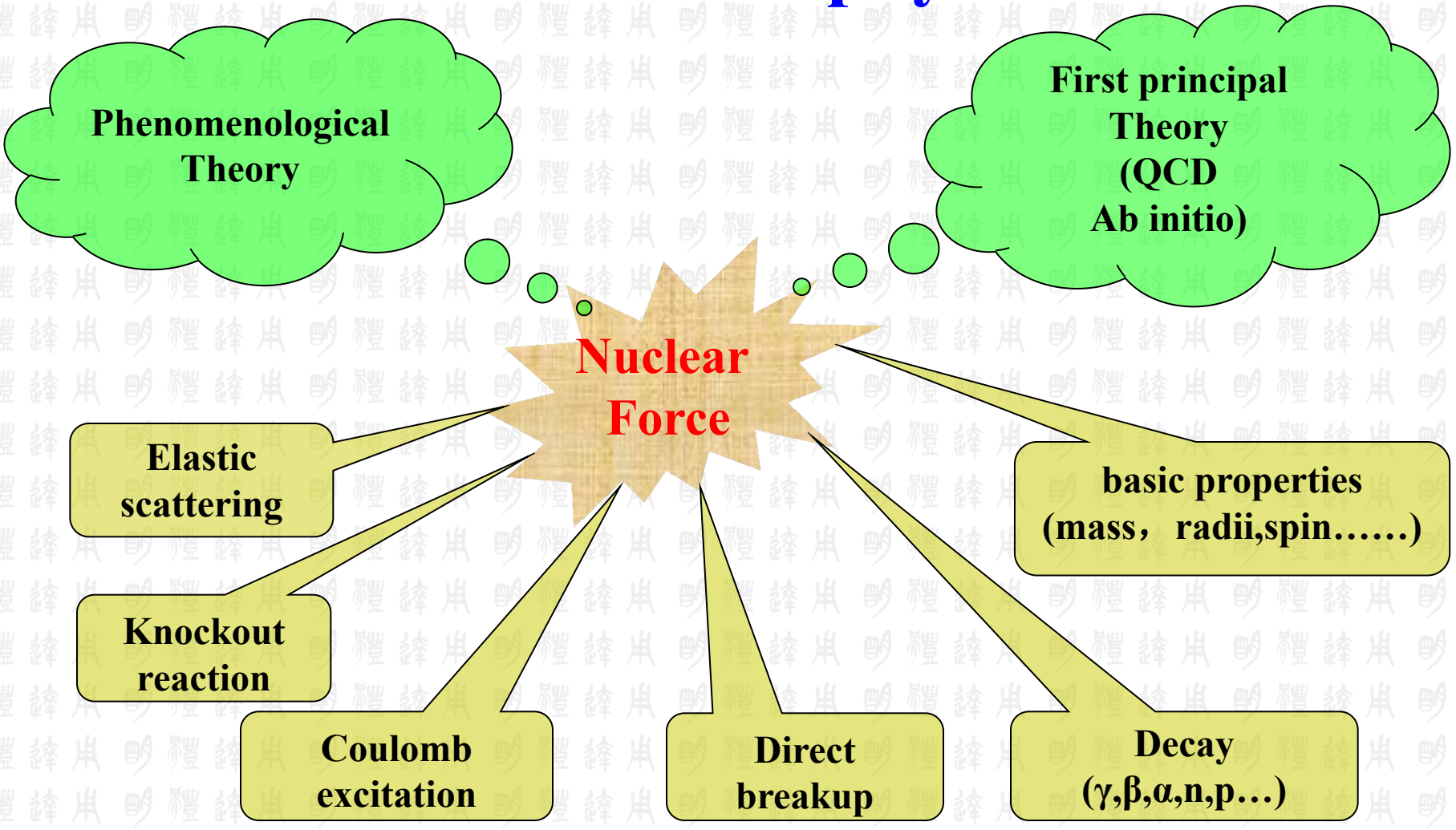
不稳定原子核的奇特结构与直接反应机制研究

王建松
湖州师范学院

报告内容

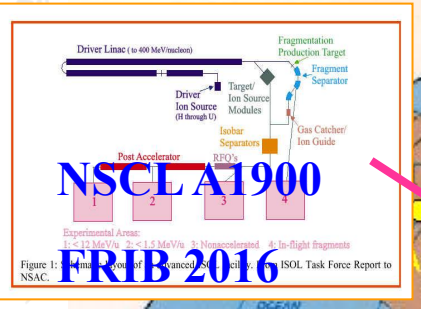
- 不稳定原子核研究背景：晕结构
- 不稳定原子核的奇特结构与直接反应
- 原子核的3核子集团（t、^{3}He）和纯中子集团
- 结论和展望

What does nuclear physics do?



The **precise** and **accurate** experimental data is the benchmark

国内外核物理实验大科学装置



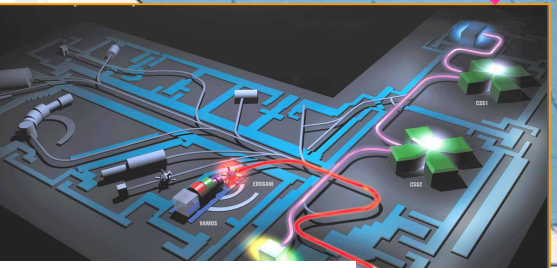
NSCL A1900

FRIB 2016

BRIF 2011

HIRFL：
RIBLL
1RIBL

L2

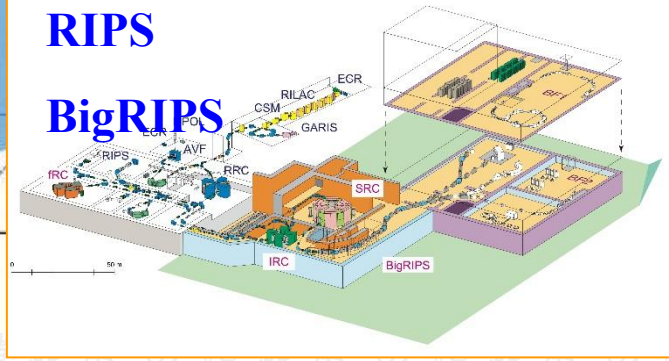


法国SPIRAL-II 2007

德国FAIR 2012

RIPS

BigRIPS



New Phenomena

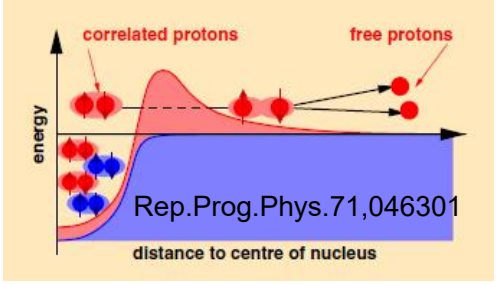
Shell Evolution

Exotic Structure

Exotic Decay Mode

New Collective Motion

HIRFL-RIBLL1

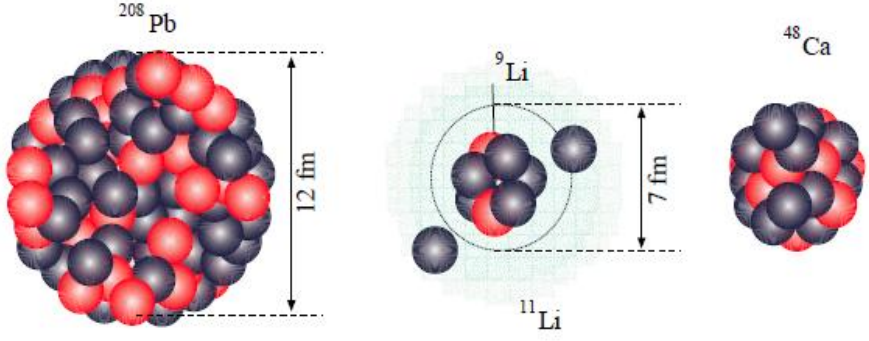


CSR-RIBLL2

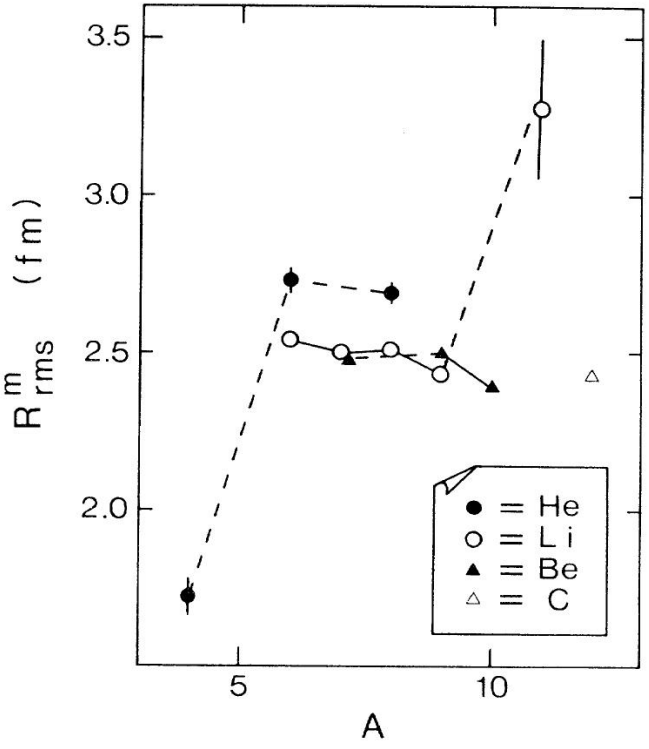
原子核晕结构的发现

TABLE I. Interaction cross sections (σ_I) in millibarns.

Beam	Target Be	C	Al
^{6}Li	651 ± 6	688 ± 10	1010 ± 11
^{7}Li	686 ± 4	736 ± 6	1071 ± 7
^{8}Li	727 ± 6	768 ± 9	1147 ± 14
^{9}Li	739 ± 5	796 ± 6	1135 ± 7
^{11}Li		1040 ± 60	
^{7}Be	682 ± 6	738 ± 9	1050 ± 17
^{9}Be	755 ± 6	806 ± 9	1174 ± 11
^{10}Be	755 ± 7	813 ± 10	1153 ± 16



Phys.Rep.389,1-59



I. Tanihata et al., PRL55(1985)2676

晕结构存在的条件

- 价核子处于s或p轨道
- 价核子的分离能很小

$$B < 270\,\mathrm{keV}\,\frac{A^2}{Z^2}\ \text{for } s\text{-states}, \tag{9}$$

$$Z < 0.44\,A^{4/3}\ \text{for } p\text{-states}, \tag{10}$$

$$B < 2\,\mathrm{MeV}\,A^{-2/3}\ \text{for both } s\text{- and } p\text{-states}, \tag{11}$$

A.S. Jensen, K. Riisager，Physics Letters B 480（2000）39–44

s,p轨道不是晕核存在的必要条件？

PHYSICAL REVIEW LETTERS **126,** 082501 (2021)

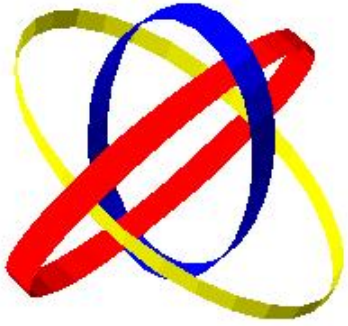
Quasifree Neutron Knockout Reaction Reveals a Small *s*-Orbital Component in the Borromean Nucleus ^{17}B

Z. H. Yang,[1,2,*] Y. Kubota,[2,3,†] A. Corsi,[4] K. Yoshida,[5] X.-X. Sun,[6,7] J. G. Li,[8] M. Kimura,[9,10,1] N. Michel,[11,12] K. Ogata,[1,13] C. X. Yuan,[14] Q. Yuan,[8] G. Authelet,[4] H. Baba,[2] C. Caesar,[15] D. Calvet,[4] A. Delbart,[4] M. Dozono,[3] J. Feng,[8] F. Flavigny,[16,‡] J.-M. Gheller,[4] J. Gibelin,[17] A. Giganon,[4] A. Gillibert,[4] K. Hasegawa,[18] T. Isobe,[2] Y. Kanaya,[19] S. Kawakami,[19] D. Kim,[20] Y. Kiyokawa,[3] M. Kobayashi,[3] N. Kobayashi,[21] T. Kobayashi,[18] Y. Kondo,[22] Z. Korkulu,[20,23] S. Koyama,[21] V. Lapoux,[4] Y. Maeda,[19] F. M. Marqués,[17] T. Motobayashi,[2] T. Miyazaki,[21] T. Nakamura,[22] N. Nakatsuka,[24] Y. Nishio,[25] A. Obertelli,[4,†] A. Ohkura,[25] N. A. Orr,[17] S. Ota,[3] H. Otsu,[2] T. Ozaki,[22] V. Panin,[2] S. Paschalis,[15,§] E. C. Pollacco,[4] S. Reichert,[26] J.-Y. Roussé,[4] A. T. Saito,[22] S. Sakaguchi,[25] M. Sako,[2] C. Santamaria,[4] M. Sasano,[2] H. Sato,[2] M. Shikata,[22] Y. Shimizu,[2] Y. Shindo,[25] L. Stuhl,[20,2] T. Sumikama,[18] Y. L. Sun,[4,†] M. Tabata,[25] Y. Togano,[22,27] J. Tsubota,[22] F. R. Xu,[8] J. Yasuda,[25]

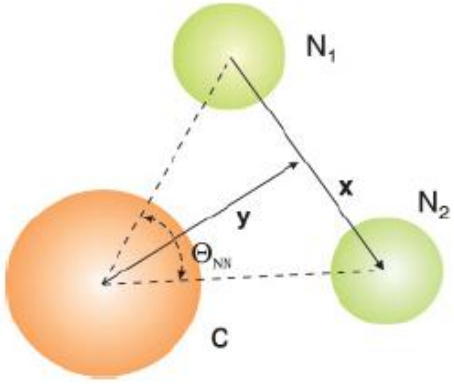
谱因子数据表明： s 波只占 9%，其余为d波

explained by the deformed relativistic Hartree-Bogoliubov theory in continuum, revealing a definite but not dominant neutron halo in ^{17}B. The present work gives the smallest *s*- or *p*-orbital component among known nuclei exhibiting halo features and implies that the dominant occupation of *s* or *p* orbitals is not a prerequisite for the occurrence of a neutron halo.

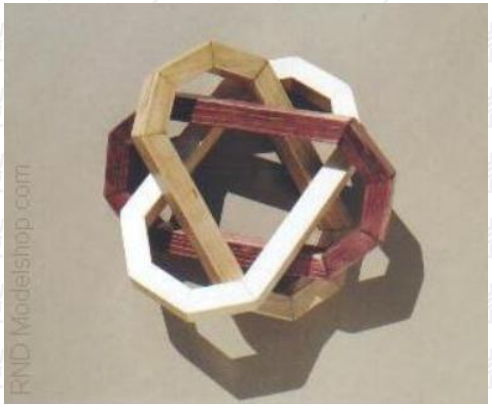
Borromean Nuclei ^{6}He



point-proton radius of ^{6}He: **1.912±0.018 fm**

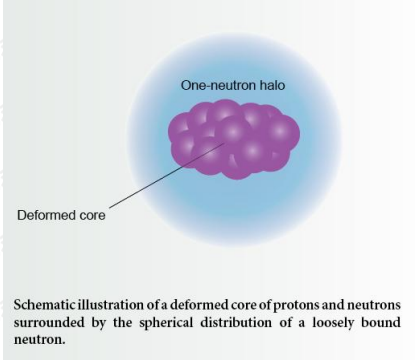


L. –B. Wang et al., PhysRevLett.93.142501(2004)



- PRL 117, 222501 (2016) "How Many-Body Correlations and α Clustering Shape ^{6}He"
- The simultaneous reproduction of its small binding energy and extended matter and point-proton radii has been a challenge for ab initio theoretical calculations based on traditional bound-state methods

理论预言可能的奇特晕结构



Schematic illustration of a deformed core of protons and neutrons surrounded by the spherical distribution of a loosely bound neutron.

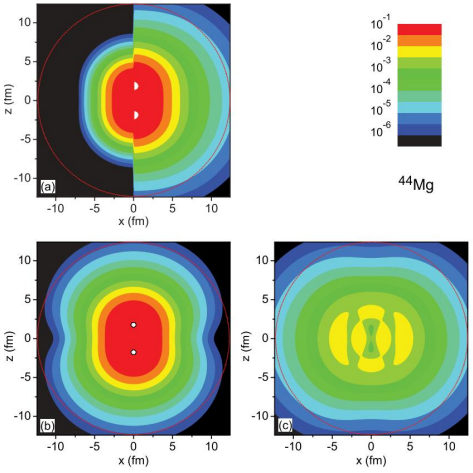
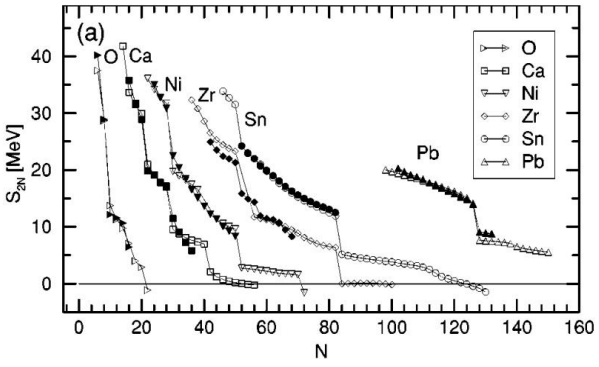
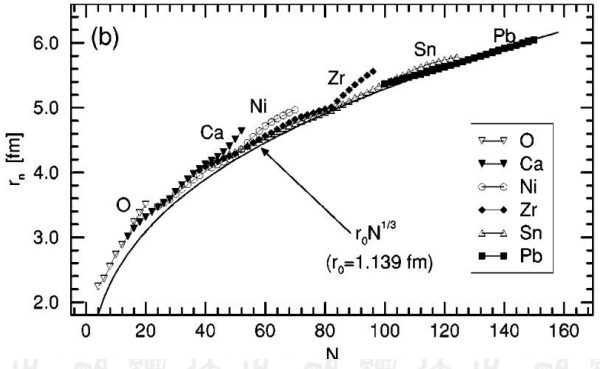
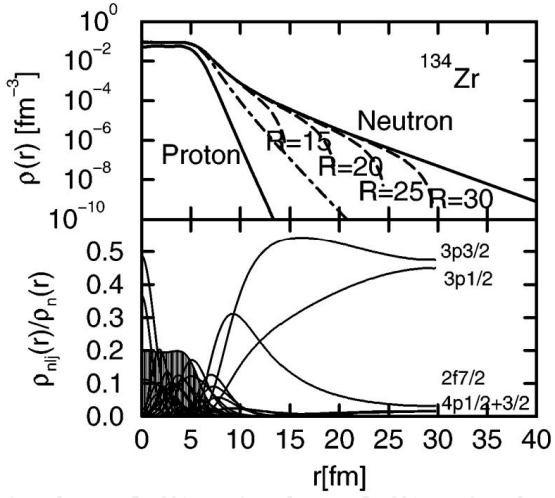


FIG. 1. (Color online) Density distributions of ^{44}Mg with the z axis as the symmetry axis. (a) The proton density (for $x < 0$) and the neutron density (for $x > 0$), (b) the density of the neutron core, and (c) the density of the neutron halo. In each plot, a dotted circle is drawn to guide the eye.





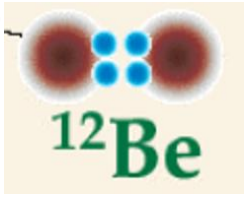
巨晕核
核芯形变



J. Meng and P. Ring, Phys. Rev. Lett. **80**, 460 (1998) cited 238 times/J. Meng et al.,Phys.Rev.C65(2002) 041302(R) /Phys.Rev. **74**, 054318 (2006)

S. G. Zhou, J. Meng, Phys. Rev. C **82**, 011301(R) (2010) cited 139 times

Light Halo Nuclei



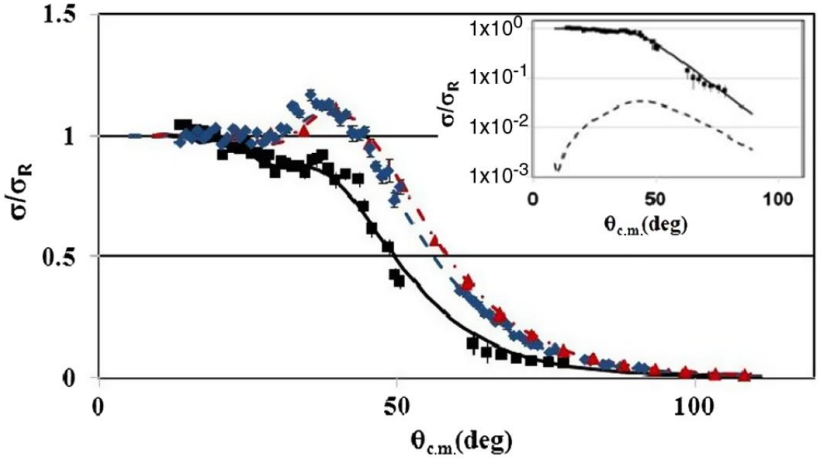
PRL123（2019）212501
PRL123（2022）212502

	Sp /S2p(MeV)		Sn（MeV）
8B	**0.136**	**6He**	**0.976(2n)**
9C	1.300	8He	3.1 (4n)
12N	**0.600**	**11Li**	**0.369(2n)**
13O	1.512	**11Be**	**0.502**
17F	**0.600**	14Be	1.266 (2n)
17Ne	**0.933 (2p)**	17B	1.385
		19C	**0.577**

^{8}B: S_p= 136.4 keV *10*, $T_{1/2}$=770 ms *3*
found in 1950 at Berkley linear acceleratc

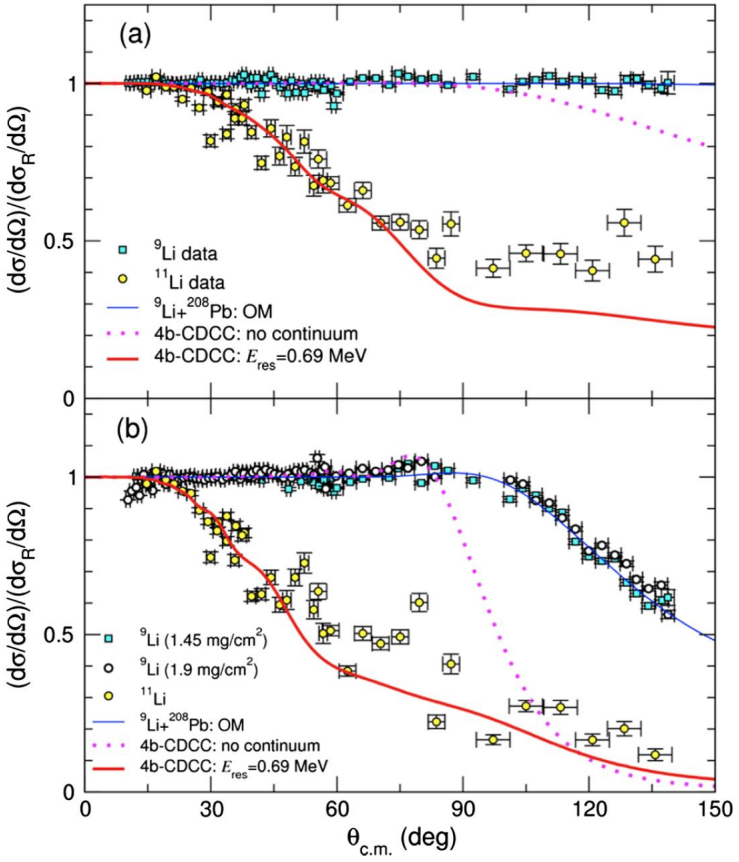
中子晕核^{11}Be、^{11}Li对弹性散射的影响

9、10、11 Be+^{64}Zn



A. Di Pietro et al., PRL 105 （2010）022701 @REX-ISOLDE at CERN

9、11 Li+^{208}Pb



M. Cubero et al., PRL 109 (2012) 262701@TRIUMF

^{11}Be在^{197}Au靶上的核心激发效应

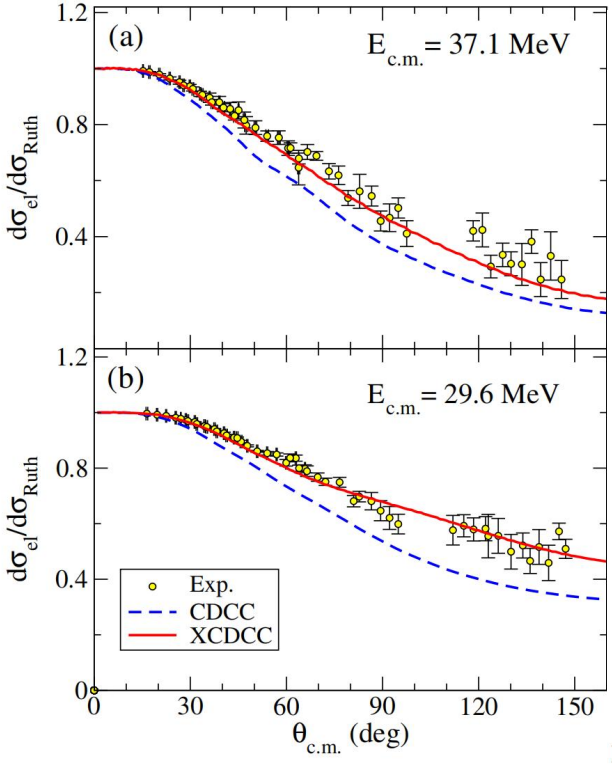


FIG. 3. Measured differential elastic scattering cross secti
(a) $E_{\mathrm{c.m.}} = 37.1$ MeV and (b) 29.6 MeV, compared wit
CDCC and XCDCC calculations described in the text.

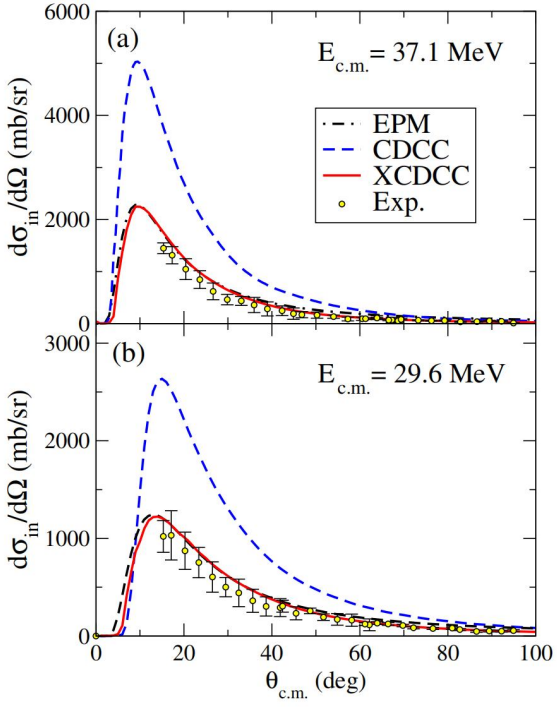
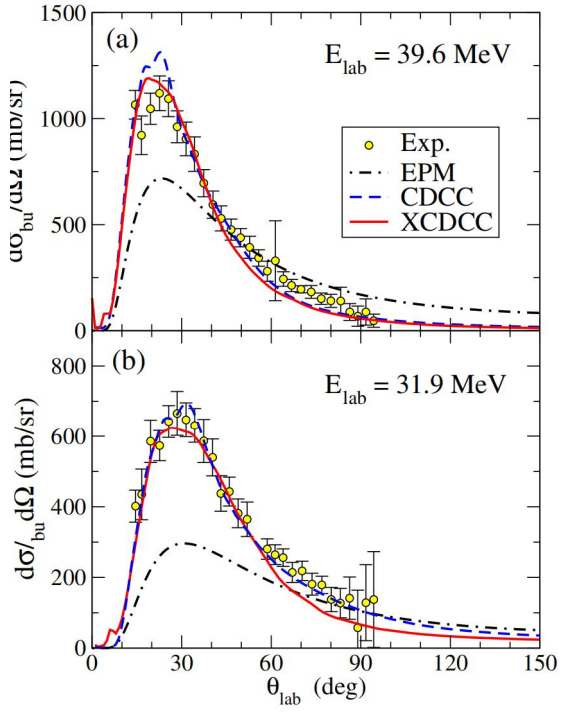


FIG. 4. Measured and calculated angular distribution of the
inelastic differential cross section of ^{11}Be + ^{197}Au, populating
the $1/2^-$ bound excited state in ^{11}Be for (a) $E_{\mathrm{c.m.}} = 37.1$ MeV
and (b) 29.6 MeV. The curves are the EPM, CDCC, and XCDCC
calculations described in the text.



5. Experimental differential breakup cross section in the
tory frame at (a) $E_{\mathrm{lab}} = 39.6$ MeV and (b) 31.9 MeV,
ared with EPM, CDCC, and XCDCC calculations described
text.

V. Pesudo, M. J. G. Borge, A. M. Moro et al., PRL 118, 152502 (2017) @ TRIUMF

^{8}B在库仑位垒附近的破裂机制研究

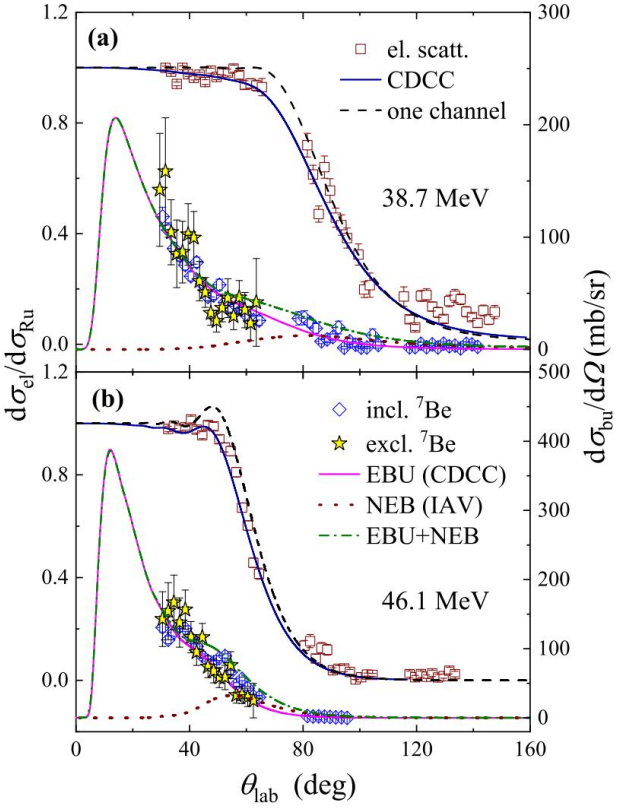


Fig. 2 | Angular distributions of elastic scattering and breakup reactions.
Squares, diamonds and stars denote the experimental data of elastic scattering, inclusive and exclusive breakup at **a** 38.7 and **b** 46.1 MeV, respectively. The elast experimental data (circles) at **a** 38.7 and **b** 46.1 MeV are compared with the simu-

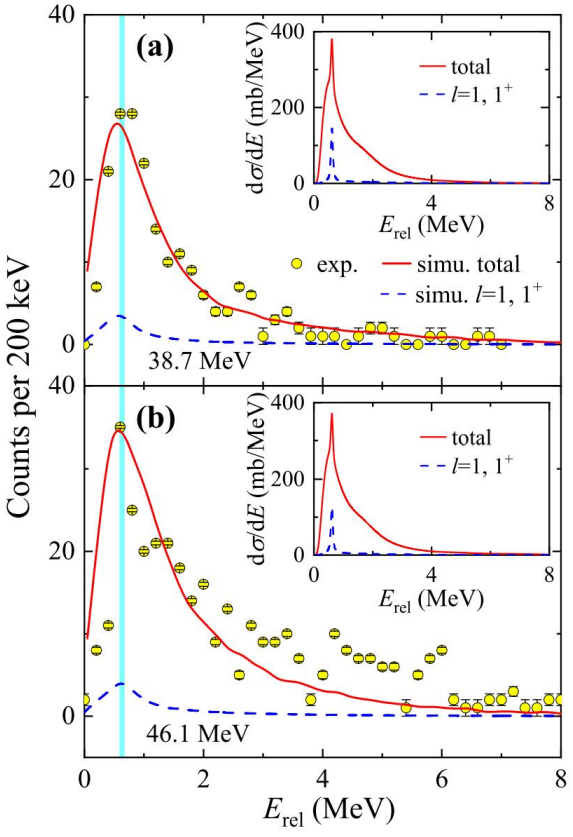
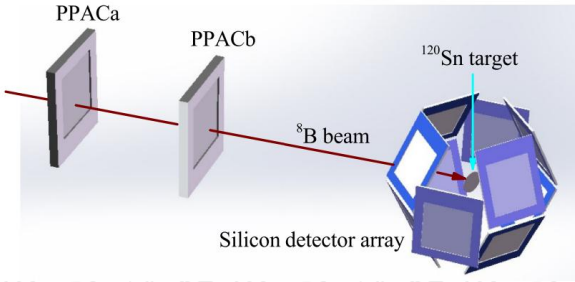


Fig. 3 | Measured E_{rel} distributions for breakup fragments ^{7}Be and proton. The



- ^{8}B具有与^{6}He等中子晕核不一样的反应机制，
- 破裂反应对弹性散射和完全融合反应影响不显著。

L. Yang C. J. Lin ..., ***JW***,Nature Communications(2022)13:7193

不稳定原子核的奇特结构与直接反应

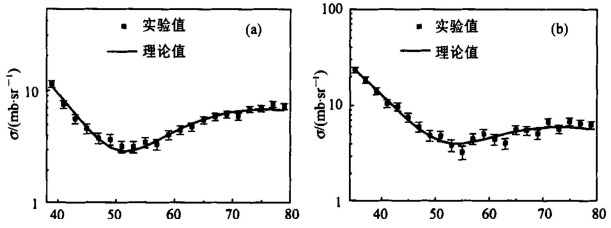
早期在RIBLL开展不稳定核弹性散射研究

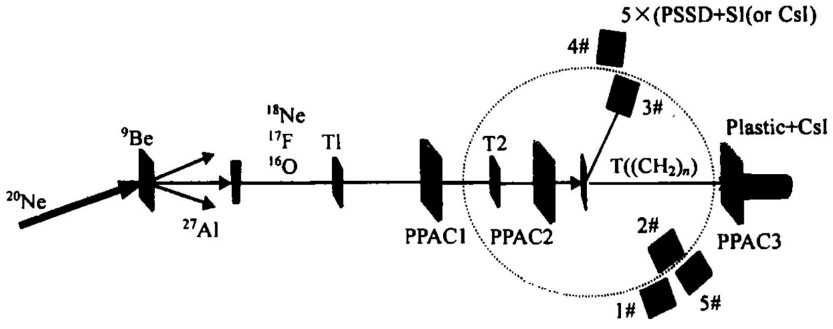
第 26 卷 第 6 期 高 能 物 理 与 核 物 理 Vol. 26, No. 6
2002 年 6 月 HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS Jun., 2002

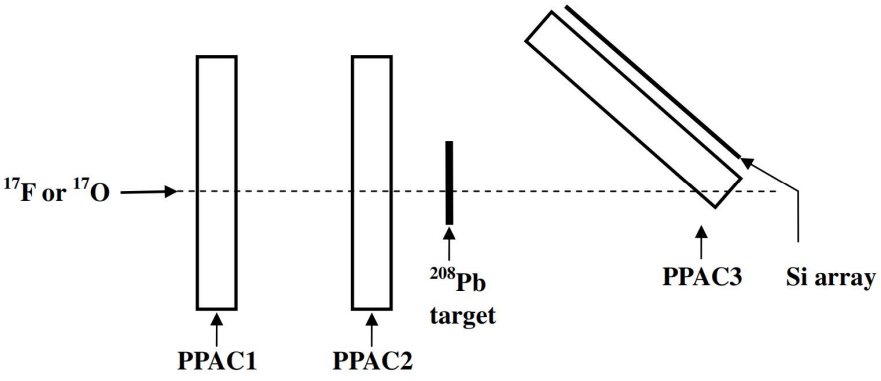
^{17}F 和 ^{18}Ne 与质子的弹性散射角分布 *

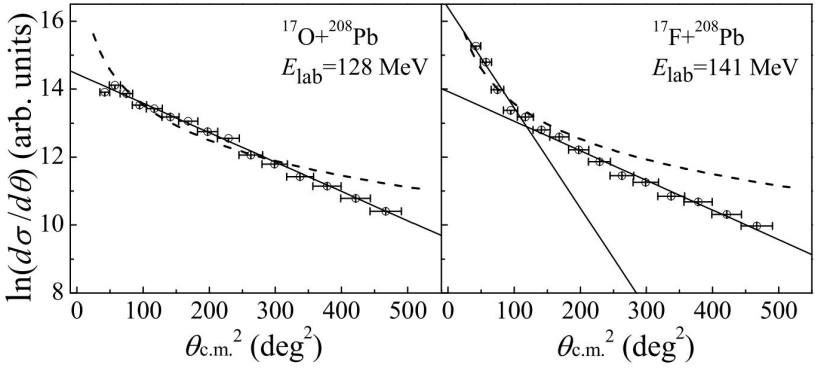
卢朝晖 吴和宇 胡荣江 诸永泰 张保国 李祖玉 魏志勇
段利敏 王宏伟 肖志刚 王素芳 靳根明 郭忠言
肖国青 朱海东 柳永英 陈克良
(中国科学院近代物理研究所 兰州 730000)

陈陶 李湘庆 李智焕
(北京大学技术物理系 北京 100871)



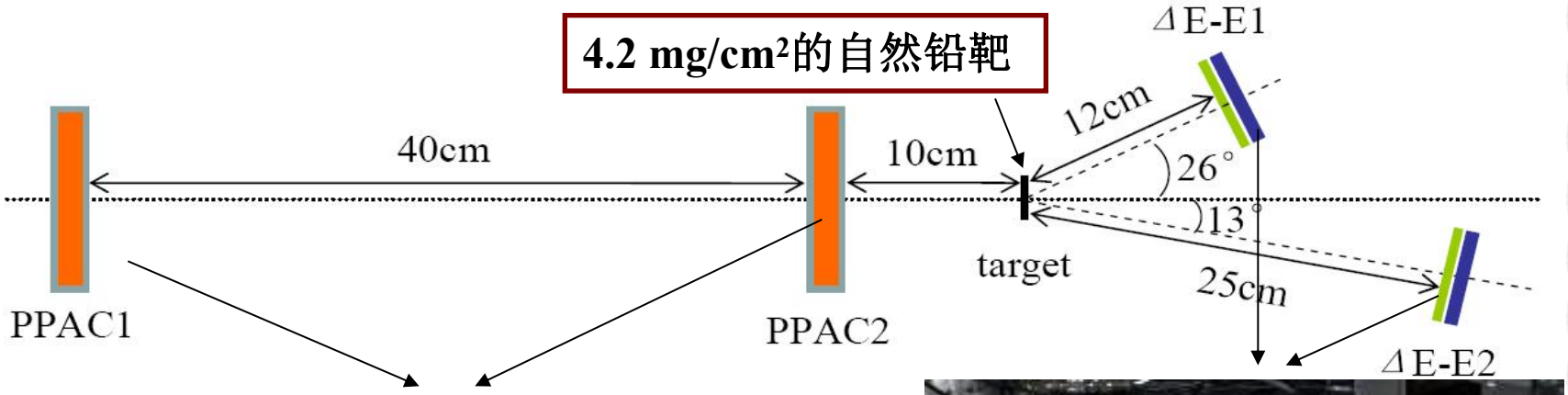


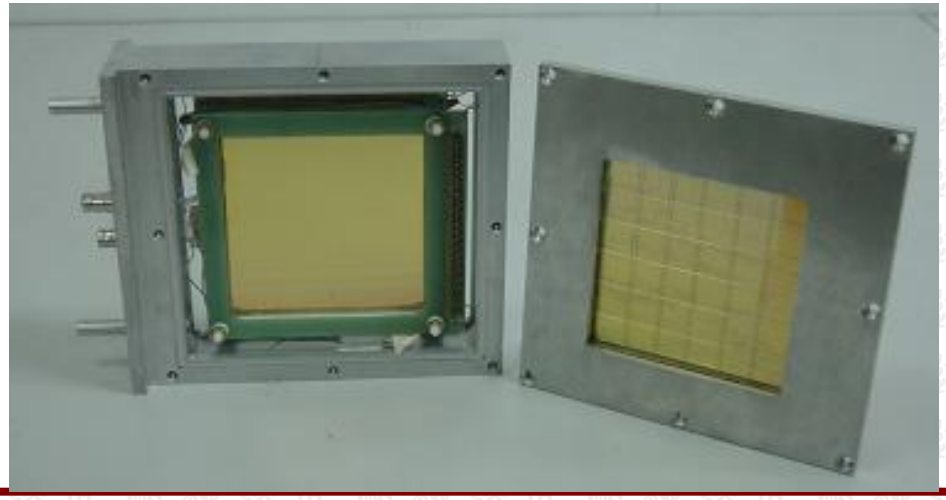




白真，王琦，韩建龙等
Chinese Physics Letters 24，3384

探测器布局

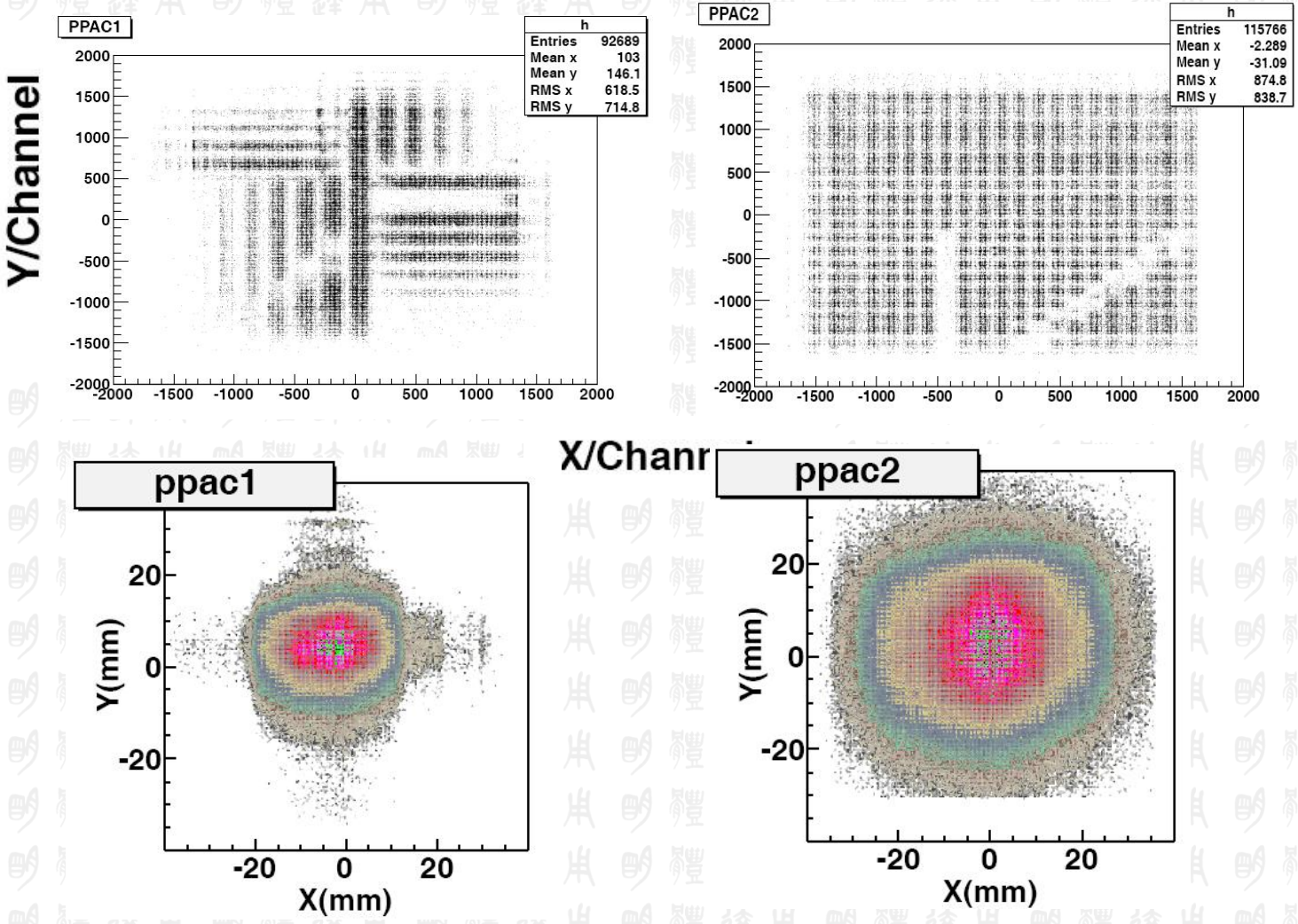




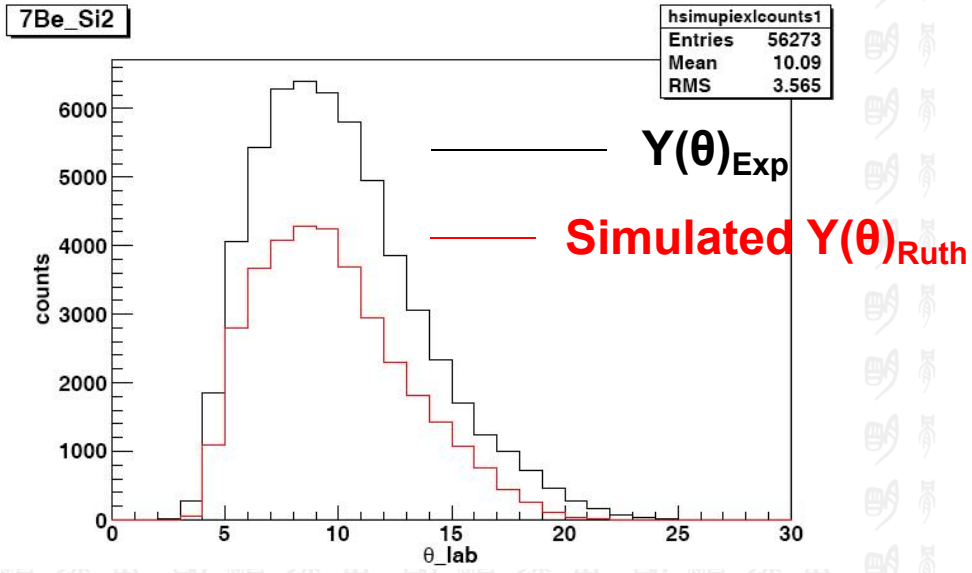
- PPAC灵敏面积为80×80 mm²，采用延迟块读出。
- 位置分辨为1 mm。
- 在PPAC上也会散射。

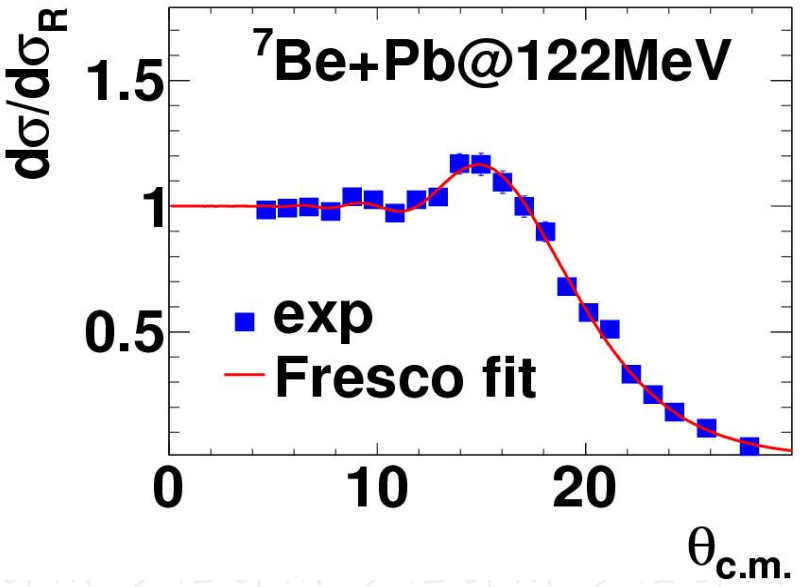
ΔE：48×48 mm²，150 μm
DSSD（48+48）
E： 50×50 mm² 1500 μm SSD
能量分辨 (α源)： 0.5 - 0.9% DSSD
1.2%-1.3% SSD

PPAC的位置刻度


PPAC1
h
Entries 92689
Mean x 103
Mean y 146.1
RMS x 618.5
RMS y 714.8
Y/Channel
PPAC2
h
Entries 115766
Mean x -2.289
Mean y -31.09
RMS x 874.8
RMS y 838.7
ppac1
Y(mm)
X(mm)
X/Chanr
ppac2
Y(mm)
X(mm)

How to Obtain the Correct ES Angular Distribution



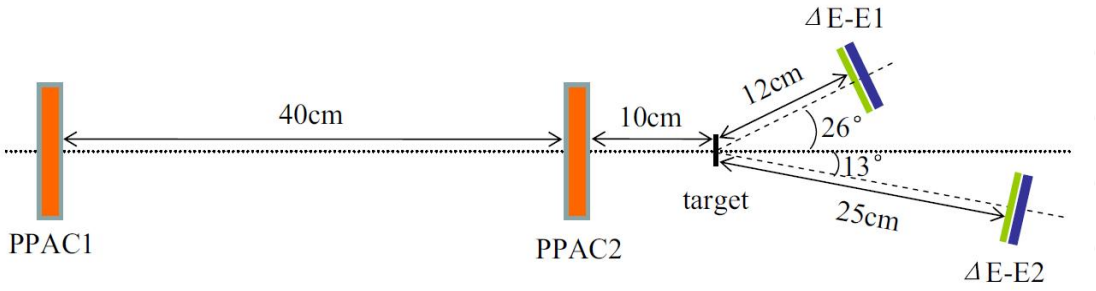


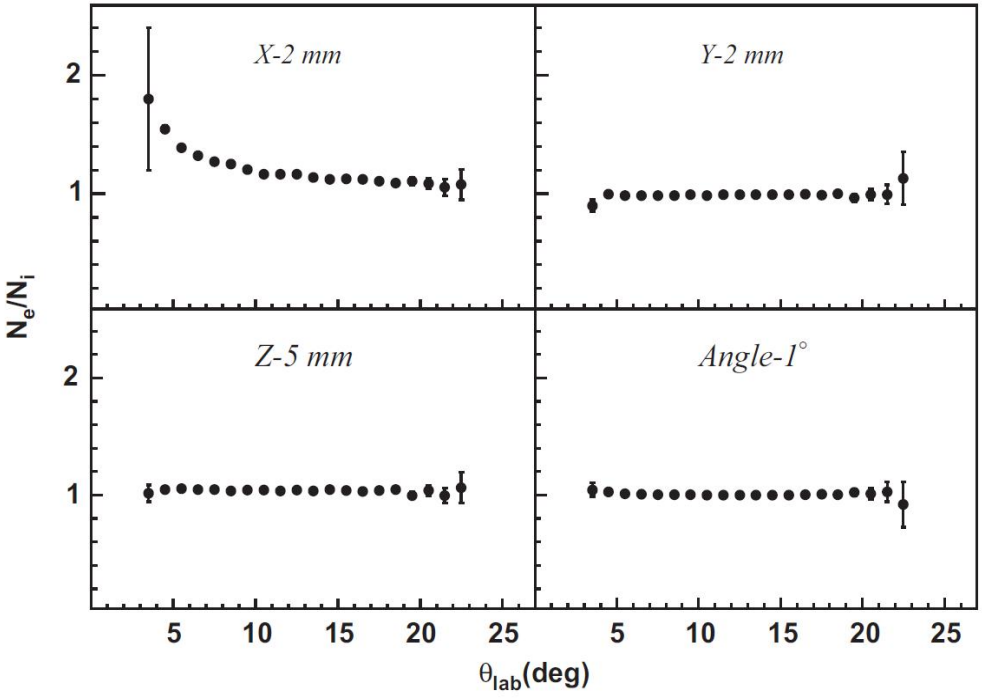
Because the secondary beams are dispersed widely, we have to simulate the Rutherford scattering events and compare with the experimental data to obtain the normalized differential cross section as the following:

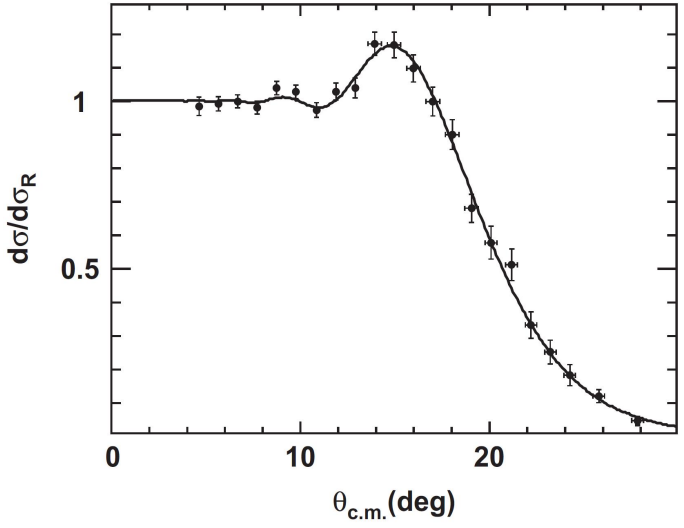
$$\sigma/\sigma_{Ruth}(\theta) = Y(\theta)_{Exp}/\ Y(\theta)_{Sim}$$

$Y(\theta)_{Exp}$, $Y(\theta)_{Sim}$ are the counts at a given angle θ from the experiment and the simulation, respectively.

Y.Y.Yang, J.S.Wang et al. NIMA701(2013)1

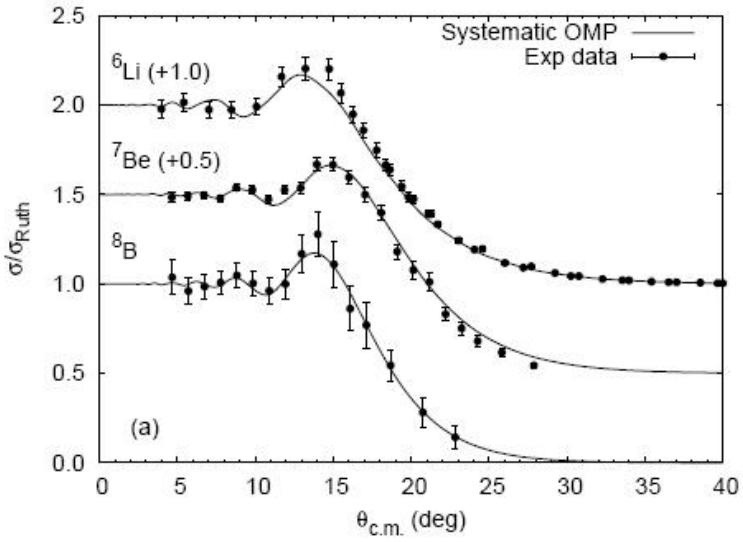


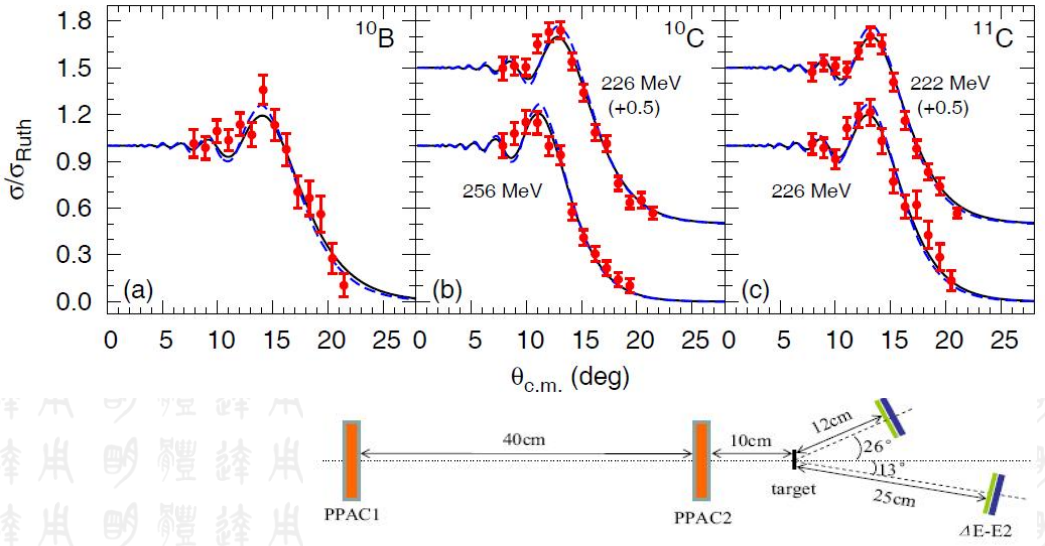




Y.Y.Yang, J.S.Wang et al. NIMA701(2013)1

轻质量奇特核的弹性散射研究





- 研究并提出了弹性散射**1/4**角的规律。
- 提出了描述不同核反应系统在低能区的核反应总截面的唯像公式
- 发展了在**RIBLL**上精确测量不稳定核弹性散的实验方法。
- 发现质子滴线核**^{8}B**、**^{9}C**与重靶弹性散射中没有库仑核势干涉峰的削弱现象。

Phys.Rev.C86 (2012)057602
Phys.Rev.C86 (2012)057603
Phys.Rev.C87 (2013)044613
Phys.Rev.C90 (2014)014606
Nucl.Inst.Meth.Phys.Res.A701(2013)1-6
Phys.Rev.C94 (2016)034614

^{8}B弹性的破裂反应截面

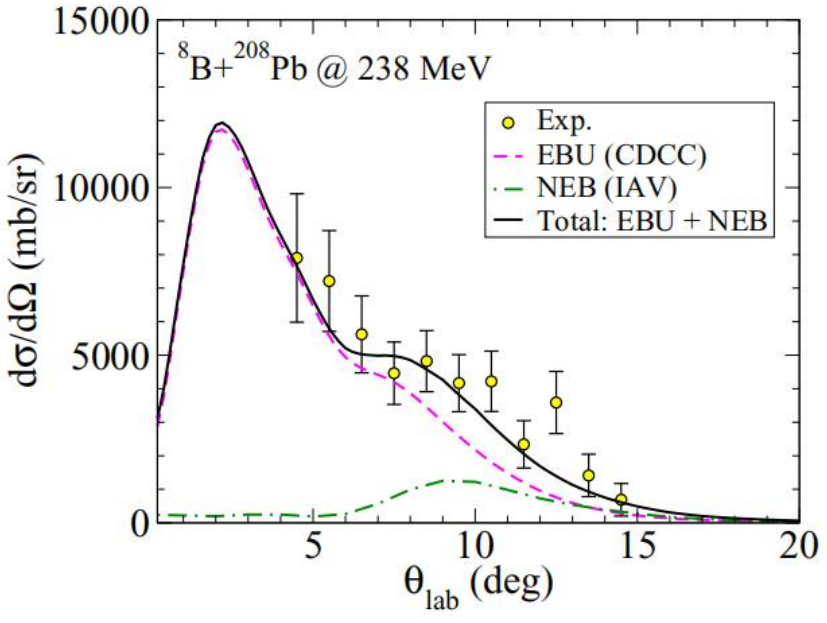
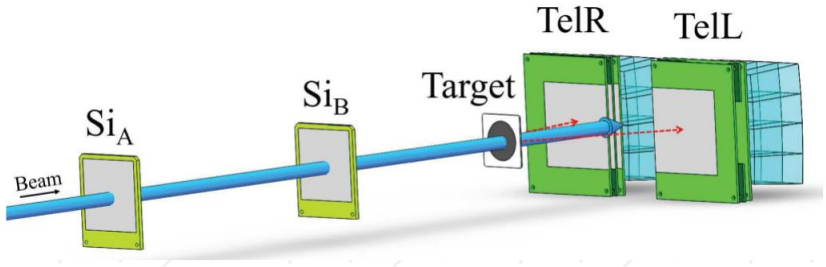
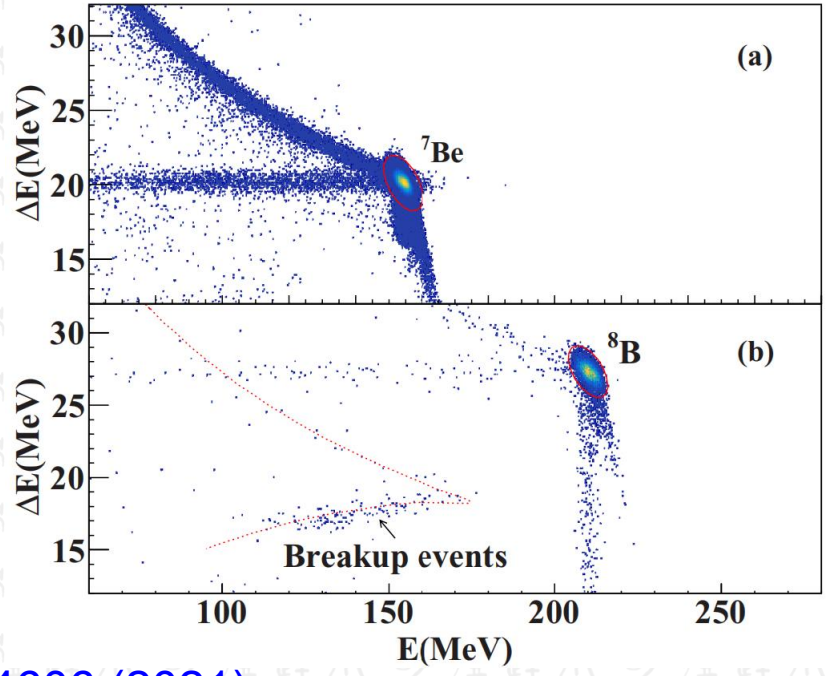
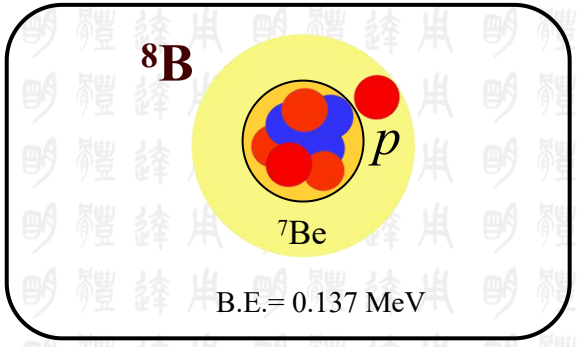


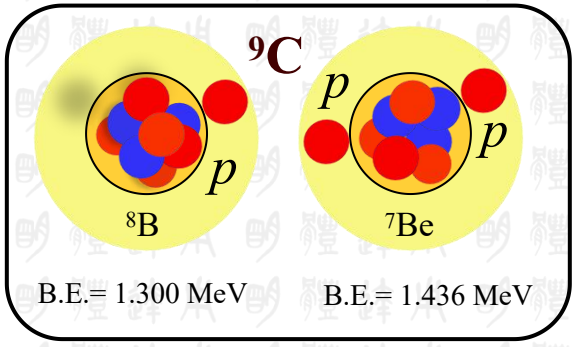
FIG. 5. Experimental ^{7}Be angular distributions from the ^{8}B + ^{208}Pb reaction at E_{lab} = 238 MeV (yellow circle) and comparisons with calculations. Error bars are statistical only.

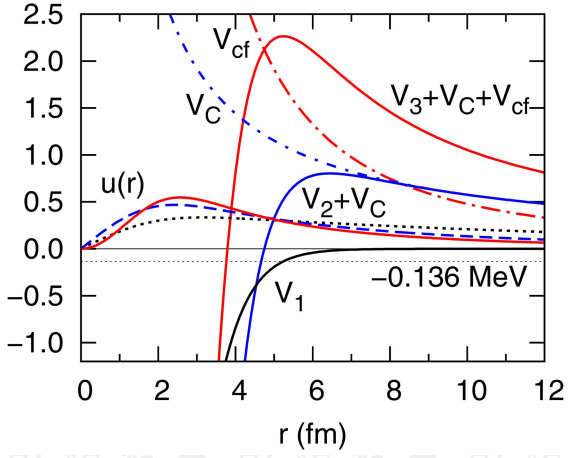


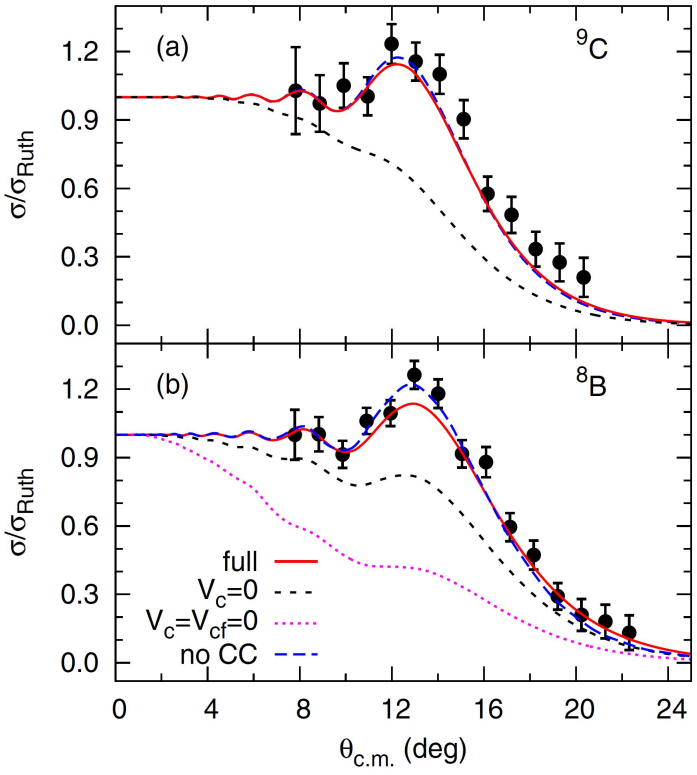


K. Wang, Y.Y.Yang,...***JW***,... PRC 103, 024606 (2021)







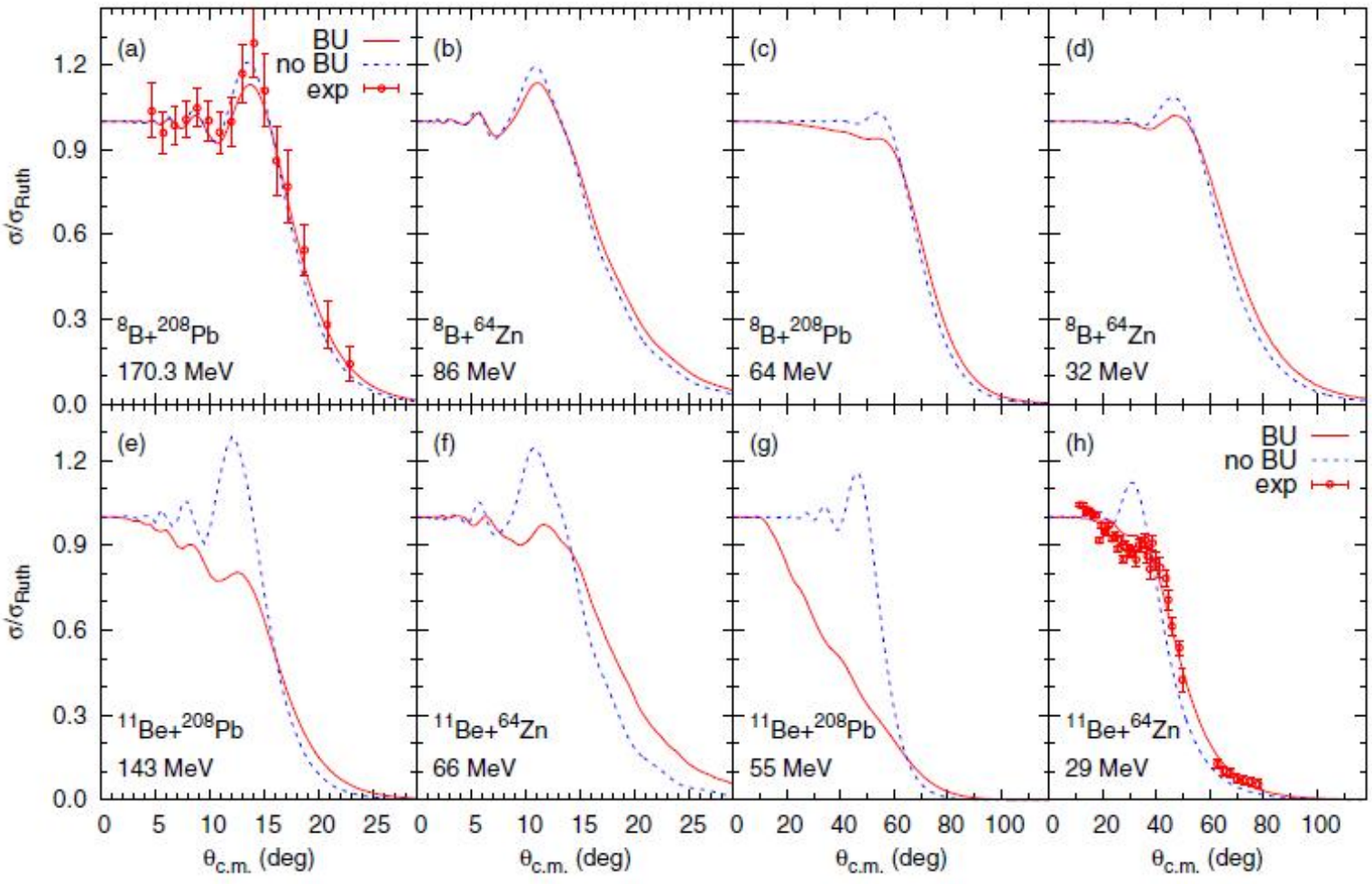


The problem is that the experiment has been done at energies where one should not expect a suppression of the Fresnel peak. **I do not think one can extract conclusions about possible halo effects of 9C by measuring its elastic scattering on lead at these relatively high energies.** The authors made a few statements in the abstract that I do not think are correct.

..... the promising halo candidate 9C shows a negligible suppression of the Coulomb rainbow at these energies, similar to that of 8B.

Y.Y.Yang, ...,***JW***,...,PRC 98, 044608 (2018)

Breakup effects in ^{8}B and ^{11}Be: CCDC Calculations



Y. Y. Yang, X. Liu, D. Y. Pang, Phys. Rev. C (2016) 94, 034614

3.5倍库仑位垒的^{11}Be弹性散射

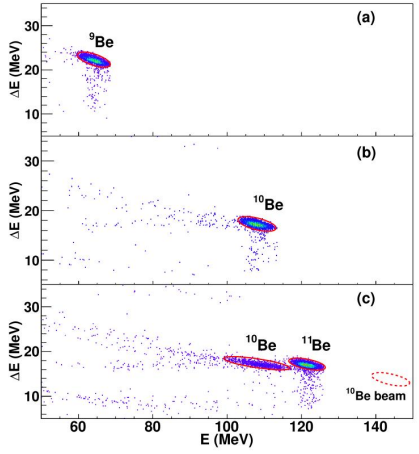


Fig. 2. The two-dimensional $\Delta E - E$ particle identification spectra for the (a) ^{9}Be, (b) ^{10}Be and (c) ^{11}Be beams within all the angles covered by the current measurement. In (c), the expected loci of ^{10}Be beam contamination are indicated and it is well separated from the group of ^{10}Be breakup fragment particles.

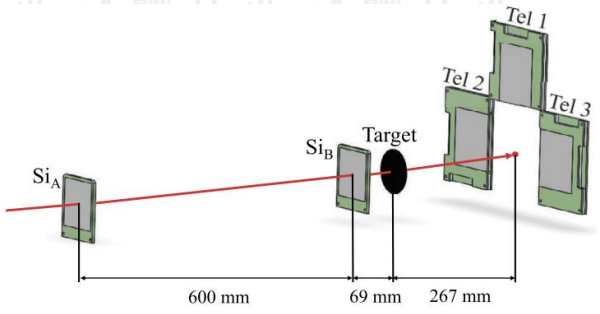


Fig. 1. Schematic view of the experimental setup.

F.F.Duan, Y. Y. Yang, ...,***JW*** et al., PhysLettB.811.135942

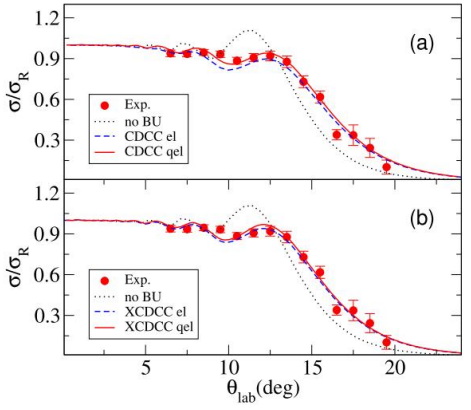


Fig. 4. Comparisons between results of CDCC (upper panel) and XCDCC (lower panel) calculations and the experimental data of the quasielastic scattering of ^{11}Be + ^{208}Pb at $E_{lab} = 140$ MeV. The dashed and dotted curves are for elastic scattering with and without including the continuum-continuum couplings, respectively. The solid curves are for quasielastic scattering, which are sums of elastic and inelastic scat-

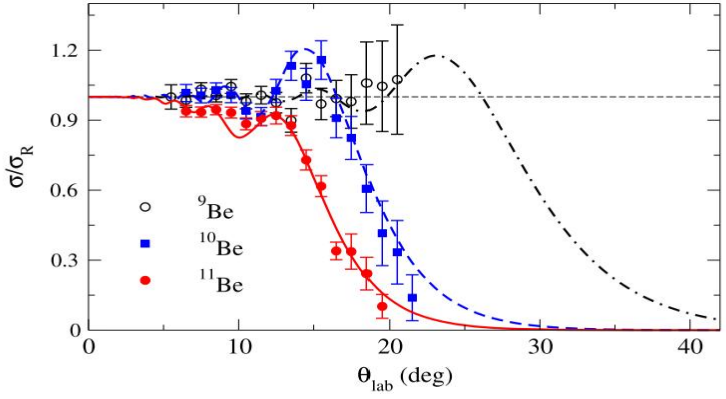


Fig. 3. Quasielastic scattering angular distributions for ^{9,10,11}Be + ^{208}Pb. The dash-dotted, dashed and solid curves are results of optical model calculations for ^{9}Be, ^{10}Be, and ^{11}Be, respectively. See the text for details.

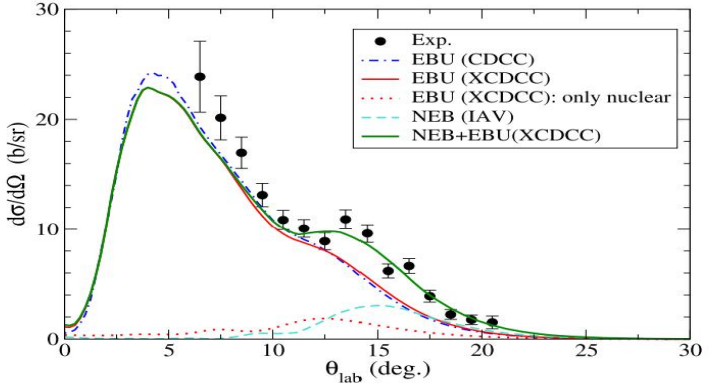


Fig. 5. Experimental differential breakup cross section for ^{11}Be + ^{208}Pb system at $E_{lab} = 140$ MeV compared with the CDCC and XCDCC calculations, for the elastic breakup part, and IAV calculations, for the NEB part. See text for the details.

5.2倍库伦位垒的^{11}Be弹散数据

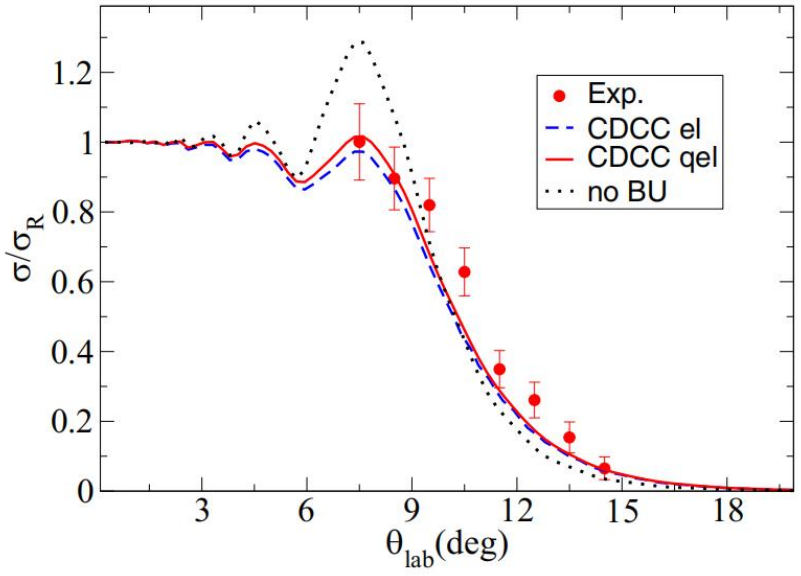


FIG. 3. The results of CDCC calculations and the experimental data of the quasielastic scattering of ^{11}Be + ^{208}Pb at E_{lab} = 210 MeV. The blue dashed, red solid, and black dotted curves are results of CDCC calculations of elastic and quasielastic scatterings and of no-continuum states, respectively.

F. F. Duan, Y.Y.Yang,...JW et al., Phys. Rev. C 105, 034602 (2022)

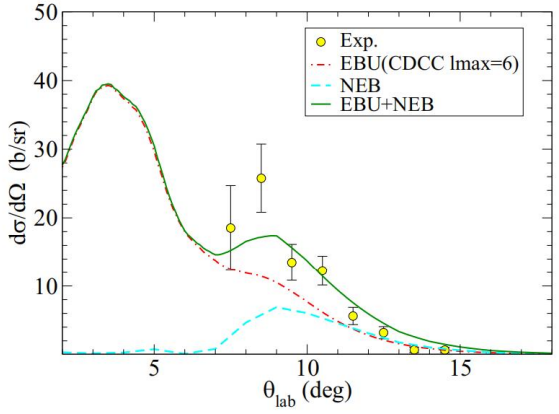


FIG. 6. Experimental breakup differential cross section, as a function of the ^{10}Be laboratory scattering angle, for the ^{11}Be + ^{208}Pb system at E_{lab} = 210 MeV compared with the calculations. See text for the details.

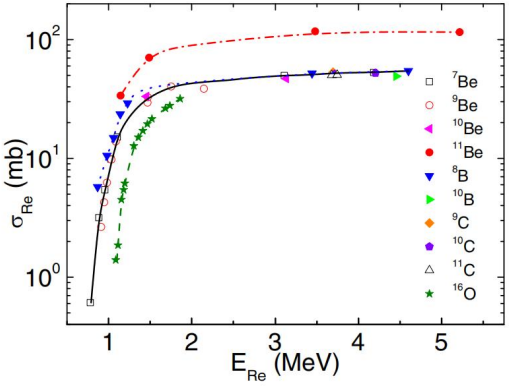
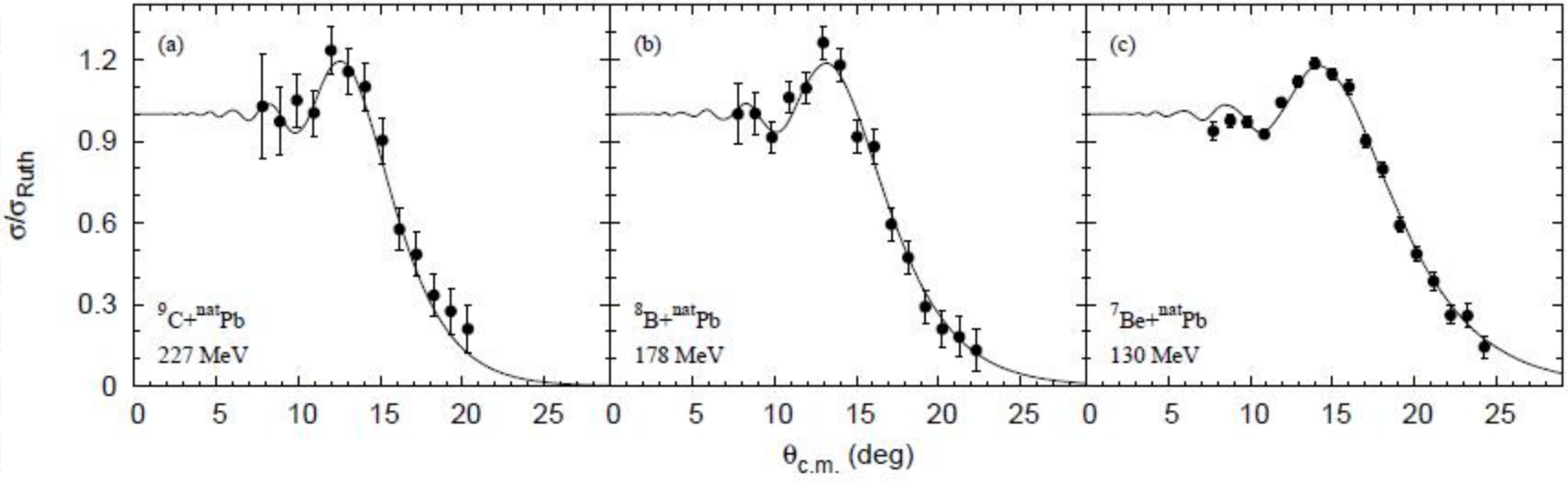


FIG. 7. Reduced reaction cross sections for several projectiles on several medium- to heavy-mass targets. The curves are to guide the eye.

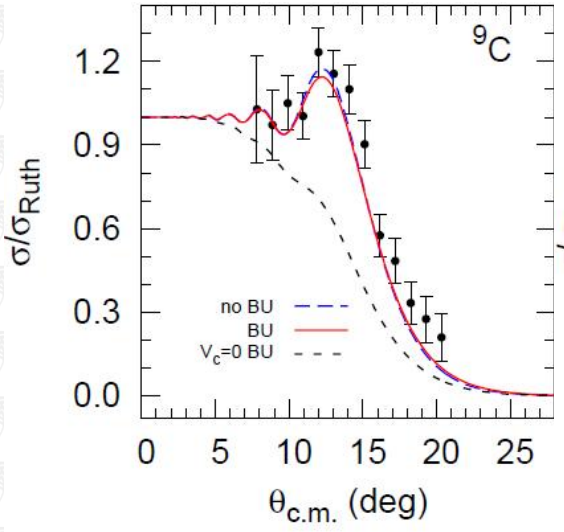
Elastic scattering of Proton Drip Line Nuclei

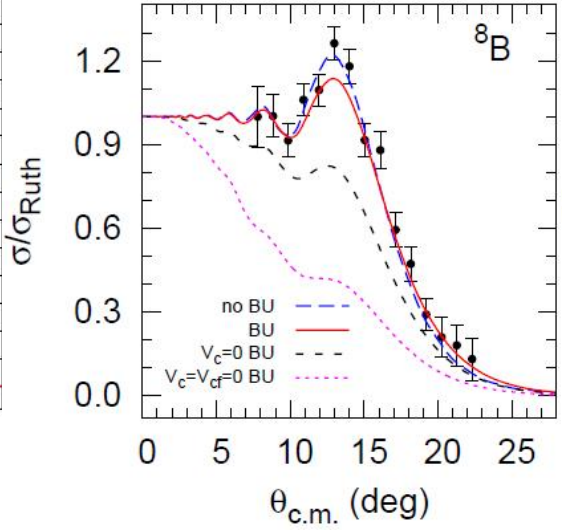


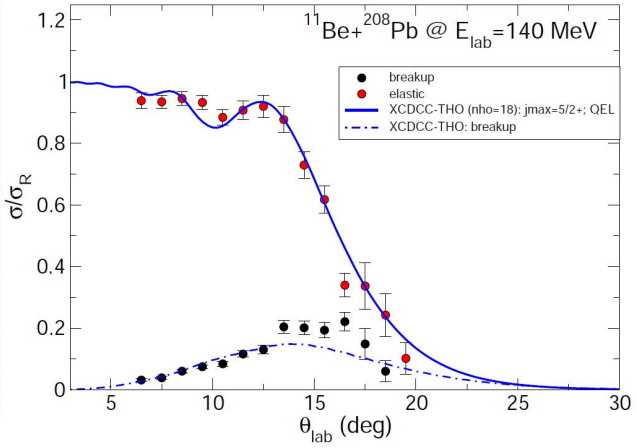
The experimental data can be reproduced by the optical model calculations with the systematic nucleus-nucleus potential of Xu and Pang.

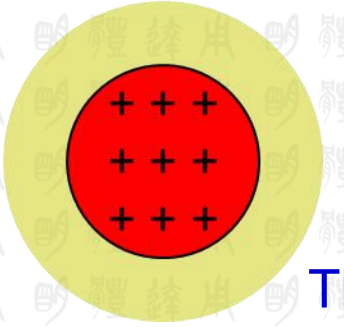
Yanyun Yang, …, ***JW*** et al. PRC98（2018）044608

Why the Coulumb rainbow peak not suppressed for proton-rich nuclei ?

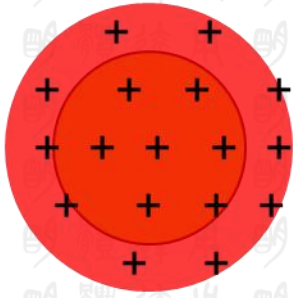








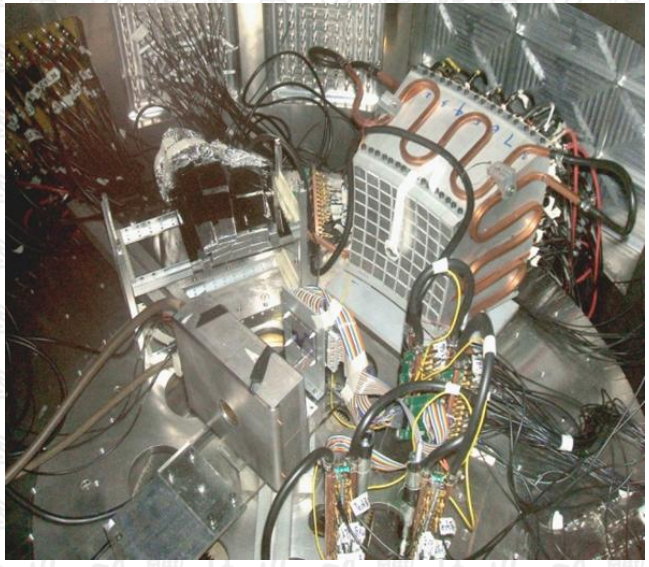
NO proton halo?

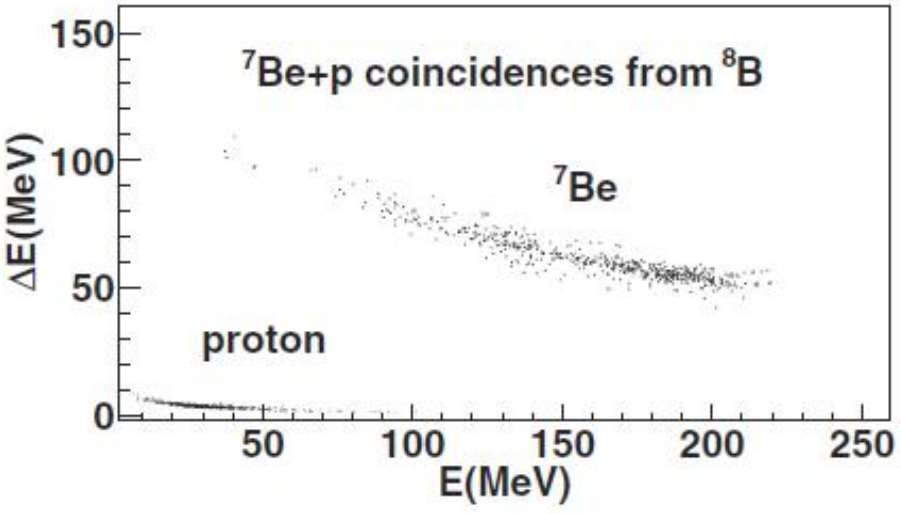


The different structure
between proton and neutron halo

^{8}B的破裂反应机研究

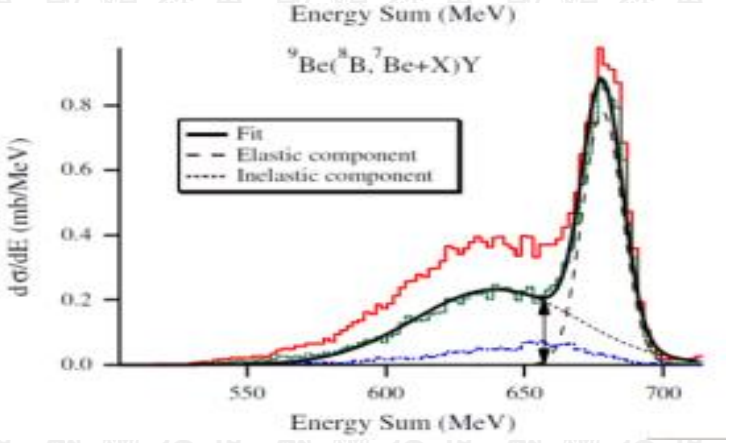
Experimental Setup

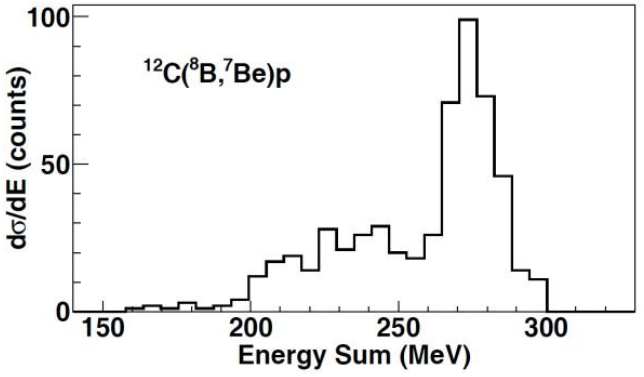




^{12}C(^{8}B,^{7}Be)p @36.7MeV/u

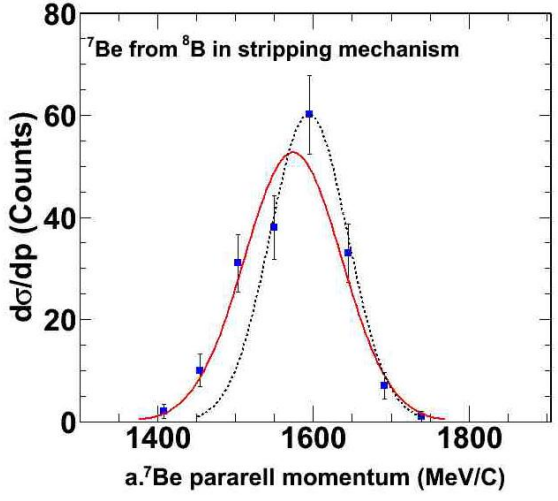
Identifying the reaction mechanism

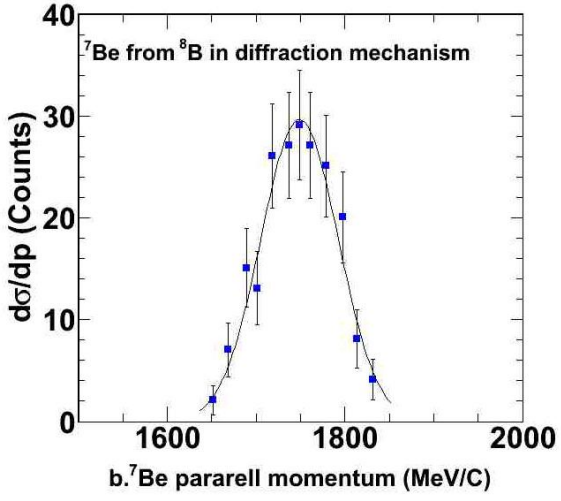




MSU ^{8}B@86.7MeV D.Bazin et al., PRL 102,232501

Present work





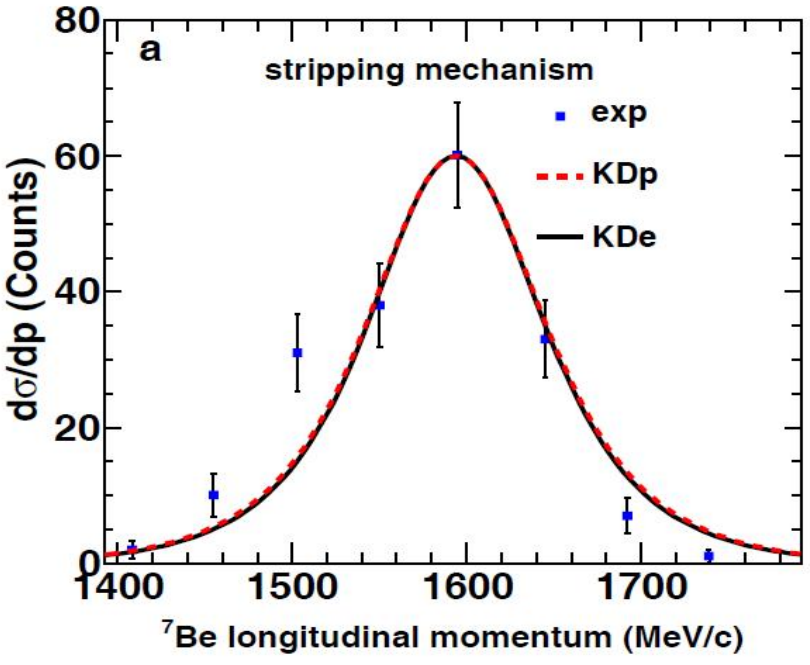
Width by fitting:
Diffractive:
92±7MeV/c
Stripping:
124±17MeV/c

Theoretical Calculations-Stripping

The stripping momentum distributions were calculated using the **eikonal approximation formalism** (PRC**70**, 034609) and the eikonal phase shifts and S-matrices of the following potentials (denoted KDe)

The complex ^{7}Be-target optical potential was calculated using the double-folding method of PRC74,064604, assuming Gaussian ^{7}Be and ^{12}C densities of rms radii 2.31and 2.32 fm. The proton-target potential was calculated from the Koning and Delaroche global parameterization (NPA**713**, 231)

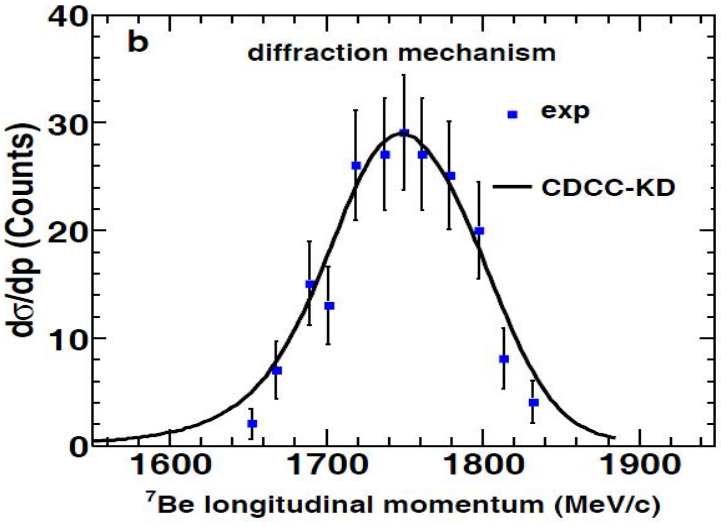
In addition, due to the relatively low beam energy, calculations were repeated using the improved description of the proton-target S-matrix (denoted KDp).



The ^{8}B(g.s.) to ^{7}Be final state radial overlaps and spectroscopic factors were taken from PRL102,232501

Calculation done by Prof. J. A. Tostevin

Theoretical Calculations-Diffraction



The diffraction mechanism differential cross sections were calculated using a CDCC (Coupled Discretized Continuum Channels) breakup model space as PRL102,232501, and the resulting momentum distributions constructed by integration over the solid angles covered by the current detection system, as is discussed in Phys. Rev. C **66**, 024607.

Calculation done by Prof. J. A. Tostevin

A summary of width calculated in different model

Summary of the distributions measured in this work and calculated in different model

	present work (MeV/c)	CDCC (MeV/c)	KDe (MeV/c)	KDp (MeV/c)	Hencken (MeV/c)	Hensen (MeV/c)	Esbensen (MeV/c)
Stripping	124(17)		103	107	151	153/75	166/82
Diffraction	92(7)	101			93		

85±4 ^{8}B@41AMeV PRL77(1996)5020

The experimental data show the width of longitudinal momentum distribution for stripping breakup is obviously wider than diffraction breakup.

S.L.Jin, J.S.Wang et al., Phys. Rev. C91,054617(2015)

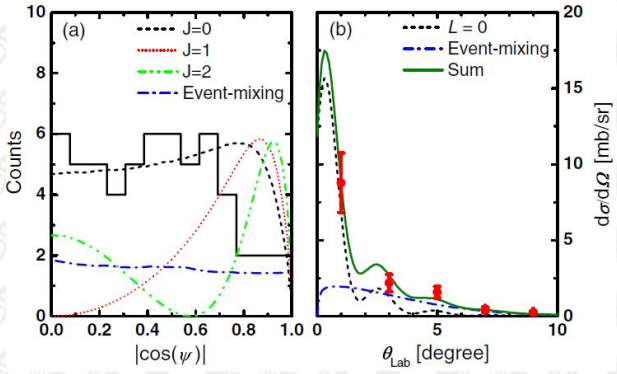
PHYSICAL REVIEW C **91**, 054617 (2015)

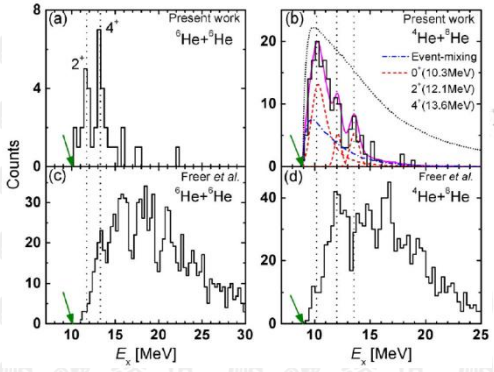
Reaction mechanism of ^{8}B breakup at the Fermi energy

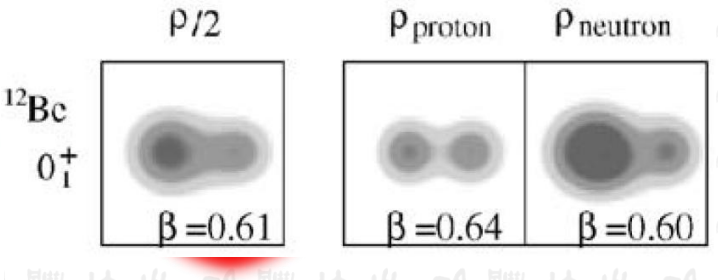
S. L. Jin (金仕纶),[1,2] J. S. Wang (王建松),[1,*] Y. Y. Yang (杨彦云),[1] P. Ma (马朋),[1] M. R. Huang (黄美容),[1] J. B. Ma (马军兵),[1] F. Fu (付芬),[1] Q. Wang (王琦),[1] M. Wang (王猛),[1] Z. Y. Sun (孙志宇),[1] Z. G. Hu (胡正国),[1] R. F. Chen (陈若富),[1] X. Y. Zhang (张雪荧),[1] X. H. Yuan (袁小华),[1] X. L. Tu (涂小林),[1] Z. G. Xu (徐志国),[1] K. Yue (岳珂),[1] J. D. Chen (陈金达),[1] B. Tang (唐彬),[1] Y. D. Zang (臧永东),[1] D. P. Wu (武大鹏),[1] Q. Hu (胡强),[1] Z. Bai (白真),[1] Y. J. Zhou (周远杰),[1,2] W. H. Ma (马维虎),[1,2] J. Chen (陈杰),[1,2] C. J. Lin (林承键),[3] X. X. Xu (徐新星),[3] Z. Z. Ren (任中洲),[4] C. Xu (许昌),[4] D. D. Ni (倪冬冬),[4] Y. H. Zhang (张玉虎),[1] H. S. Xu (徐瑚珊),[1] and G. Q. Xiao (肖国青)[1]

原子核的3核子（t、^{3}He）集团和纯中子集团

^{12}Be 的团簇结构研究



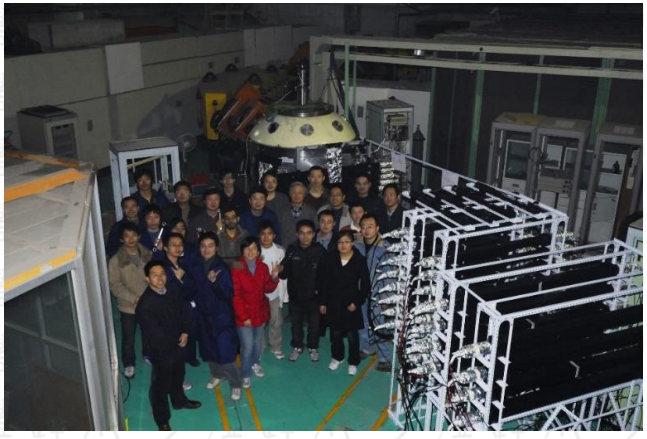




Phys. Rev. Lett. 112(2014) 162501
Phys. Rev. C 91（2015）024304

Kanada en`yo et al., AMD calculations

- ***First observation of enhanced monopole transition in ^{12}Be*** **at excitation energy of 10.3 MeV, evidence for the existence of ^{4}He+^{8}He molecular rotation, an intensely investigated topic in the past decade**
- ***A new technique*** **of measurement at zero degree is developed to study the molecular states in exotic nuclei**

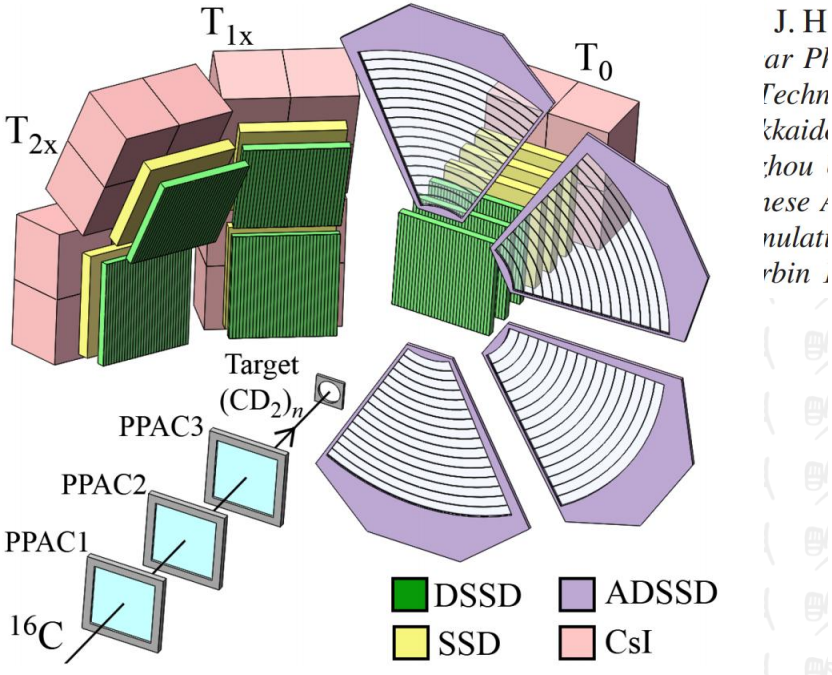


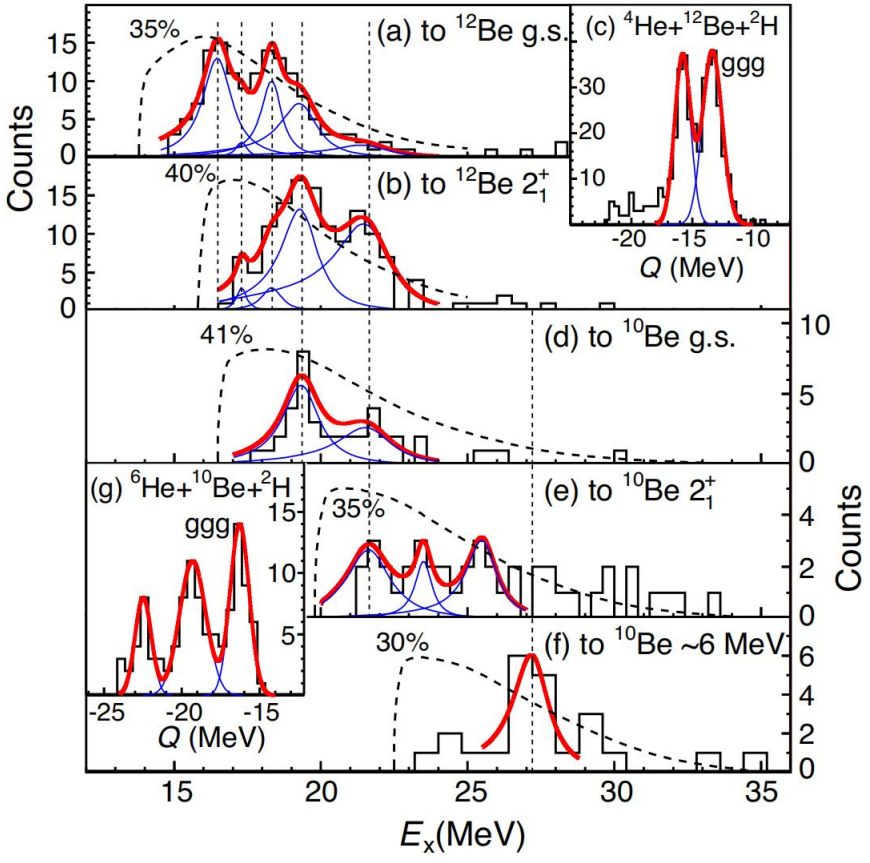
^{16}C的链状分子结构

PHYSICAL REVIEW LETTERS **124,** 192501 (2020)

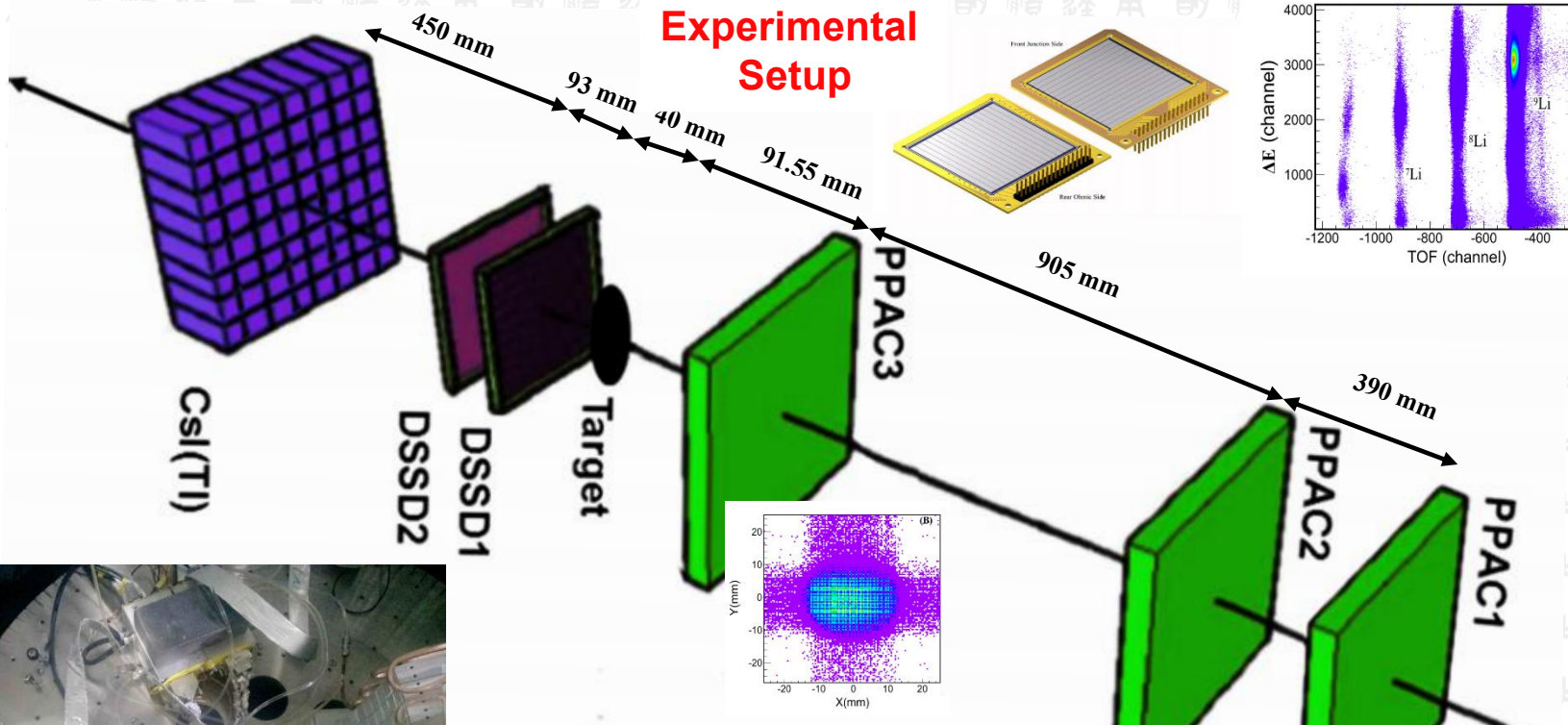
Positive-Parity Linear-C

Y. Liu,[1] Y. L. Ye,[1,*] J. L. Lou,[1] X. F. Yang,[1] T. Baba,[2] I
H. Hua,[1] J. S. Wang,[4,5] Y. Y. Yang,[5] P. Ma,[5] Z. Bai,[5] Q. Hu
J. Feng,[1] H. Y. Wu,[1] J. X. Han,[1] S. W. Bai,[1] G. Li,[1] H. Z. Y



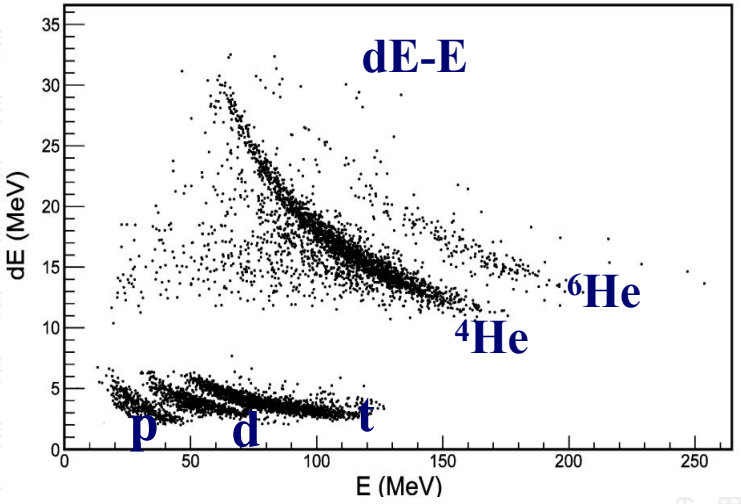


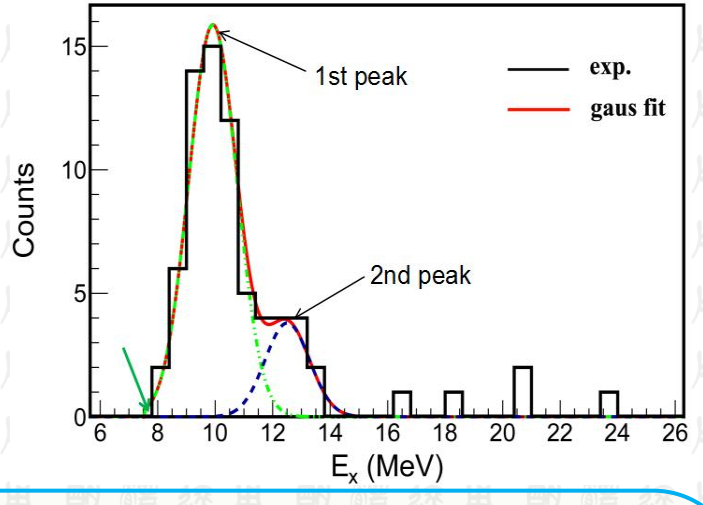
Experimental Setup

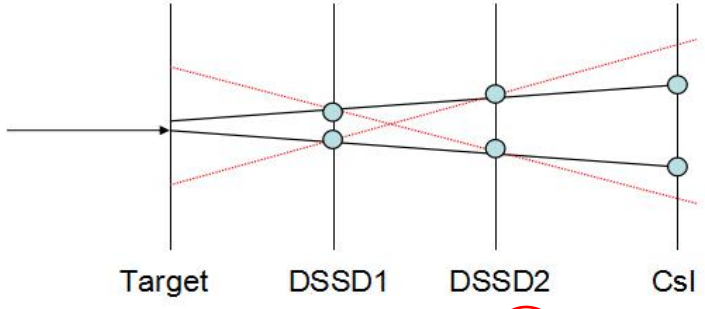


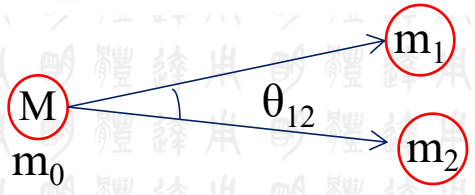
Primary：^{12}C@ 53.7 MeV/u
Target：^{9}Be（3038 μm）
RIB：^{9}Li@295 MeV
Intensity：1.1x10^{3} particles/s
Purity：99%

Event Selection and Reconstruction









Invarant mass:

$$M=\sqrt{(E_1+E_2)^2-[|\mathbf{P}_1|^2+|\mathbf{P}_2|^2+2*|\mathbf{P}_1|*|\mathbf{P}_2|*\cos(\theta_{12})]}\ ;$$

$$E_i=T_i+m_i\ ;\ |\mathbf{P}_i|^2=T_i*T_i+2*T_i*m_i\ ;\ \theta_{12}=<\mathbf{P}_1,\mathbf{P}_2>\ ;$$

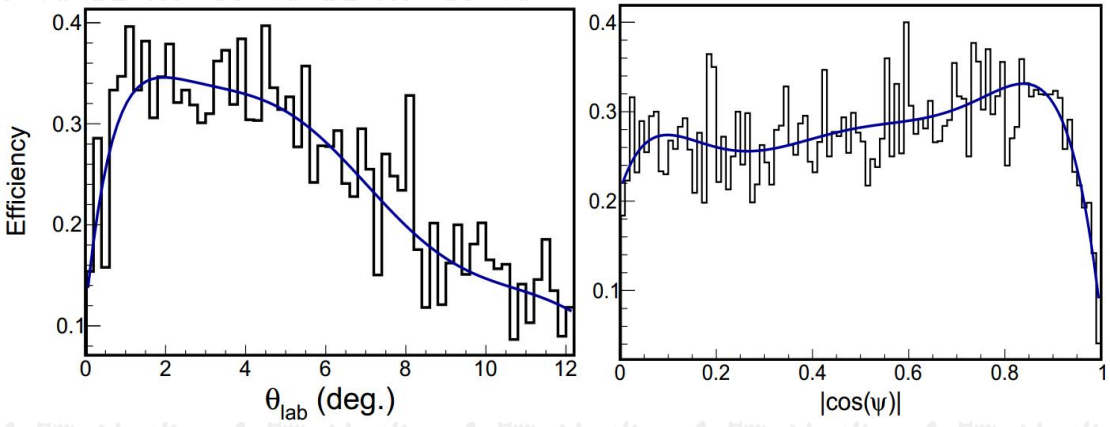
Excitation energy: $E_X=M-m_0$

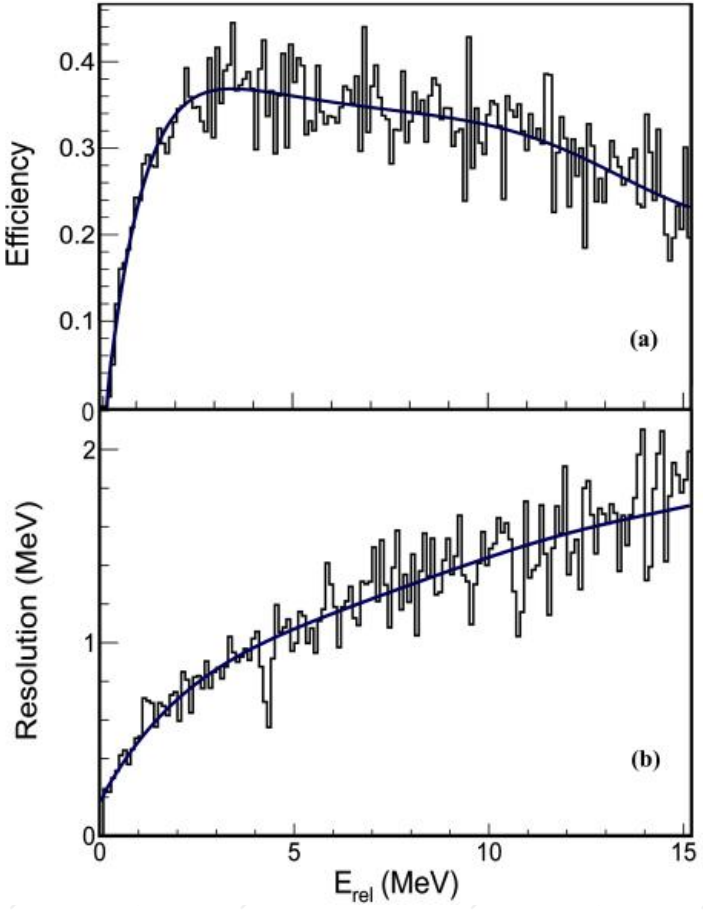
Relative energy: $E_{rel}=E_x-E_{thr}$

Threshold energy of ^{6}He+t : E_{thr}=7.588 MeV

Simulation of Detector efficiency

A Monte Carlo simulation is performed to determine the detection efficiency according to the geometry, assuming isotropic emission of the fragments in the center of mass frame.



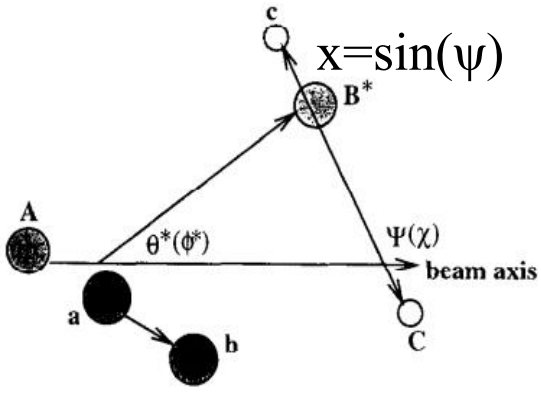


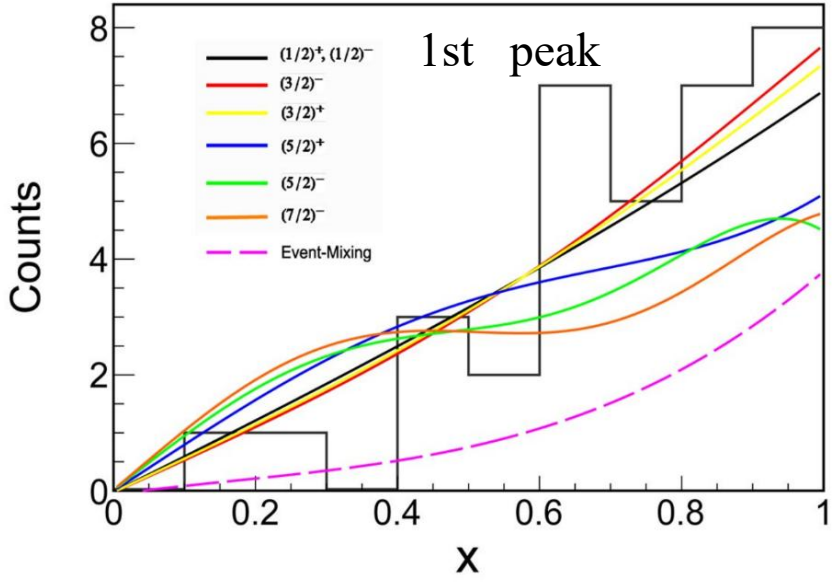
Angular Correlation Analysis

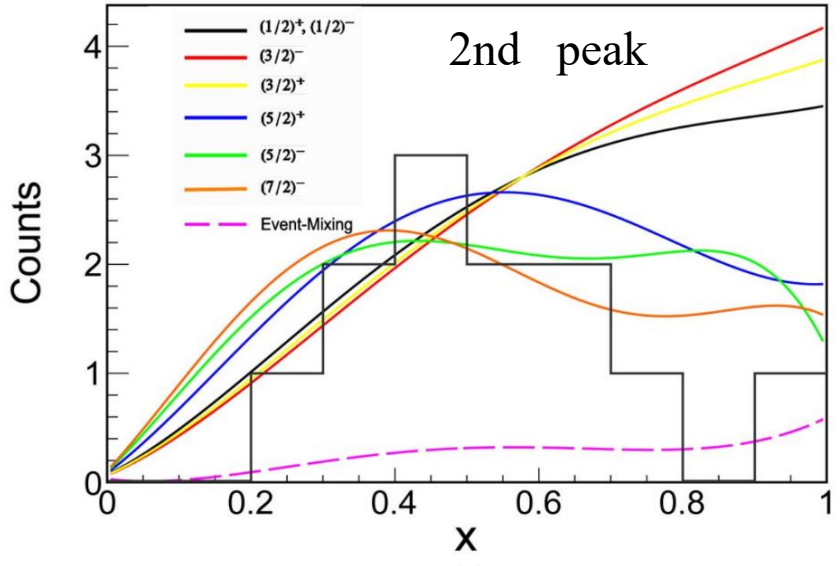
G. Finkel et al., Phys. Rev. C19 (1979) 1782

$$N(\Omega^*,\Omega_\psi) \propto \sum_{m_{Li}=-\frac{3}{2}}^{\frac{3}{2}} \sum_{m_t=-\frac{1}{2}}^{\frac{1}{2}} \left| \sum_{m_{Li^*}} T_{m_{Li^*}}^{m_{Li}} (Lm_L Sm_t \mid J_{Li^*} m_{Li^*}) Y_L^{m_L}(\psi,\chi) \right|^2$$

The relative momentums of the two clusters are determined to be 1 for the 1st peak and 2 for the 2nd peak respectively.

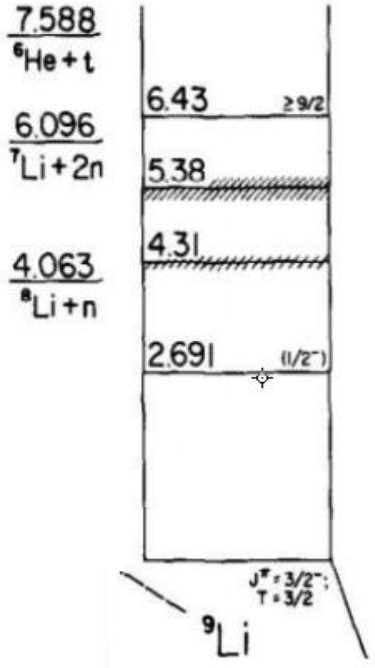


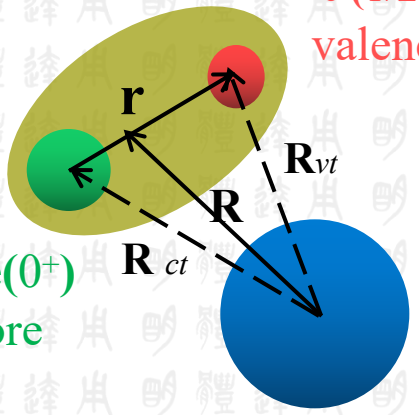




CDCC Analysis

^{9}Li modeled as 2-body projectile

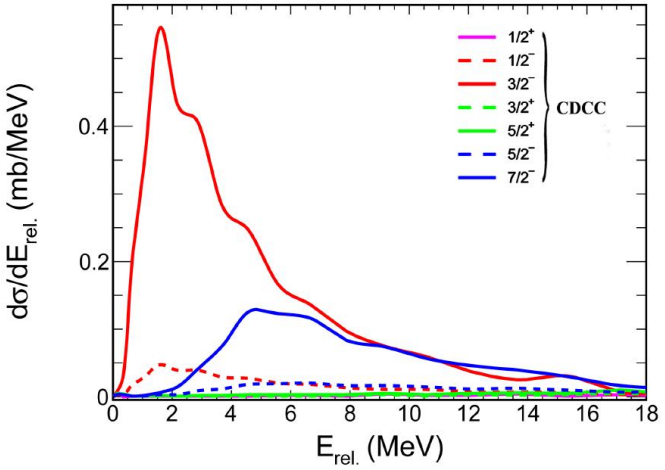


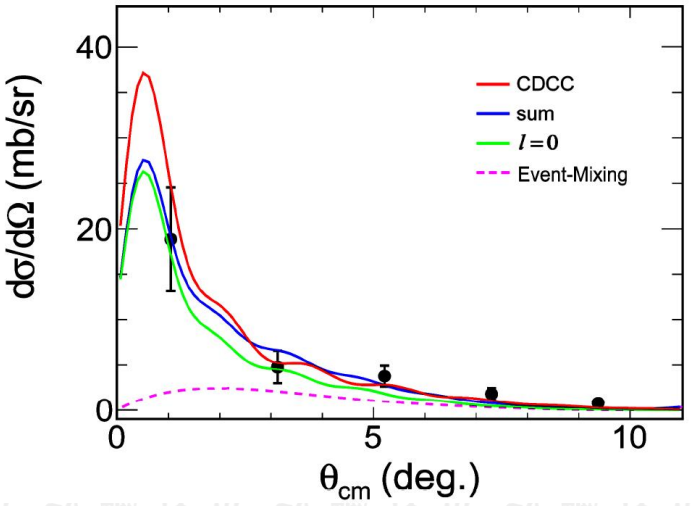


t (1/2⁺) valence

^{6}He(0⁺) core

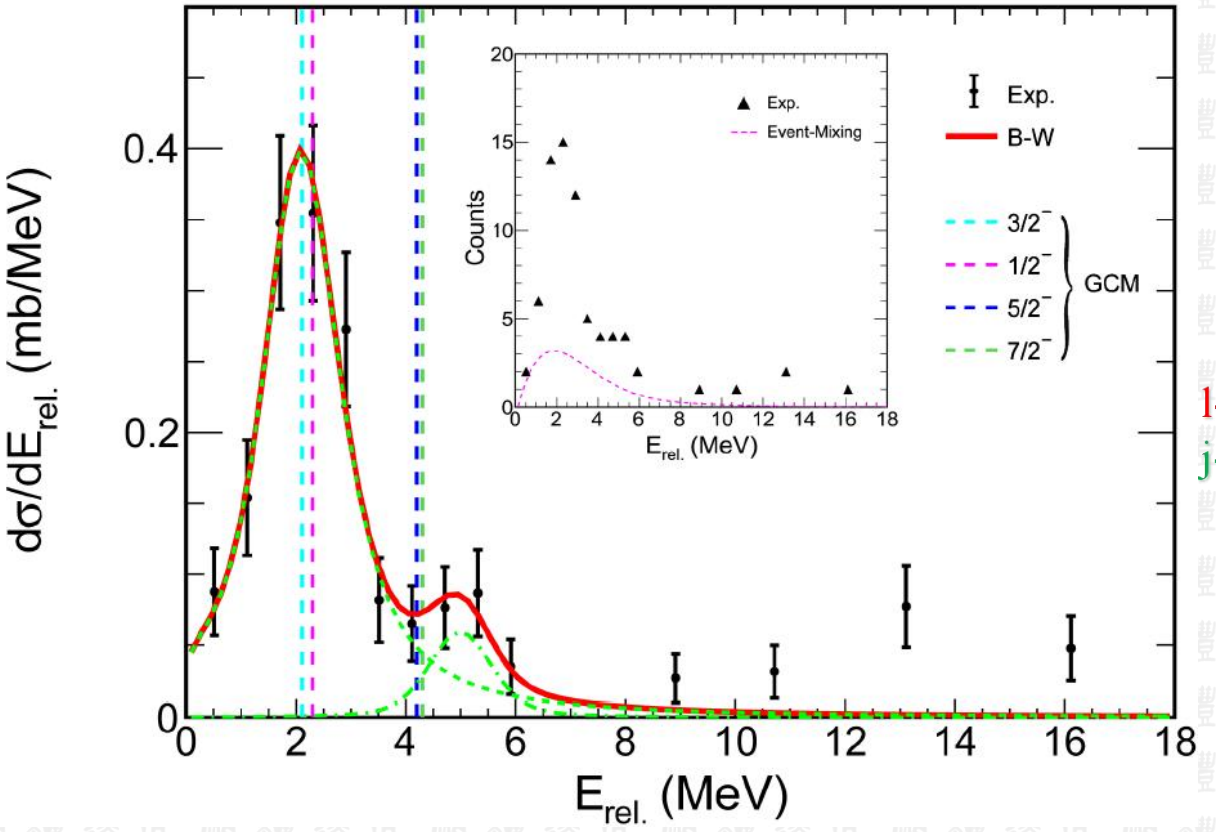
^{208}Pb target



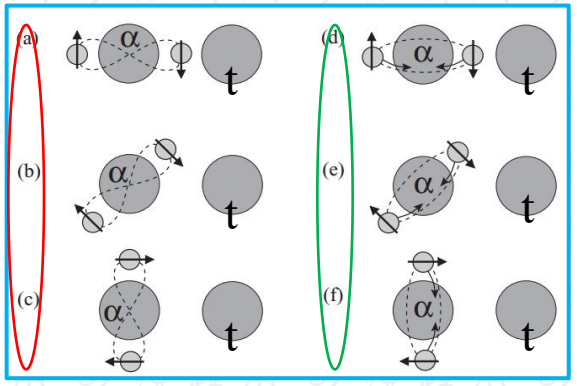


^{9}Li ground state p3/2^{-}

Comparison with GCM predictions



l-s
j-j

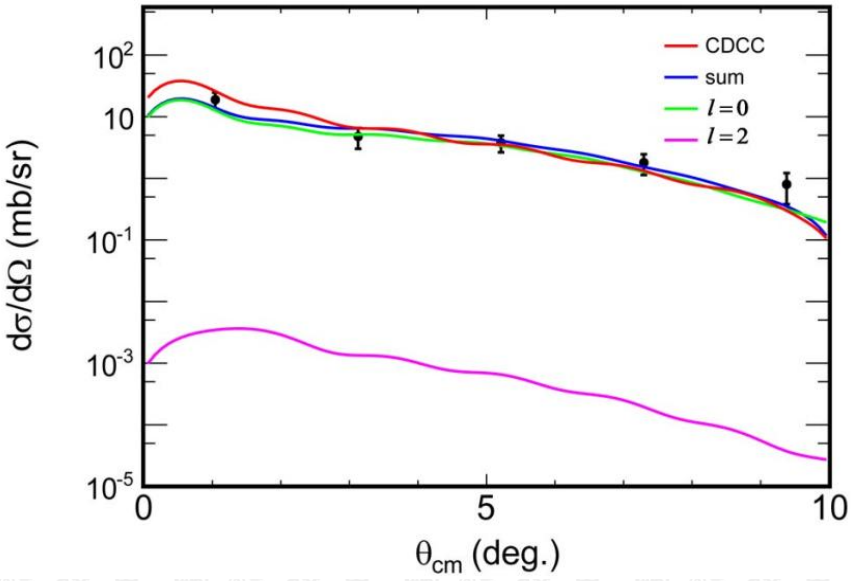


Y. Kanada-En'yo and T. Suhara, PRC 85, 024303(2012).
Yoshiko Kanada-En'yo, PRC 94, 024326 (2016).

Multipole-Decomposition Analysis

$$\left(\frac{d\sigma}{d\Omega}\right)_{\exp} = \sum_l a_l \cdot \left(\frac{d\sigma}{d\Omega}\right)_{l,DWBA}$$

the DWBA cross sections exhausting the full EWSR for the transferred angular momentum l



Monopole transition potential:

$$G_0(r) = \alpha_0^U [3U(r) - r\frac{dU(r)}{dr}]$$

Quadrupole transition potential :

$$G_2(r) = -\delta_2^U \frac{dU(r)}{dr}$$

D. J. Horenet al.Phys Rev C 52(1995) 1554
B. Bonin et al., Nucl. Phys. A 430 (1984) 349-396

a_0=0.023(4)； $M(IS0)$=5.0±0.5(stat.) fm²； GCM:~6 fm²； Systematic error:14%

Kanada-En‘Yo Y. Phys.Rev.C 94 (2016) 024316.

Conclusions for t+^{6}He cluster of ^{9}Li*

- Two resonant states are clearly observed with the excitation energies at 9.8 MeV and 12.6 MeV and spin-parity of $3/2^-$ and $7/2^-$ respectively by the method of angular correlation analysis and verified by the continuum discretized coupled channels (CDCC) calculation
- A monopole matrix element about 4 fm^2 for the $3/2^-$ state is extracted from the DWBA calculations
- These experimental results consist with the prediction of generator coordinate method (GCM), supporting the feature of clustering structure of two neutron-rich clusters in the ^{9}Li*

W. H. Ma et al., PhysRevC.103(2021)L061302

PHYSICAL REVIEW C **103**, L061302 (2021)

Letter

Observation of ^{6}He $+t$ cluster states in ^{9}Li

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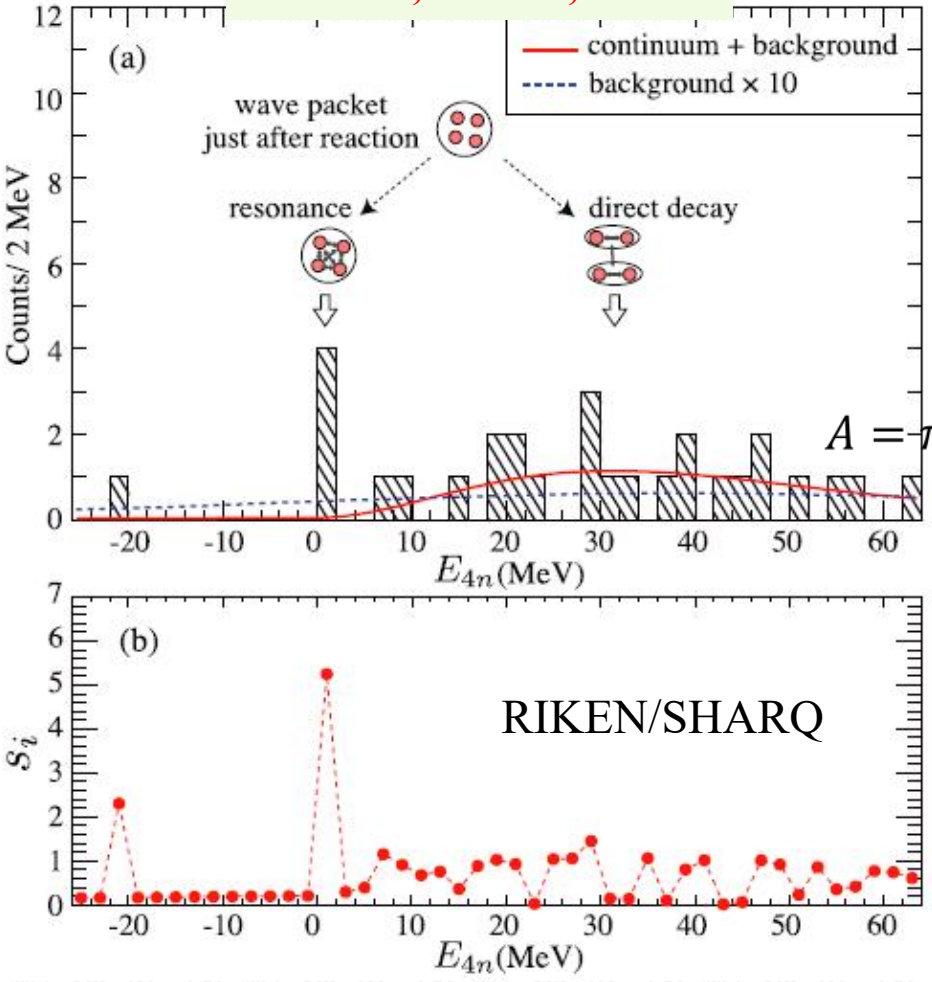
2016年热门话题：4n 共振态

PRL116,052501,2016

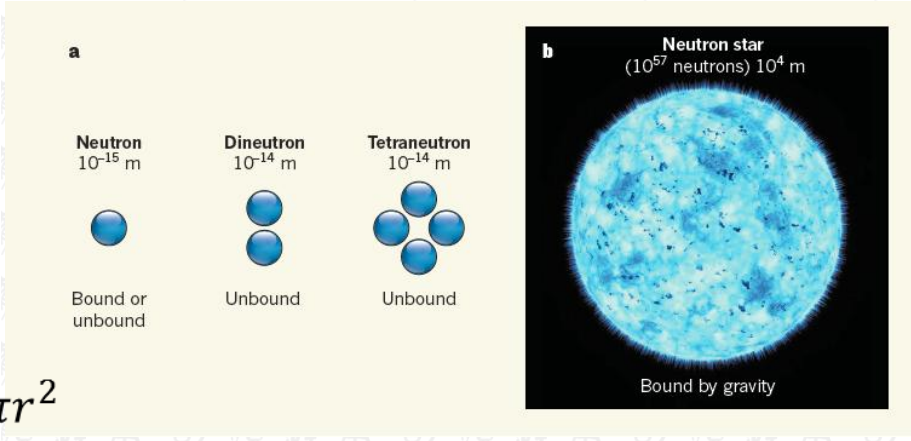


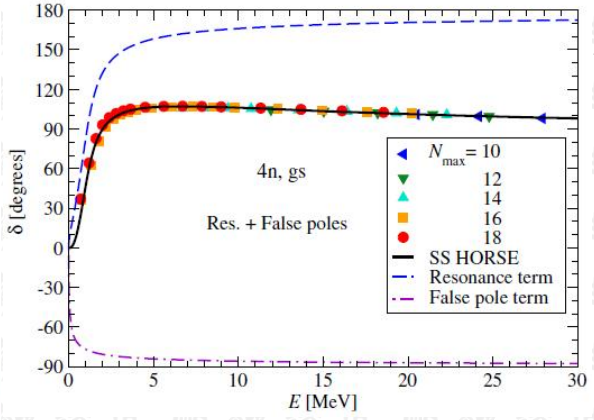
RIKEN/SHARQ

$A = \pi r^2$

$E_r = 0.83 \pm 0.65(stat) \pm 1.25(syst)MeV$

Nature532.448(2016)





$E_r = 0.844MeV$
$\Gamma = 1.378MeV$

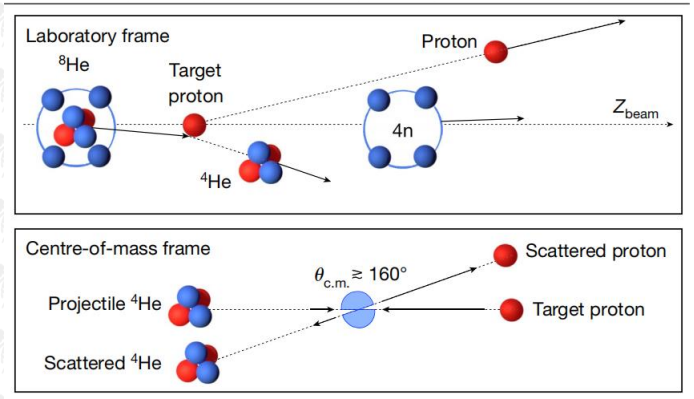
$E_r = b^2 - a^2/2$

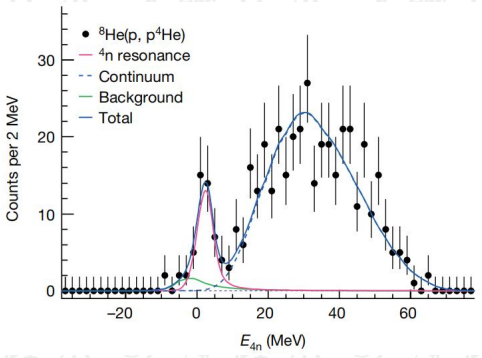
$\Gamma = 2a\sqrt{b^2 - a^2/4}$

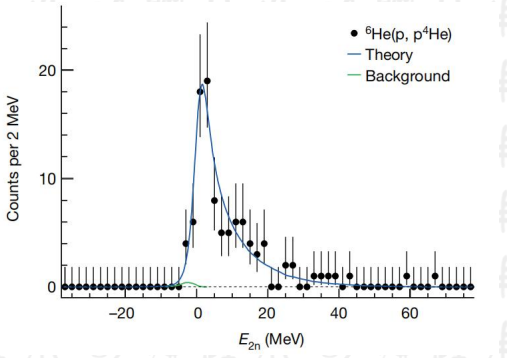
$\delta_r(E) = -\tan^{-1}[a\sqrt{E}/(E - b^2)]$

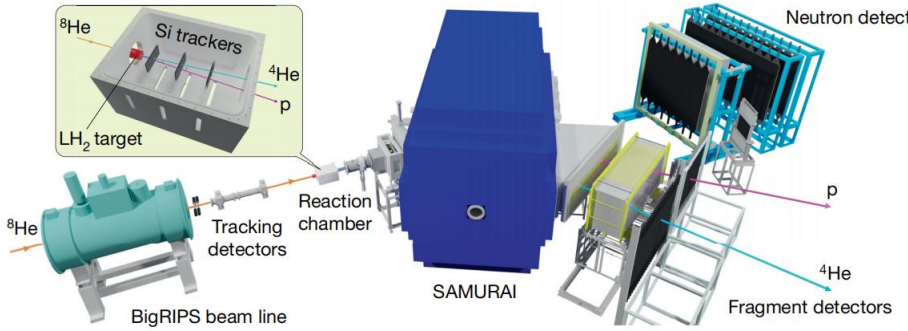
PRL117,182502,2016

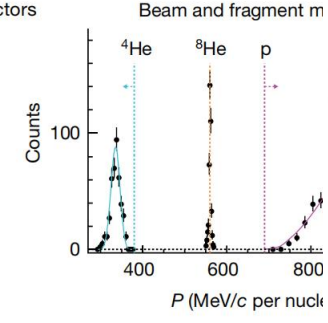
准束缚4中子态

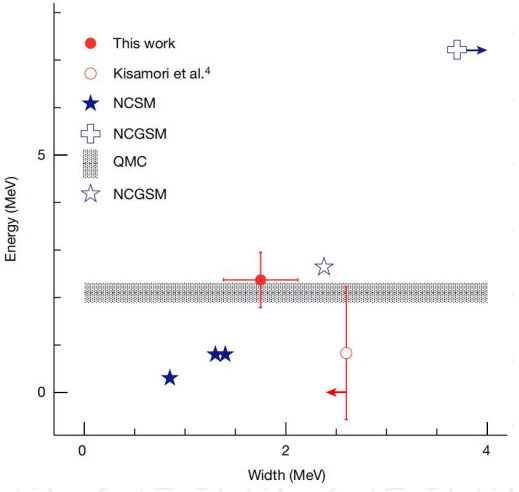






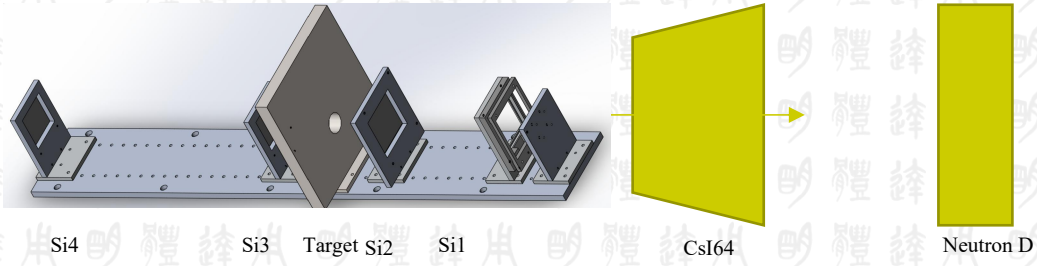


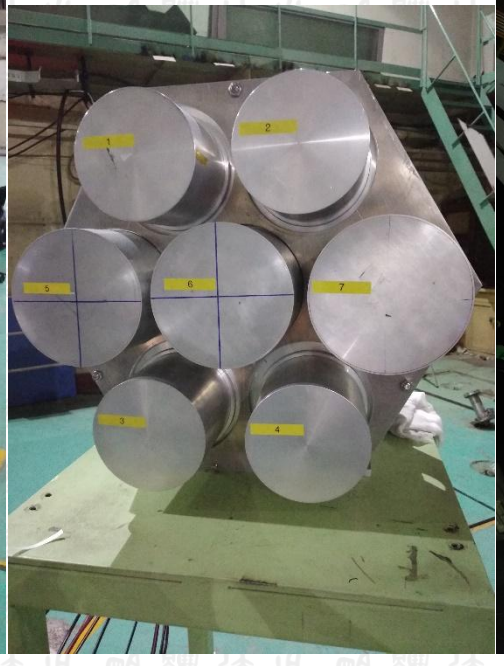


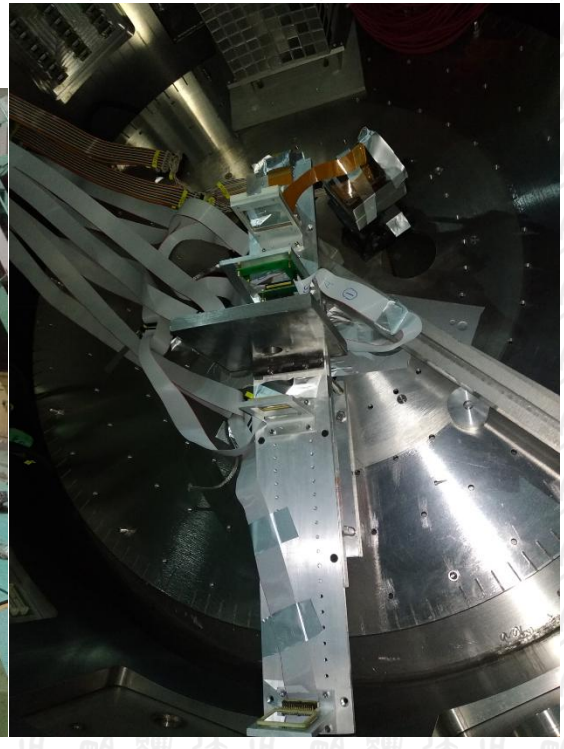


M. Duer et al., nature.606.678（2022）/ J. G. Li et al., PRC 100.054313(2019)

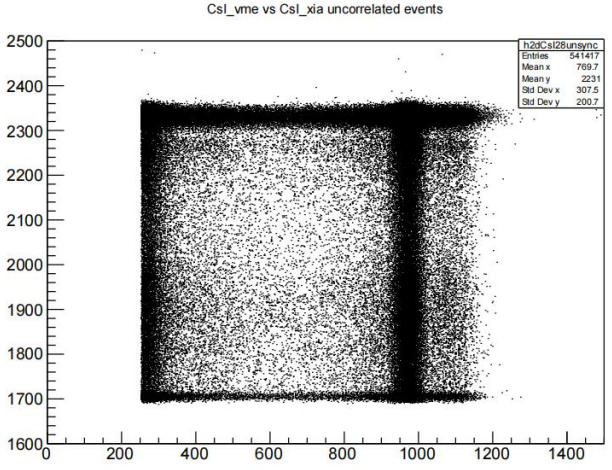
$^{6}He+^{208}Pb$反应探测器布局图

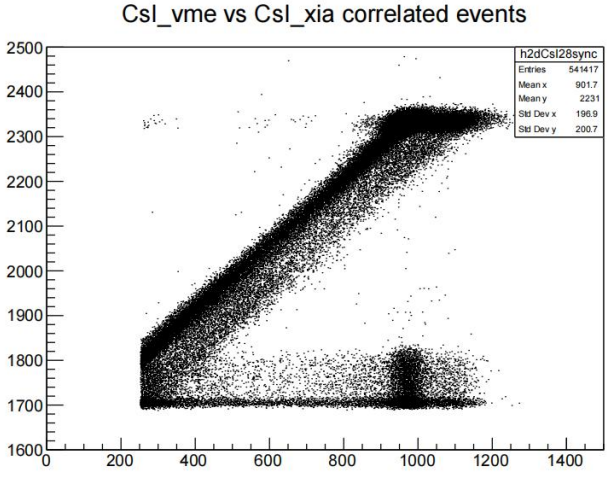


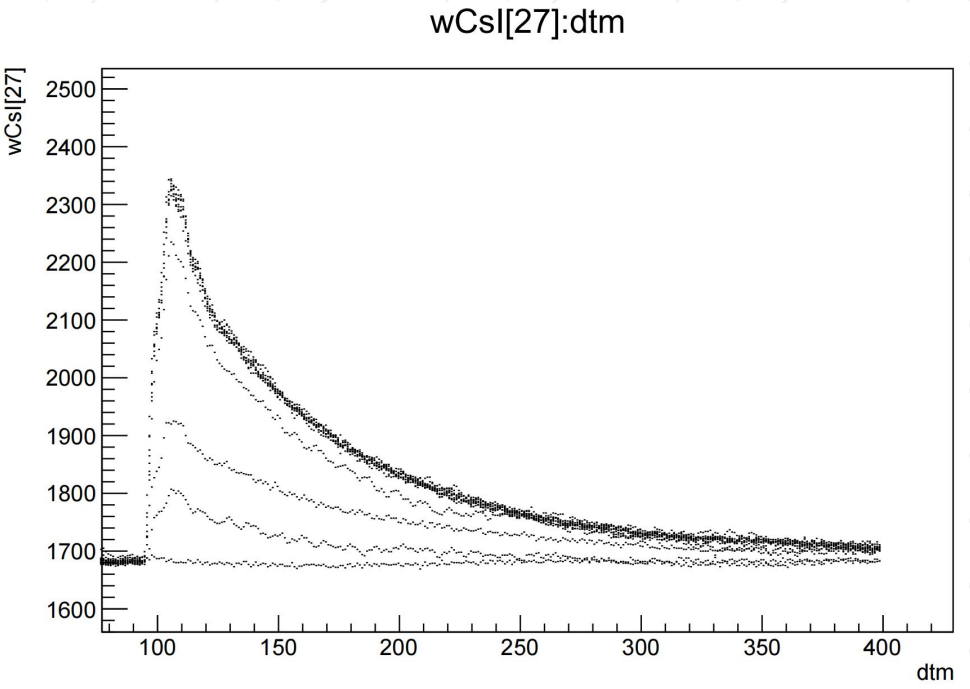




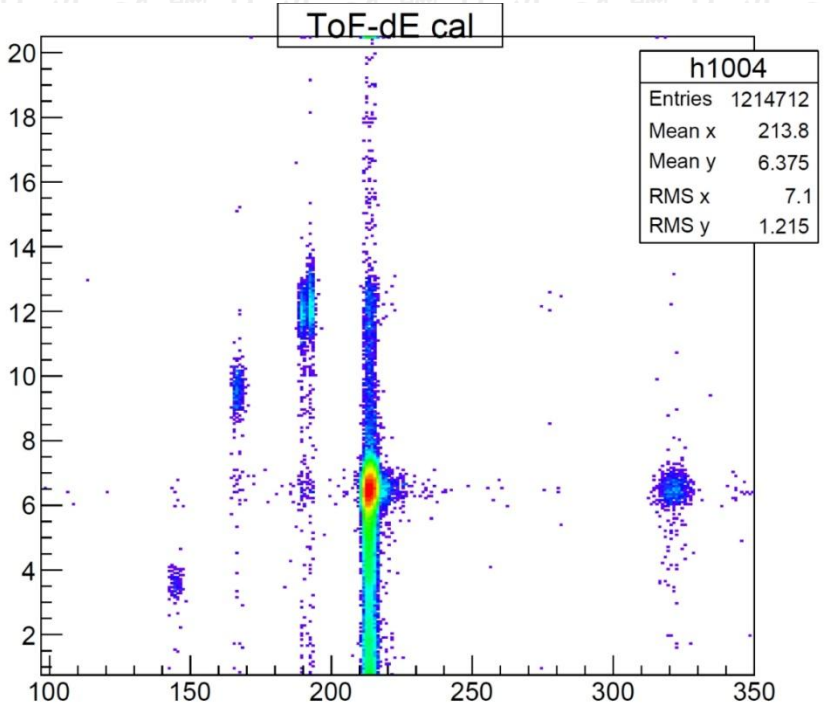
VME与XIA获取系统的同步

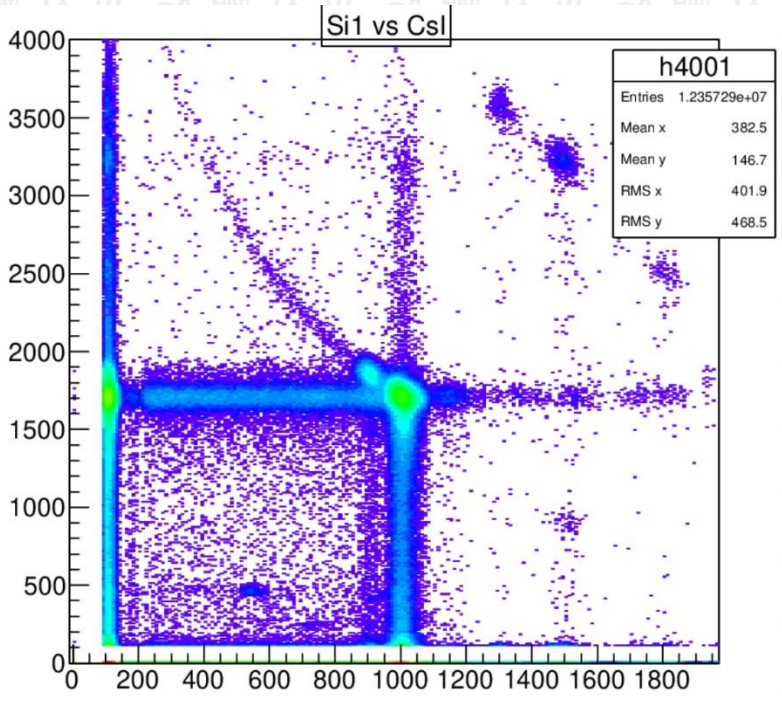






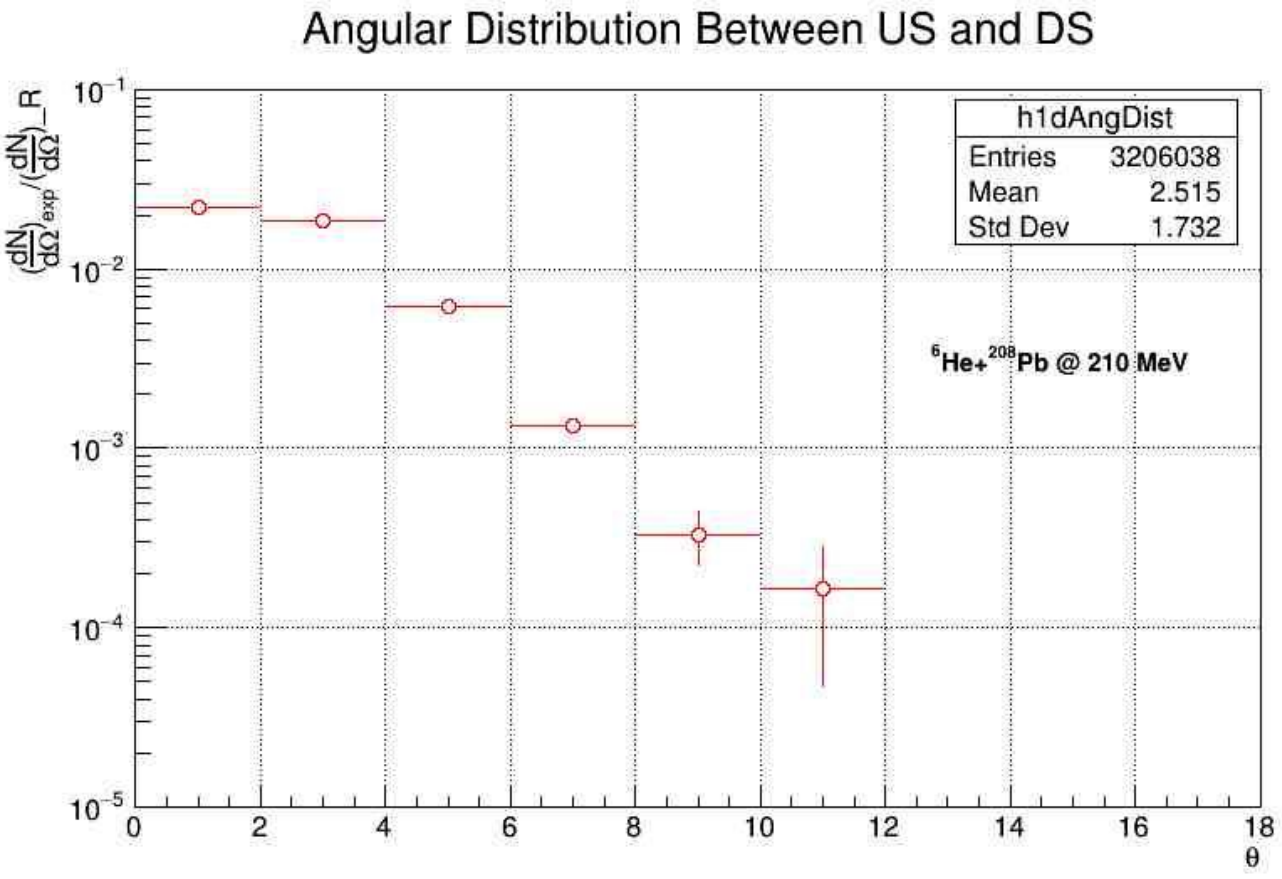
$^{6}He+^{208}Pb$实验图谱





初级束：$^{12}C^{6+}$,能量为53.98MeV/u，流强为37enA。
RIBLL1终端顺利调试出^{6}He次级束流，T1和T2符合计数为2700pps，纯度为98.7%

$^{6}He+^{208}Pb$的弹性散射截面初步结果（10倍库仑位垒）



总结与展望

- 中子晕核有明确一致的实验特征和理论解释，其弹性散射有明显的晕核效应。
- 质子晕（？）^{8}B的直接反应机制与中子晕核截然不同。
- 对于质子晕核^{8}B和其他质子滴线核的理解还需要更多的实验和理论：

  1）直接测量^{8}B的电荷半径（在线离子束激光谱仪）

  2）测量不同能区^{8}B破裂碎片p与^{7}Be的关联
- 2n、4n等纯中子集团需要更多的实验研究
- t、^{3}He集团结构可能会是一个新的研究方向

Collaborators

IMP:

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Spain： A. Moro ； **India：** S. Mukerjee

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Surrey Univ.: J. A. Tostevin

Thanks for your attention !