PROBING THE CLUSTERING EFFECTS IN NUCLEAR EXCITATIONS

Yanlin Ye
School of Physics and State Key Lab of Nuclear Physics and Technology , Peking University

COMEX5, Sept. 14-18, 2015 in Krakow, Poland

Outline

I. Clustering phenomena

II. How to probe

II.1 for ground states

II.2 for excited states

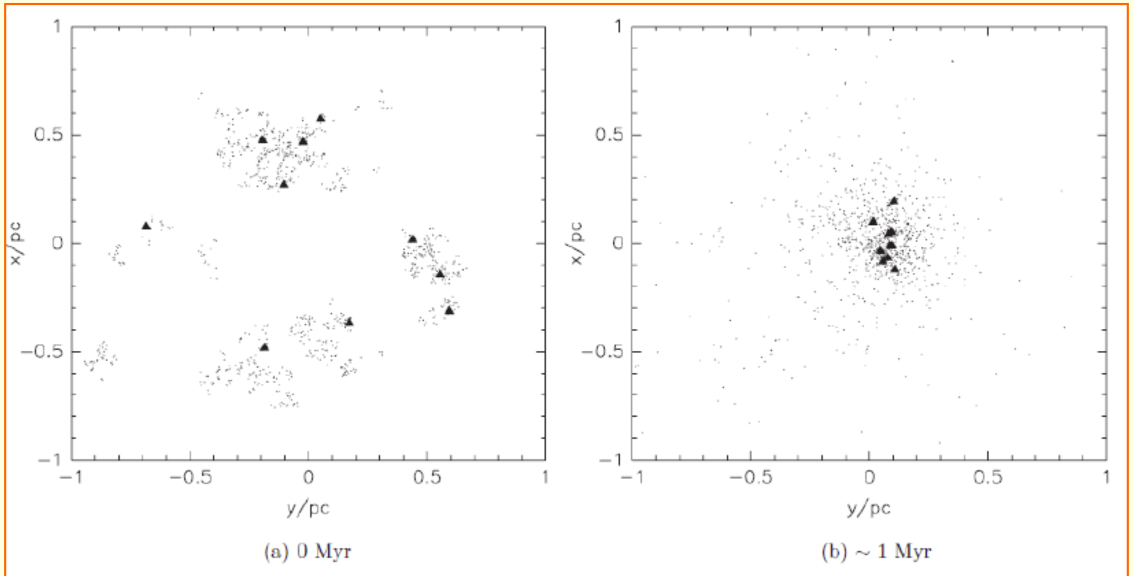
III. Newly performed experiments

IV. Summary

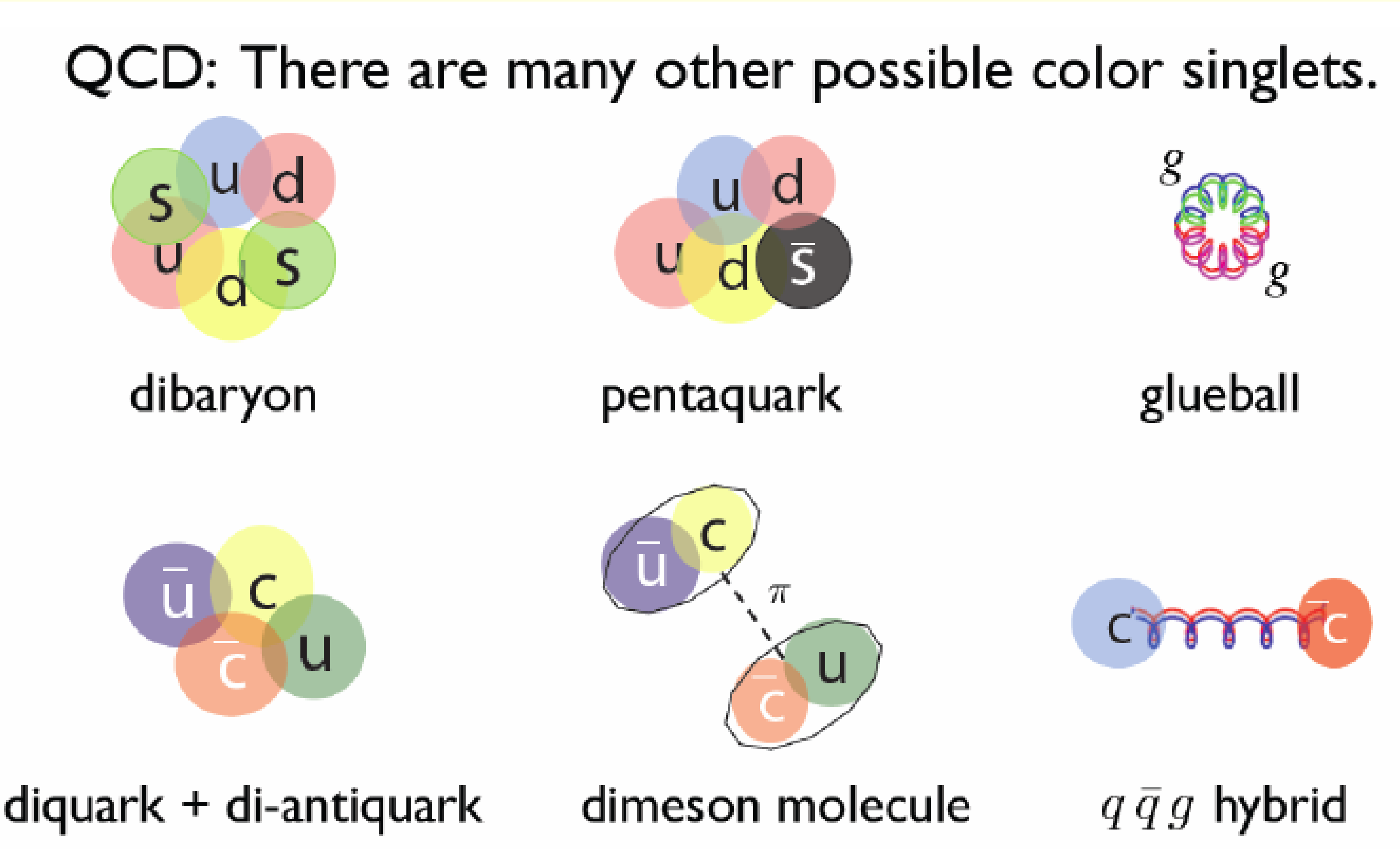
Clustering in the universe

Annu.Rev. Astron. Astrophysics 41(2003)57

疏散星团 M45（昴星团）



Clustering in hadrons

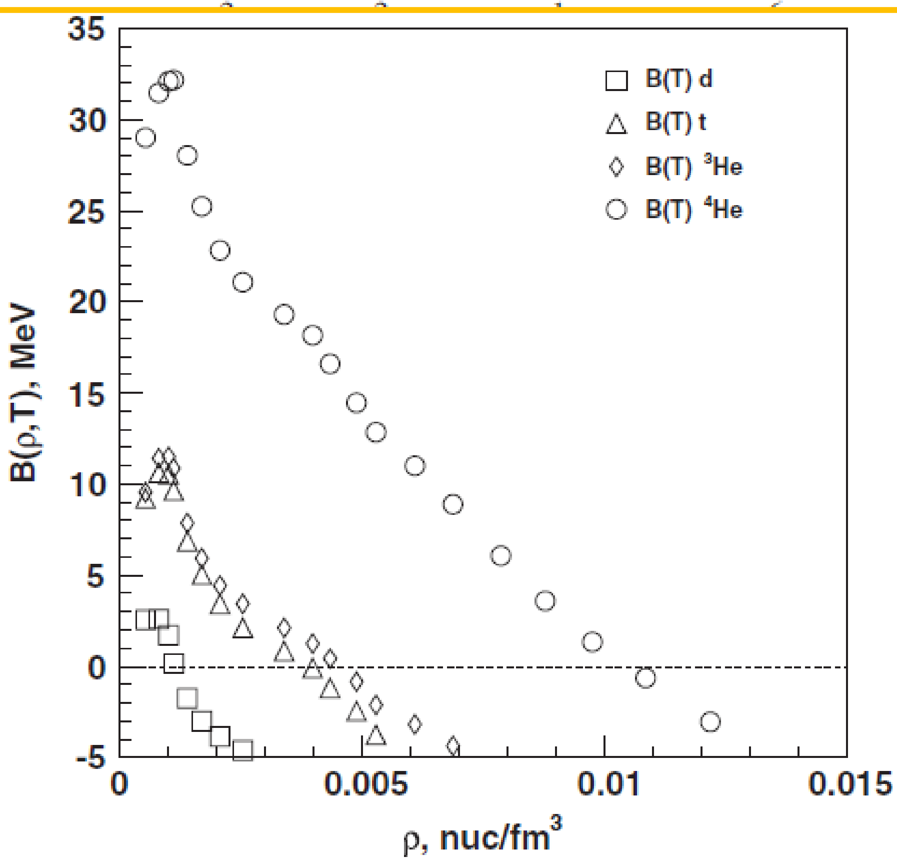


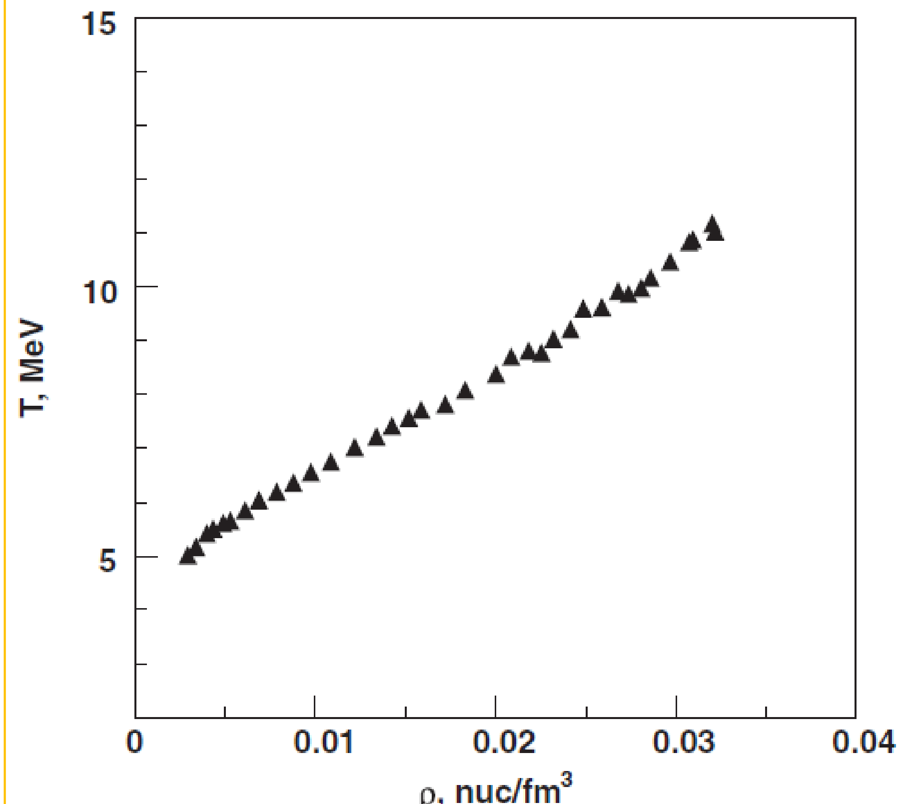
Clustering in HI Collisions

PRL 108, 062702 (2012) PHYSICAL REVIEW LETTERS week ending 10 FEBRUARY 2012

Experimental Determination of In-Medium Cluster Binding Energies and Mott Points in Nuclear Matter

K. Hagel,[1] R. Wada,[2,1] L. Qin,[1] J. B. Natowitz,[1] S. Shlomo,[1] A. Bonasera,[1,3] G. Röpke,[4] S. Typel,[5] Z. Chen,[2]



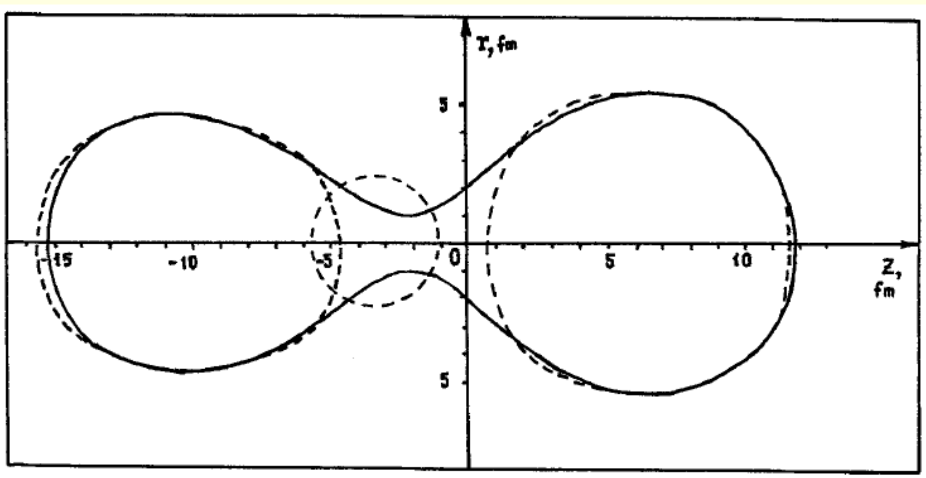


Clustering in the fission process

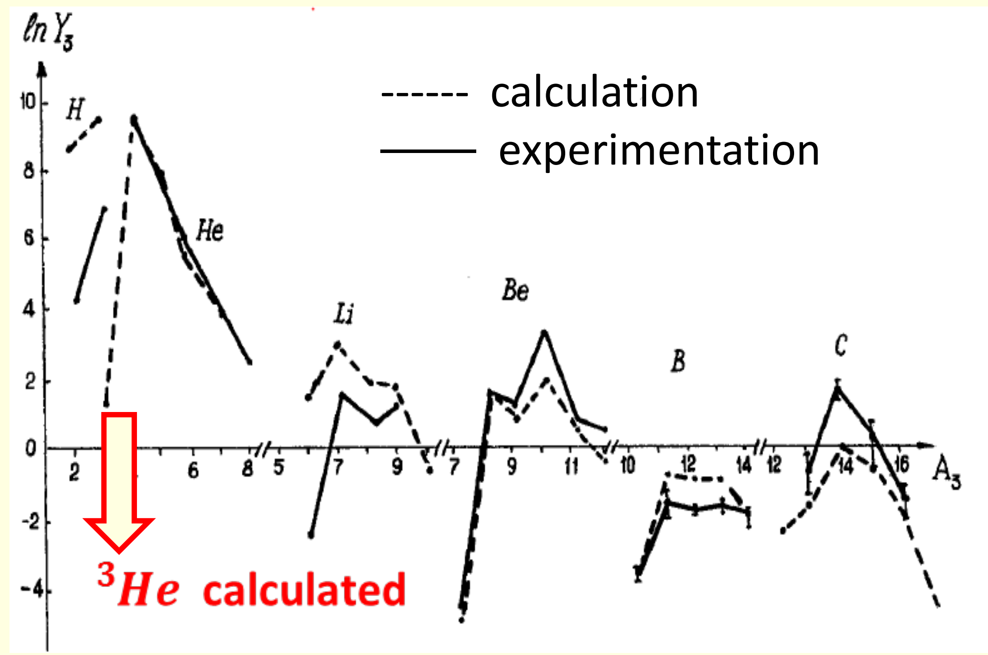
PHYSICAL REVIEW C **90**, 011601(R) (2014)

Nucleation and cluster formation in low-density nucleonic matter: A mechanism for ternary fission

S. Wuenschel,[1] H. Zheng,[1] K. Hagel,[1] B. Meyer,[2] M. Barbui,[1] E. J. Kim,[1,3] G. Röpke,[4] and J. B. Natowitz[1]
[1]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*



Ternary fission system of ^{236}U



Comparison of ^{236}U

α-preformation in heavy nuclei: a long standing problem

Phys. Scr. 89 (2014) 054027 (6pp)
doi:10.1088/0031-8949/89/5/054027

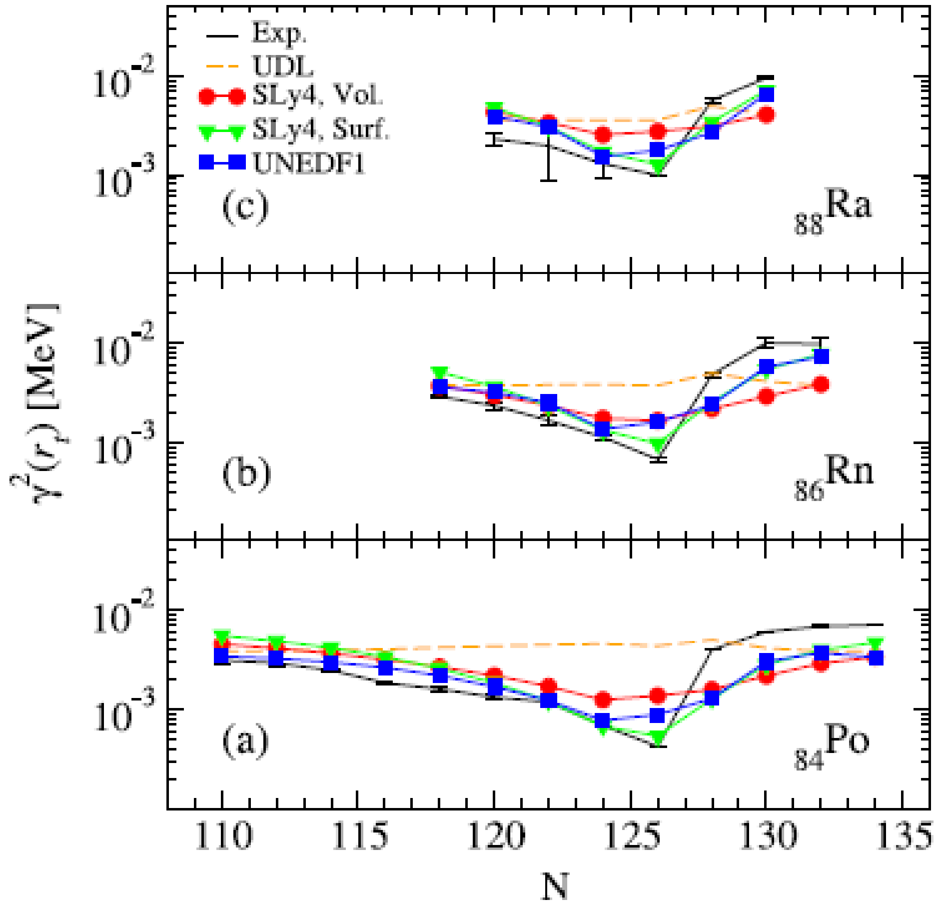
Alpha-particle formation and decay rates from Skyrme–HFB wave functions

D E Ward, B G Carlsson and S Åberg

Mathematical Physics, LTH, Lund University, PO Box 118, S-22100 Lund, Sweden

cluster, called the *formation amplitude* [15],

$$g_L(r_{\alpha D}) = \int \mathcal{A}\left[\Phi_J^{(D)}(\xi_D),\, \Phi_0^{(\alpha)}(\xi_\alpha) Y_L(\hat{r}_{\alpha D})\right]^*_{IM} \times \Psi_{IM}^{(M)}(\xi_M)\, d\xi_D\, d\xi_\alpha\, d\hat{r}_{\alpha D},$$



Model	$\mathcal{M}$
SLy4, volume pairing	–3.7897
SLy4, surface pairing	–3.1409
UNEDF1	–5.7080
UDL	0.2111

Figure 5. Reduced widths at the touching radius, as a function of the mother nucleus neutron number. The error bars show experimental values, the dashed line results from the UDL formula. The circles, triangles and squares show results from microscopic HFB calculations using different effective interactions. The microscopic results are normalized with the constant factor $10^{-\mathcal{M}}$.

Clustering in stable light nuclei

464 Supplement of the Progress of Theoretical Physics, Extra Number, 1968

The Systematic Structure-Change into the Molecule-like Structures in the Self-Conjugate 4*n* Nuclei

Kiyomi IKEDA,*) Noboru TAKIGAWA and Hisashi HORIUCHI

Depar *kyo, Tokyo*

Clustering in unstable nuclei – a new area

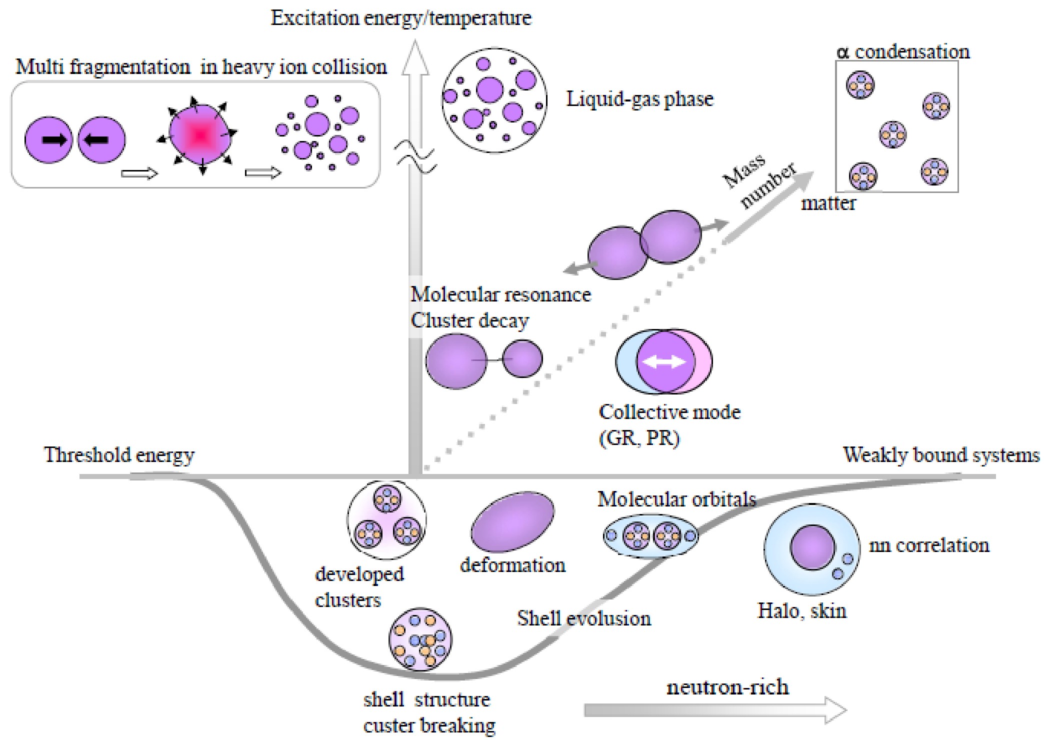
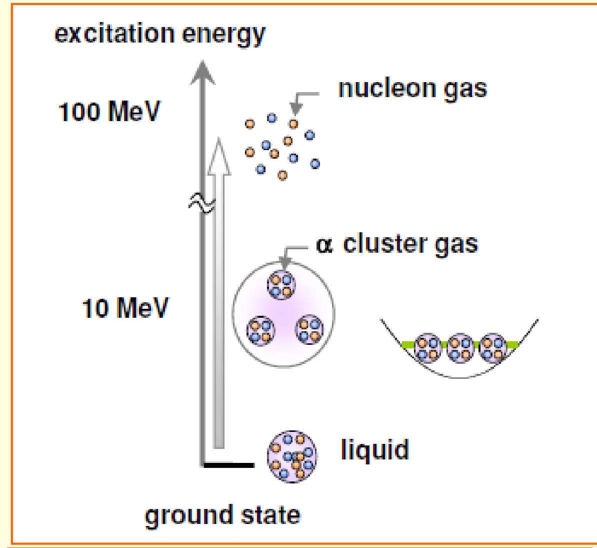
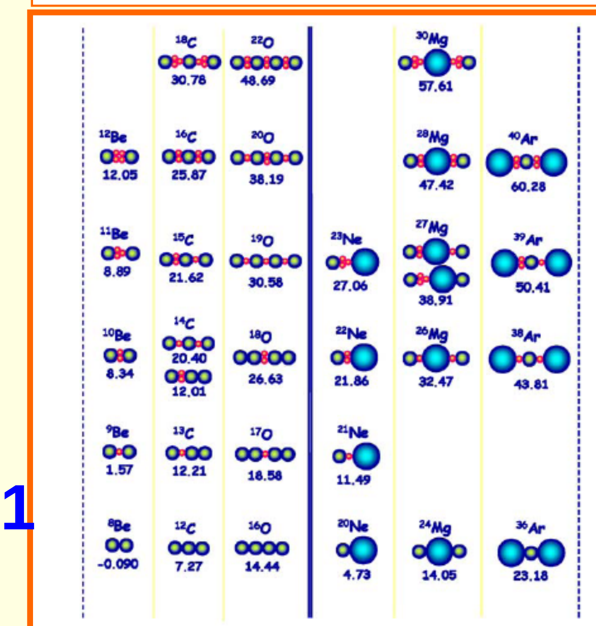


Fig. 1. Schematic figure for rich phenomena in nuclear systems.





PTEP,2012,01A202

JPG37(10)064021
PR432(06)43

Impact on the nuclear-astrophysics

Progress of Theoretical Physics Supplement No. 196, 2012

Alpha-Cluster Dominance in the αp Process in Explosive Hydrogen Burning

Shigeru KUBONO,[1] N. Binh DAM,[2] S. HAYAKAWA,[1] H. HASHIMOTO,[1] D. KAHL,[1] H. YAMAGUCHI,[1] Y. WAKABAYASHI,[3] T. TERANISHI,[4] N. IWASA,[5] T. KOMATSUBARA,[6] S. KATO,[7] A. CHEN,[8] S. CHERUBINI,[9] S. H. CHOI,[10] I. S. HAHN,[11] J. J. HE,[12] Hong Khiem LE,[2] C. S. LEE,[13] Y. K. KWON,[13] S. WANAJO[14] and H.-T. JANKA[14]

[1] *Center for Nuclear Study, University of Tokyo, Wako 351-0198, Japan*

Nucleosynthesis by alpha particles and heavier 4n nuclei are of great interest as they would involve nuclear cluster resonances. The role of nuclear clustering is discussed for nucleosynthesis with the Cluster Nucleosynthesis Diagram (CND) proposed before, especially those involving alpha induced reactions, based on our recent works of (α,p) reactions with low energy RI beams. We present experimental results that alpha resonances play a crucial role for the (α,p) reaction cross sections. Molecular resonances are also briefly discussed along this line for O- and C-burning.

Outline

I. Clustering phenomena

II. How to probe

II.1 for ground states

II.2 for excited states

III. Some new experiments

IV. Summary

Need theoretical predictions

Theory: **AMD, GCM(RGM), MO, GTCM, FMD, OCM, TCSM, TCHO(DHO), …**

Progress of Theoretical Physics Supplement No. 192, 2012

Recent Developments in Nuclear Cluster Physics

Hisashi HORIUCHI,[1,2] Kiyomi IKEDA[3] and Kiyoshi KATŌ[4]

[1] *Research Center for Nuclear Physics, Osaka University, Ibaraki 567-0047, Japan*

Progress in Particle and Nuclear Physics 82 (2015) 78–132

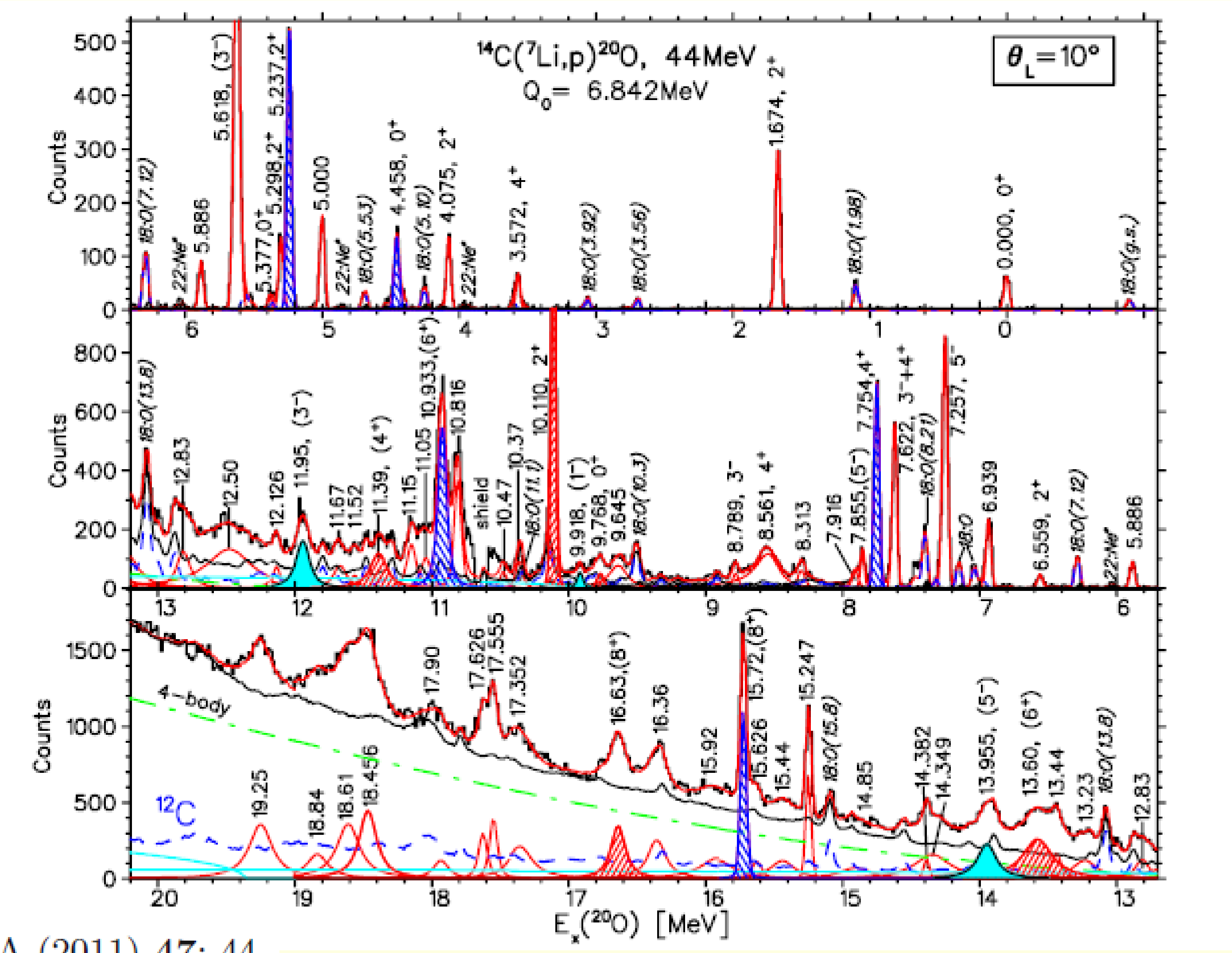
Review

Cluster models from RGM to alpha condensation and beyond

Y. Funaki [a,*], H. Horiuchi [b,c], A. Tohsaki [b]

[a] *Nishina Center for Accelerator-Based Science, The institute of Physical and Chemical Research (RIKEN), Wako 351-0198, Japan*
[b] *Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki 567-0047, Japan*
[c] *International Institute for Advanced Studies, Kizugawa 619-0225, Japan*

Need firstly inclusive (missing mass) observations (an example)



Eur. Phys. J. A (2011) **47**: 44

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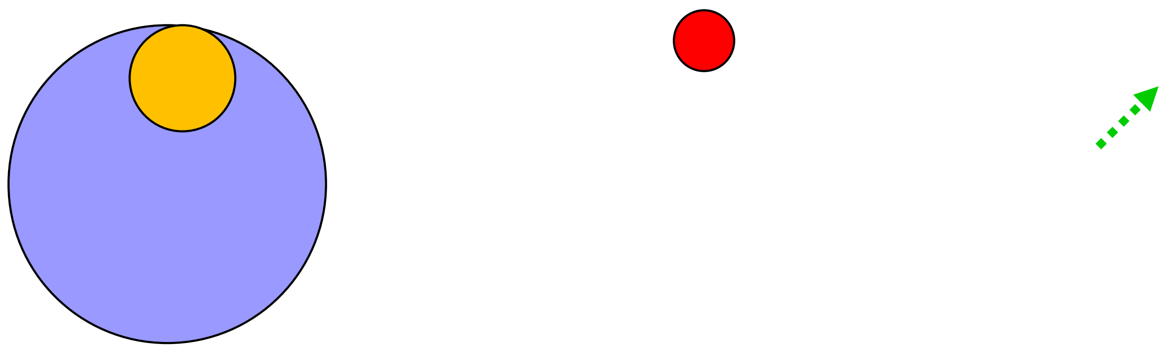
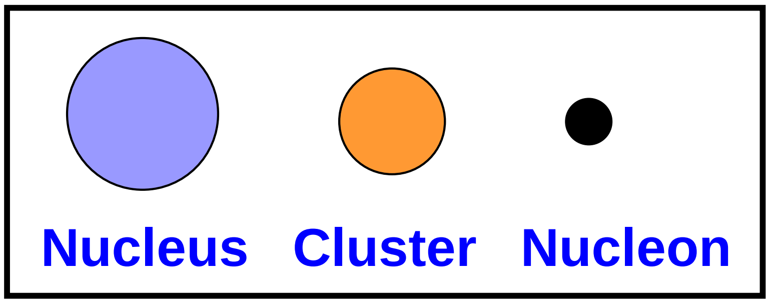
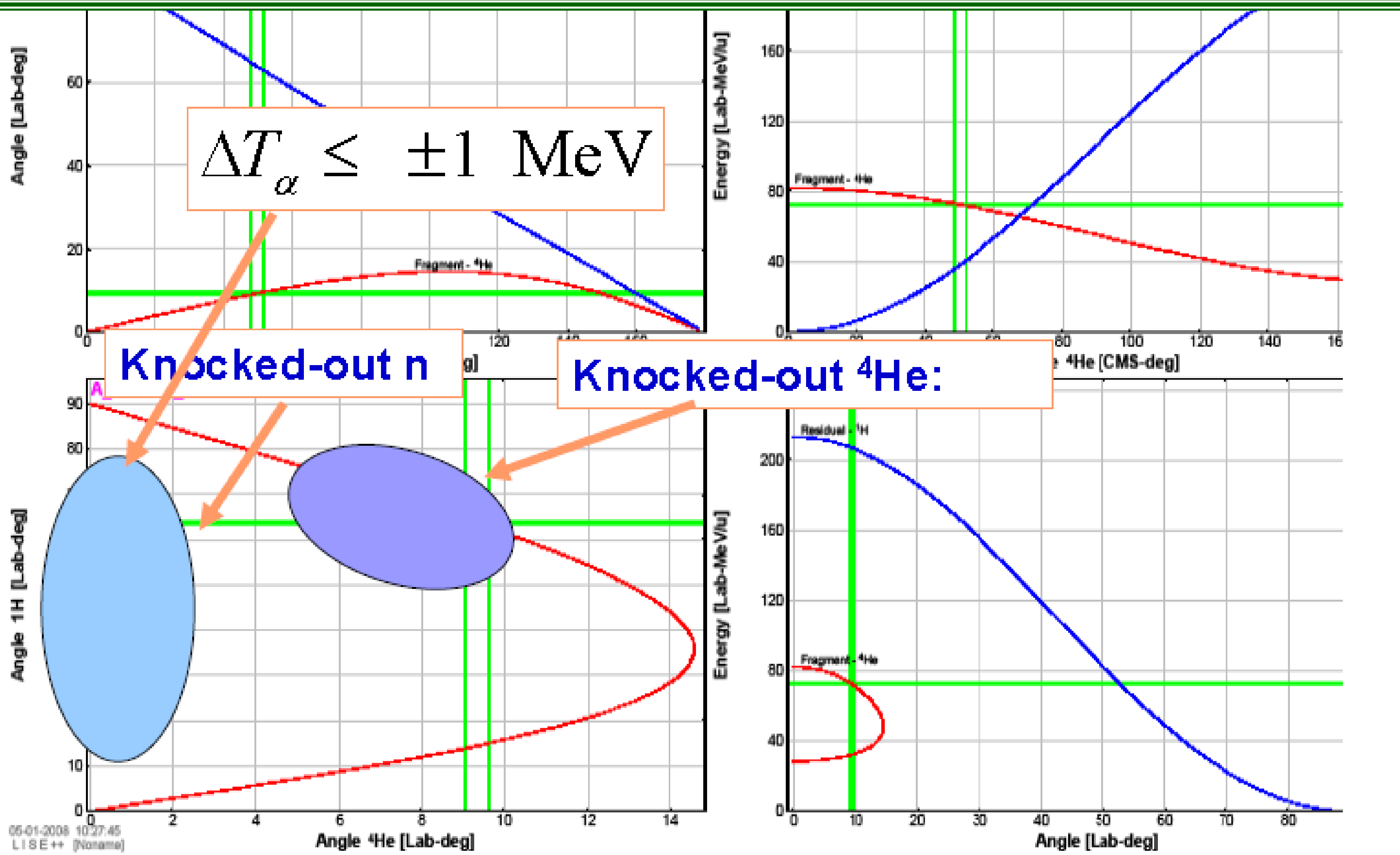
Knockout reaction （p, pC) in studying the ground state clustering





Ex.: ^{8}He(p, p^{6}He) 2n

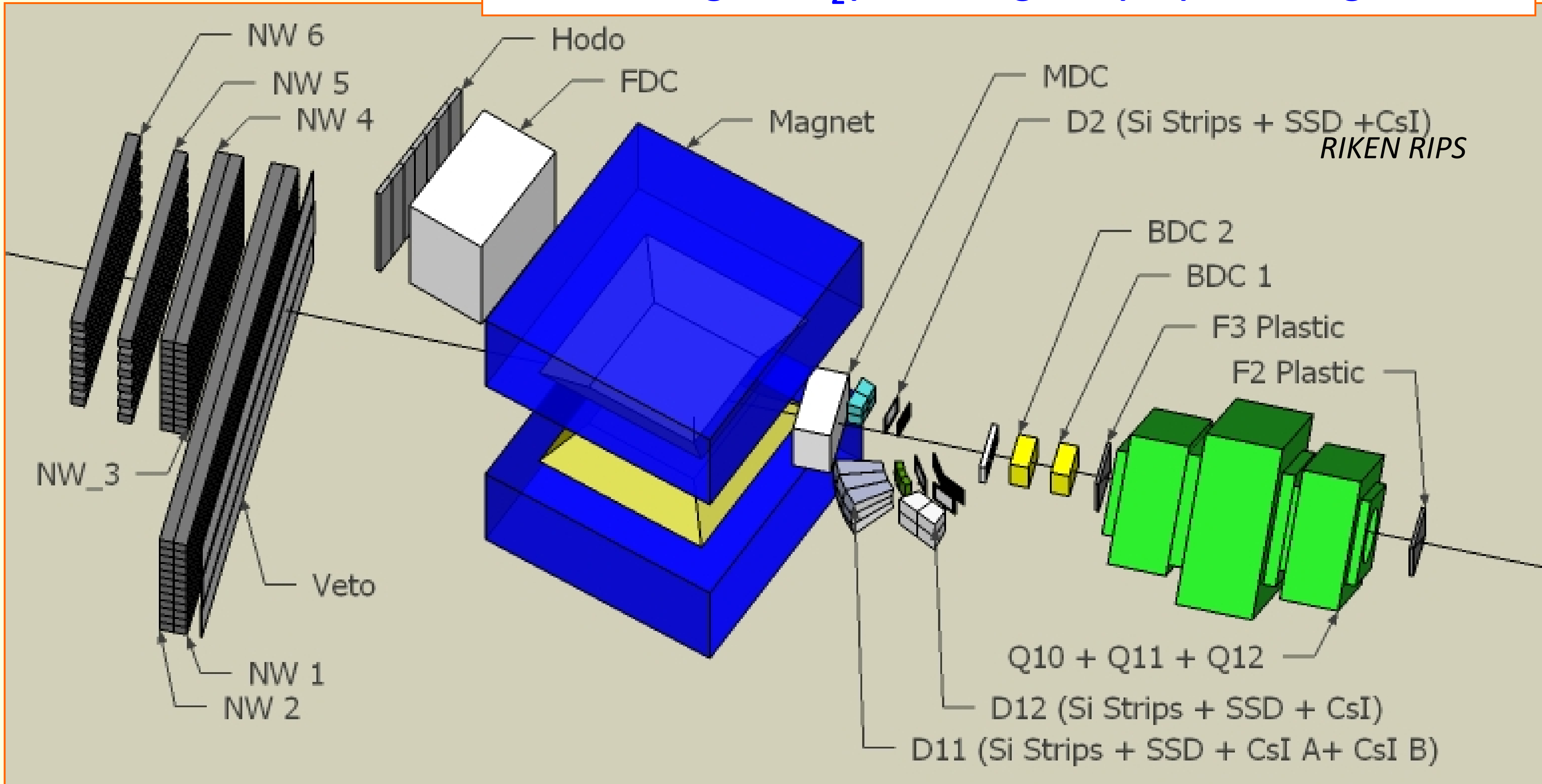


PKU group experiment at RIKEN

^{8}He + H,C at 82.3 MeV/u

Physics Letters B 707 (2012) 46–51

- **Primary Beam: ^{13}C, 115MeV/A, 470enA**
- **Primary Target: Be(12mm), F1 Wedge: Al(962mg/cm^2)**
- **Second Beam ^{8}He, 82MeV/A ~3*10^{5}pps**
- **Second Target: CH_2(0.0830mg/cm^2), C(0.1339mg/cm^2**



CPC(HEP & NP), 2012, **36**(2): 127–131 Chinese Physics C Vol. 36, No. 2, Feb., 2012

Probing the halo and cluster structure of exotic nuclei*

YE Yan-Lin(叶沿林)[1) LÜ Lin-Hui(吕林辉) CAO Zhong-Xin(曹中鑫) XIAO Jun (肖军)

School of Physics and State Key Laboratory of Nuclear Physics and Technology,
Peking University, Beijing 100871, China

Criterion for a sudden knockout

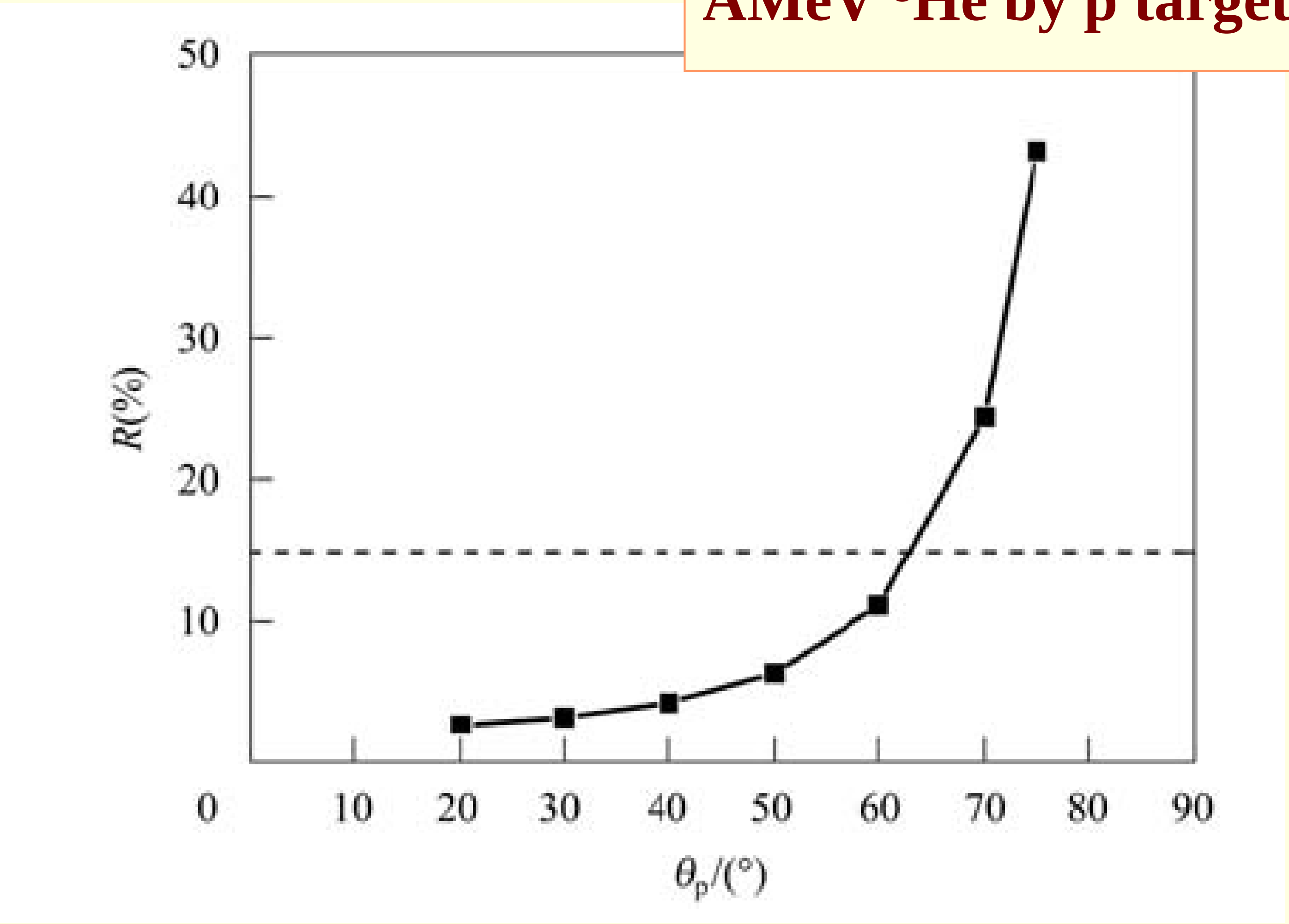
$$R = \Delta p_{\mathrm{B,rel}} / p_{\mathrm{p}} < 0.15$$

[26]. Assuming that projectile A is composed of B and C (A=B+C) and B makes a quasi-free collision with the target (a proton target for example), according to momentum conservation the magnitude of the momentum of the recoiled proton $p_{\rm p}$ in the laboratory system is equal to that transferred to constituent B, the latter is exactly the same as the relative momentum $p_{\rm B,rel}$ of B seen in the projectile rest frame. After the sudden collision, B tends to leave spectator C by overcoming the attraction force between them and will lose part of its momentum according to:

$$\Delta p_{\rm B,rel} = \int f \mathrm{d}t = \int \frac{\mathrm{d}\Phi}{\mathrm{d}r} \mathrm{d}t = \int \frac{\mathrm{d}\Phi}{v_{\rm r}}$$

$$\approx \frac{m_{\rm B} S_{\rm B}}{p_{\rm B,rel}} = \frac{m_{\rm B} S_{\rm B}}{p_{\rm P}} \left(\text{for } \Delta p_{\rm B,rel} \ll p_{\rm P}\right). \quad (1)$$

^{6}He core knockout from 80 AMeV ^{8}He by p target



RMP38(1966)121; RMP45(1973)6

- Three arguments:

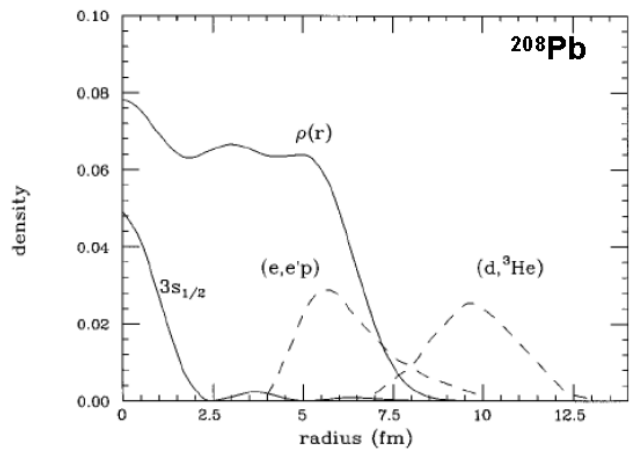
  i) mean free path: $R = \frac{1}{\rho\sigma}$ must be large enough to avoid multi-scattering

  ii) wave length: small enough to avoid collective excitation (no problem for a proton)

  iii) high momentum transfer for a localized interaction

  requiring high energy (100-1000 MeV p) for probing inner orbits; but moderate energy is ok for probing surface nucleons (low binding)

Differing Sensitivity to the BSWF



V.R. Pandharipande et al., Rev. Mod. Phys. 69 (1997) 981.

- **low binding energy is in favor of the sudden knockout assumption**
- **heavier fragment knockout requires higher incident energy.**
- **sudden knockout is better satisfied by a specific range of the recoiled proton angle.**

^{6}He core and recoil p correlation

For ^{8}He beam at 82.3 MeV/u;

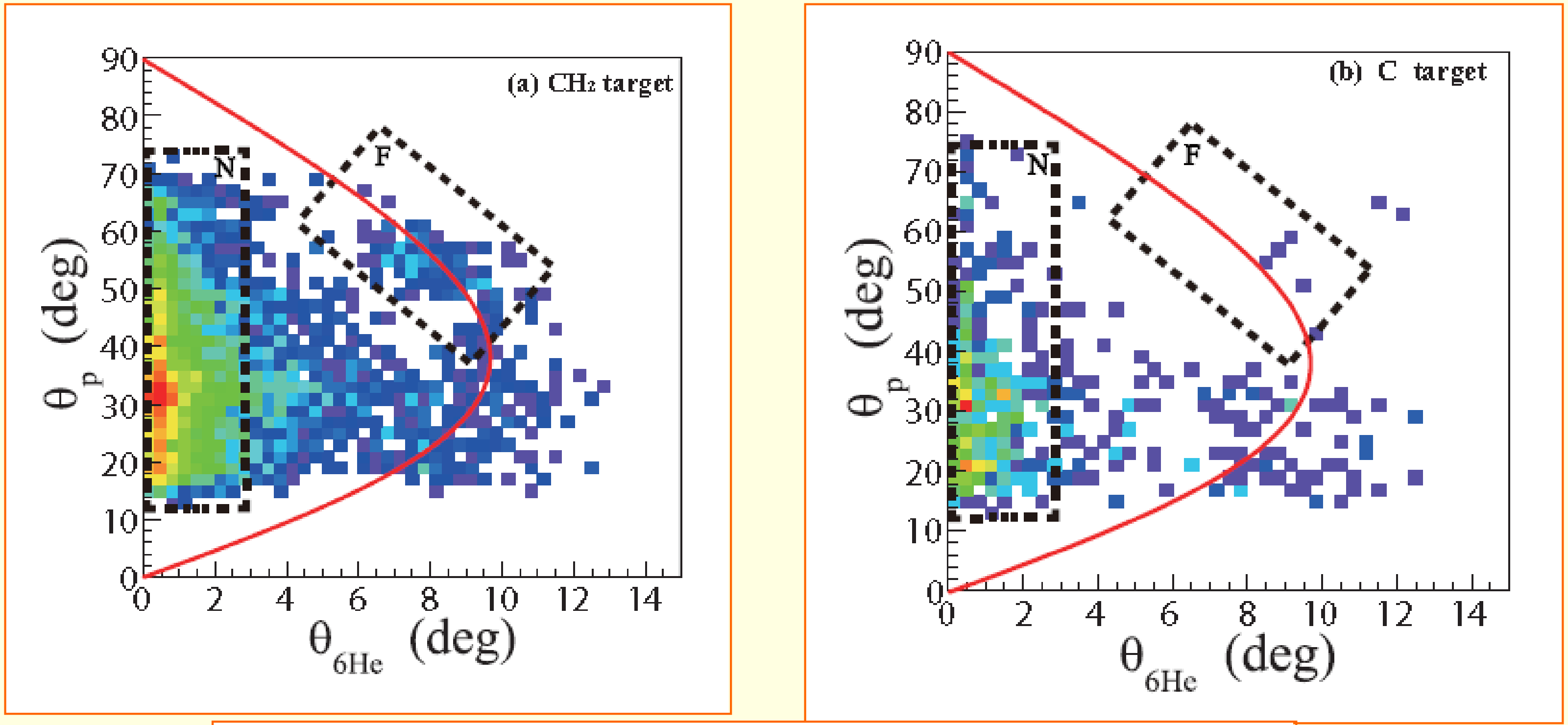
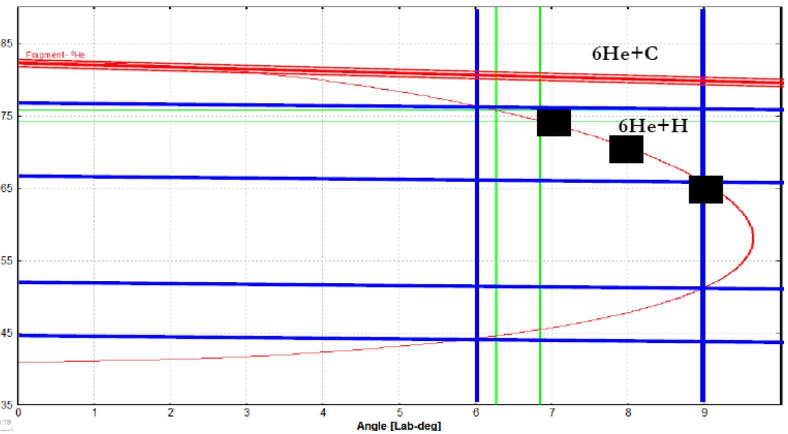
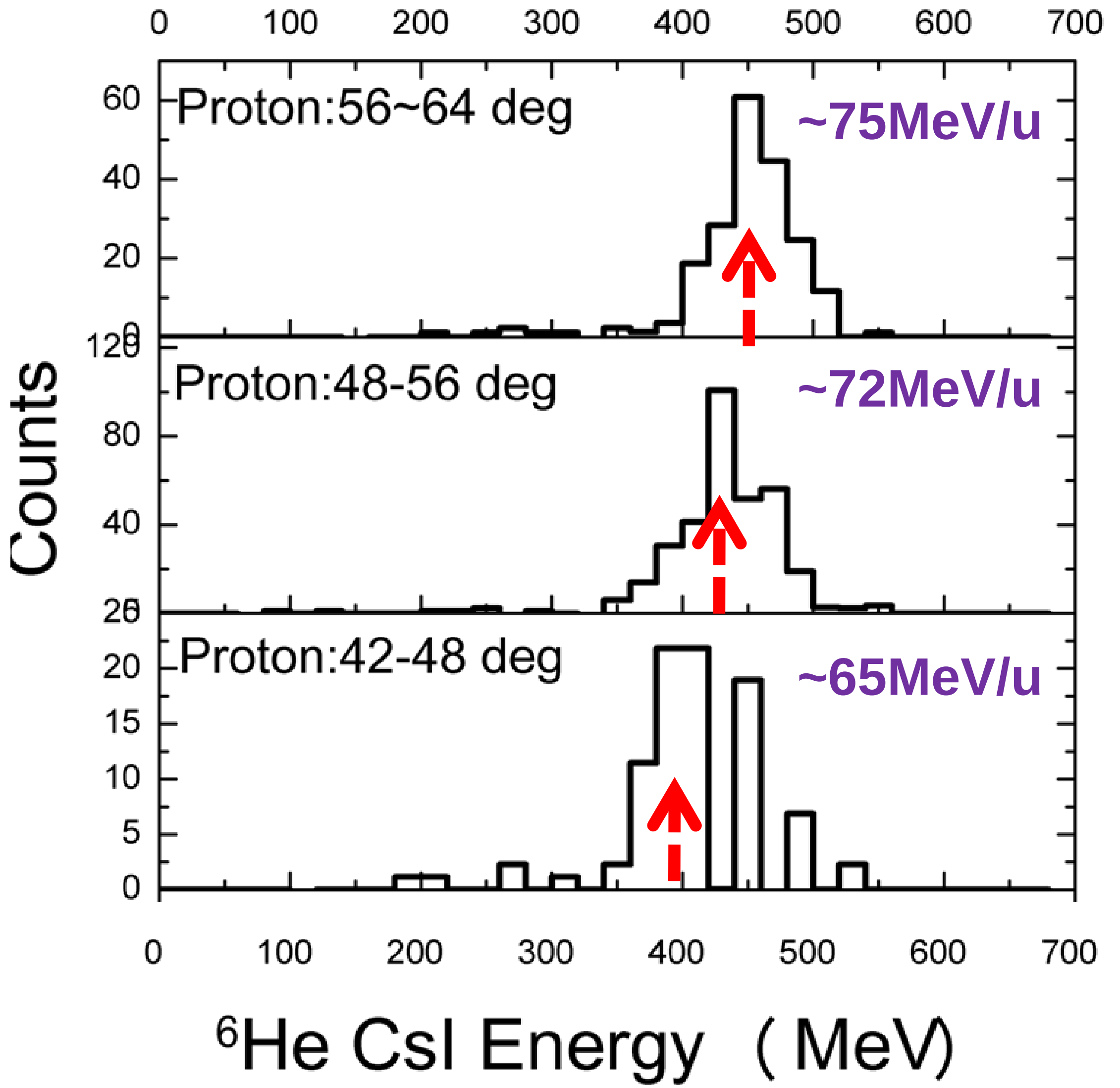


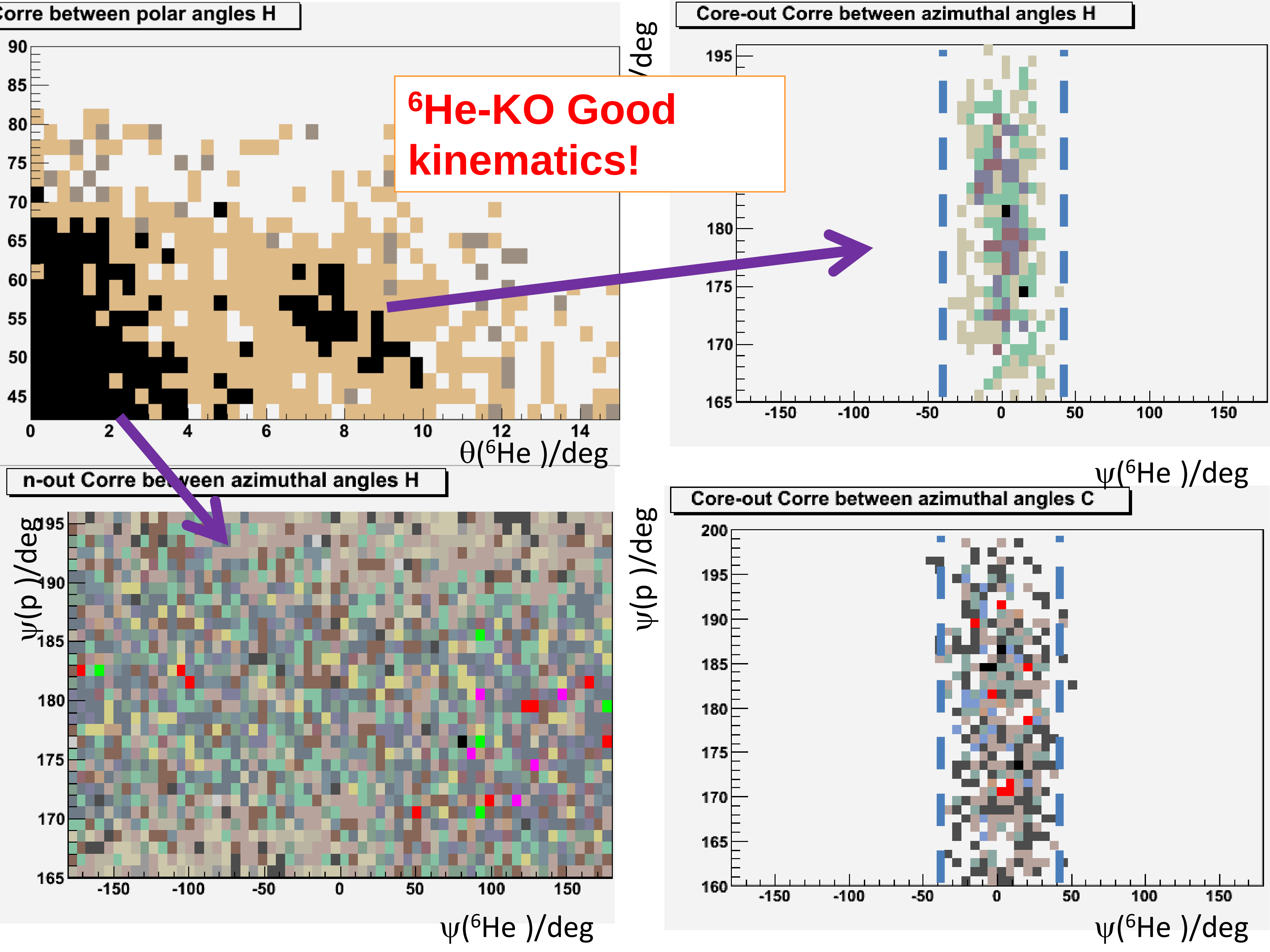
Figure 2: Polar angle correlations between the recoil protons and the forward moving ^{6}He fragments for (a) CH_2 target and (b) Carbon target, measured in the experiment using ^{8}He beam at 82.3 MeV/u. The solid curve is the kinematics relation for ^{6}He + p free scattering at 82.3 MeV/u. The frames with dashed line denote the event selection for the core fragment knockout (frame F) and the valence neutron knockout (frame N), respectively.

^{6}He E-angle



Very good knockout kinematics!





Corre between polar angles H
θ(6He)/deg
6He-KO Good kinematics!
Core-out Corre between azimuthal angles H
ψ(6He)/deg
n-out Corre between azimuthal angles H
ψ(p)/deg
ψ(6He)/deg
Core-out Corre between azimuthal angles C
ψ(p)/deg
ψ(6He)/deg

For ^{6}He core knockout events

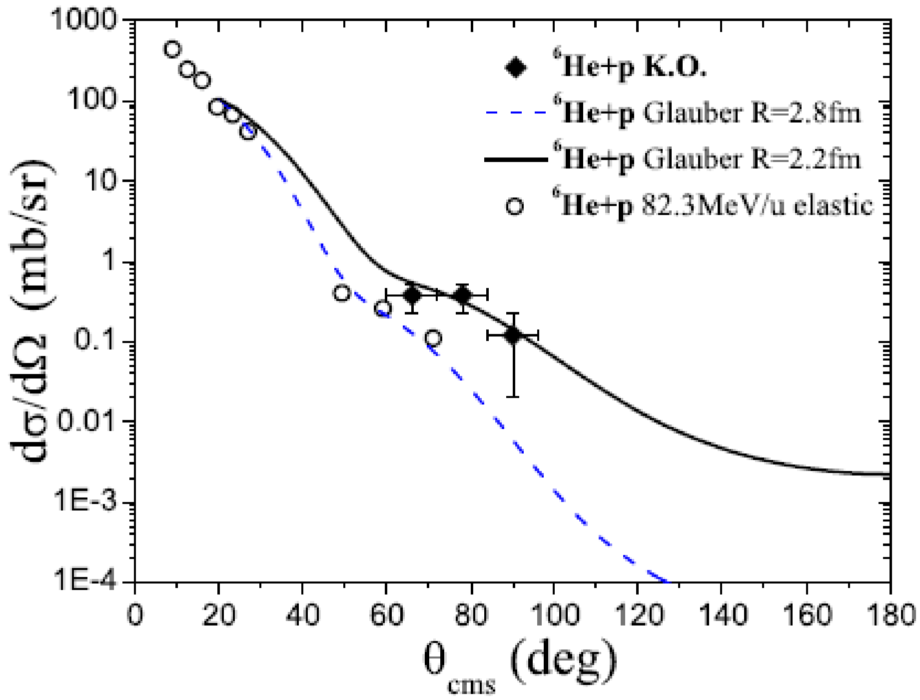


Figure 4: Differential cross sections for ^{6}He core fragments knocked out (K.O.) from ^{8}He projectiles at 82.3 MeV/u (the fulled diamonds). Data for elastic scattering of ^{6}He on proton target are also presented by the circles [22]. The dashed line represents the Glauber model calculation for elastic scattering, whereas the solid line displays the same kind of calculation but with a reduced matter radii for ^{6}He.

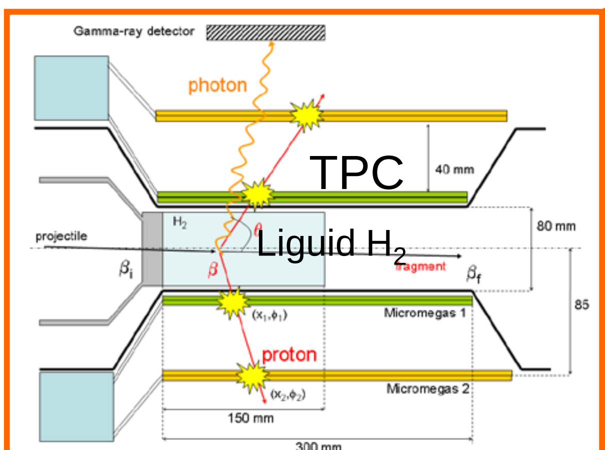
Great opportunities at BigRIPS + SAMURAI
Ex: Proposals for ^{14}Be, $^{18\text{-}20}$C, $^{15\text{-}19}$F……

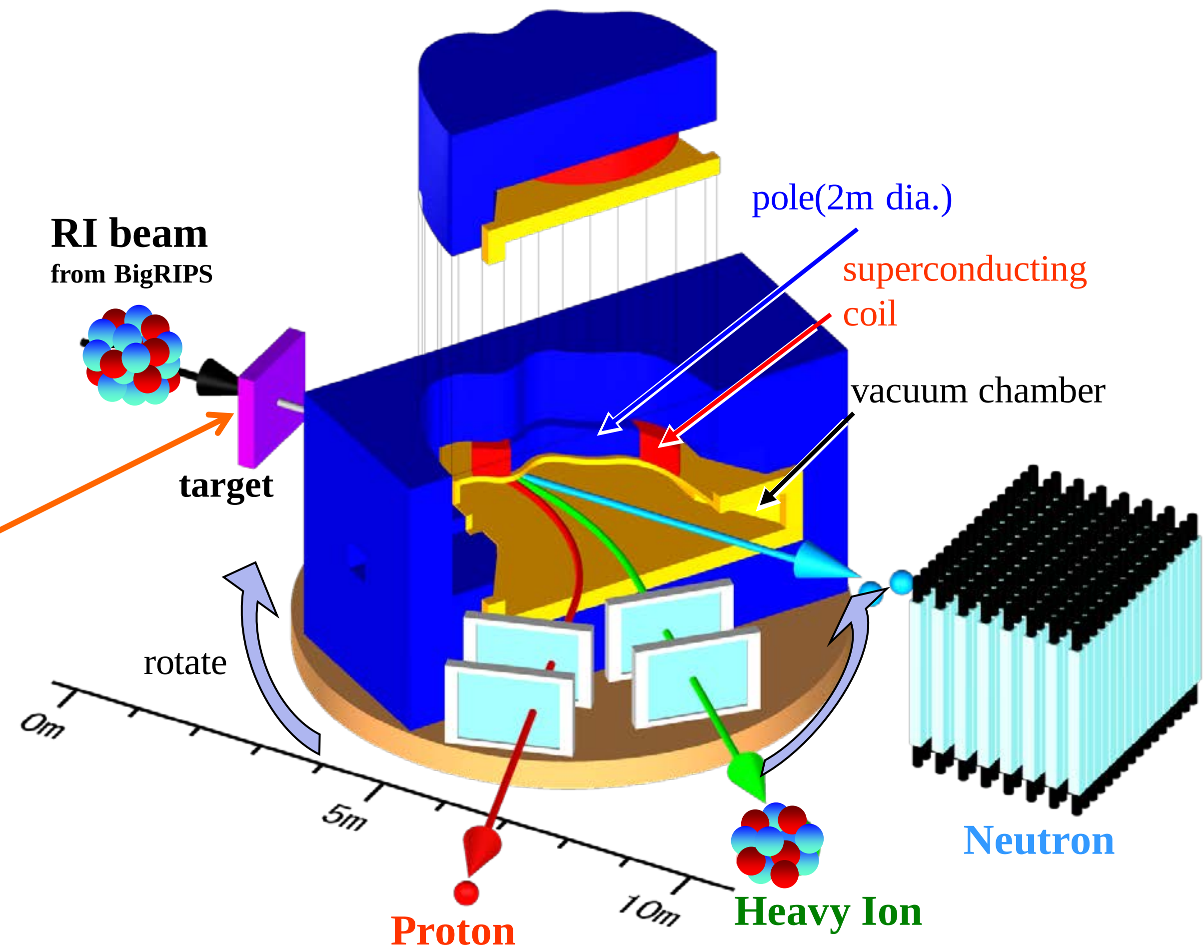
MINOS:

MagIc Numbers Off Stability

Δ x<3mm FWHM

Eff. >85%





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Clustering in excited states

Well established cluster states:

0^+_2 (7.65 MeV) state in ^{12}C,

0^+_2 (6.05 MeV) and 0^+_3 (12.05 MeV) in ^{16}O;

0^+_4 (8.03 MeV) in ^{20}Ne

……..

a band in ^{10}Be

0^+_3 (10.3 MeV) in ^{12}Be

……

Optimum beam energy 20-30 MeV/u

PHYSICAL REVIEW C, VOLUME 63, 034615

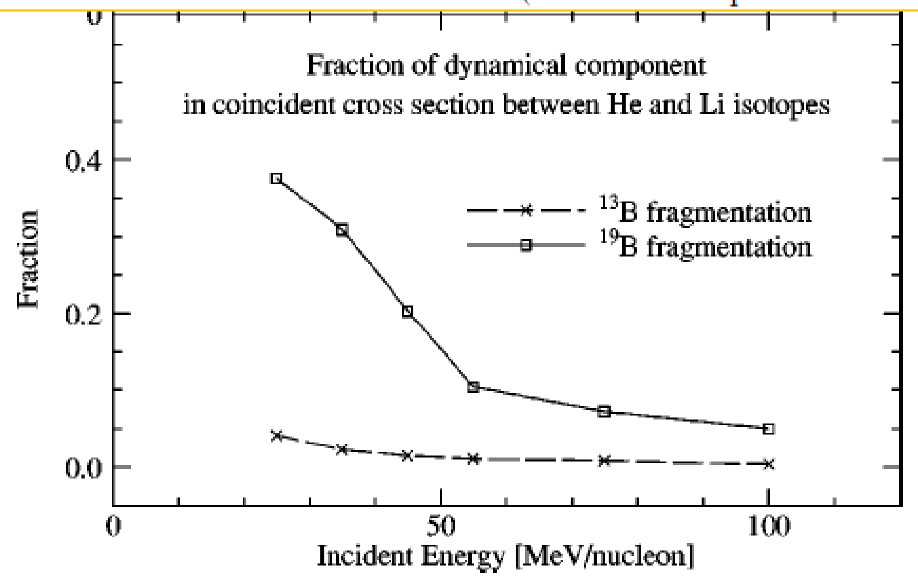
Incident-energy dependence of the fragmentation mechanism reflecting the cluster structure of the ^{19}B nucleus

Hiroki Takemoto
Advanced Science Research Center, Japan Atomic Energy Research Institute, Tokai, Ibaraki 319-1195, Japan

Hisashi Horiuchi
Department of Physics, Kyoto University, Kyoto 606-8502, Japan

Akira Ono
Department of Physics, Tohoku University, Sendai 980-8578, Japan

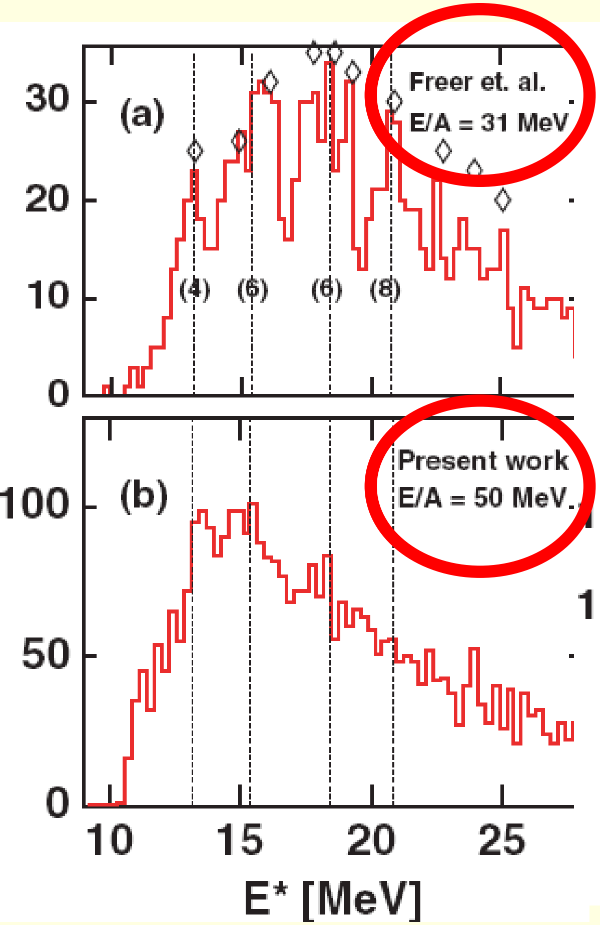
(Received 7 September 2000; published 21 February 2001)



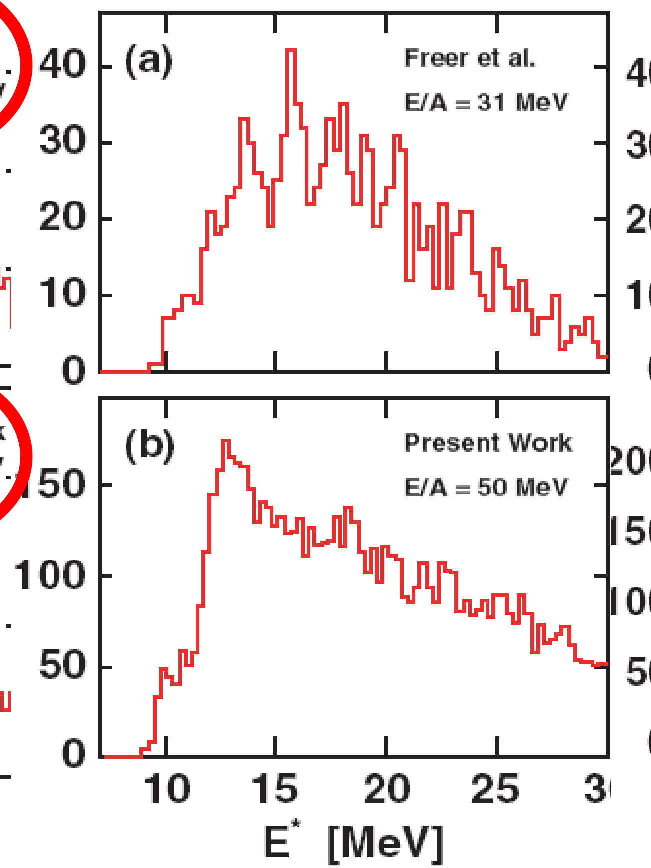
the fraction of the dynamical component of the coincident cross sections between He and Li isotopes in 13B+14N and 19B+14N reactions.

Freer et al., PRL82(1999) 1383; PRC63 (2001)034301
Charity et al., PRC76(2007)064313

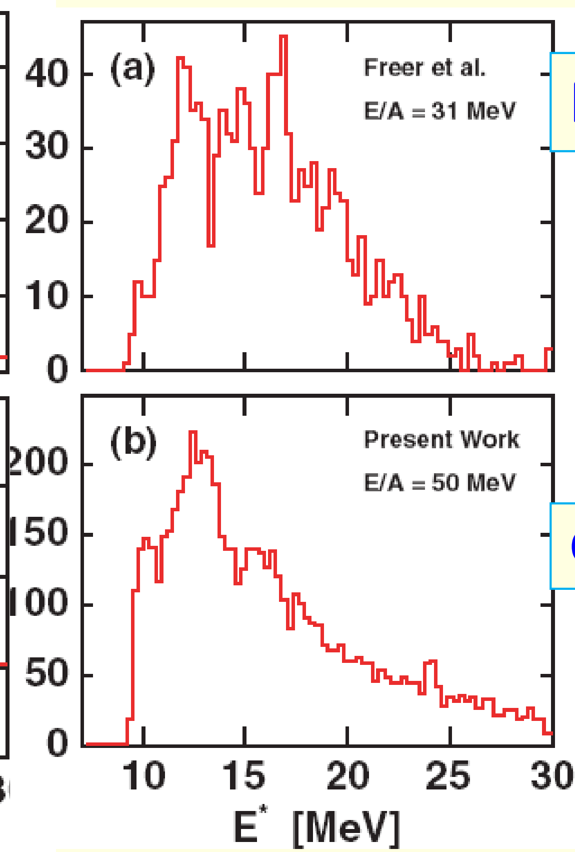
no small angle (low E_{rel}) detection



^{6}He+^{6}He,CH$_2$



^{4}He+^{8}He,with P

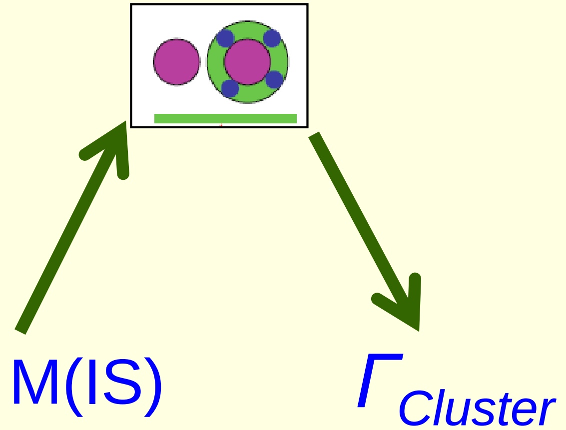


Freer

Charity

^{4}He+^{8}He, with C

Observables determining the cluster formation in a resonant state (Ex: ^{12}Be, 10.3 MeV state)



i) E_x - spin systematics:

high moment of inertia

ii) Large cluster decay width:

large $\Gamma_{Cluster}/\Gamma$; $\gamma^2_{Cluster}$; $\theta^2_{Cluster}$

iii) Characteristic transition strength

large M(IS) !!

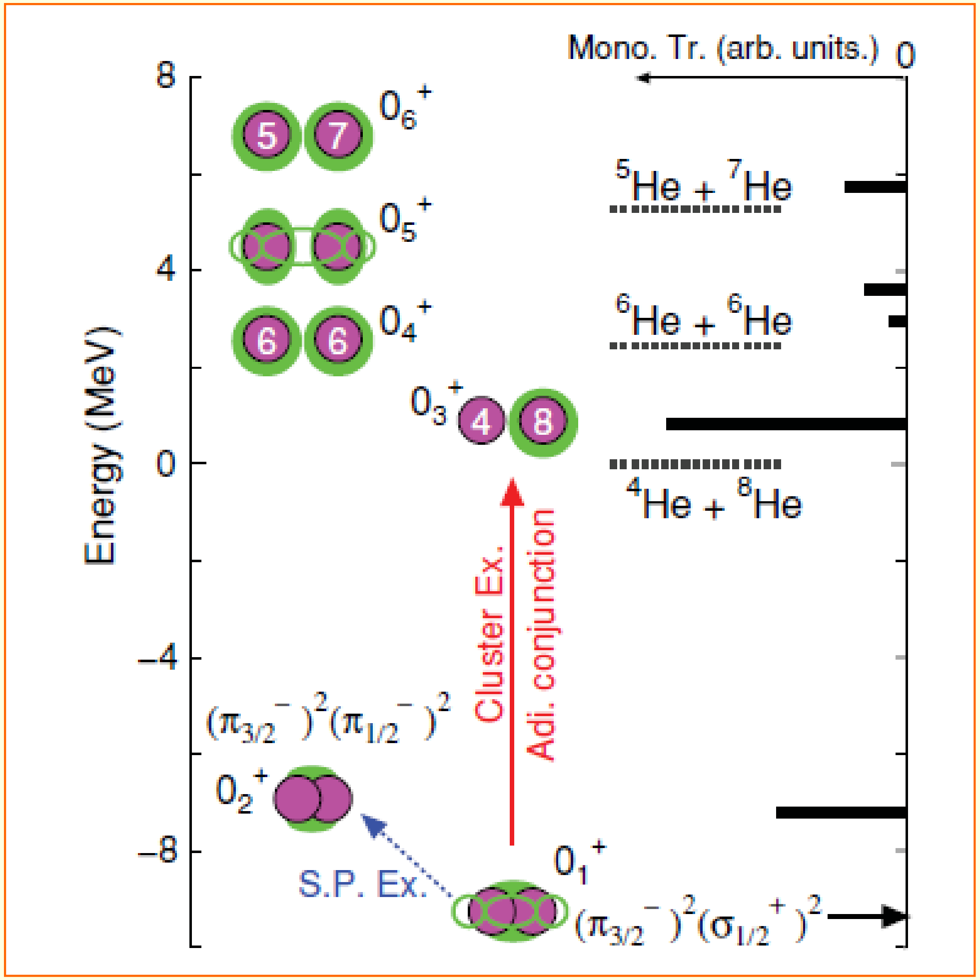
Ex:

PHYSICAL REVIEW C **83**, 044319 (2011)

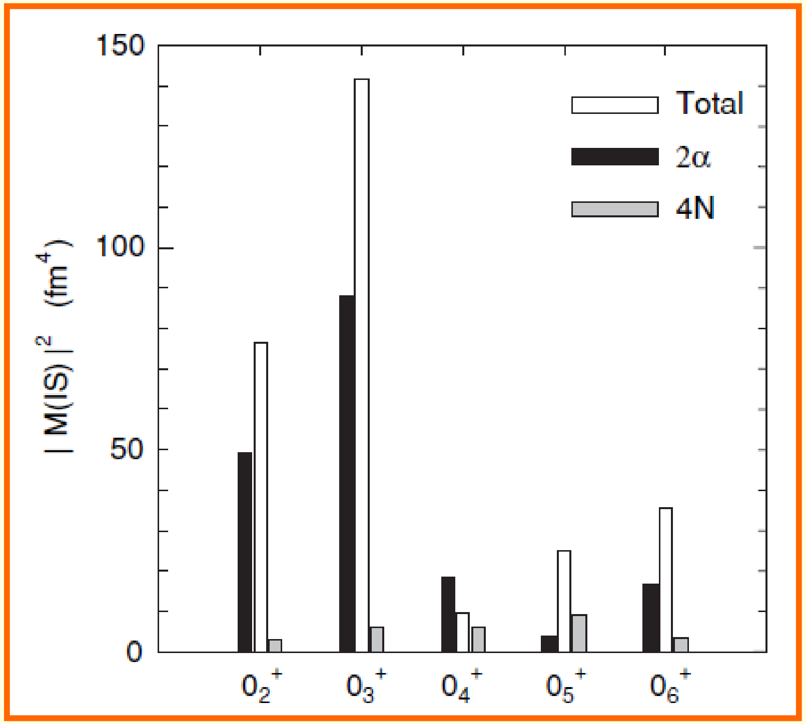
Imprint of adiabatic structures in monopole excitations of ^{12}Be

Makoto Ito

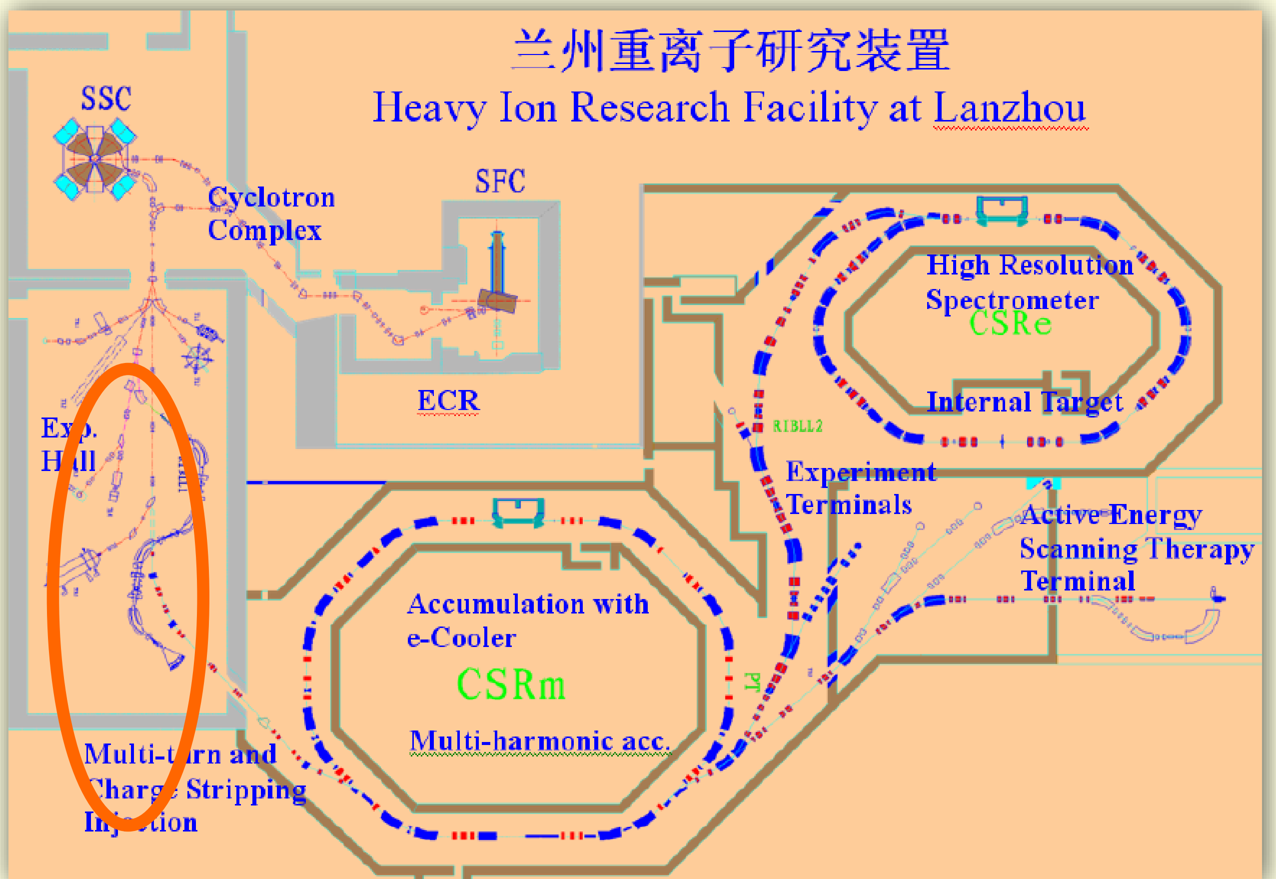
Department of Pure and Applied Physics, Kansai University, Yamate-cho 3-3-35, Suita 564-8680, Japan,
Research Center for Nuclear Physics (RCNP), Osaka University, Mihogaoka 10-1, Suita 567-0047, Japan, and
RIKEN Nishina Center for Accelerator-based Science, RIKEN, Wako, 351-0198 Saitama, Japan

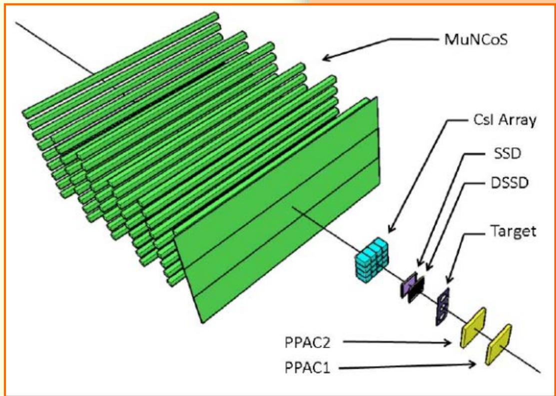


$$M(IS) = M^{2\alpha}(IS) + M^{4N}(IS),$$
$$M^{2\alpha}(IS) = \langle 0_\nu^+ | \sum_{i\in 2\alpha} r_i^2 | 0_1^+ \rangle,$$
$$M^{4N}(IS) = \langle 0_\nu^+ | \sum_{i\in 4N} r_i^2 | 0_1^+ \rangle.$$



Ex: An exp. at RIBLL1@HIRFL, Lanzhou





Beam: ^{12}Be, 29.0MeV/u, ~3000pps

Target: Carbon, 100 mg/cm^2

DSSD: 32 2mm-stip, 300μm, covering 0^0-12^0 Lab.

CsI(Tl): 4 x 4, 2.5cm*2.5cm*3cm,

Detection focused on the most forward angles

Collaborators

PRL 112, 162501 (2014) PHYSICAL REVIEW LETTERS week ending 25 APRIL 2014

Observation of Enhanced Monopole Strength and Clustering in ^{12}Be

Z. H. Yang (杨再宏),[1] Y. L. Ye (叶沿林),[1,*] Z. H. Li (李智焕),[1] J. L. Lou (楼建玲),[1] J. S. Wang (王建松),[2] D. X. Jiang (江栋兴),[1] Y. C. Ge (葛愉成),[1] Q. T. Li (李奇特),[1] H. Hua (华辉),[1] X. Q. Li (李湘庆),[1] F. R. Xu (许甫荣),[1] J. C. Pei (裴俊琛),[1] R. Qiao (乔锐),[1] H. B. You (游海波),[1] H. Wang (王赫),[1,3] Z. Y. Tian (田正阳),[1] K. A. Li (李阔昂),[1] Y. L. Sun (孙叶磊),[1] H. N. Liu (刘红娜),[1,3] J. Chen (陈洁),[1] J. Wu (吴锦),[1,3] J. Li (李晶),[1] W. Jiang (蒋伟),[1] C. Wen (文超),[1,3] B. Yang (杨彪),[1] Y. Y. Yang (杨彦云),[2] P. Ma (马朋),[2] J. B. Ma (马军兵),[2] S. L. Jin (金仕纶),[2] J. L. Han (韩建龙),[2] and J. Lee (李晓菁)[3]

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[2]*Institute of Modern Physics, Chinese Academy of Science, Lanzhou 730000, China*
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(Received 10 December 2013; published 22 April 2014)

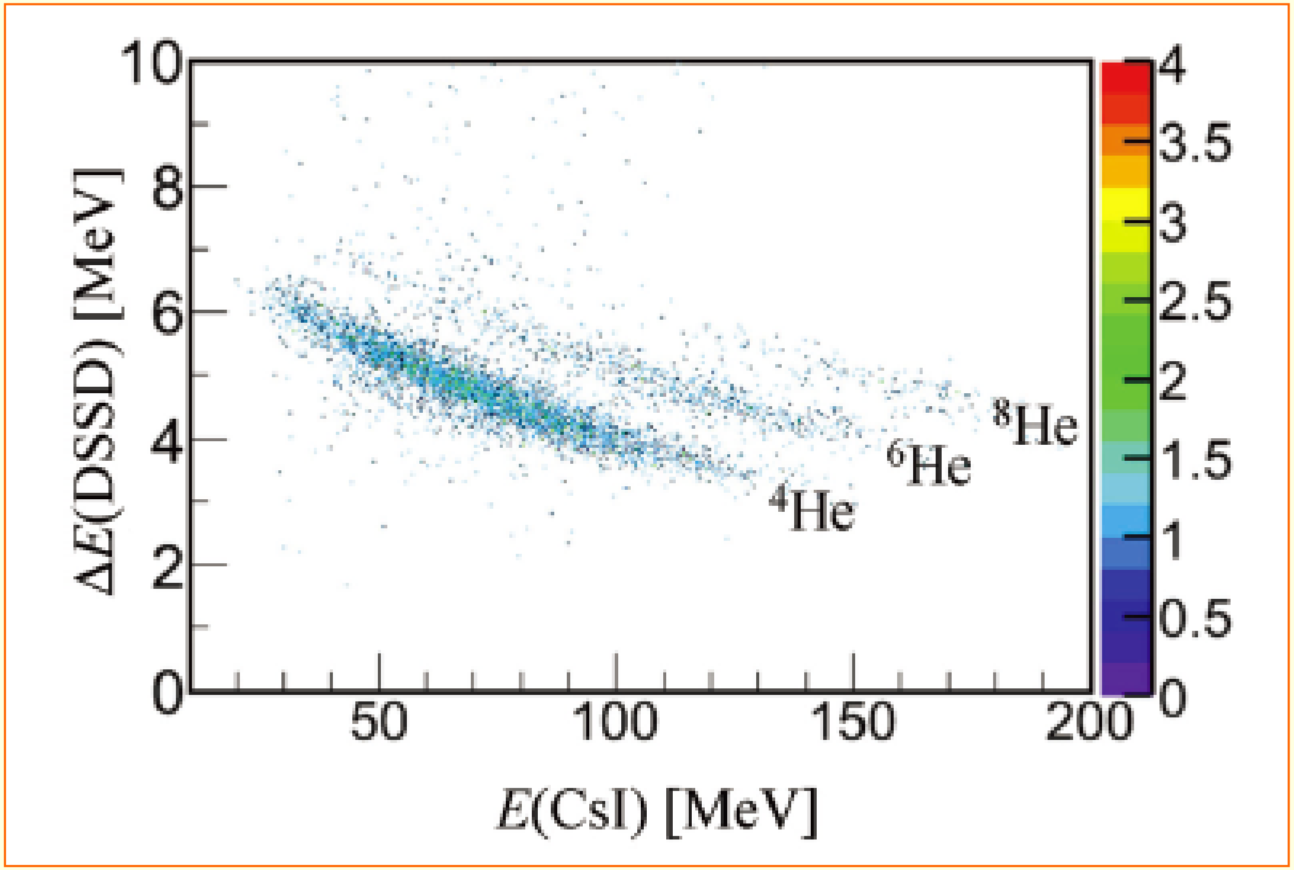
In a recent breakup-reaction experiment using a ^{12}Be beam at 29 MeV/nucleon, the 0^+ band head of the expected ^{4}He + ^{8}He molecular rotation was clearly identified at about 10.3 MeV, from which a large monopole matrix element of 7.0 ± 1.0 fm^2 and a large cluster-decay width were determined for the first time. These findings support the picture of strong clustering in ^{12}Be, which has been a subject of intense investigations over the past decade. The results were obtained thanks to a specially arranged detection system around zero degrees, which is essential in determining the newly emphasized monopole strengths to signal the cluster formation in a nucleus.

PHYSICAL REVIEW C 91, 024304 (2015)

Helium-helium clustering states in ^{12}Be

SCIENCE CHINA
Physics, Mechanics & Astronomy
September 2014 Vol. 57 No. 9: 1613–1617

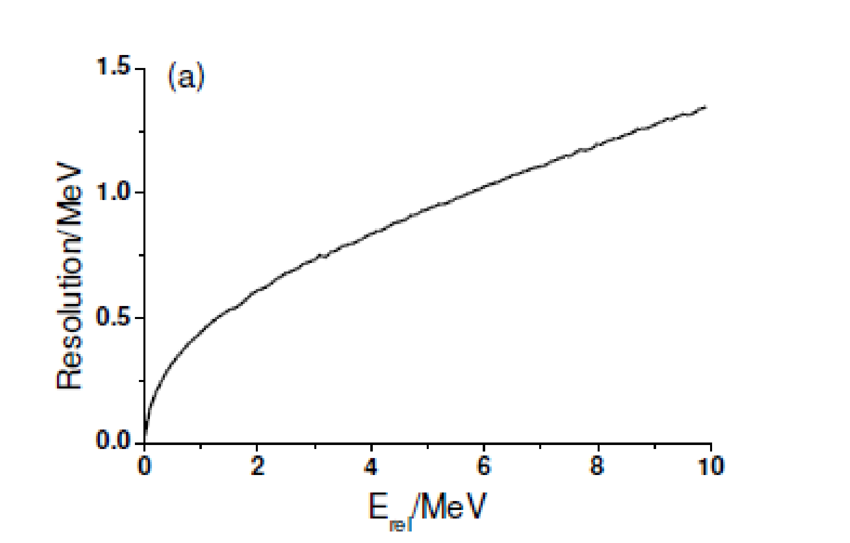
PID for 2-^{x}He fragments



Uniform calibration of the Si strips and treatment of PID under intense direct beam:

[IEEE-NS 61(2014)596, NIMA728(2013)52]

Resolution and efficiency



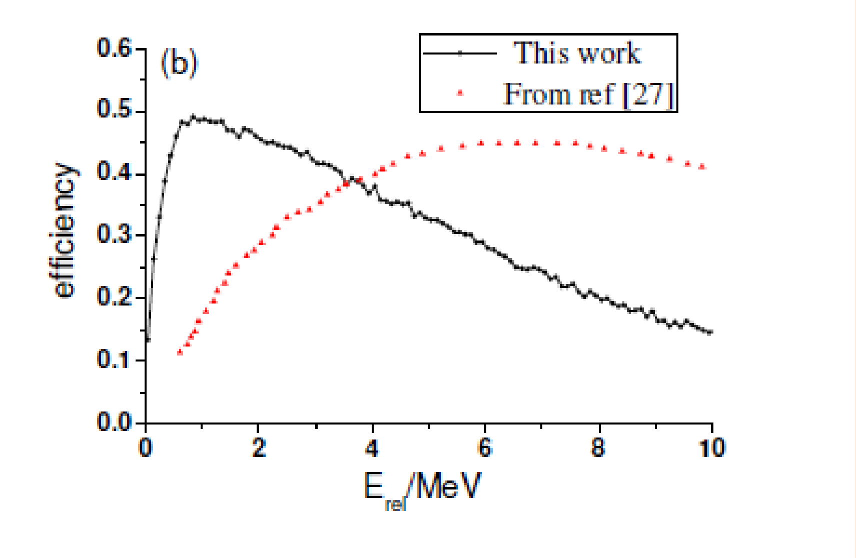
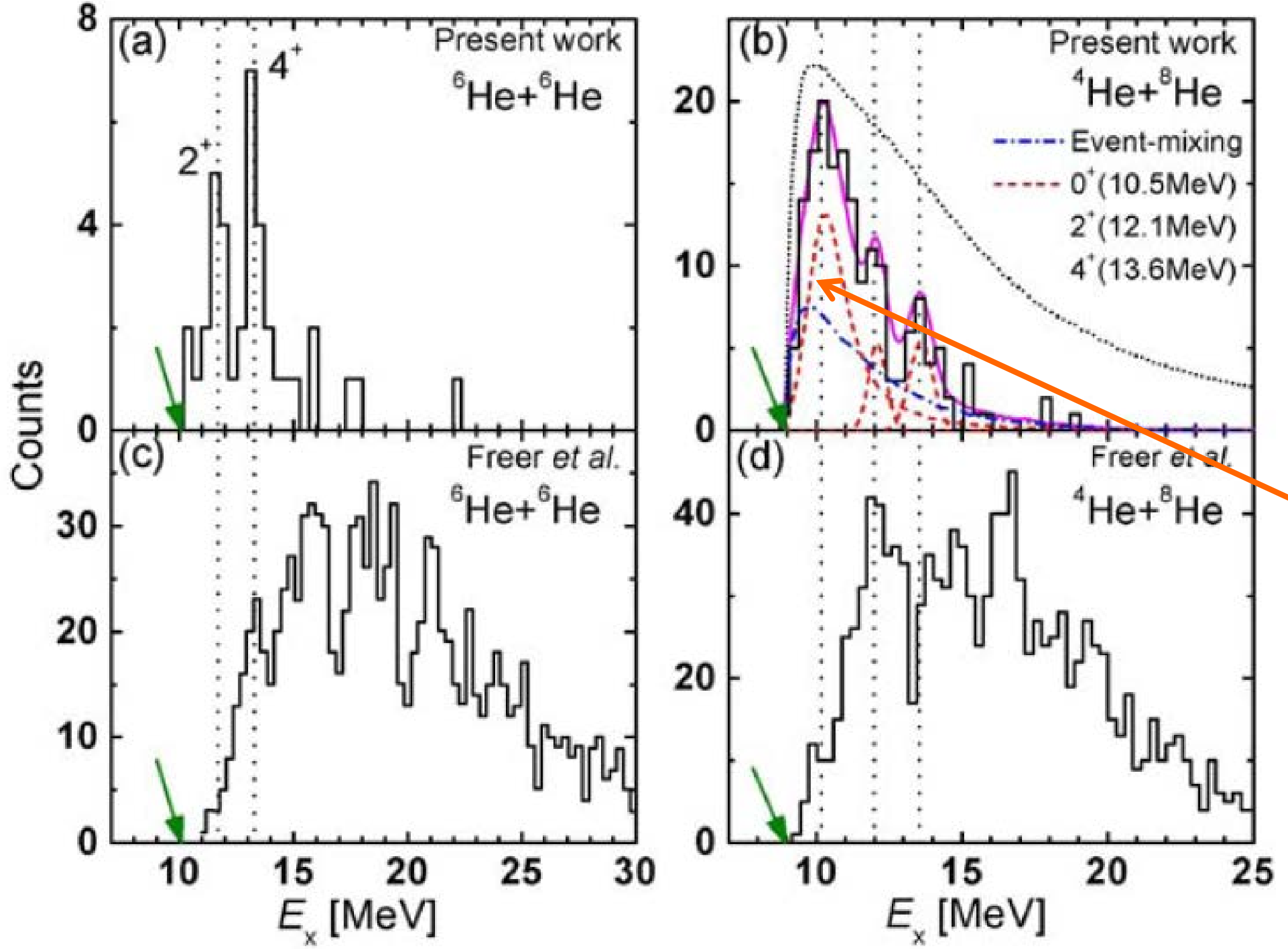


FIG. 2. Resolution(FWHM) of E_{rel} (a) and detection efficiency (b) for ^{12}Be decaying into ^{4}He+^{8}He. Similar results are also obtained for ^{12}Be decaying into ^{6}He+^{6}He. And for comparison, the efficiency obtained from reference[27] was also shown.



Large and unusual 10.3 MeV state; pure 0⁺ !!

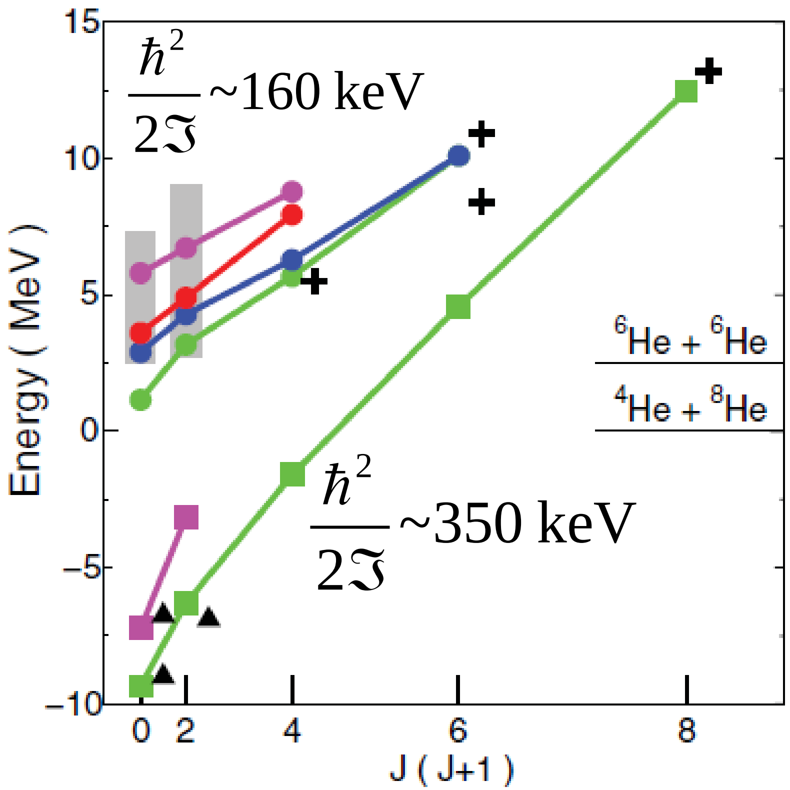
Our exp:	^{6}He+^{6}He		11.7	13.3	MeV
	^{4}He+^{8}He	10.3	12.1	13.6	MeV

i) Determination of the moment of inertia

PRL 100, 182502 (2008) PHYSICAL REVIEW LETTERS week ending 9 MAY 2008

Coexistence of Covalent Superdeformation and Molecular Resonances in an Unbound Region of ^{12}Be

M. Ito,[1] N. Itagaki,[2] H



For E_x:

Q value in inelastic scattering,

or reconstruction from binary decay:

$$E_{\rm rel} = M^* - M_a - M_b = \sqrt{M^2} - M_a - M_b$$

$$M^2 = M_a{}^2 + M_b{}^2 + 2(T_a + M_a)(T_b + M_b)$$

$$- 2\sqrt{(T_a{}^2 + 2T_a M_a)(T_b{}^2 + 2T_b M_b)} \cos\theta$$

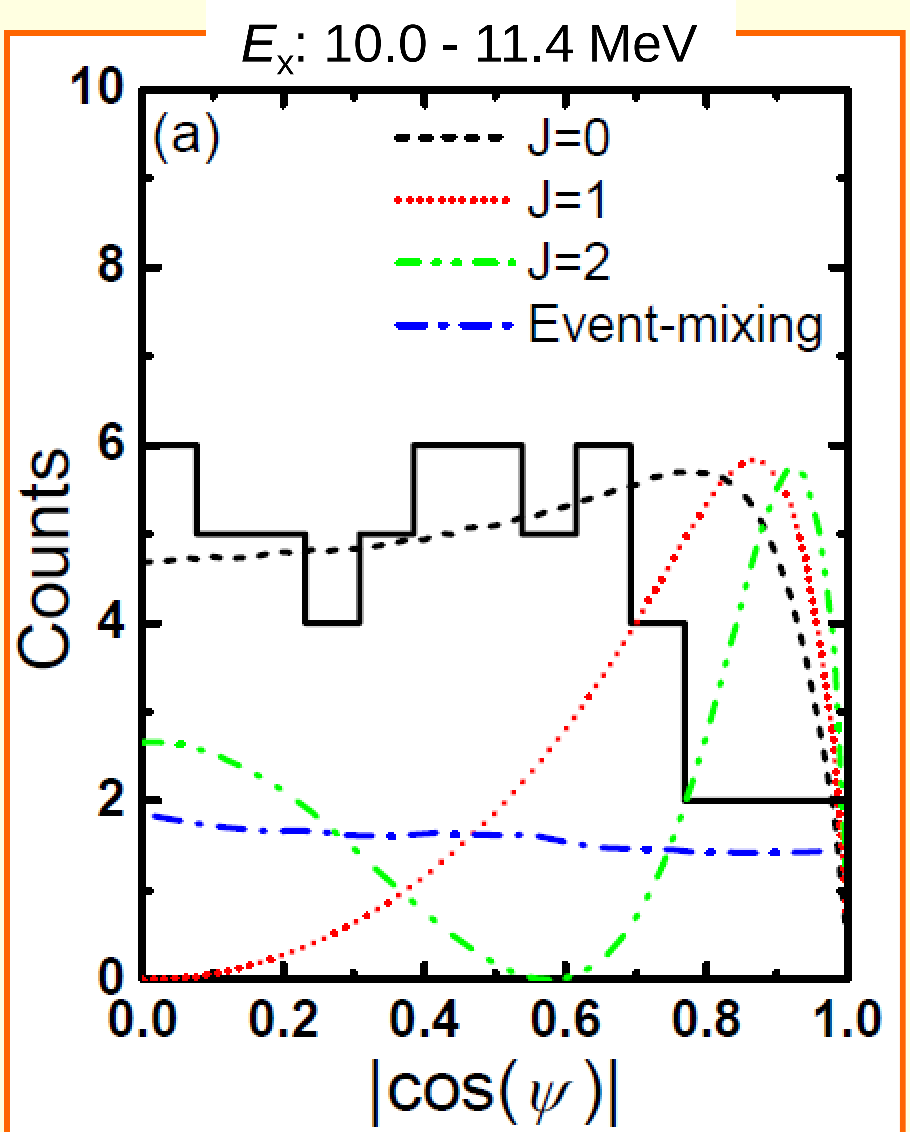
$$E_x = E_{\rm rel} + E_{\rm thre}$$

For J (quite difficult):

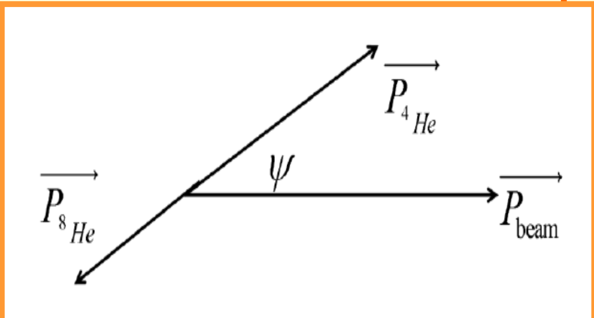
angular distribution of inelastic scattering,

or angular correlation from binary decay.

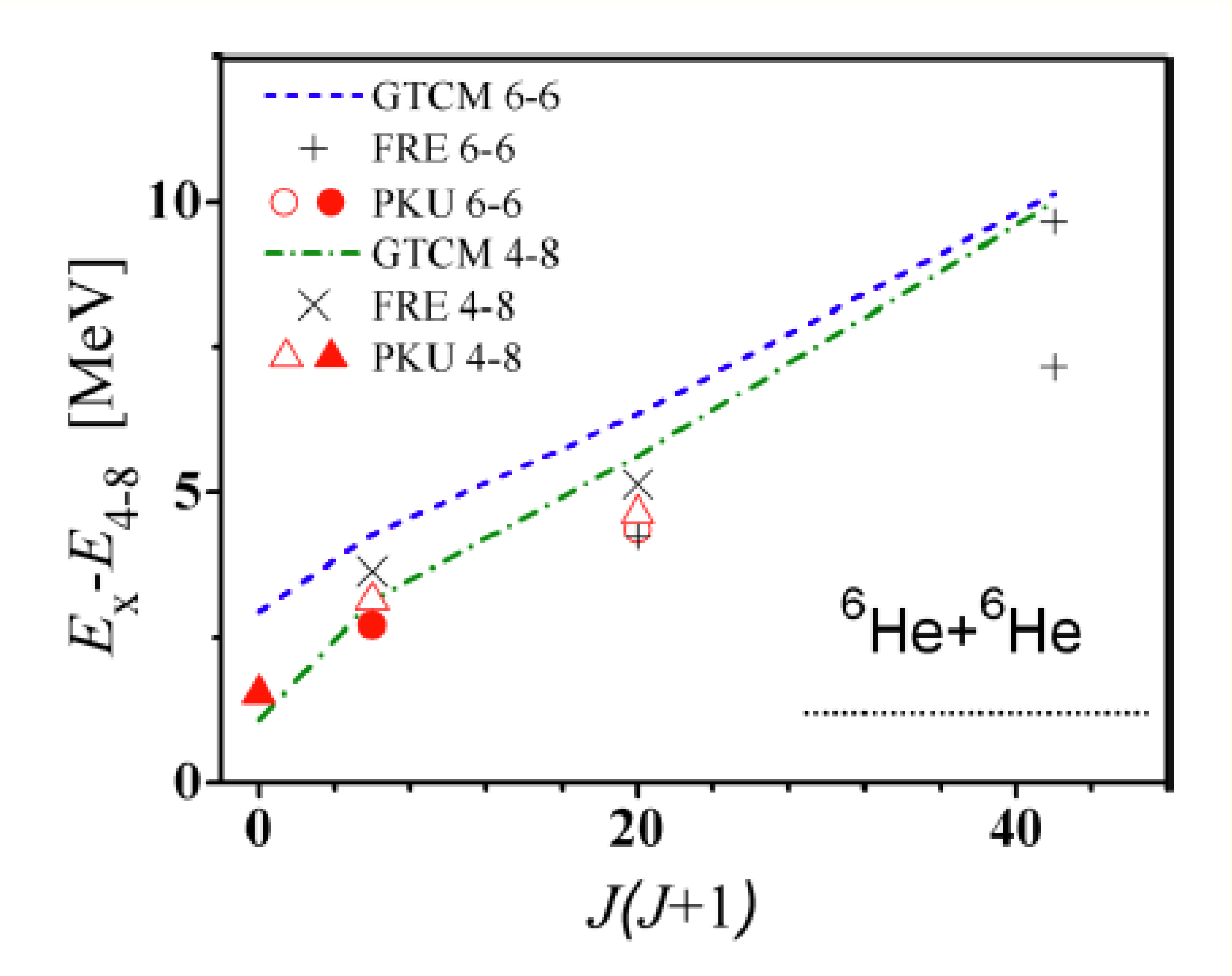
Angular correlation analysis for the 10.3 MeV state in ^{12}Be decaying into ^{4}He + ^{8}He



For small angle inelastic scattering leading to a resonant state with an angular momentum *J*, which subsequently breaks up into spin-0 fragments, the projected angular correlation spectrum is proportional to $| P_J(\cos(\Psi) |^2$, with Ψ being the fragment c.m. angle relative to the beam direction.



Confirming the MR band with a large moment of inertia



ii) Determination of the cluster decay width and the cluster SF

SCIENCE CHINA
Physics, Mechanics & Astronomy

2014 Vol. 57 No. 9: 1613–1617

Determination of the cluster spectroscopic factor of the 10.3 MeV state in ^{12}Be†

YANG ZaiHong, YE YanLin*, LI ZhiHuan, LOU JianLin, XU FuRong, PEI JunCheng,

$$N(E) \propto \frac{\Gamma(E)}{[E - E_r - \Delta(E)]^2 + [\Gamma(E)/2]^2}.$$

$$\Gamma = \Gamma_\gamma + \Gamma_\mathrm{n} + \Gamma_\mathrm{p} + \Gamma_\alpha + \cdots$$

the partial is of probability meaning,

not energy meaning： $\Gamma_\mathrm{i} / \Gamma = \sigma_\mathrm{i} / \sigma$

R-matrix analysis

$$\Gamma_\alpha(E) = 2\gamma_\alpha^2 P_l(E), \quad P_l(E) = \frac{ka}{(F_l(ka))^2 + (G_l(ka))^2},$$

$$\theta_\alpha^2 = \frac{\gamma_\alpha^2}{\gamma_\mathrm{W}^2}, \quad \gamma_\mathrm{W}^2 = \frac{3\hbar^2}{2\mu a^2}.$$

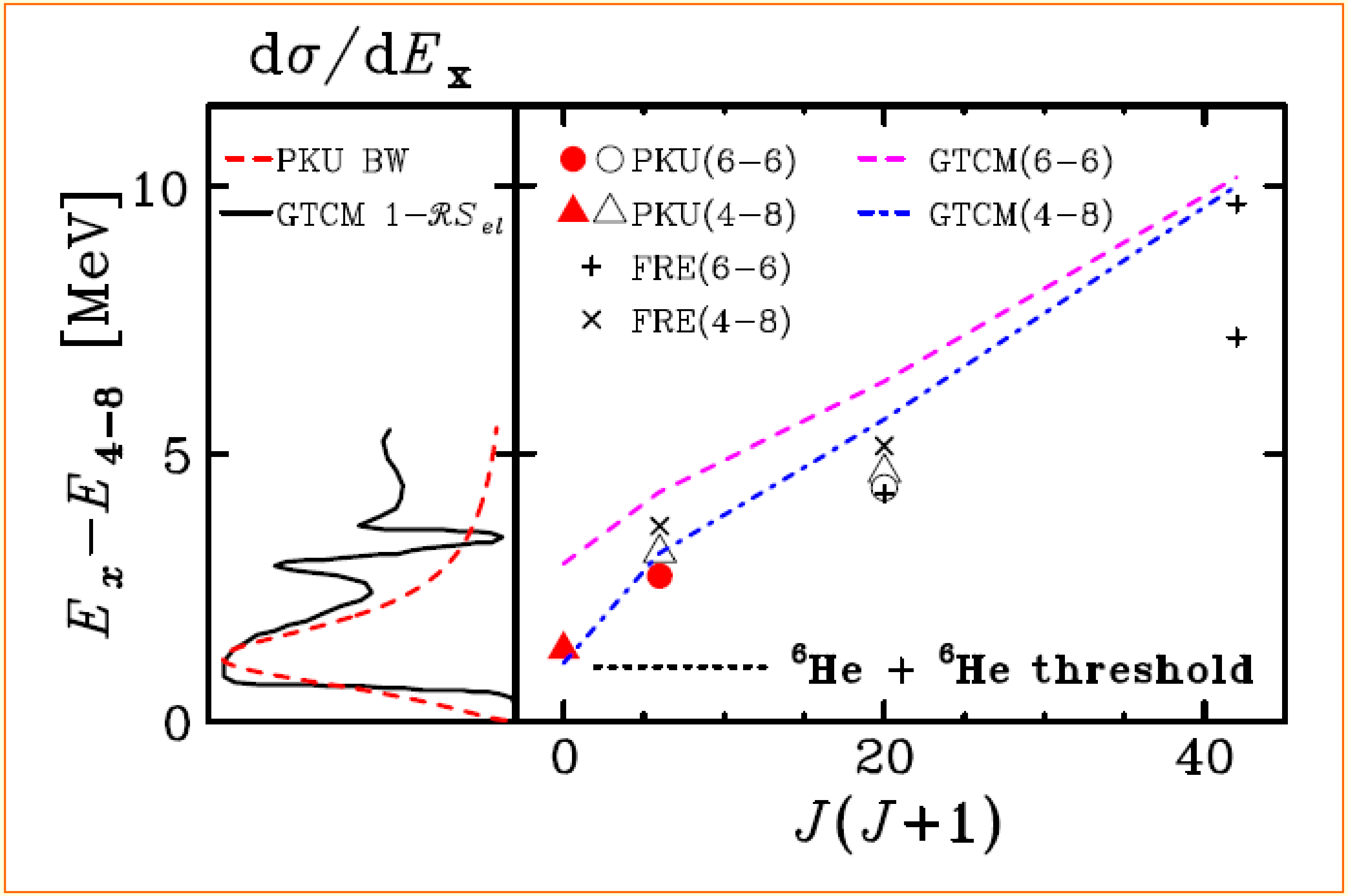
where E is the decay energy (or relative energy) and a the channel radius. The latter is generally given by $a = r_0(A_1^{1/3} + A_2^{1/3})$ with $r_0 \approx 1.4$ fm. For ^{12}Be decaying into ^{4}He+^{8}He, the channel radius is about a =5 fm. This value was also adopted in AMD calculations [32]. In eq. (2) $F_l(ka)$ and $G_l(ka)$ are regular and irregular Coulomb wave functions [9,31].

All possible decay channels

10.3 MeV(0+) state: $\Gamma = 1.5(2)$ MeV; $\Gamma = \Gamma_{He} + \Gamma_{Be}$

表格 6.3.2　^{12}Be 各破碎道概率的相空间估算。

反应道	阈值 [MeV]	概率 （E_x=15MeV）	概率 （E_x=12MeV）	文献结果[33]
^{4}He+^{8}He	9. 6	39%	27. 6 %	36 %
^{6}He+^{6}He	10. 1	21%	13. 1%	19. 3 %
^{4}He+^{6}He+2n	11. 08	0. 19%	1. 1E-3 %	0. 027 %
^{11}Be+n	3. 17	44. 3%	38. 3%	40. 9 %
^{10}Be+2n	3. 67	10. 4%	5. 6 %	3. 7 %
^{9}Be+3n	10. 48	0. 098%	2. 1E-3 %	0. 028 %
^{8}Be+4n	12. 06	6. 9E-5 %	----------	3. 4E-6 %



10.3 MeV(0+) state: $\Gamma = 1.5(2)$ MeV; $\Gamma = \Gamma_{He} + \Gamma_{be}$

Kosheninnilov[12]: $\Gamma_{Be}/\Gamma = 0.28 \pm 0.12$

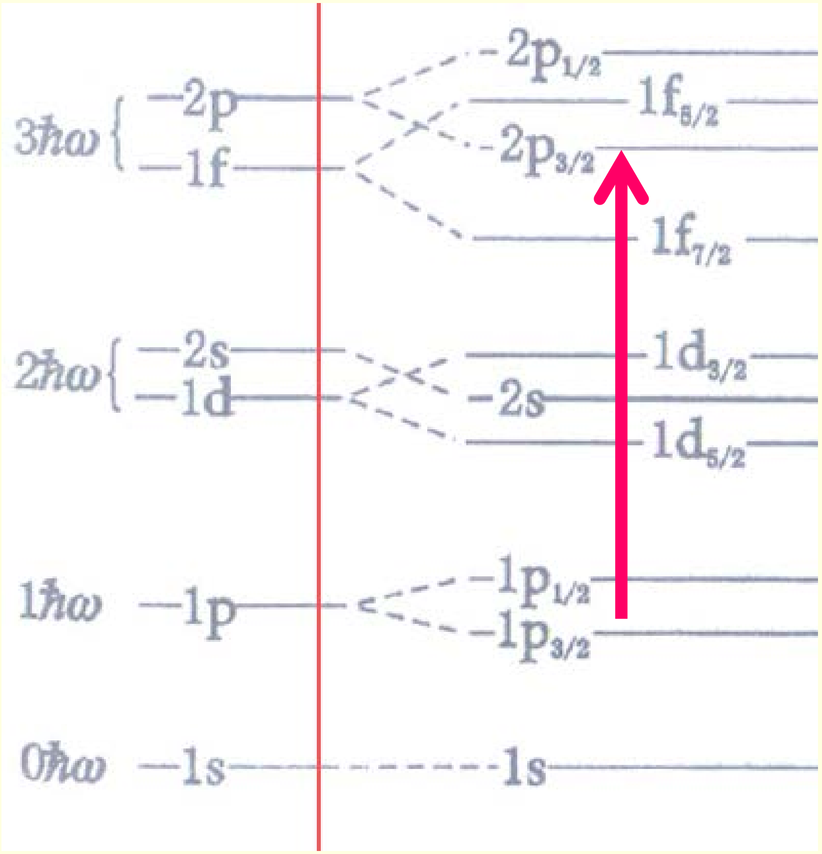
$\Gamma_{He}/\Gamma = 1 - \Gamma_{Be}/\Gamma = 0.72(12)$; $\Gamma_{He} = 1.1(2)$ **MeV**

$\gamma^2_{He} = 0.50(9)$; $\theta^2_{He} = 0.53(10)$ （**comparable to ^{8}Be)**

Ex: Determination of the monopole transition strength

T. Yamada et al., PRC85,034315(2012); PTP120,1139(2008)

Isoscaler monopole excitation means a jump of about 35 MeV in a simple single-particle picture. A strong M(IS) for E_x below ~15 MeV is an indicator of cluster formation



From T. Yamada:

Duality in g.s w.f: mean-field and cluster degrees of freedom

$$\frac{1}{\sqrt{16!}}\det\left|(0s)^4(0p)^{12}\right|\times[\phi_{cm}(\mathbf{R}_{cm})]^{-1}$$: closed shell

c.o.m. w.f. of ^{16}O

$$\phi_{cm}(\mathbf{R}_{cm})=\left(\frac{32\nu}{\pi}\right)^{3/4}\exp(-16\nu\mathbf{R}_{cm}^2)$$

$$=N_0\sqrt{\frac{12!4!}{16!}}\mathcal{A}\left\{\left[u_{40}(\xi_3,3\nu)\phi_{L=0}(^{12}\mathrm{C})\right]_{J=0}\phi(\alpha)\right\}$$

relative wf (S-wave)

$$=N_2\sqrt{\frac{12!4!}{16!}}\mathcal{A}\left\{\left[u_{42}(\xi_3,3\nu)\phi_{L=2}(^{12}\mathrm{C})\right]_{J=0}\phi(\alpha)\right\}$$

relative wf (D-wave)

α-degree of freedom

Bayman-Bohr theorem

Nucl. Phys. 9, 596 (1958/1959

➔G.S. has mean-field-type and α-cluster degrees of freedom.

Activation of mean-field-type degree of freedom in g.s
➔ Excitation of 1p1h states (3-bump structure)

Dual nature

Activation of α-cluster degree of freedom in g.s
➔ Excitation of α+^{12}C cluster states: 2nd 0+, 3rd 0+

IS monopole operator

$$\mathcal{O}=\sum_{i=1}^{16}(r_i-R_{cm})^2=\underbrace{\sum_{i=1}^{4}(\mathbf{r}_i-\mathbf{R}_\alpha)^2+\sum_{i=5}^{16}(\mathbf{r}_i-\mathbf{R}_{12C})^2}_{\text{internal parts}}+\underbrace{3(\mathbf{R}_\alpha-\mathbf{R}_{12C})^2}_{\text{relative part}}$$

Extracting the monopole strength

PHYSICAL REVIEW C 91, 024304 (2015)

Helium-helium clustering states in ^{12}Be

Z. H. Yang,[1] Y. L. Ye,[1,*] Z. H. Li,[1] J. L. Lou,[1] J. S. Wang,[2] D. X. Jiang,[1] Y. C. Ge,[1] Q. T. Li,[1] H. Hua,[1] X. Q. Li,[1] F. R. Xu,[1] J. C. Pei,[1] R. Qiao,[1] H. B. You,[1] H. Wang,[1,3] Z. Y. Tian,[1] K. A. Li,[1,2] Y. L. Sun,[1] H. N. Liu,[1,3] J. Chen,[1] J. Wu,[1,3] J. Li,[1] W. Jiang,[1] C. Wen,[1,3] B. Yang,[1] Y. Liu,[1] Y. Y. Yang,[2] P. Ma,[2] J. B. Ma,[2] S. L. Jin,[2] J. L. Han,[2] and J. Lee[3]
[1]*State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China*

$$M(\mathrm{E0}) = \langle f | \sum_{i=1}^{A} \frac{1+\tau_{3i}}{2} (\boldsymbol{r}_i - \boldsymbol{R}_{\mathrm{c.m.}})^2 | \mathrm{g.s.} \rangle,$$

$$M(\mathrm{IS},0) = \langle f | \sum_{i=1}^{A} (\boldsymbol{r}_i - \boldsymbol{R}_{\mathrm{c.m.}})^2 | \mathrm{g.s.} \rangle,$$

$$S(\mathrm{IS},0) = \sum_{\mathrm{f}} |M(\mathrm{IS},0)|^2 E_{\mathrm{f}} = \frac{2\hbar^2}{m} A R_{\mathrm{rms}}^2$$

fraction of the EWSR

DWBA analysis of the resonance CS

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{exp}} = \sum_L a_L \left(\frac{d\sigma}{d\Omega}\right)_{L,\mathrm{DWBA}} .$$

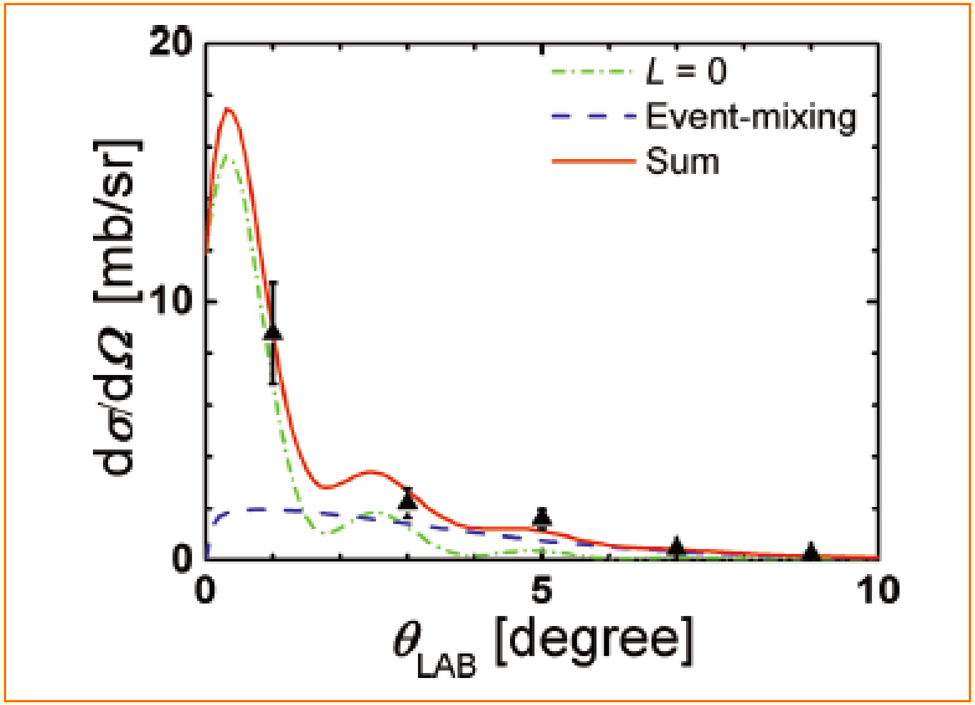
transition potential

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

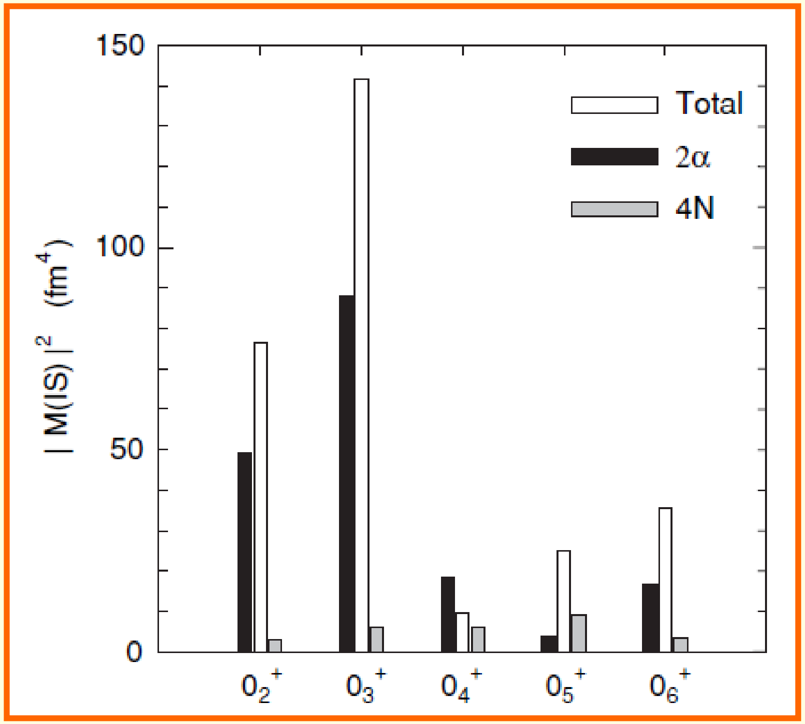
$$(\alpha_0^m)^2 = \frac{\hbar^2}{2m}\frac{4\pi}{AE_x}\frac{1}{R_{\mathrm{rms}}^2}$$

$$\delta_0 = \alpha_0^U R_U = \alpha_0^m c.$$

DWBA analysis



GTCM prediction



Fraction: 0.034(10) x 2.2.

EWSR: 6727.9 fm^4 MeV,

M(IS): 7.0 +/- 1.0 fm^2,

M(IS) (cluster) ~ 9.0 fm^2

Outline

I. Clustering phenomena

II. How to probe

II.1 for ground states

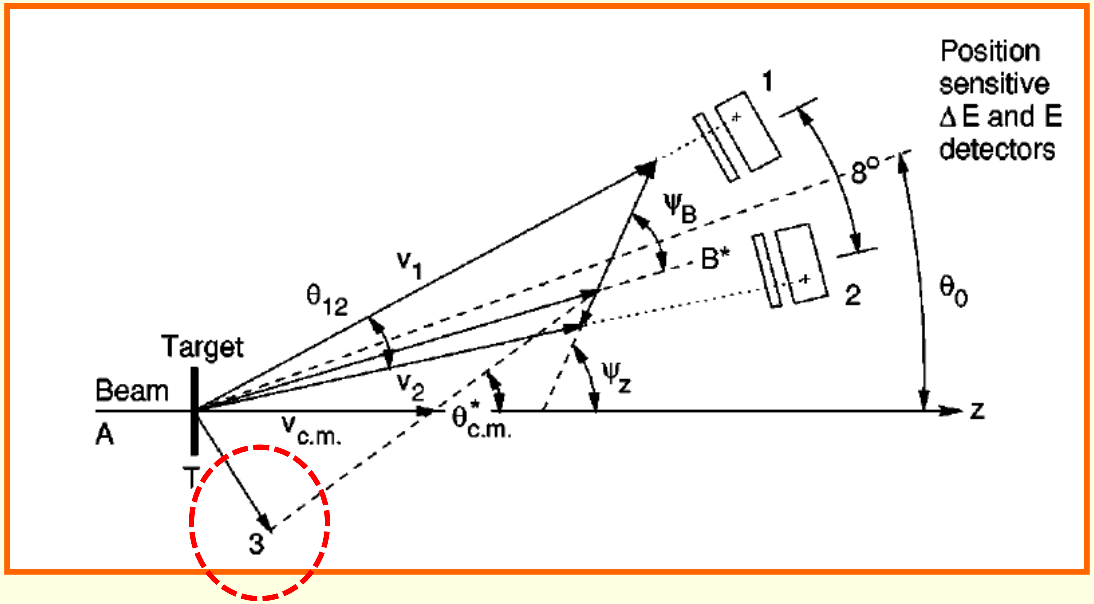
II.2 for excited states

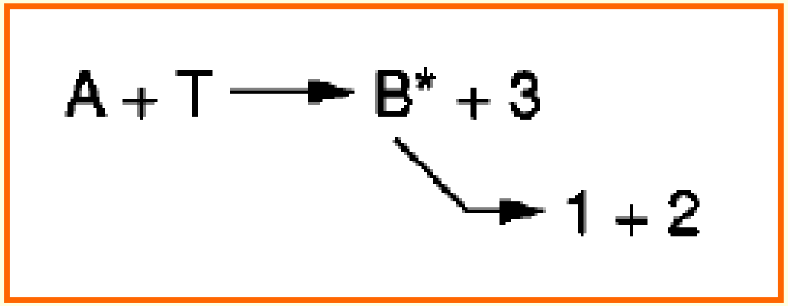
III. Newly performed experiments

^{20}O, ^{10}Be, ^{14}C

IV. Summary

missing mass (inelastic or transfer)



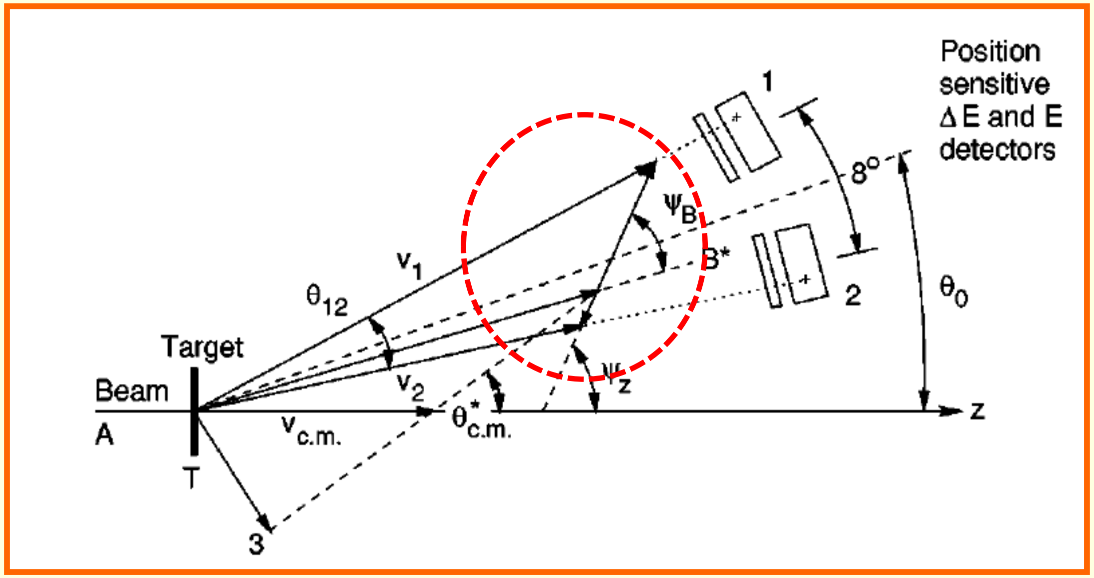


$$Q = T_3 + T_{B*} - T_A = m_T + m_A - m_3 - m_{B*}$$

$$m_{B*} = m_T + m_A - m_3 - Q$$

$$Q = \left(\frac{m_A}{m_B} - 1\right)T_A + \left(\frac{m_3}{m_B} + 1\right)E_3 - \frac{2\left(m_A m_3 T_A T_3\right)^{1/2} \cos\theta}{m_B}$$

invariant mass



$$A + T \longrightarrow B^* + 3$$
$$\qquad\qquad \hookrightarrow 1 + 2$$

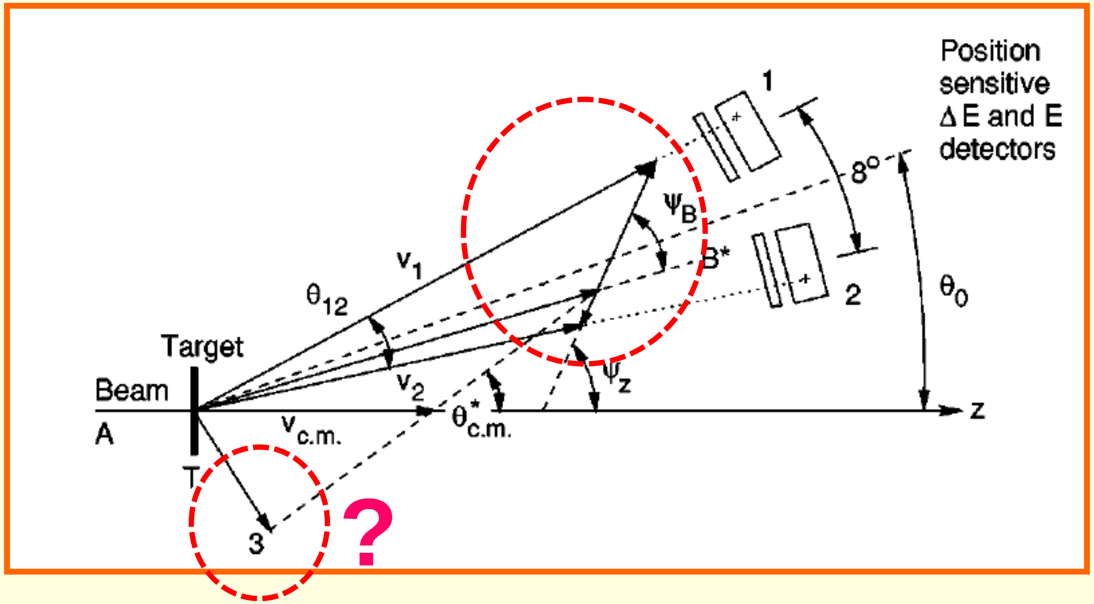
$$E_{\mathrm{B}*} = E_1 + E_2, \qquad \vec{p}_{\mathrm{B}*} = \vec{p}_1 + \vec{p}_2$$

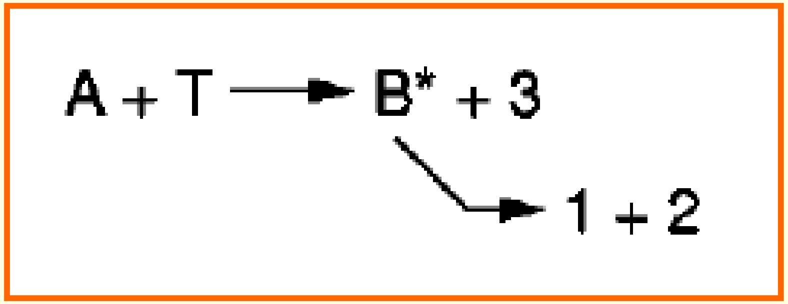
$$m_{\mathrm{B}*}c^2 = [E^2_{\mathrm{B}*} - c^2 p^2_{\mathrm{B}*}]^{1/2} = [(E_1 + E_2)^2 - c^2 \,|\, \vec{p}_1 + \vec{p}_2 \,|^2]^{1/2}$$

$$E_{\mathrm{S}} = (m_1 + m_1 - m_{\mathrm{B}})c^2$$

$$E_{\mathrm{x}} = m_{\mathrm{B}*}c^2 \text{-} m_{\mathrm{B}}c^2 = E_{\mathrm{S}} + E_{\mathrm{rel}}$$

RI beam & recoil target: IM + MM

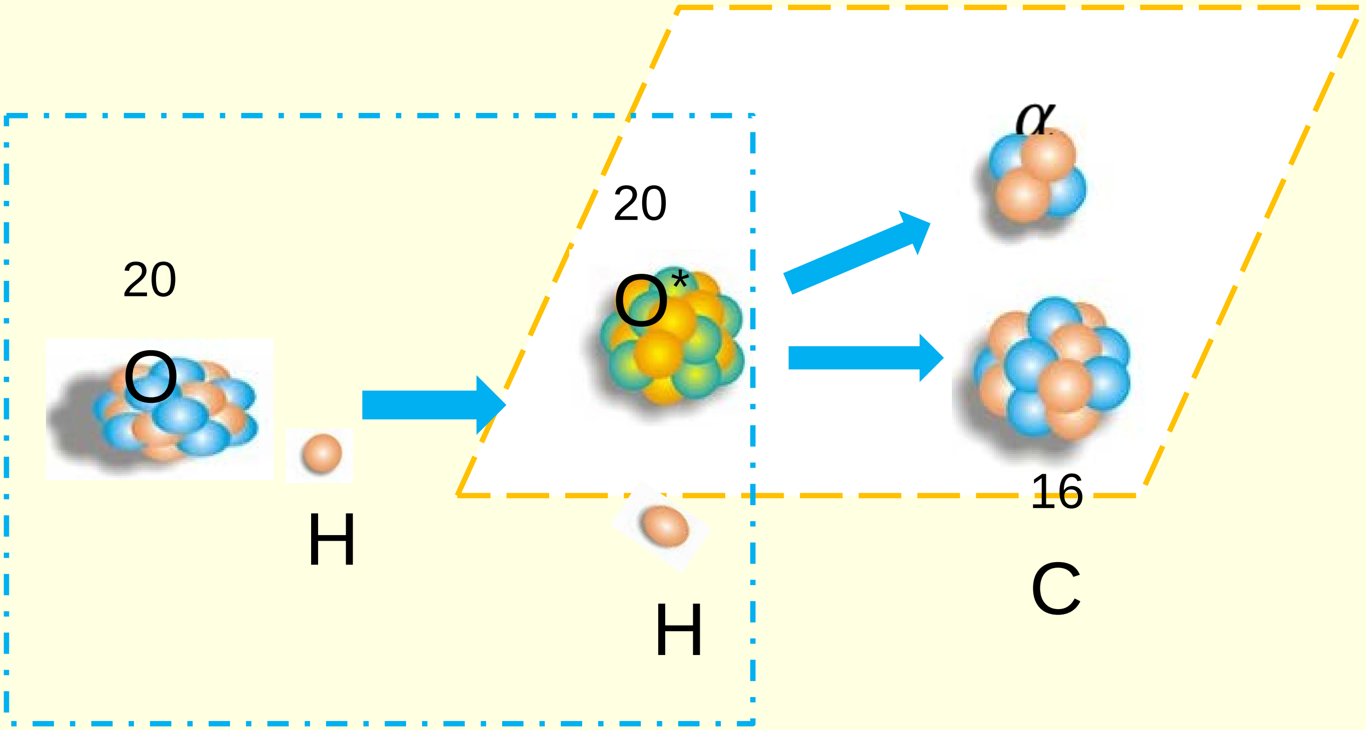




good experiences for IM measurement

■ MM at low recoil energies?

A new experiment in Lanzhou for ^{20}O



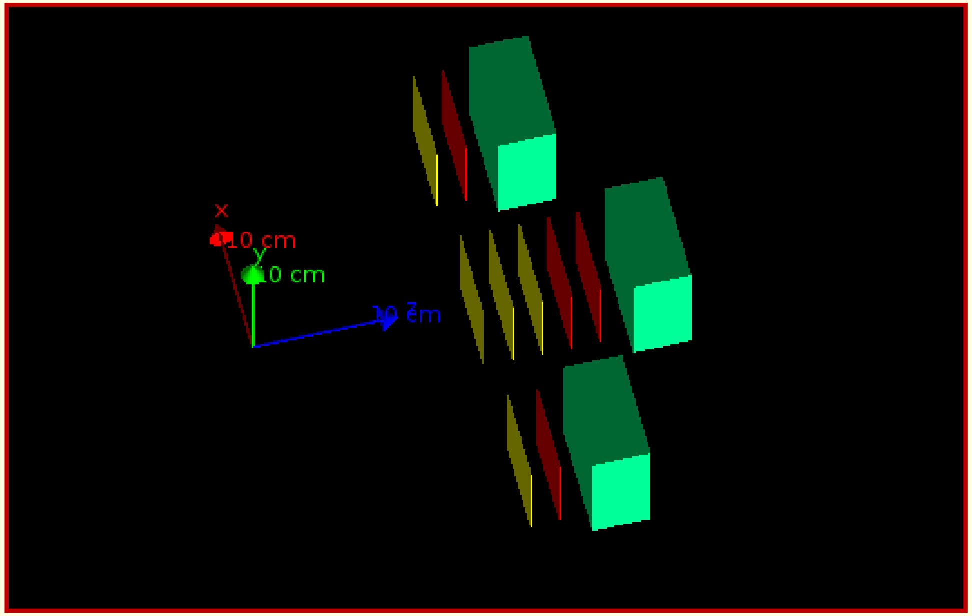
$^{20}O + p \rightarrow$ $^{20}O^* + p$ **(MM)**

$^{20}O^* \rightarrow$ $^{16}C + \alpha$ **(IM)**

Beam: ^{20}O (>10^4 pps); **target:** CH_2;
Measurement: breakup & reconstruction for 0_3^+; 0^-

Main goals:

Cluster states in ^{20}O;

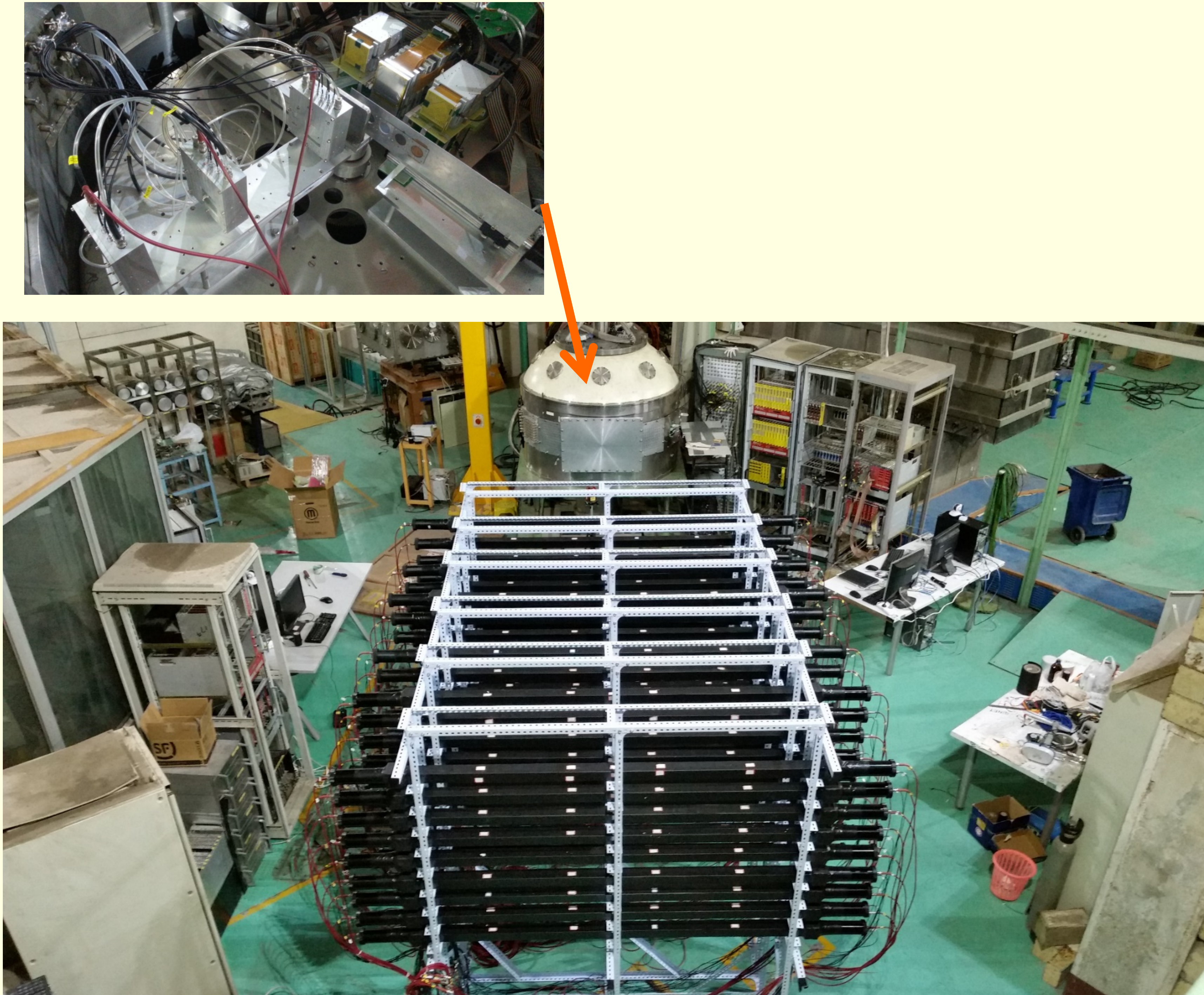


Target: $(CH_2)n$, thickness: 100um and 10um

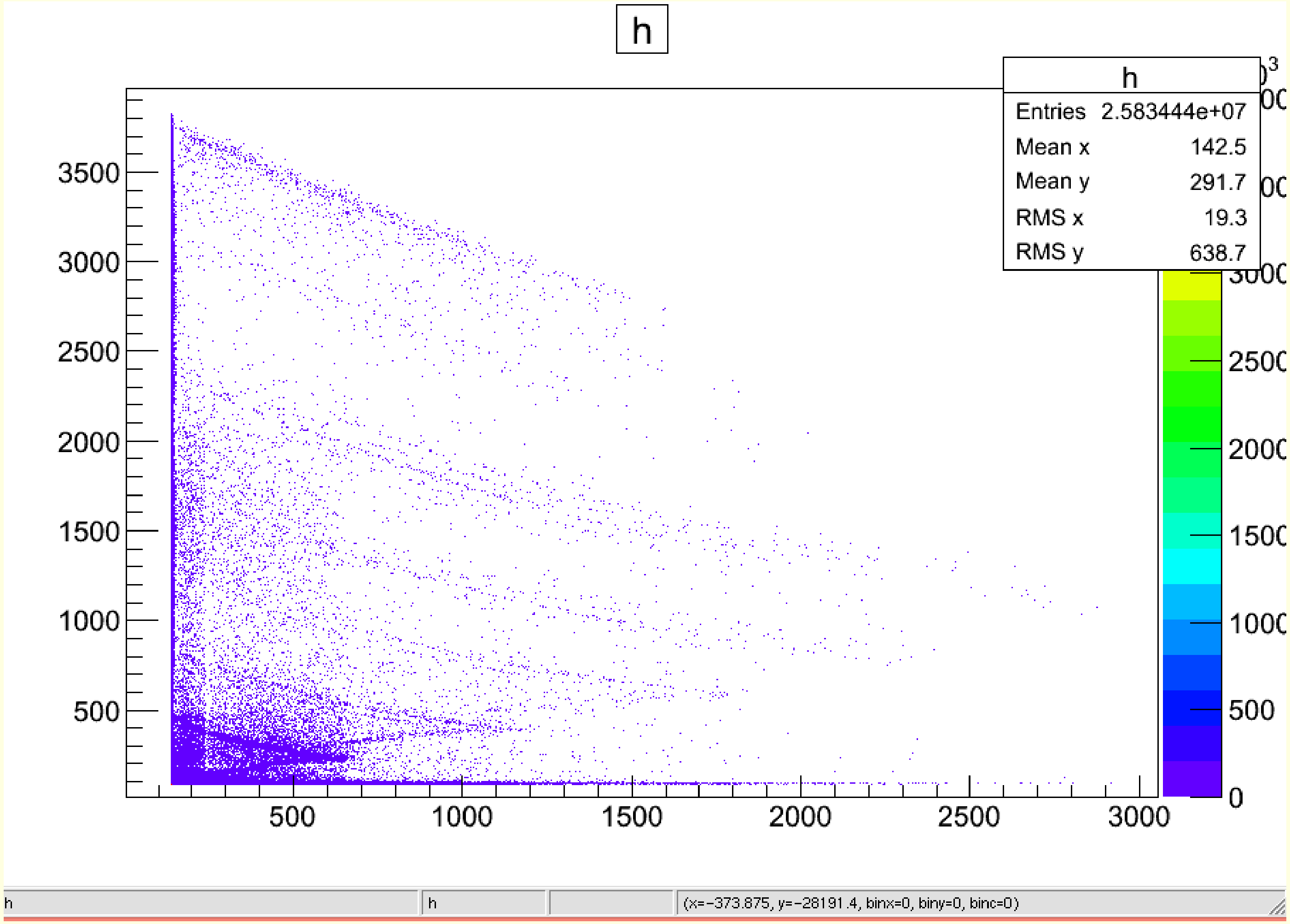
Reaction:

$$^{20}O + p \rightarrow {}^{20}O^* + p$$

$$^{20}O^* \rightarrow {}^{16}C + \alpha$$



Online PID



h
h
Entries 2.583444e+07
Mean x 142.5
Mean y 291.7
RMS x 19.3
RMS y 638.7
3500
3000
2500
2000
1500
1000
500
500
1000
1500
2000
2500
3000
0
(x=-373.875, y=-28191.4, binx=0, biny=0, binc=0)

Progress of Theoretical Physics, Vol. 119, No. 3, March 2008

Cluster Structures in Oxygen Isotopes

Naoya FURUTACHI,[1] Masaaki KIMURA,[2] Akinobu DOTÉ,[3]
Yoshiko KANADA-EN'YO[4] and Shinsho ORYU[1]

Cluster structures of ^{16}O, ^{18}O and ^{20}O are investigated using the antisymmetrized molecular dynamics (AMD) plus generator coordinate method (GCM). We have found the $K^\pi = 0_2^+$ and 0^- rotational bands of ^{18}O that have prominent ^{14}C+α cluster structure. The clustering systematics are richer in ^{20}O. We suggest the presence of a $K^\pi = 0_2^+$ band that is a mixture of the ^{12}C+α+4n and ^{14}C+^{6}He cluster structures. $K^\pi = 0_3^+$ and 0^- bands that have prominent ^{16}C+α cluster structure are also found.

AMD+GCM framework

Finally, we perform GCM calculations by employing β as the generator coordinate. The same choice of the generator coordinate has been made in Hartree-Fock+GCM calculations, and also in the study of the clustering properties of ^{20}Ne[33] and ^{44}Ti.[34] The final wave function is given by a superposition of basis wave functions $\Phi^{J\pm}_{MK_i}(\beta_i)$, with the generator coordinate β_i and K quantum number, where $|K| \leq 4$ and $|K| \leq 3$ are taken for positive and negative parity states, respectively. The wave function that describes a certain state is given by

$$\Psi_n^{J\pm} = \sum_i c_i^n \Phi^{J\pm}_{MK_i}(\beta_i), \tag{2·9}$$

where c_i is determined by solving the Hill-Wheeler equation,

$$\delta(\langle\Psi_n^{J\pm}|\hat{H}|\Psi_n^{J\pm}\rangle - \epsilon_n\langle\Psi_n^{J\pm}|\Psi_n^{J\pm}\rangle) = 0. \tag{2·10}$$

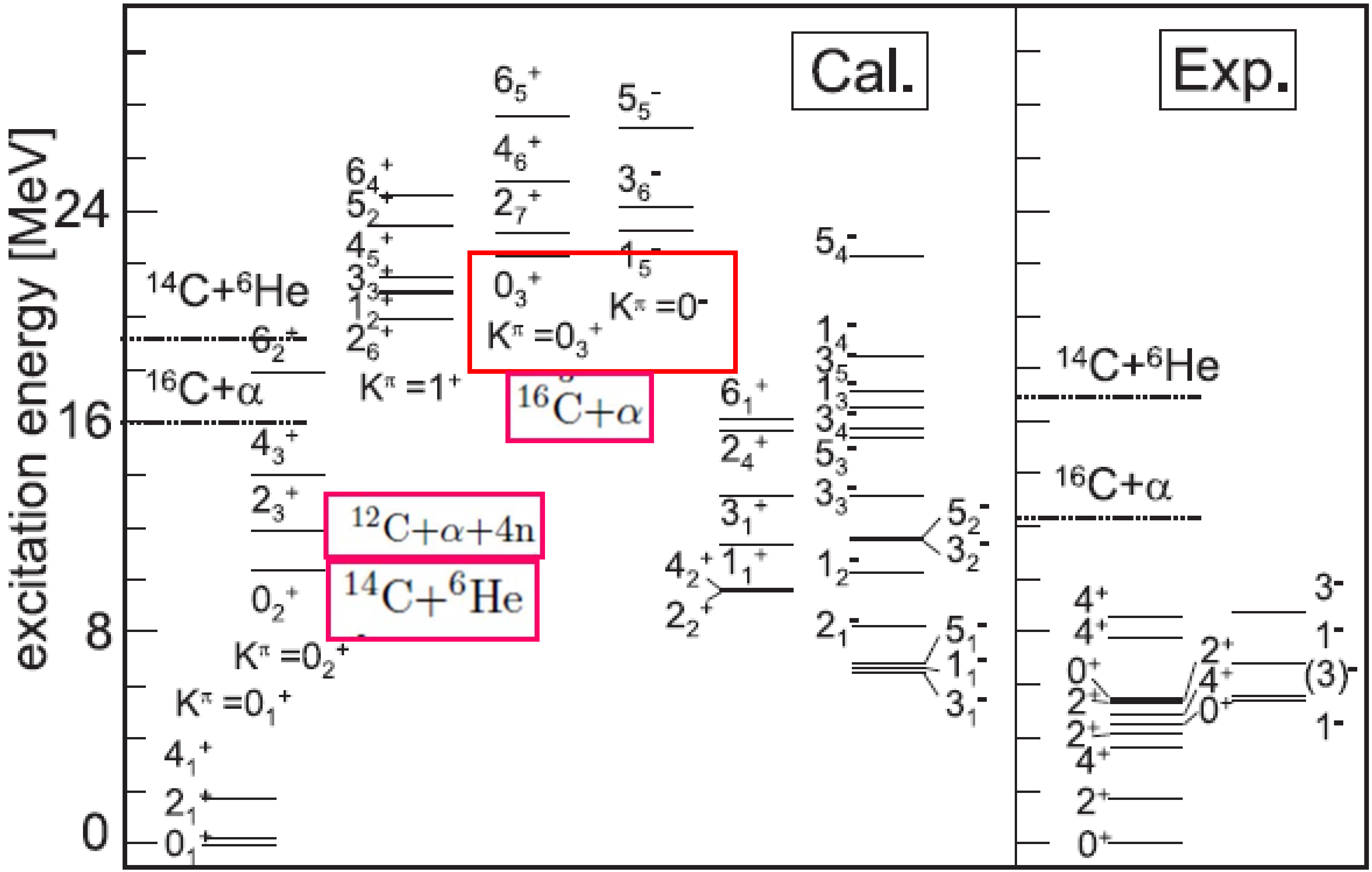


Fig. 9. Level scheme of ^{20}O.

Eur. Phys. J. A (2011) **47**: 44

Structures in ^{20}O from the ^{14}C(^{7}Li, p) reaction at 44 MeV

H.G. Bohlen[1], W. von Oertzen[1,a], M. Milin[3,b], T. Dorsch[1,2], R. Krücken[2], T. Faestermann[2], R. Hertenberger[4], Tz. Kokalova[1,c], M. Mahgoub[2], C. Wheldon[1,c], and H.-F. Wirth[2,4]

[1] Helmholtz-Zentrum Berlin, Hahn-Meitner-Platz 1, D-14109 Berlin, Germany
[2] Department of Physics, Faculty of Science, University of Zagreb, Bijenička 32, HR-10000 Zagreb, Croatia
[3] Technische Universität München, James-Franck-Str. 1, D-85748 Garching, Germany
[4] Sektion Physik der Universität München, Am Coulombwall 1, D-85748 Garching, Germany

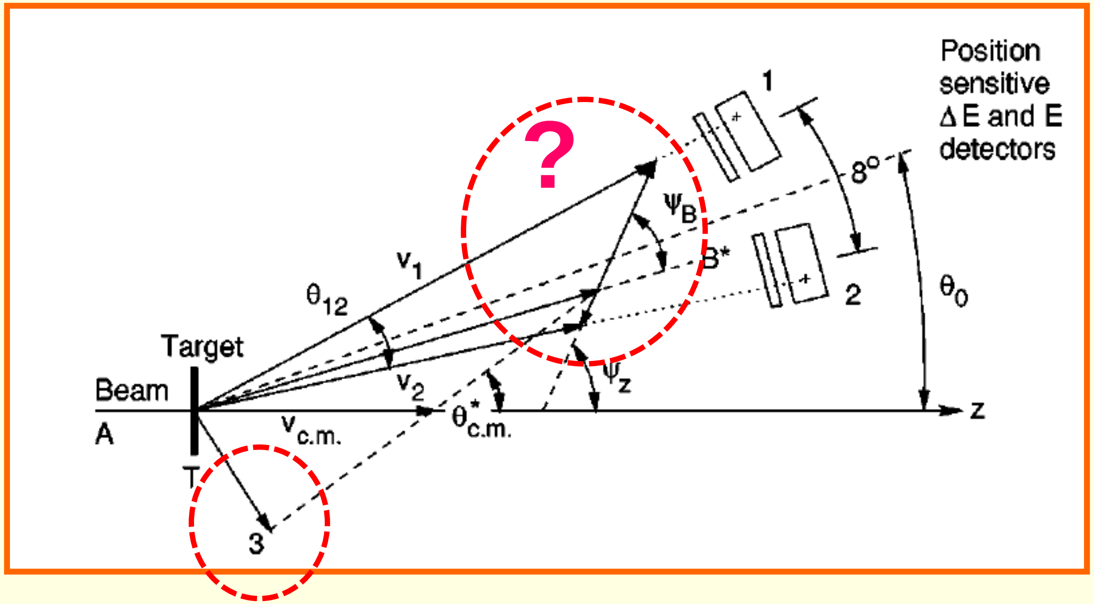
Table 2. Experimental excitation energies E_x, spin-parities J^π and widths, given for different K^π rotational bands proposed for ^{20}O: the parity doublet bands 0_2^+ and 0_2^-, and the parity doublet bands 0_4^+ and 0_4^-. Assignments, which are made from the $(2J+1)$, may have to be confirmed independently, and are given in brackets.

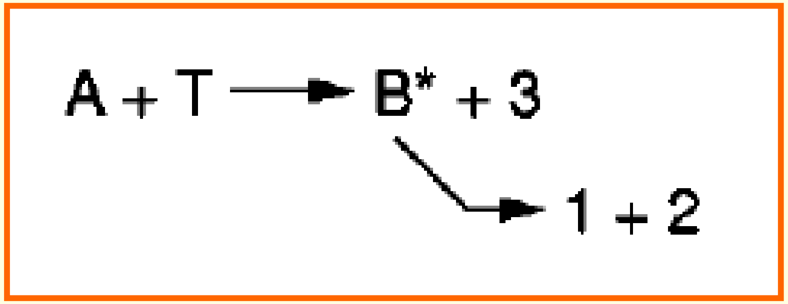
$K^\pi = 0_2^+$			$K^\pi = 0_2^-$			$K^\pi = 0_4^+$			$K^\pi = 0_4^-$		
E_x (MeV)	J^π	Γ (keV)	E_x (MeV)	J^π	Γ (keV)	E_x (MeV)	J^π	Γ (keV)	E_x (MeV)	J^π	Γ (keV)
4.458	0^+		9.918	(1^-)	20	9.768	0^+	20	11.67	(1^-)	100
5.237	2^+		11.95	(3^-)	90	10.11	2^+	5	12.83	(3^-)	100
7.754	4^+		13.96	(5^-)	150	11.39	(4^+)	110	13.44	(5^-)	65
10.93	(6^+)	40	18.46	(7^-)	140	13.60	(6^+)	250	17.35	(7^-)	210
16.36	(8^+)	90				16.63	(8^+)	110			
						18.61	(10^+)	190			

Three strange narrow states

E_x [MeV]	Γ [keV]	$\left(\frac{d\sigma}{d\Omega}\right)_{cm}$ [μb/sr] $\theta_{Lab} = 10^\circ$	$\left(\frac{d\sigma}{d\Omega}\right)_{cm}$ [μb/sr] $\theta_{Lab} = 20^\circ$	$\left(\frac{d\sigma}{d\Omega}\right)_{cm}$ [μb/sr] $\theta_{Lab} = 39^\circ$	J^π
12.50(3)	400(50)	23.5(5)	16.9(5)	16.5(3)	
12.537(9)	15(5)	<0.2	2.2(2)	0.9(1)	
12.83(2)	100(10)	6.6(3)	4.0(3)	2.8(2)	
13.23(2)	200(20)	11.4(5)	8.0(3)	5.9(2)	
13.44(1)	65(15)	6.3(3)	12.2(4)	5.4(2)	(5^-)
13.60(1)	250(50)	29.3(5)	16.4(4)	16.9(3)	(6^+)
13.955(8)	150(20)	16.1(4)	15.7(4)	7.5(2)	(5^-)
14.349(6)	300(30)	21.1(4)	15.0(4)	10.1(2)	
14.382(8)	4(3)	2.2(2)	1.4(2)	0.5(1)	
14.85(5)	40(7)	2.0(5)	2.1(2)	1.7(1)	
15.015(5)	100(10)	*cont.*	5.5(3)	0.3(2)	
15.247(5)	5(3)	10.2(3)	8.2(3)	5.0(2)	
15.44(2)	200(20)	10.6(3)	7.9(3)	5.6(2)	
15.626(5)	60(10)	3.8(2)	*overlap*	*overlap*	
15.72(1)	2(1)	18.9(4)	12.8(5)	10.3(3)	

Stable beam & excited target: MM + IM





- good experiences for MM measurement
- IM at low recoil energies ?

A new experiment at CIAE - Beijing

Beam: 45MeV ^{9}Be 2pnA(1*10^{10}pps) (proposed 20pnA)

Target: 0.9um ^{9}Be / Au

Duration: ~ 90 hours

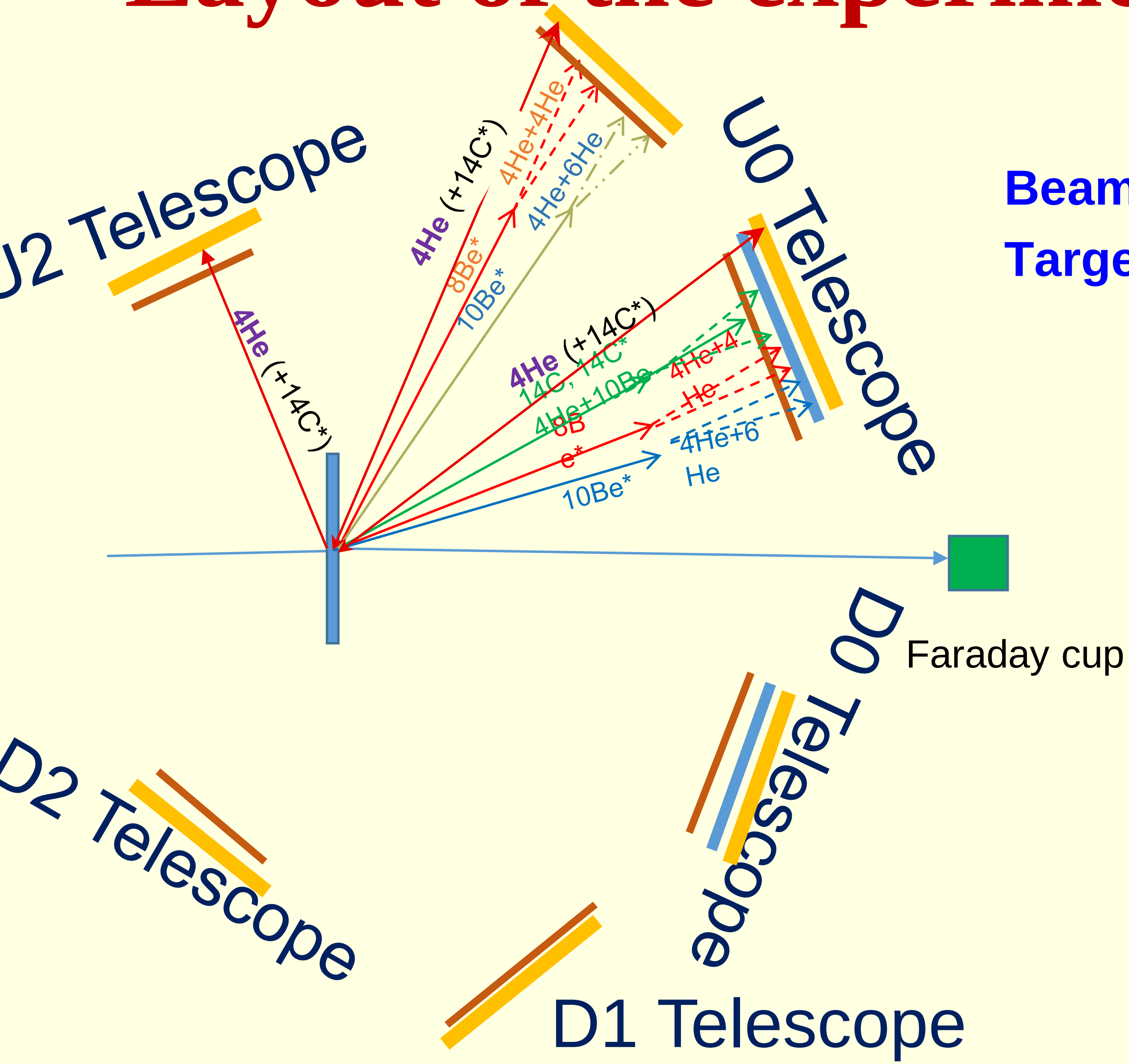
$^{9}Be + ^{9}Be \rightarrow ^{10}Be(7.542) + ^{8}Be(g.s.)$ Q=-2.39MeV

$^{10}Be(7.542) \rightarrow ^{4}He + ^{6}He$ Q=0.13MeV (IM)

$^{8}Be(g.s.) \rightarrow ^{4}He + ^{4}He$ Q=92keV (MM)

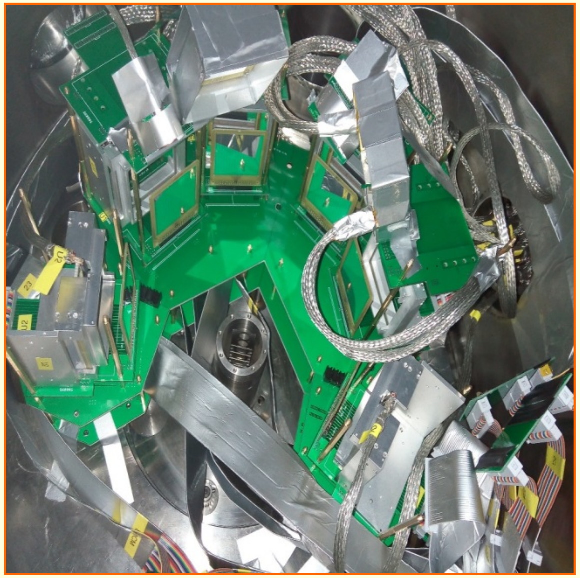
$^{4}He + ^{14}C$ Q= 17.25 MeV

Layout of the experiment



Beam :　9Be, 45MeV,　2pnA

Target:　9Be, 0.9um ;　Au

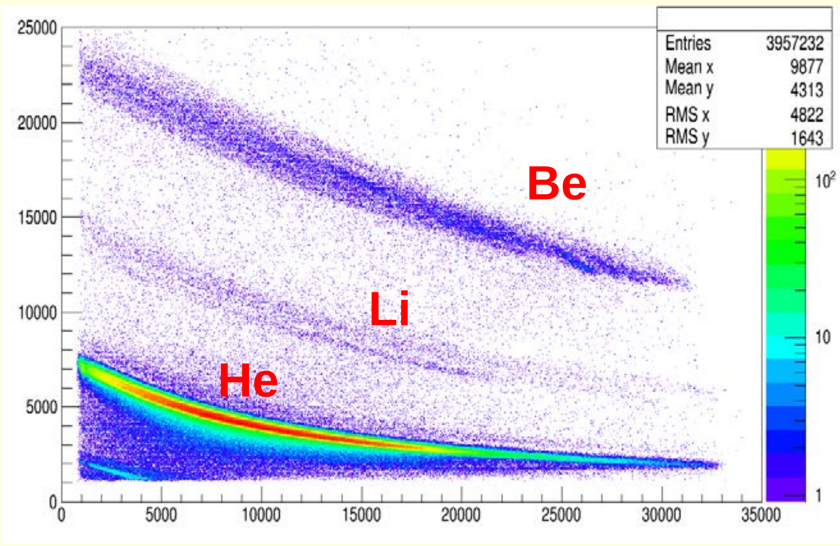


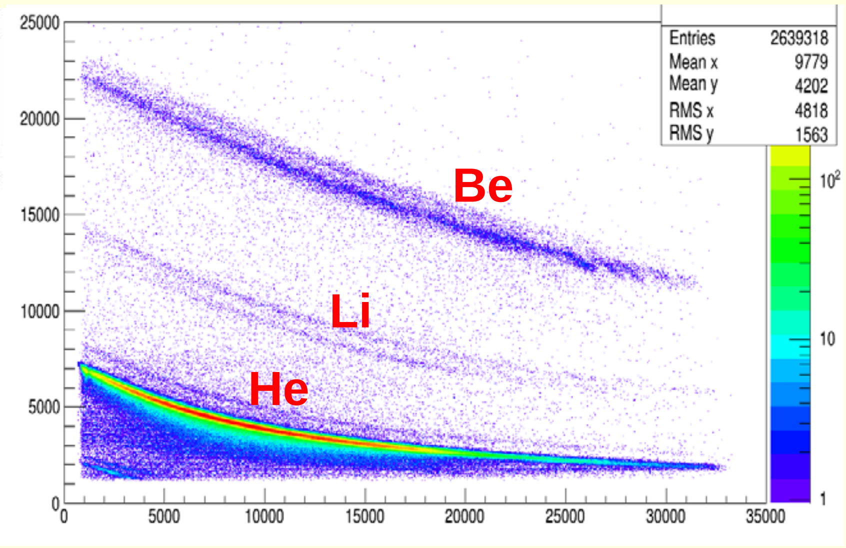
Online PID

D0 Telescope-PID

U0 Telescope-PID

ΔE_W1(keV)



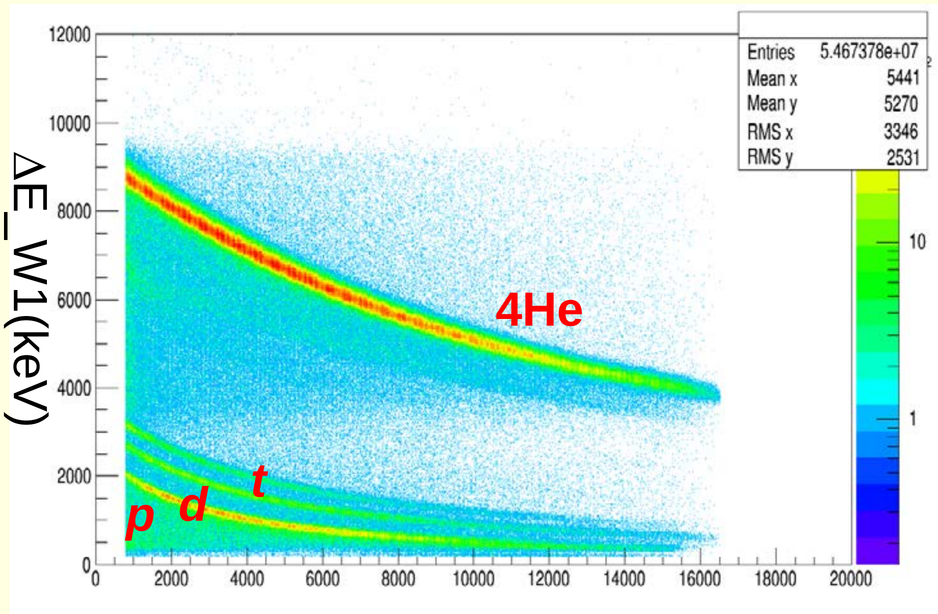


E_BB7(keV)

E_BB7(keV)

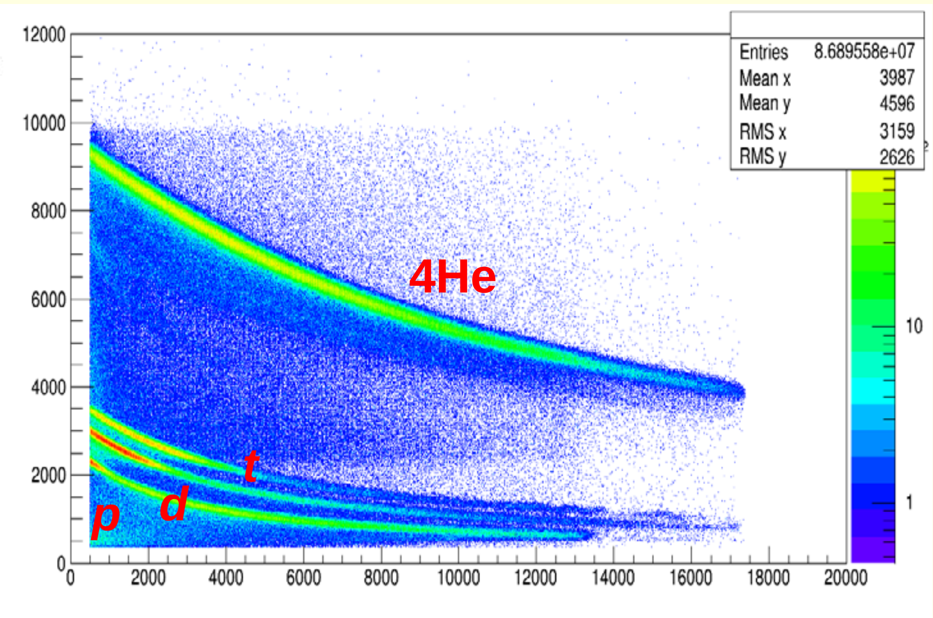
Online PID

D2 Telescope-PID



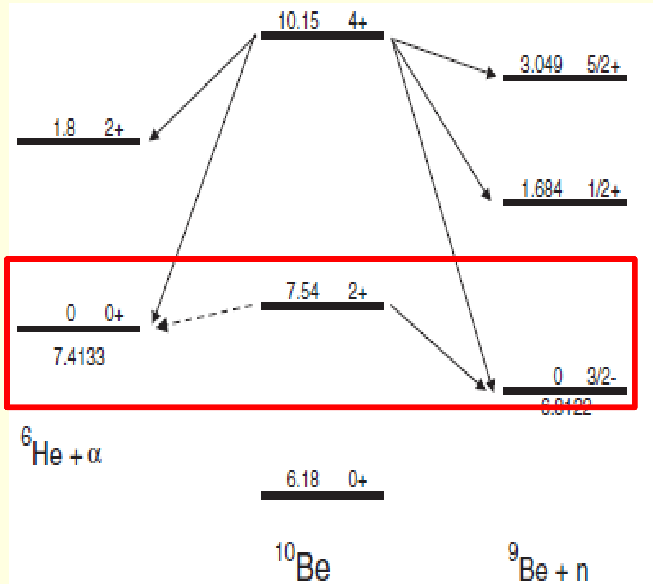
E_SSD(keV)

U2 Telescope-PID



E_SSD(keV)

^{10}Be , 2_2^+ state, 7.54 MeV



- The 2_3^+ state may have cluster structure.
- The 2_3^+ state decay through n decay and α decay. The nucleon spectroscopic factor is very small (1%).
- α decay threshold : 7.41 MeV
- α decay branching ratio : $3.5(12)\times 10^{-3}$ [4]

Initial state		Decay	Final state		E_n or E_α	Γ_{expt}	ℓ or L,N	Γ_{sp}	S
E_x	J^π		E_x	J^π					
7.54	2^+	^{9}Be + n	0	$3/2^-$	0.730	6.3(8)	1	~700	⩽0.01
		^{6}He + α	0	0^+	0.129	$22(8) \times 10^{-3}$	2,2	0.43×10^{-3} [a]	51(19) [a]

Outline

I. Clustering everywhere

II. How to observe

II.1 for ground states

II.2 for excited states

III. newly performed experiments

IV. Summary

Summary

- Clustering is a general phenomenon in light unstable nuclei.
- Consistent evidences are required to experimentally justify a cluster state, such as large momentum of inertial, large cluster decay partial width and large selective excitation strength.
- QFS at higher energies for GS and MM + IM measurements at lower energies for RS are good ways to probe the cluster structure.

A lot to be measured !!

- broad 0_3^+ state in ^{12}C ; 0_2^+ state in ^{16}O;
- 0_3^+ and 0_4^+ in ^{10}Be ;
- monopole in ^{16}O;^{13}C; ^{20}Ne;
- chain states in ^{14}C and ^{16}C ;
- molecular bands in ^{18}O , ^{18}Ne;
- ^{12}Be systematics (^{6}He+^{6}He ?);
- cluster + GR, ^{24}Mg,^{28}Si ;
- ……

Thank you for your attention!

谢 谢 ！