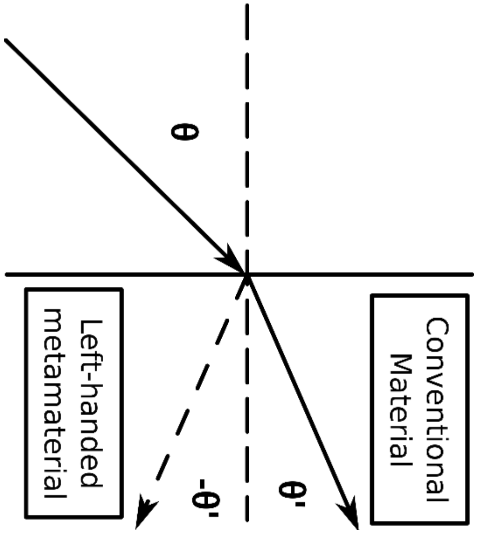
  equivalent local potential in Schrödinger equation

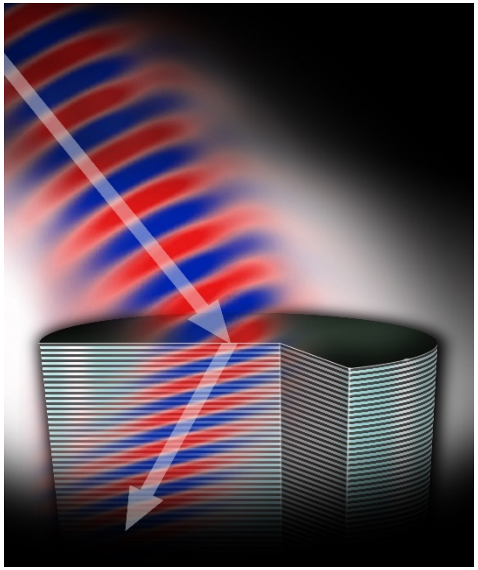


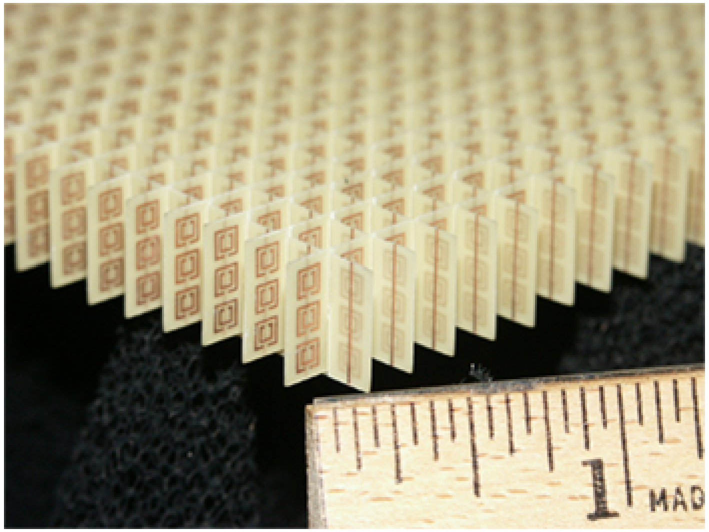
four-body



Negative Index Metamaterial







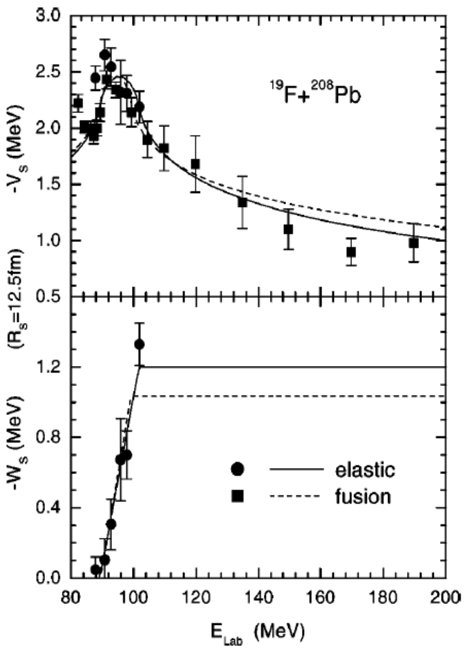
R.A. Shelby, D.R. Smith, S. Schultz, "Experimental Verification of a Negative Index of Refraction", Science **292**, 77 (2001).

Negative refractive index metamaterials offer the possibility of revolutionary applications, such as subwavelength focusing [1], **invisibility cloaking** [2], and "trapped rainbow" **stopping of light** [3].

PRL 105, 127401 (2010).

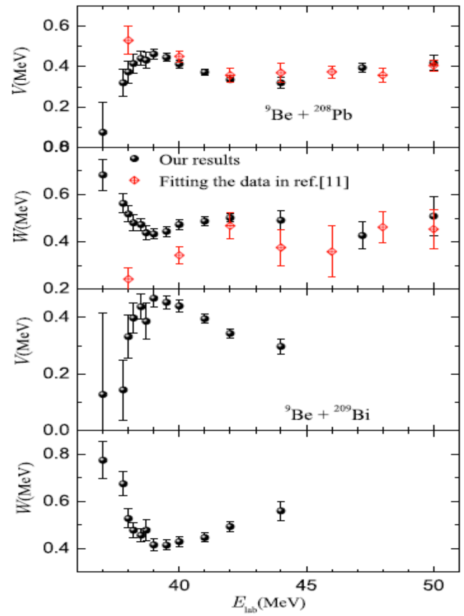
唯象光学势

^{17}F+^{208}Pb



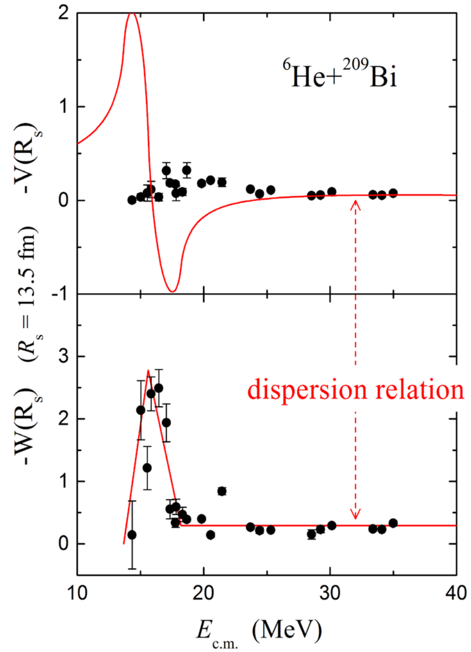
C.J. Lin et al.,
PRC **63**, 064606 (2001).

^{9}Be+^{208}Pb,^{209}Bi



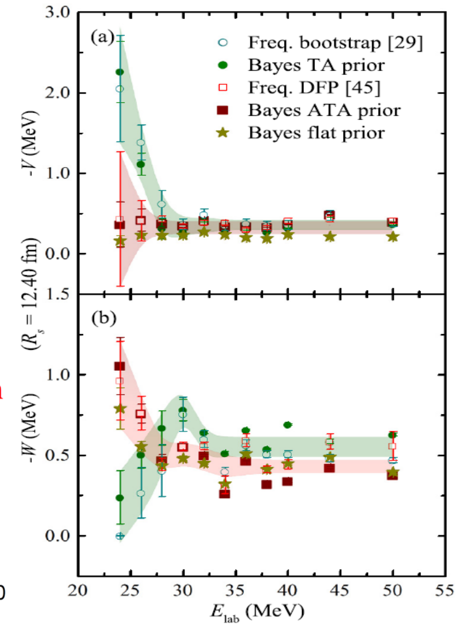
N. Yu et al.,
JPG **371**, 075108 (2010).

^{6}He+^{209}Bi



L. Yang et al.,
PRL **119**, 042503 (2017).

Bayes analyses



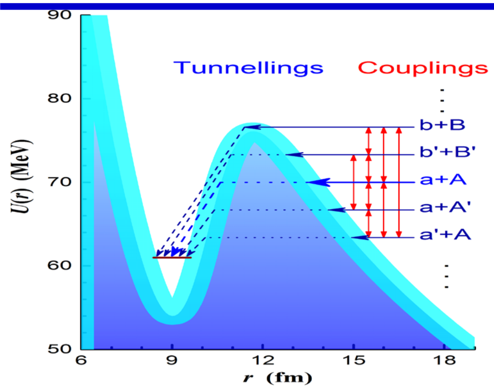
L. Yang et al.,
PLB **119**, 042503 (2020).

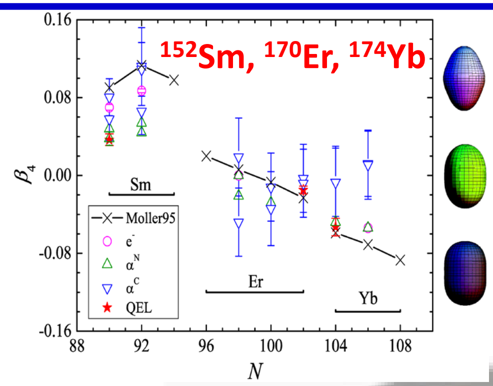
★ 紧束缚核体系：阈异常，色散关系 ← 因果关系；

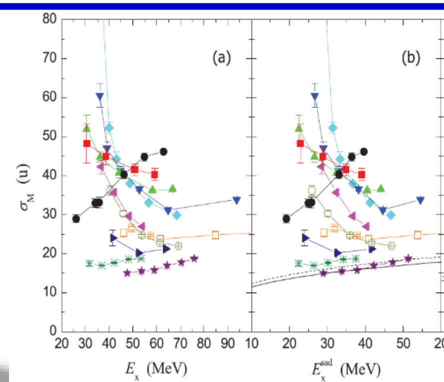
★ 弱束缚核体系：反常阈异常，色散关系不成立。

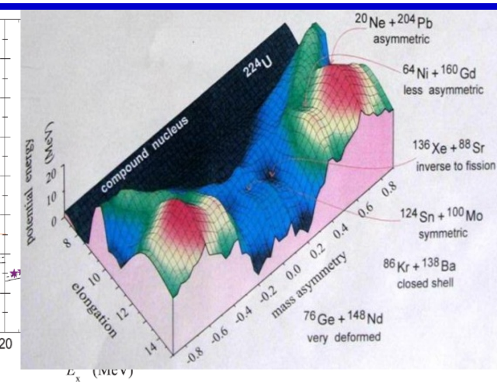
中国原子能科学研究院
中核集团 CHINA INSTITUTE OF ATOMIC ENERGY

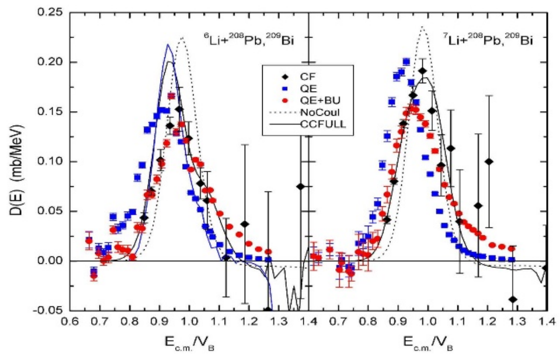
核反应组

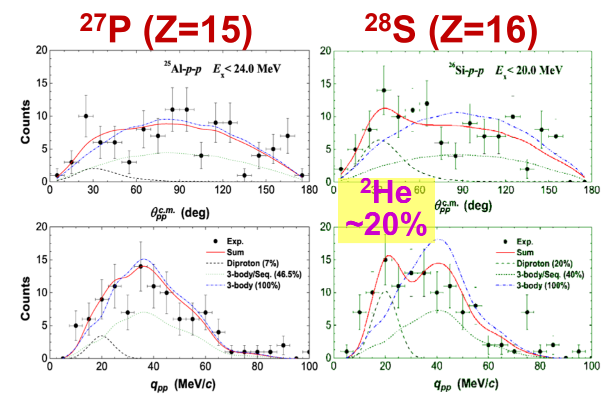


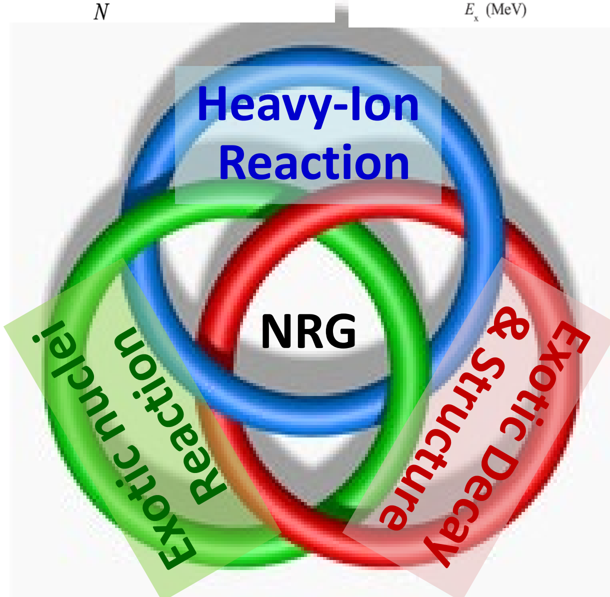


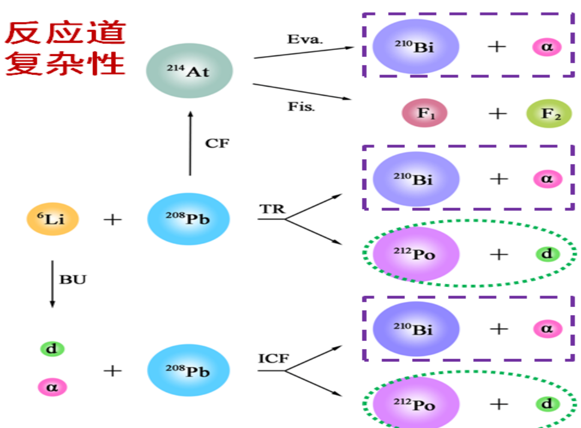


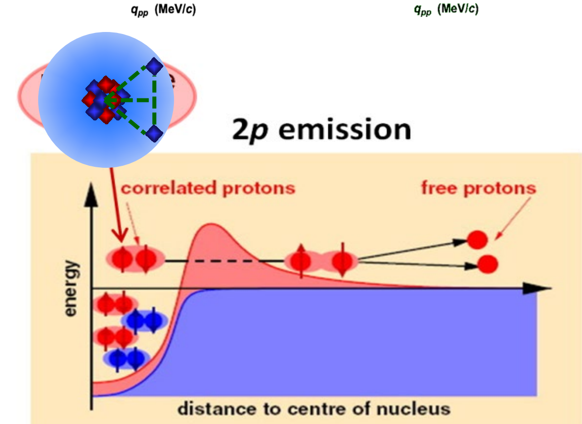












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Phys. Rev. Lett. **125**, 192503 (2020).
Phys. Lett. B **807**, 135540 (2020).
Phys. Rev. Lett. **119**, 042503 (2017).
Phys. Lett. B **766**, 312 (2017).