Clustering and its observation in unstable nuclei

Yanlin Ye

School of Physics and State Key Lab. of Nucl. Phys.&Tech. Peking University

CUSTIPEN Workshop, 2014.08.11, PKU

Outline

I. Historical background

II. How to observe

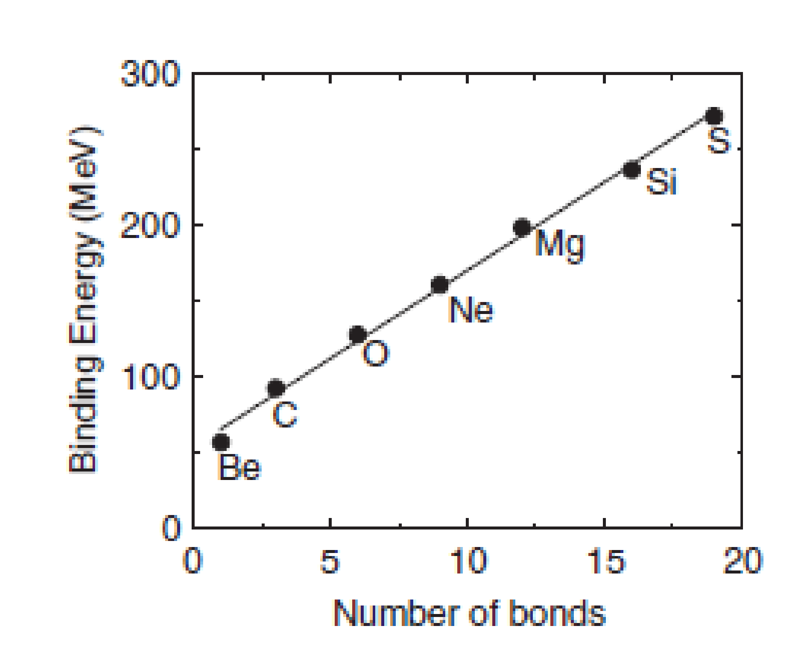
III. ^{12}Be — an example

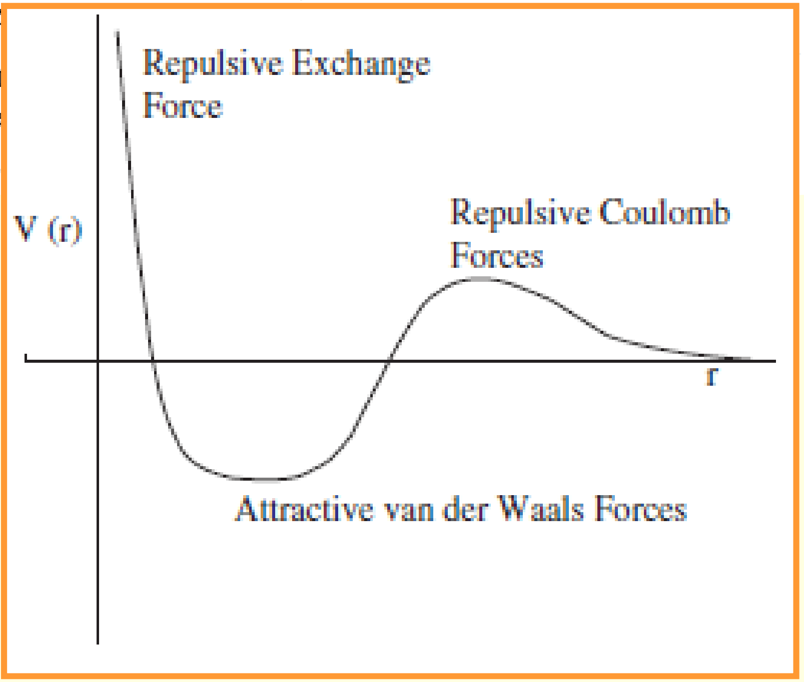
IV. Future perspectives

NOVEMBER 1, 1938 PHYSICAL REVIEW VOLUME 54

The Alpha-Particle Model of the Nucleus

L. R. HAFSTAD
Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.





alternating independent-particle and clustering structure — a unique feature of nuclear many-body system.

Prog. Theo. Phys. Volume 25 ,1961 , P853

Letters to the Editor

Interaction between Alpha Particles

Ichirô Shimodaya, Ryozo Tamagaki
and Hajime Tanaka

Department of Physics
Hokkaido University
Sapporo

February 18, 1961

treme tightness. In this note, by applying the pion-theoretical potentials recently verified in two-nucleon problems,[2)] interactions between α-particles are investigated from the viewpoint of the cluster model, without taking account of the polarization effects of α-particles.

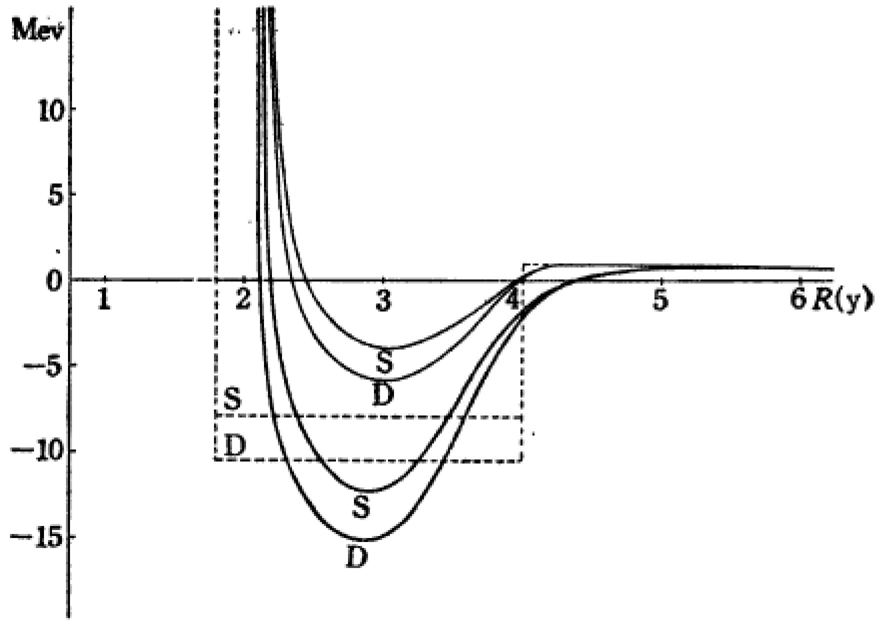
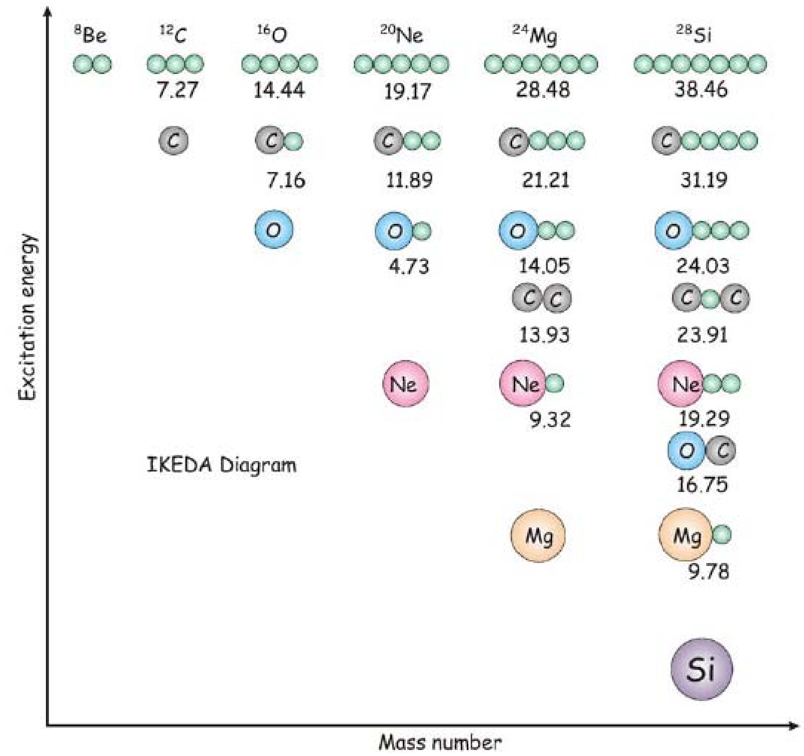


Fig. 1. The dashed lines represent the phenomenologically determined α-α interactions for *S*- and D-states.[3)] The upper curves are obtained from the potential with an attractive TPEP only in the singlet even state and the lower curves from the potential with an additional attractive TPEP in the triplet even and triplet odd states.

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

Kiyomi IKEDA,*) Noboru TAKIGAWA and Hisashi HORIUCHI

Department of Physics, University of Tokyo, Tokyo



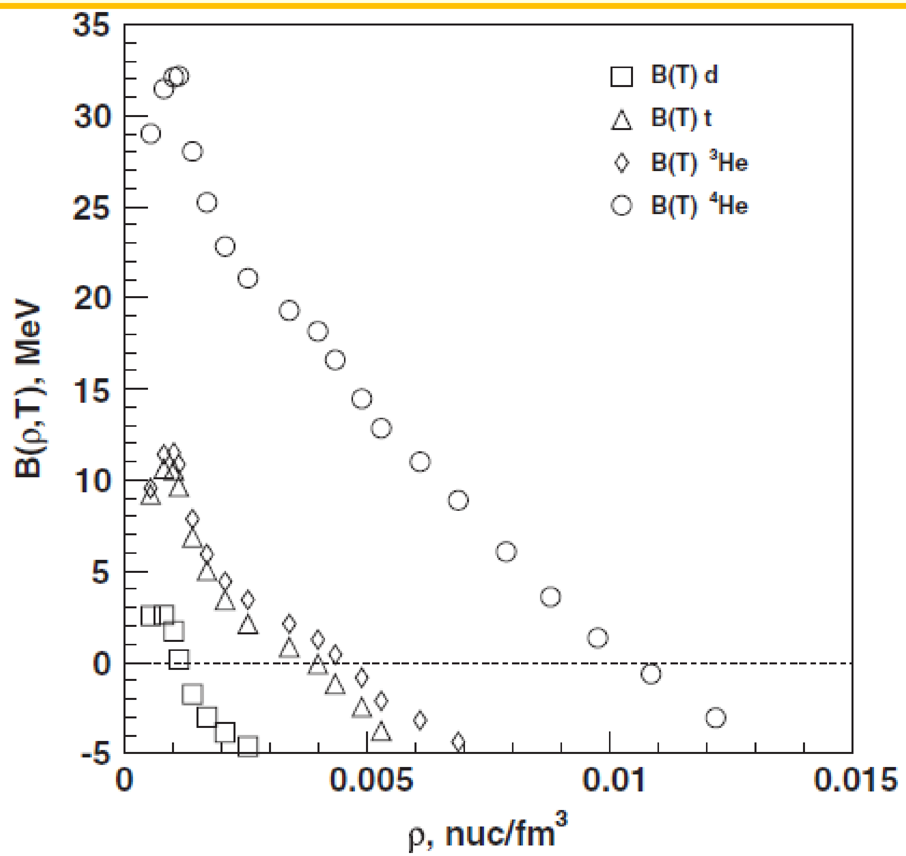
Idea of the relative tightness of a cluster inside a nucleus

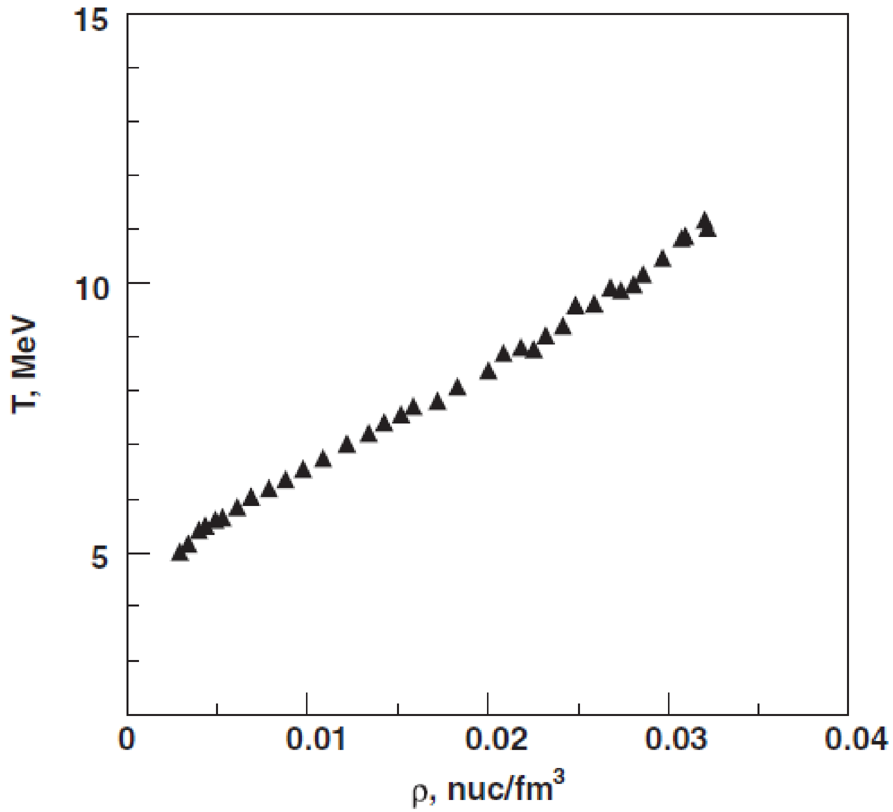
PRL 108, 062702 (2012) PHYSICAL REVIEW LETTERS week ending 10 FEBRUARY 2012

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] M. Huang,[2] J. Wang,[2] H. Zheng,[1] S. Kowalski,[6] C. Bottosso,[1] M. Barbui,[1] M.R. D. Rodrigues,[1] K. Schmidt,[1] D. Fabris,[7] M. Lunardon,[7] S. Moretto,[7] G. Nebbia,[7] S. Pesente,[7] V. Rizzi,[7] G. Viesti,[7] M. Cinausero,[8] G. Prete,[8] T. Keutgen,[9] Y. El Masri,[9] and Z. Majka[10]

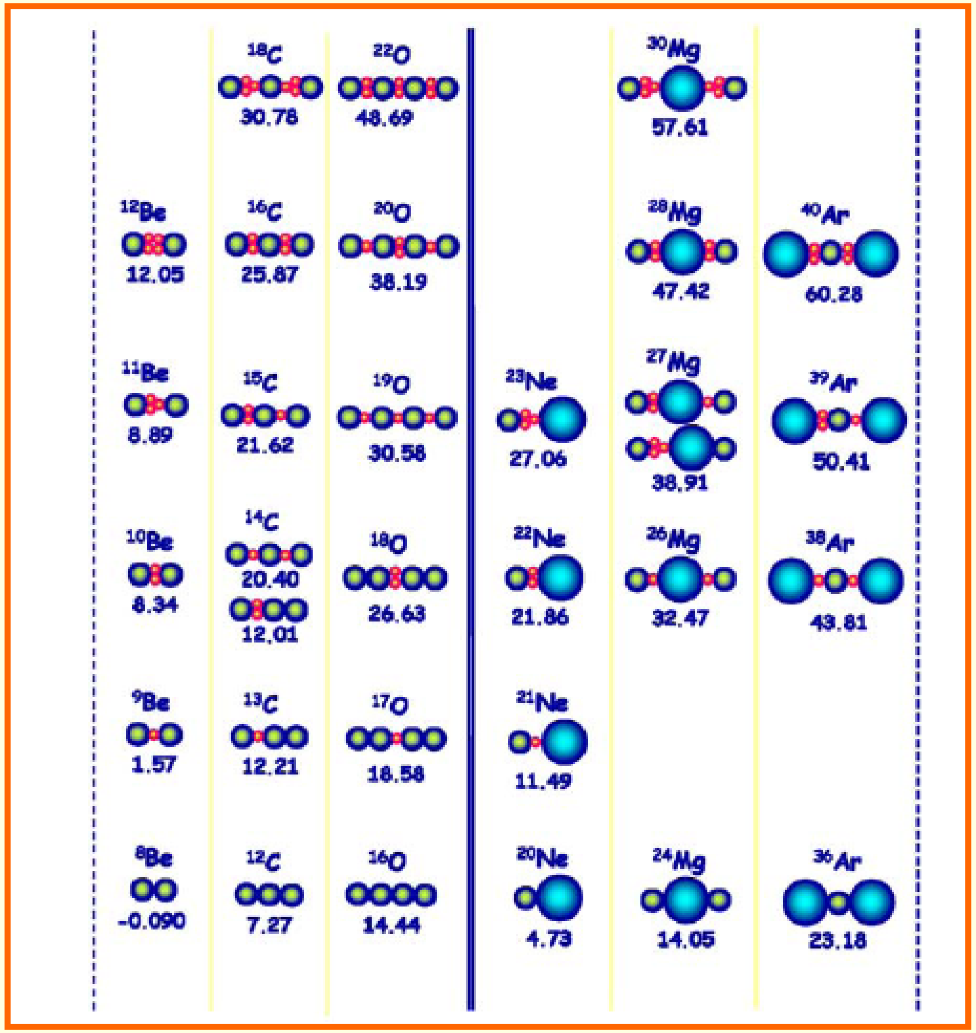
[1]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*





for unstable nuclei

Physics Reports 432 (2006) 43–113



Unstable nuclei: much more cluster configurations (and thresholds) within a small E_x interval.
— richness of nuclear clustering

PTEP,2012,01A202

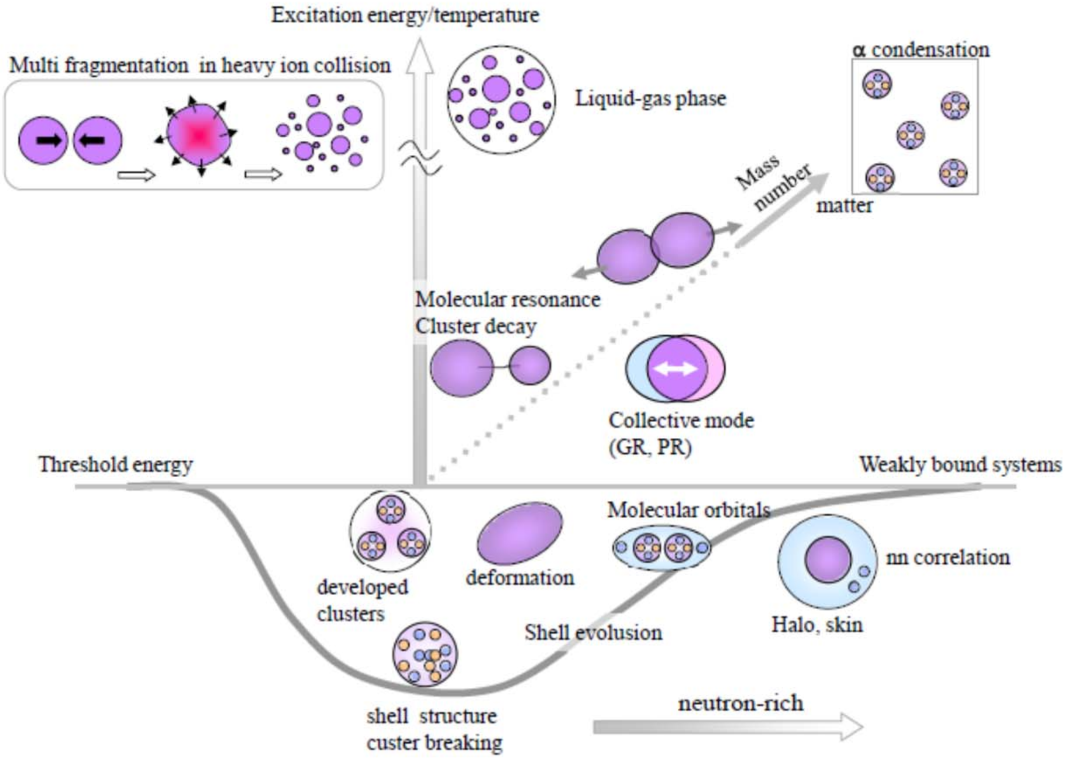


Fig. 1. Schematic figure for rich phenomena in nuclear systems.

Recent progress

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]

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

Experiment:

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

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

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

……

VOLUME 68, NUMBER 19 1992 PHYSICAL REVIEW LETTERS

AMD

Fragment Formation Studied with Antisymmetrized Version of Molecular Dynamics with Two-Nucleon Collisions

A. Ono, H. Horiuchi, T. Maruyama, and A. Ohnishi
Department of Physics, Kyoto University, Kyoto 606, Japan
(Received 27 December 1991)

reaction process. The antisymmetrized version of molecular dynamics [3–5], which Feldmeier called fermionic molecular dynamics, treats explicitly the wave function of the total system and hence is able to describe quantum-mechanical effects such as shell effects. However, until now the two-nucleon collision process has not been incorporated into the framework, which has made this framework insufficient for the description of fragment formation.

The present authors have succeeded in incorporating two-nucleon collisions into the antisymmetrized version of molecular dynamics. This means the construction of a new microscopic simulation framework of the heavy-ion reaction. Hereafter we call this new simulation framework simply AMD. The aims of this paper are first to ex-

$$|\Phi(\mathbf{Z})\rangle = \frac{1}{\sqrt{A!}} \det[\varphi_i(j)], \quad \varphi_i = \phi_{\mathbf{Z}_i}\chi_{\alpha_i},$$

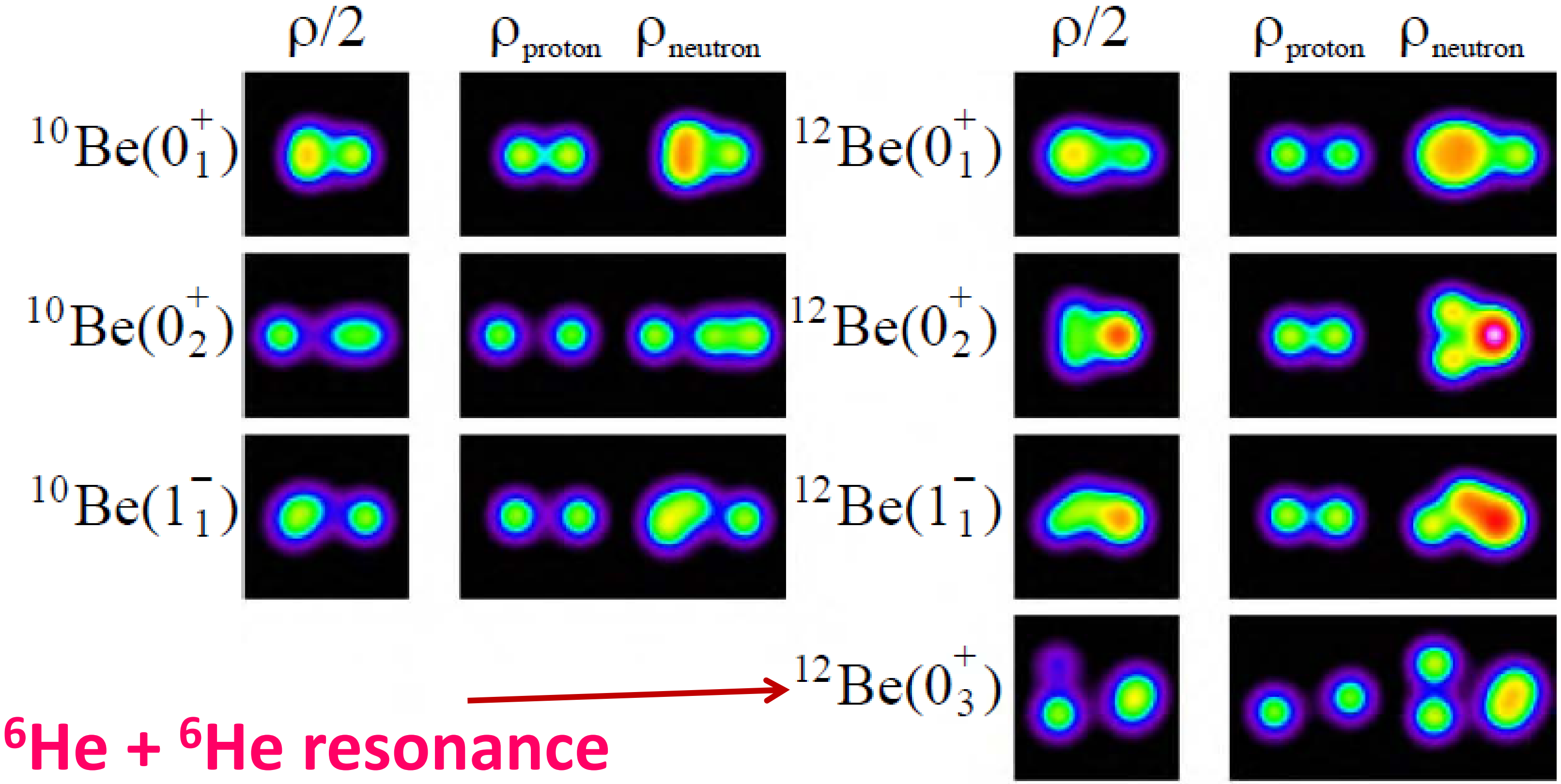
$$\mathcal{H} = \langle H \rangle - T_0 A + T_0'(A - N_F).$$

AMD

PHYSICAL REVIEW C 68, 014319 (2003)

Cluster structures of the ground and excited states of ^{12}Be studied with antisymmetrized molecular dynamics

Y. Kanada-En'yo
Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization, Ibaraki 305-0801, Japan
H. Horiuchi
Department of Physics, Kyoto University, Kyoto 606-8502, Japan



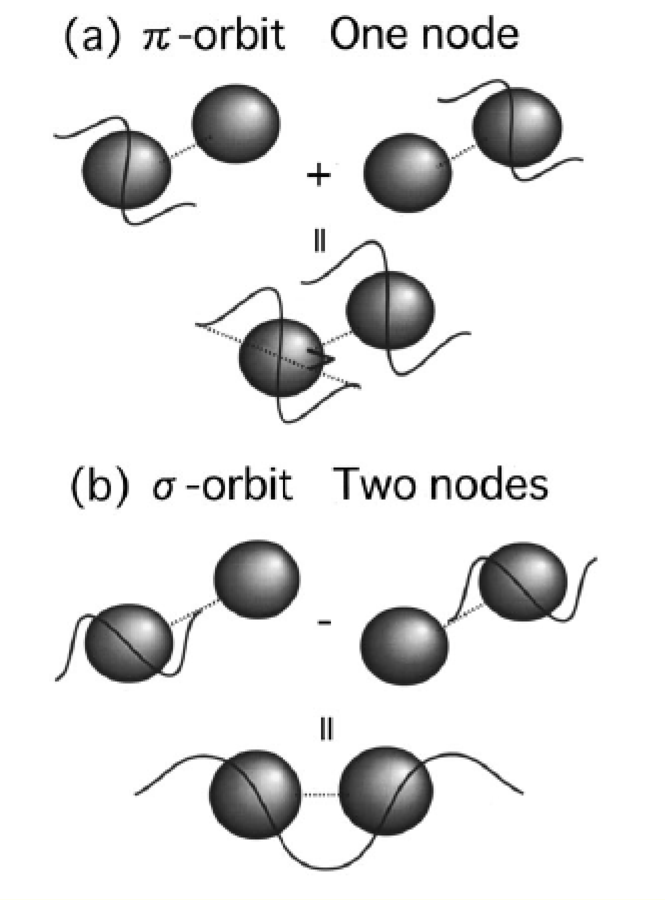
^{6}He + ^{6}He resonance

MO

PHYSICAL REVIEW C, VOLUME 61, 044306 2000

Molecular orbital structures in ^{10}Be

N. Itagaki[1,*] and S. Okabe[2]
[1]Graduate School of Science, Hokkaido University, Sapporo 060-0810, Japan



GTCM

Physics Letters B 588 (2004) 43–48

Application of the generalized two-center cluster model to ^{10}Be

M. Ito [a], K. Kato [b], K. Ikeda [c]

[a] Institute of Physics, University of Tsukuba, 305-8571 Tsukuba, Japan
[b] Division of Physics, Graduate School of Science, Hokkaido University, 060-0810 Sapporo, Japan
[c] RI Beam Science Laboratory, RIKEN (The institute of Physical and chemical Research), Wako 351-0198, Saitama, Japan

Using atomic orbitals as basis。

$$\Psi^{J^\pi}(^{10}\mathrm{Be}) = \int dS \sum_K \Phi_K^{J^\pi}(^{10}\mathrm{Be};\ S) = \int dS \sum_{K\beta} C_\beta^{J^\pi K}(S)\Phi_K^{J^\pi}(S),$$

$$\begin{aligned}\Phi_K^{J^\pi}(^{10}\mathrm{Be};\ S) &= \hat{P}_K^J \mathcal{A}\left\{\psi_L(\alpha)\psi_R(\alpha)\sum_m d_m^{J^\pi K}\varphi(m) \times \sum_n d_n^{J^\pi K}\varphi(n)\right\} \\ &= \sum_{m,n} C_{m,n}^{J^\pi K}(S)\Phi_{m,n}^{J^\pi K}(S),\end{aligned}$$

$$\begin{aligned}\Phi_{m,n}^{J^\pi K}(S) &= \hat{P}_K^J \mathcal{A}\{\psi_L(\alpha)\psi_R(\alpha)\varphi(m)\varphi(n)\} \\ &\equiv \hat{P}_K^J \hat{\Phi}_{m,n}^\pi(^{10}\mathrm{Be};\ S),\end{aligned}$$

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I. Historical background

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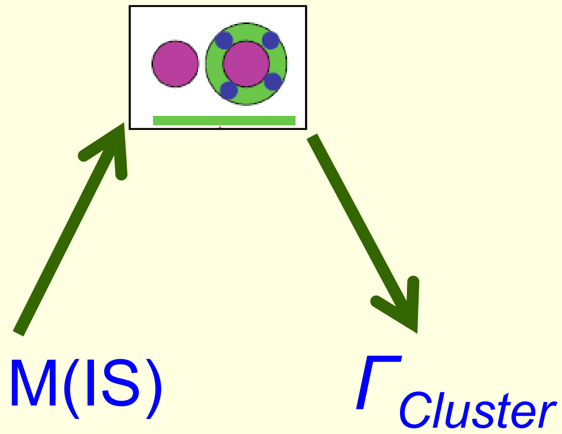
observables for determining the cluster formation in a resonant state



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

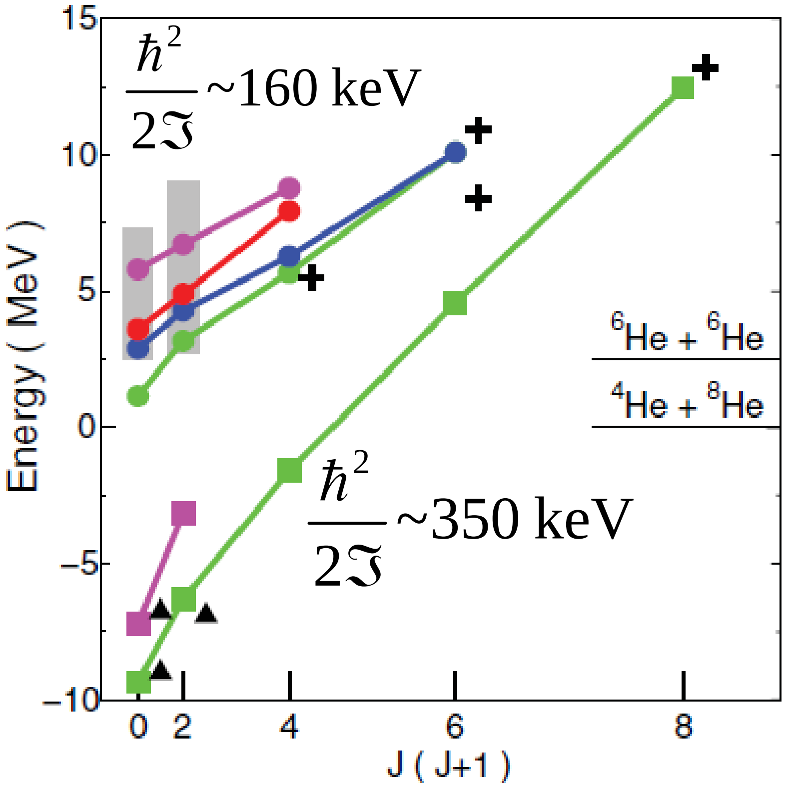
large M(IS) !!

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:

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

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

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

For J (quite difficult):

angular distribution of inelastic scattering,

or angular correlation from binary decay.

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,

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

$$\Gamma = \Gamma_\gamma + \Gamma_n + \Gamma_p + \Gamma_\alpha + \cdots$$

the partial is of probability meaning,

not energy meaning: $\Gamma_i / \Gamma = \sigma_i / \sigma$

R-matrix analysis

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

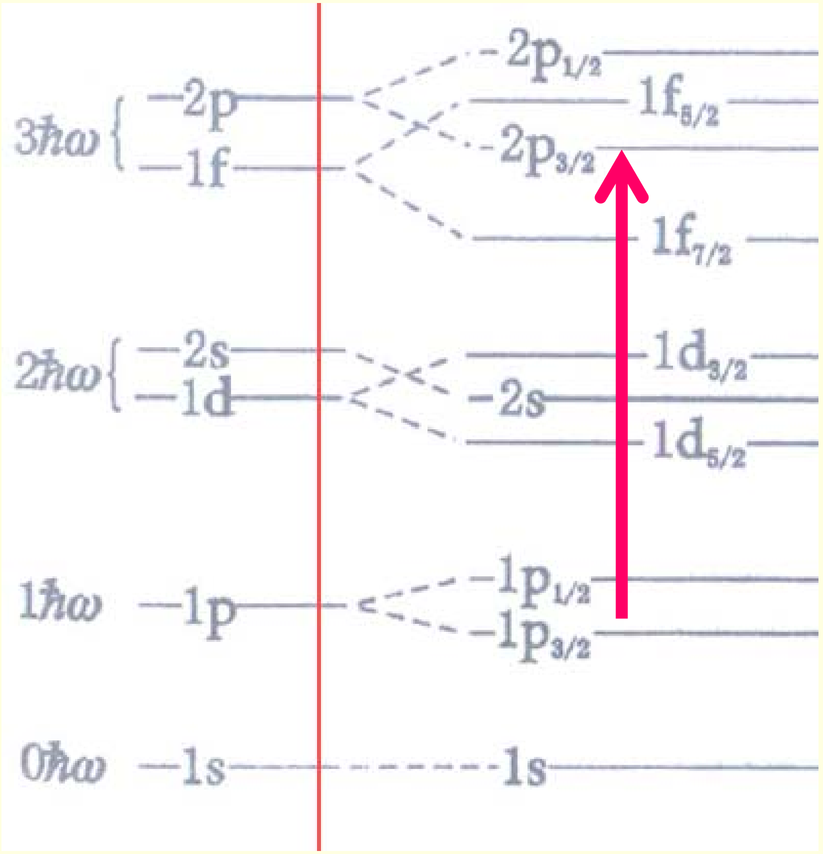
$$\theta_\alpha^2 = \frac{\gamma_\alpha^2}{\gamma_W^2}, \quad \gamma_W^2 = \frac{3\hbar^2}{2\mu a^2}.$$

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].

iii) Determination of the monopole transition strength

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

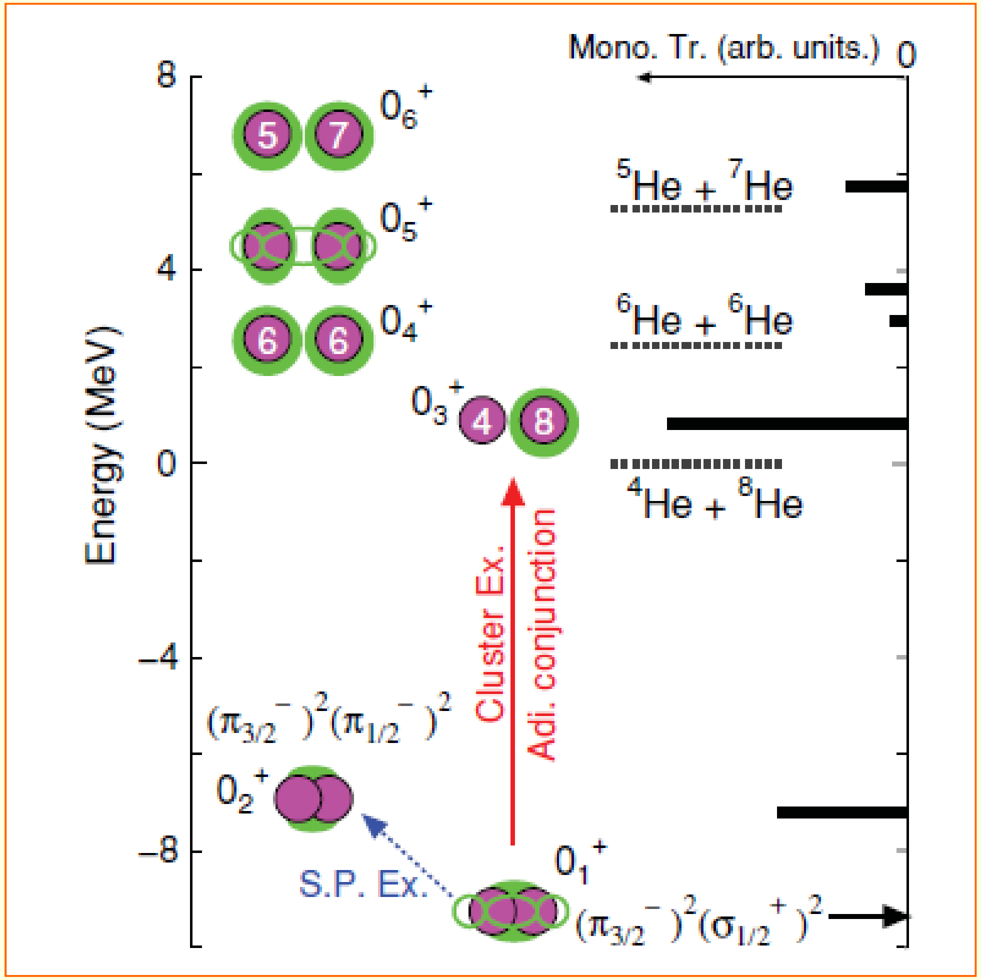
Isoscaler monopole excitation means a jump of about 35 MeV in a simple single-particle picture. A strong M(IS) for E_x below 20 MeV is an indicator of cluster formation



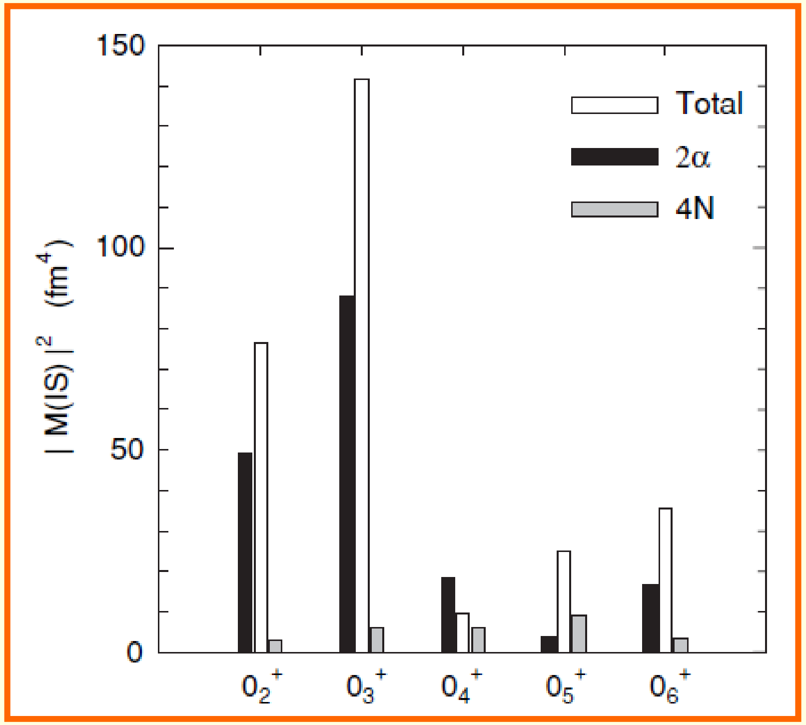
PHYSICAL REVIEW C **83**, 044319 (2011)

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



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



Determining the monopole strength

Monopole Strength Function

$$S(E)=\sum_n \delta(E-E_n)\left|\left\langle 0_n^+\left|\widehat{O}\right|0_1^+\right\rangle\right|^2$$

$$\widehat{O}=\sum_{i=0}^{16}(\mathbf{r}_i-\mathbf{R}_{\mathrm{cm}})^2$$

$$R(E)=\left\langle 0_1^+\left|\frac{\widehat{O}^\dagger\widehat{O}}{E-H+i\varepsilon}\right|0_1^+\right\rangle$$

$\left|0_n^+\right\rangle$: **resonance state with** E_n - $i\Gamma_n/2$

$$S(E)=-\frac{1}{\pi}\mathrm{Im}[R(E)]$$
$$=\frac{1}{\pi}\sum_n\frac{\Gamma_n/2}{(E-E_n)^2+(\Gamma_n/2)^2}\left|M(0_n^+-0_1^+)\right|^2$$

IS-monopole m.e.: $M(0_n^+-0_1^+)=\left\langle 0_n^+\left|\widehat{O}\right|0_1^+\right\rangle$

Energy weighted sum rule (EWSR):

$$\sum_n(E_n-E_1)\left|M(0_n^+-0_1^+)\right|^2=\frac{2\hbar^2}{m}\times 16\times R^2,\quad R=\sqrt{\frac{1}{16}\left\langle 0_1^+\left|\sum_{i=1}^{16}(\mathbf{r}_i-\mathbf{R}_{\mathrm{cm}})^2\right|0_1^+\right\rangle}$$

Outline

I. Historical background

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Freer et al., PRL82(1999) 1383; PRC63 (2001)034301

Charity et al., PRC76(2007)064313

no small angle (low E_{rel}) detection

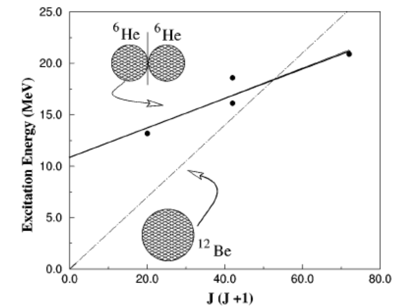
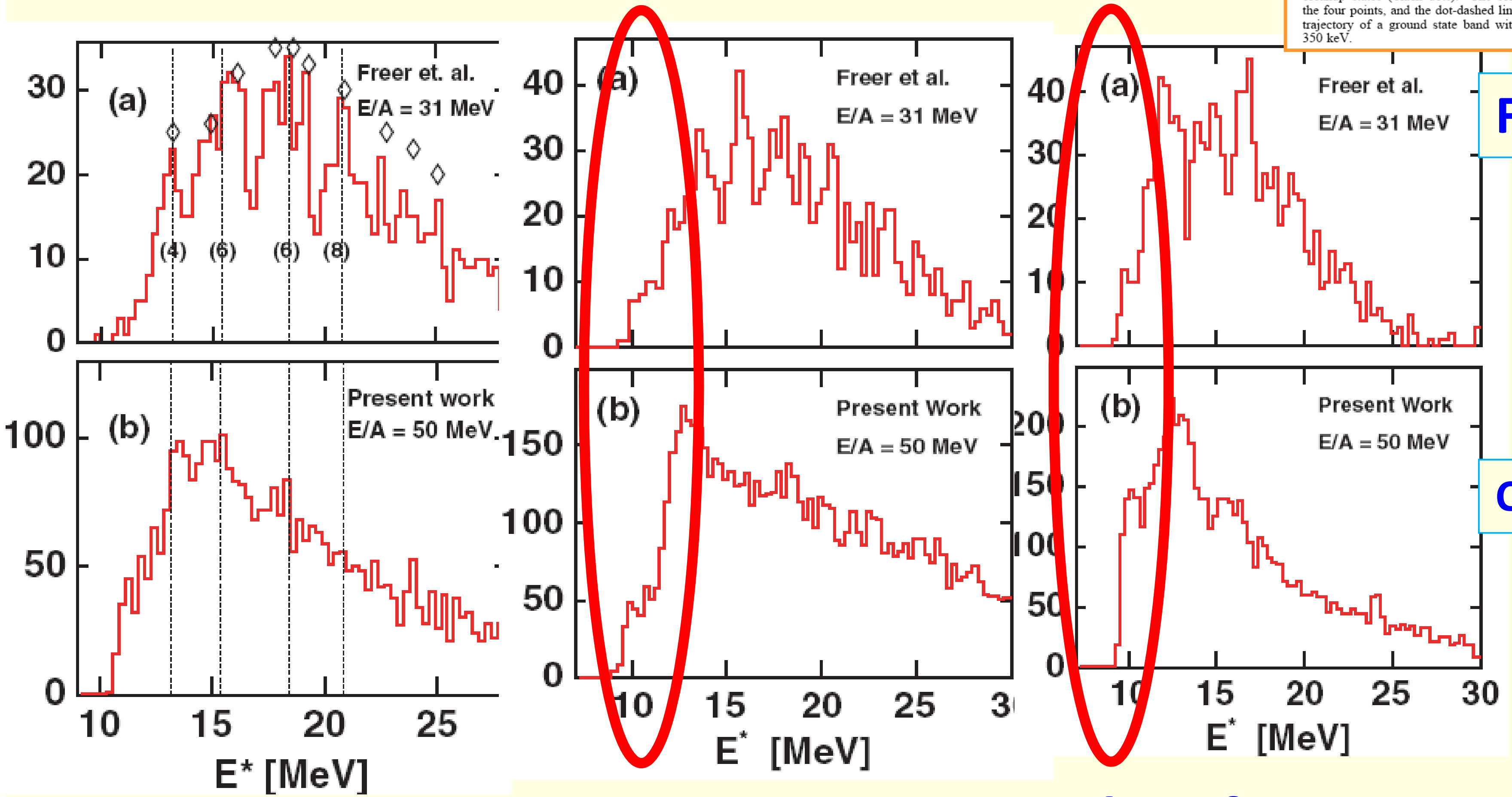


FIG. 4. The energy-spin systematics of the ^{6}He + ^{6}He breakup states (black dots). The solid line is a linear fit to the four points, and the dot-dashed line shows the extrapolated trajectory of a ground state band with a rotational energy of 350 keV.



Freer

Charity

^{6}He+^{6}He,CH_2

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

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

PHYSICAL REVIEW C **85**, 044308 (2012)

Formations of loose clusters in an unbound region of ^{12}Be

Makoto Ito
Department of Pure and Applied Physics, Kansai University, Yamatecho 3-3-35, Suita, Japan,

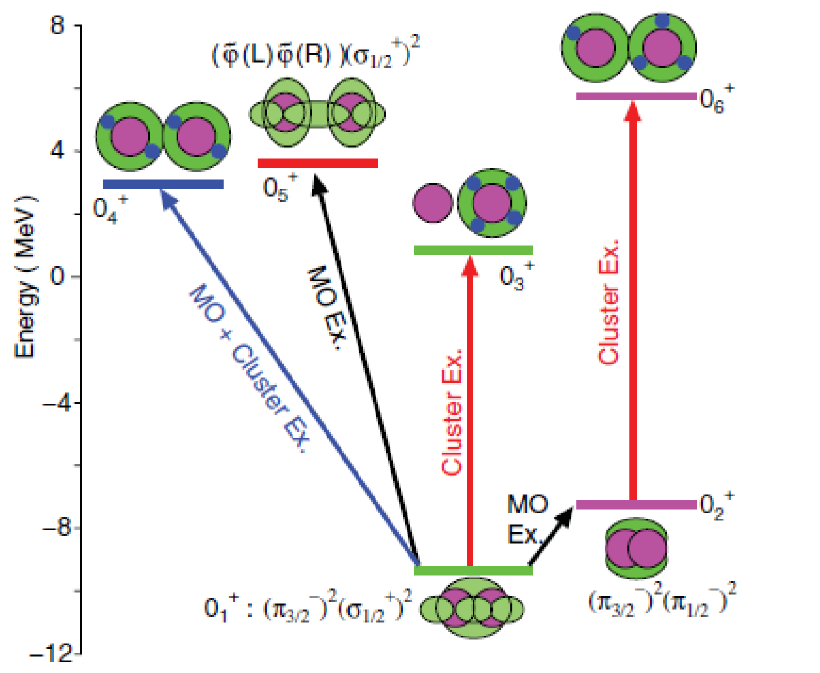
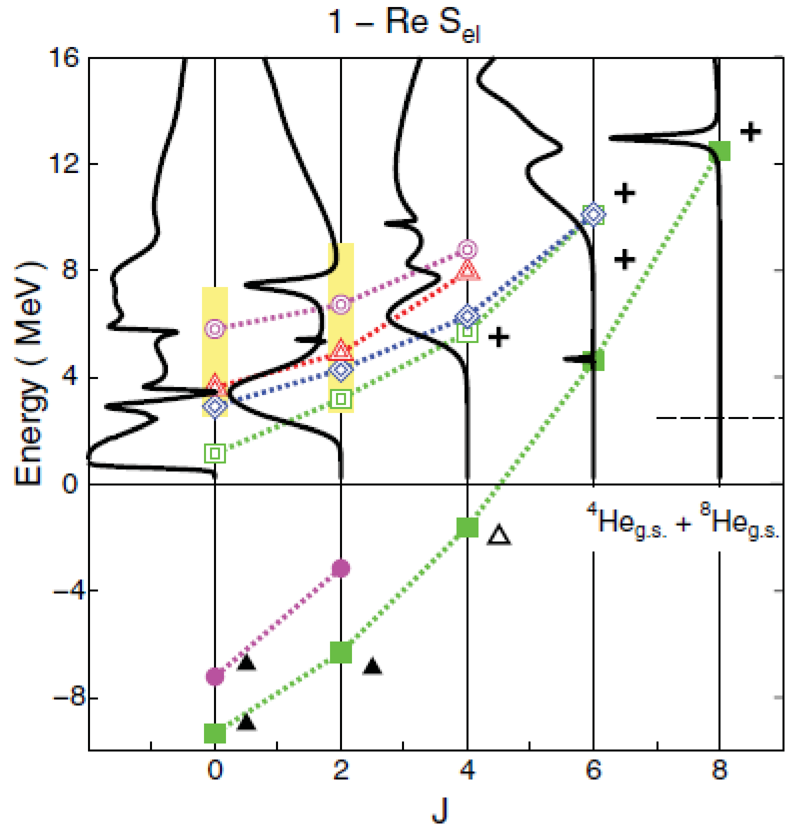


FIG. 8. (Color online) Energy spectra classified by the excitation degrees of freedom ($J^\pi = 0^+$). See text for details.



A new exp. at RIBLL1@HIRFL, Lanzhou

Collaborators

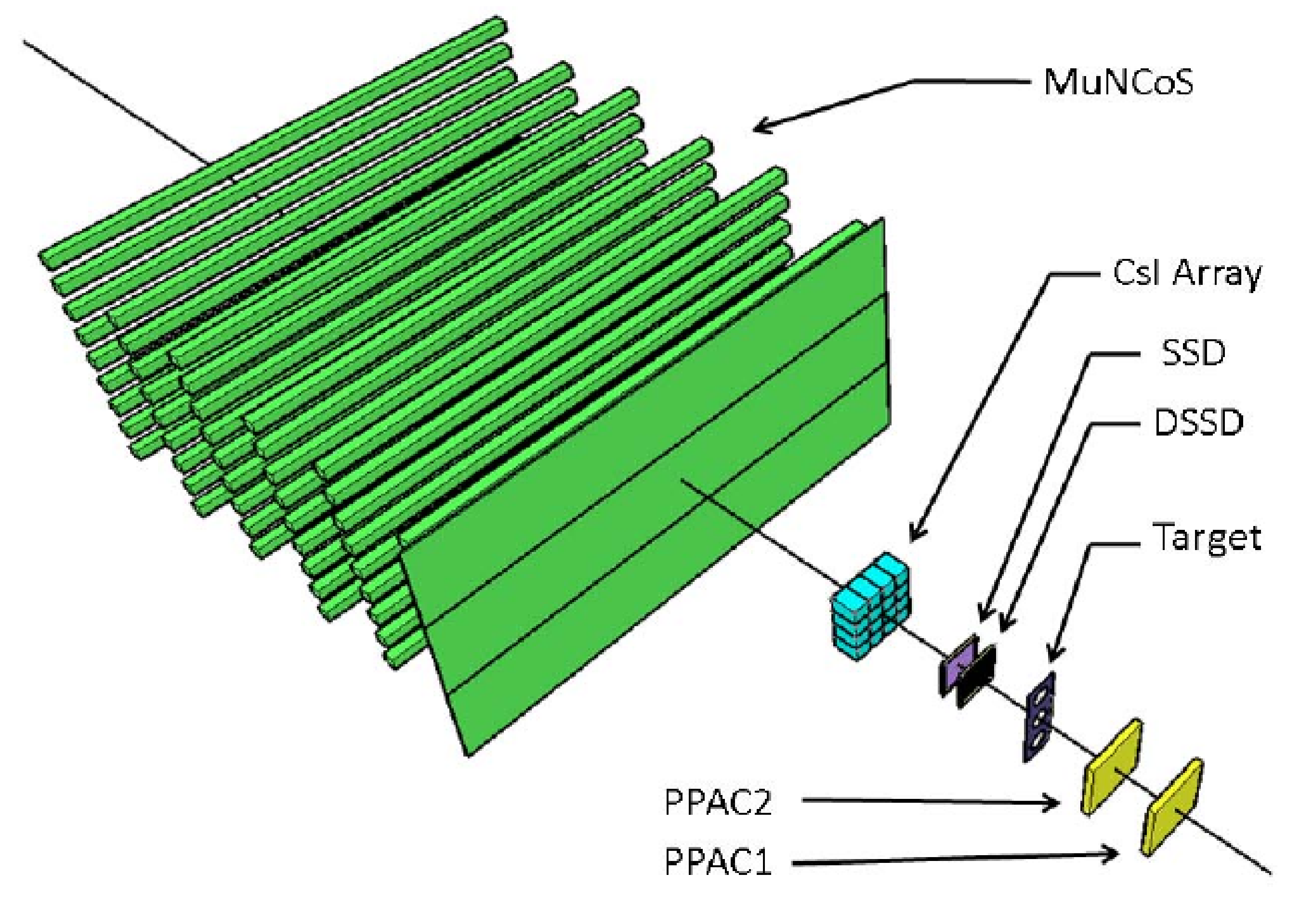
PRL **112,** 162501 (2014) PHYSICAL REVIEW LETTERS week ending 25 APRIL 2014

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]

[1]*State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China*
[2]*Institute of Modern Physics, Chinese Academy of Science, Lanzhou 730000, China*
[3]*RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*

(Received 10 December 2013; published 22 April 2014)



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

Resolution and efficiency

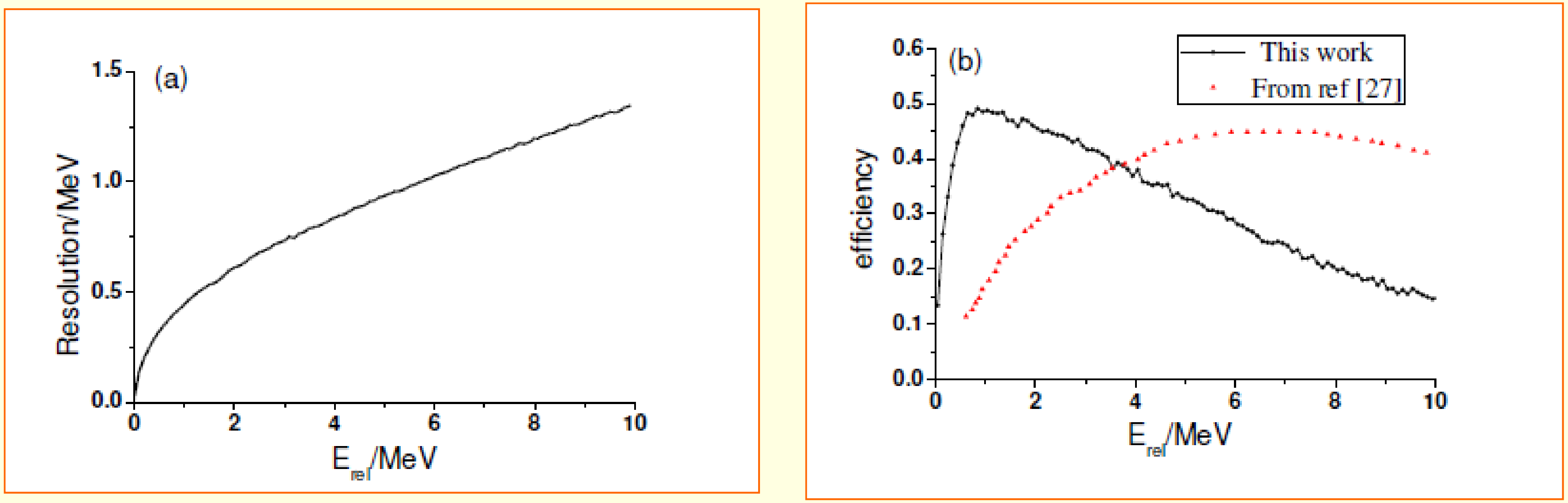
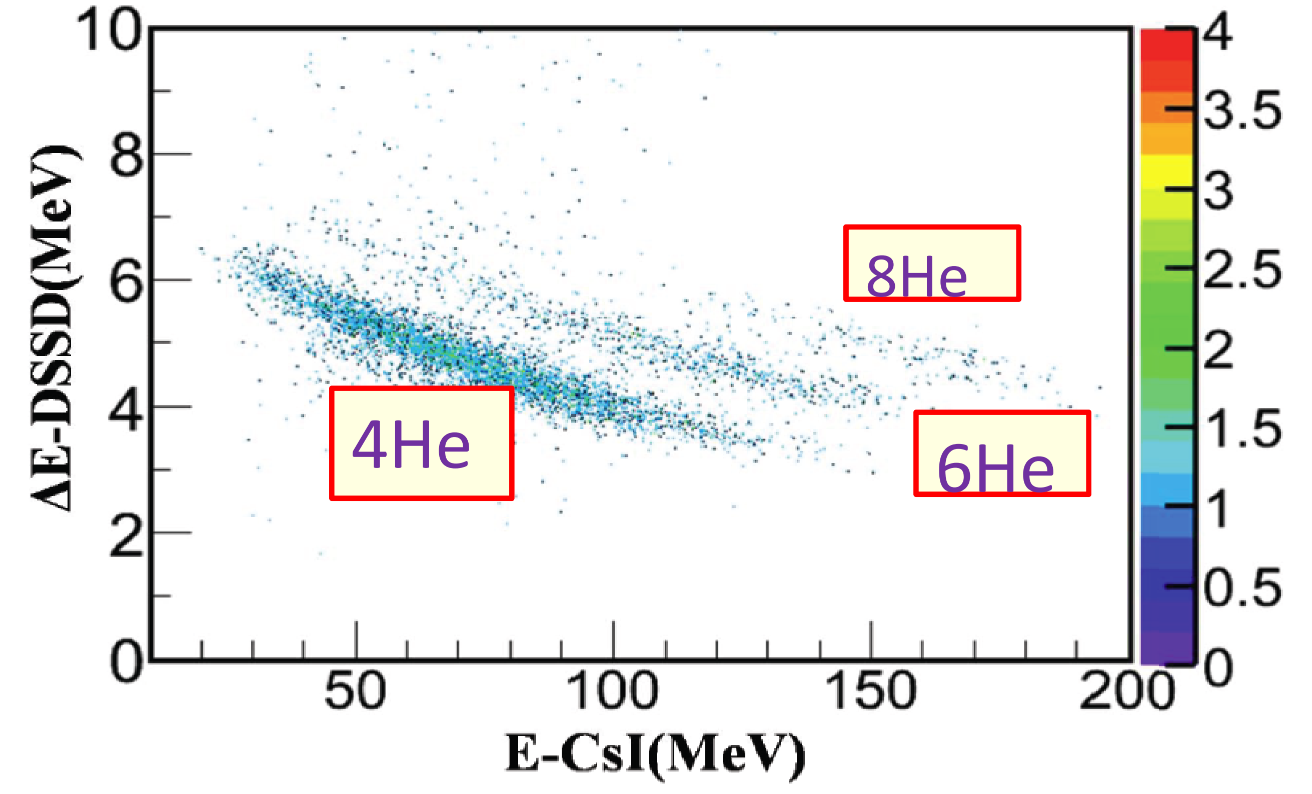


FIG. 2. Resolution(FWHM) of E_{rel} (a) and detection efficiency (b) for ^{12}Be decaying into ^{4}He+^{8}He. Similar results are also obtained for ^{12}Be decaying into ^{6}He+^{6}He. And for comparison, the efficiency obtained from reference[27] was also shown.

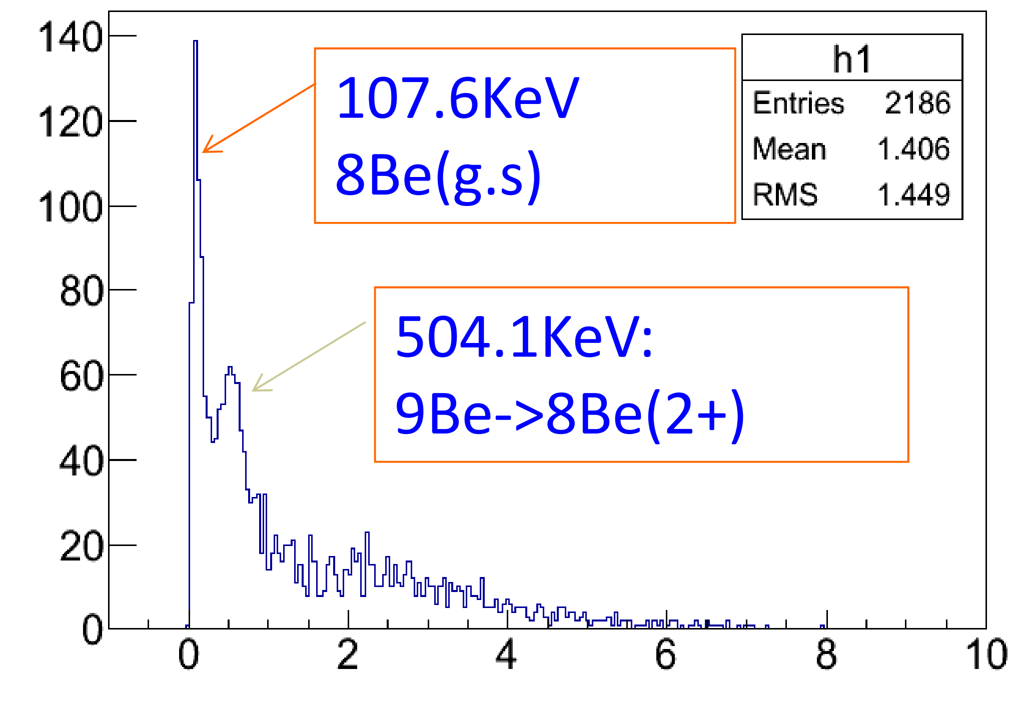
PID for 2-^{x}He fragments



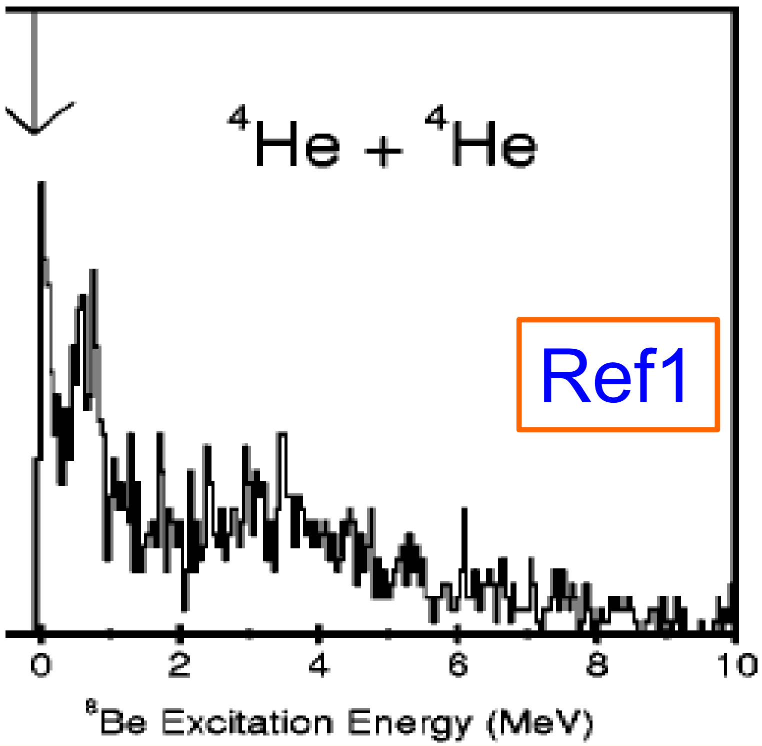
Uniform calibration of the Si strips and treatment of PID under intense direct beam:

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

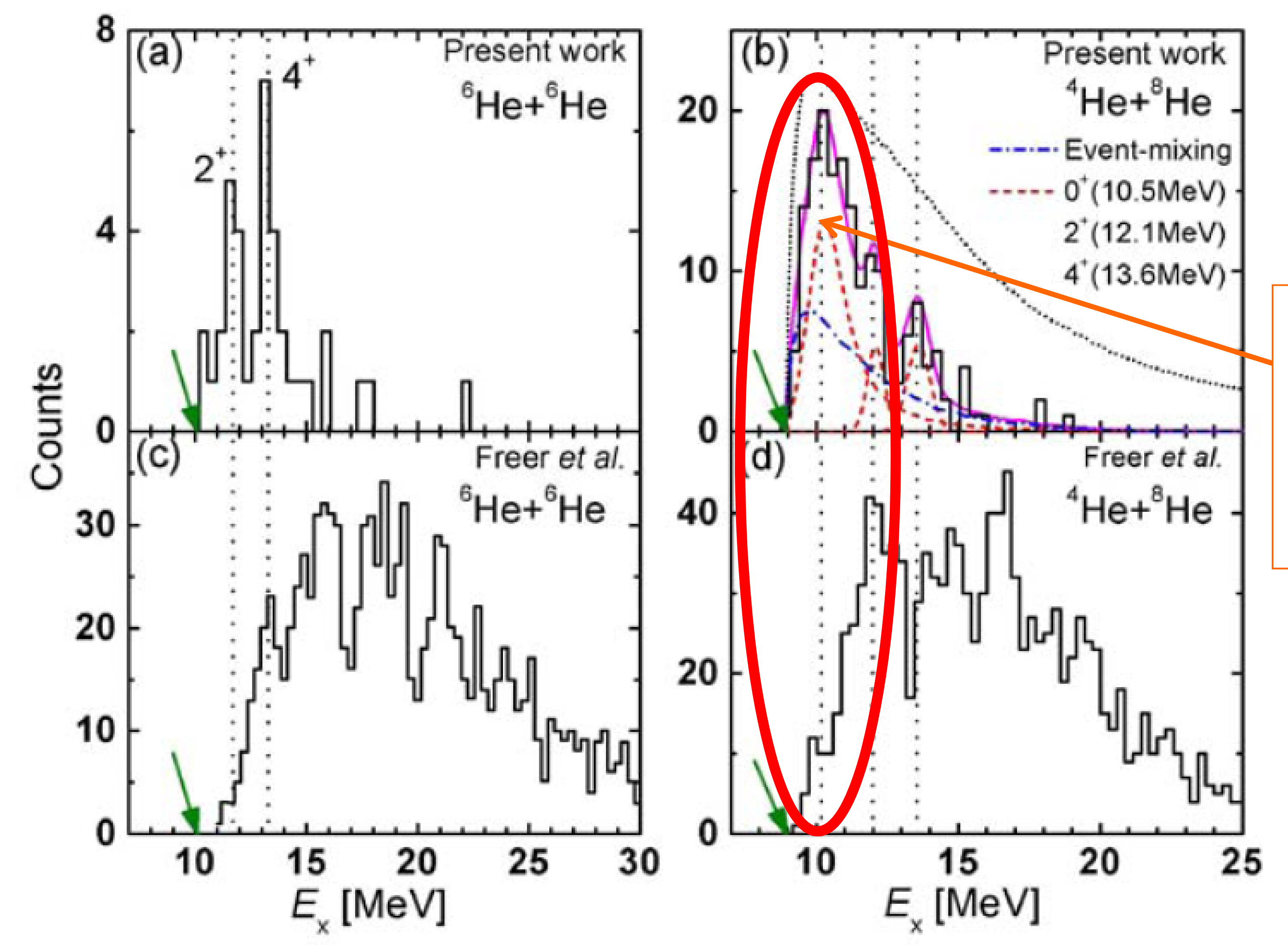
verification for ^4He + ^4He channel



Excitation Energy---^4He+^4He



Ref1: PLB580(04)129-^{14}Be breakup

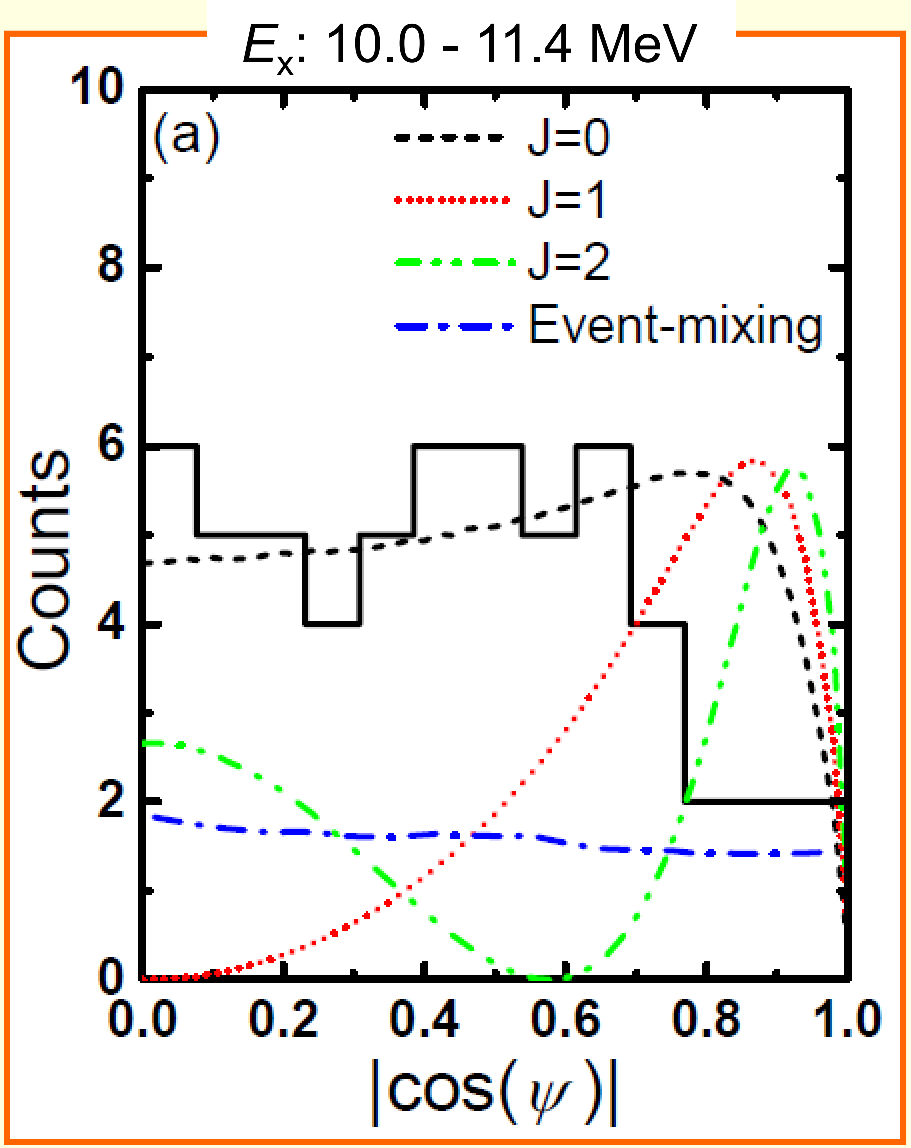


Large and unusual 10.3 MeV state;

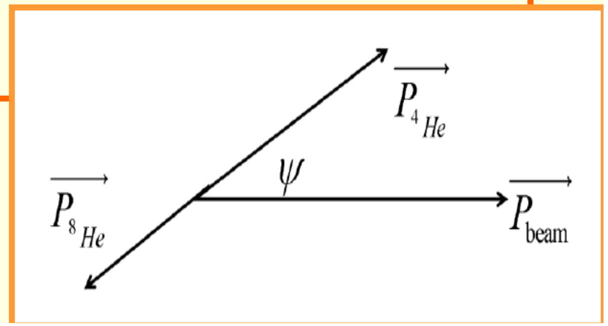
Our exp: $^6He+^6He$ 11.7 13.3 MeV

$^4He+^8He$ 10.3 12.1 13.6 MeV

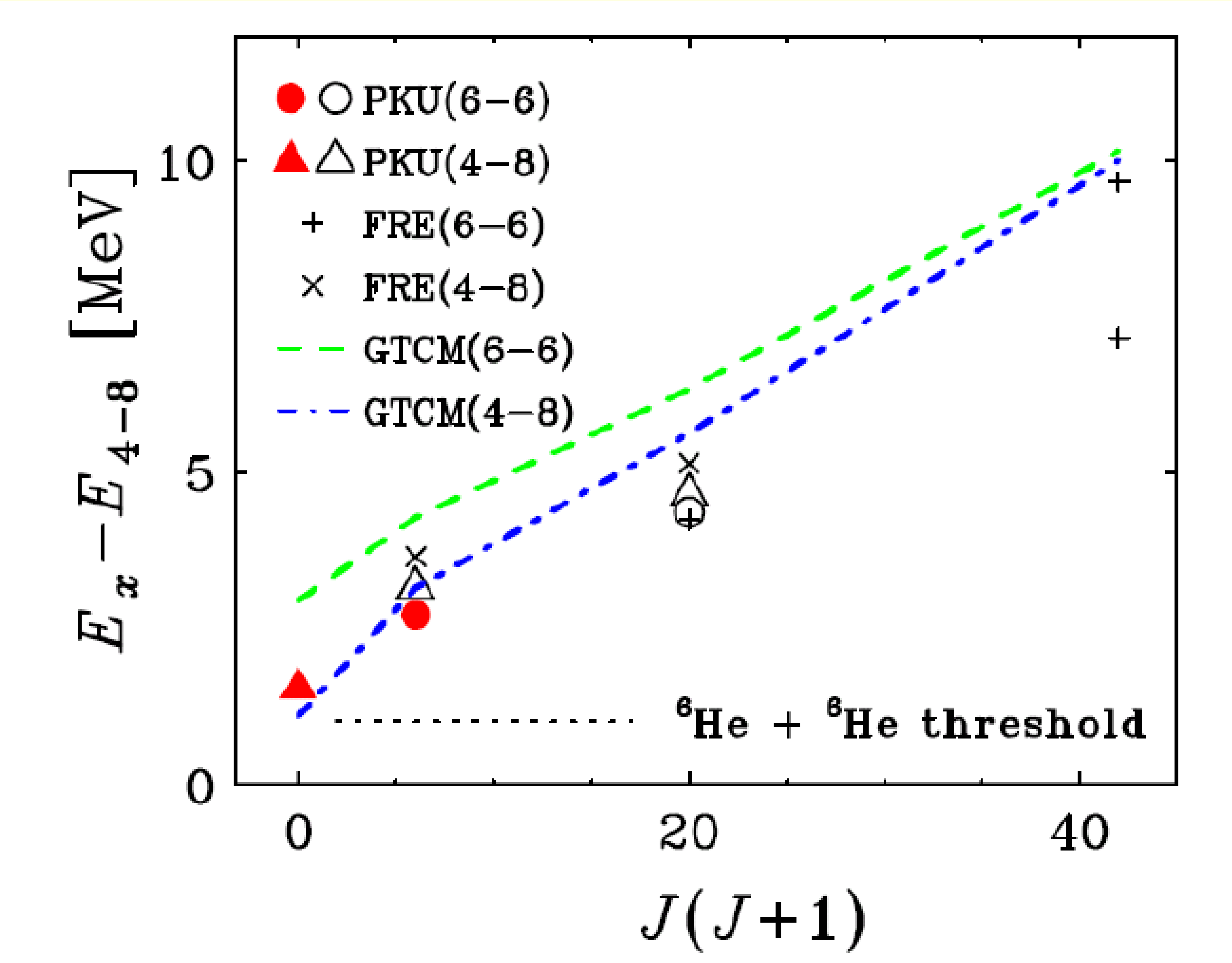
Spin: Angular correlation analysis for the 10.3 MeV state in ^4He + ^8He channel



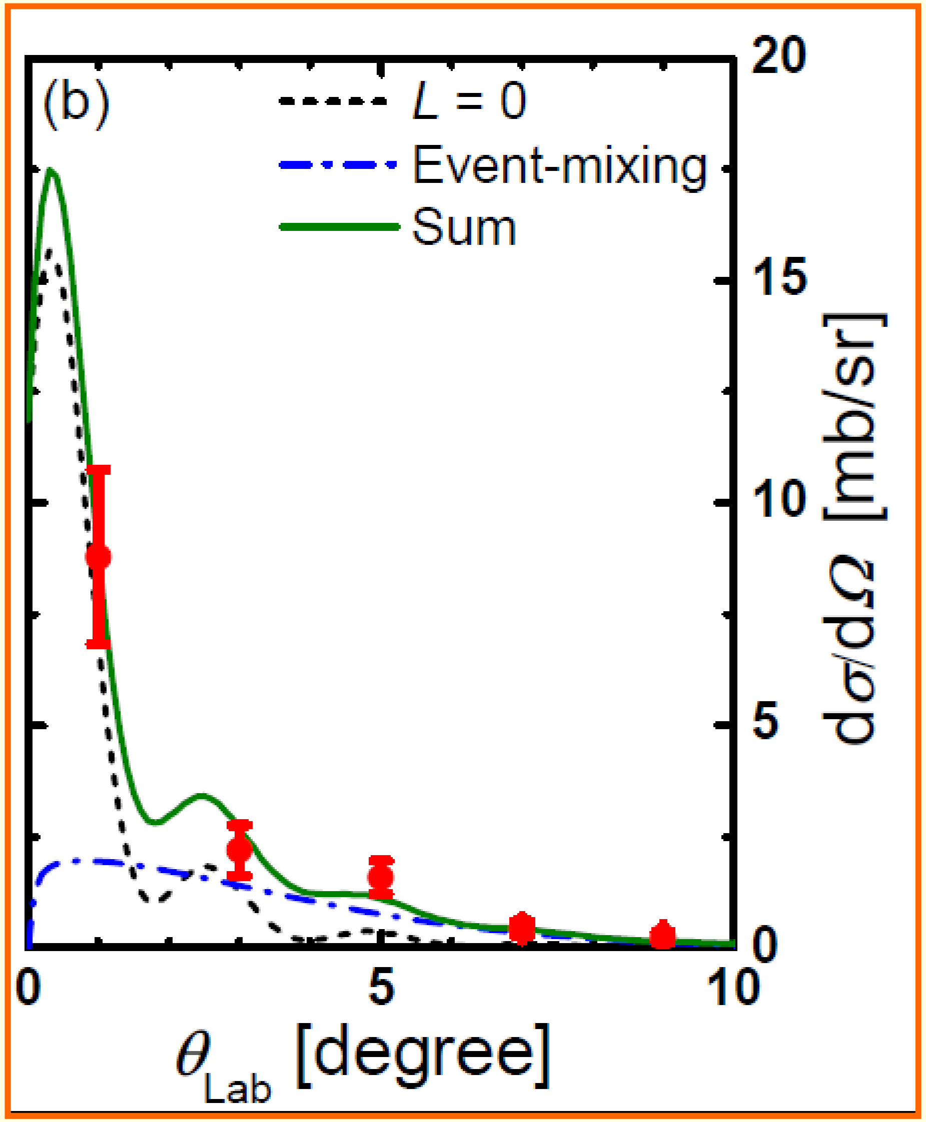
For small angle inelastic scattering leading to a resonant state with an angular momentum *J*, which subsequently breaks up into spin-0 fragments, the projected angular correlation spectrum is proportional to $|P_J(\cos(\Psi)|^2$, with Ψ being the fragment c.m. angle relative to the beam direction.



Confirming the MR band with large moment of inertia



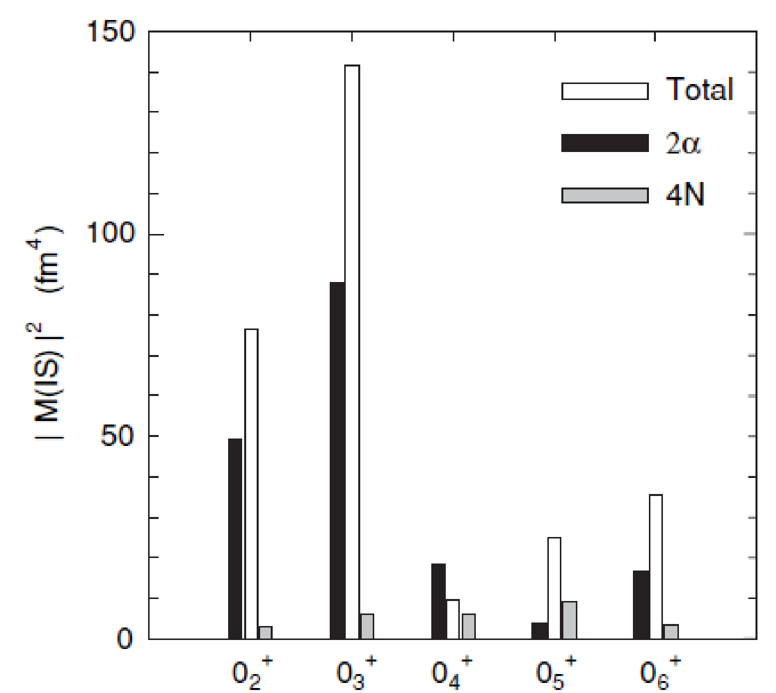
DWBA calculation



Fraction: 0.034(10) x 2.2.

EWSR：6727.9 fm^4 MeV,

M(IS)： **7.0 +/- 1.0 fm^2**,



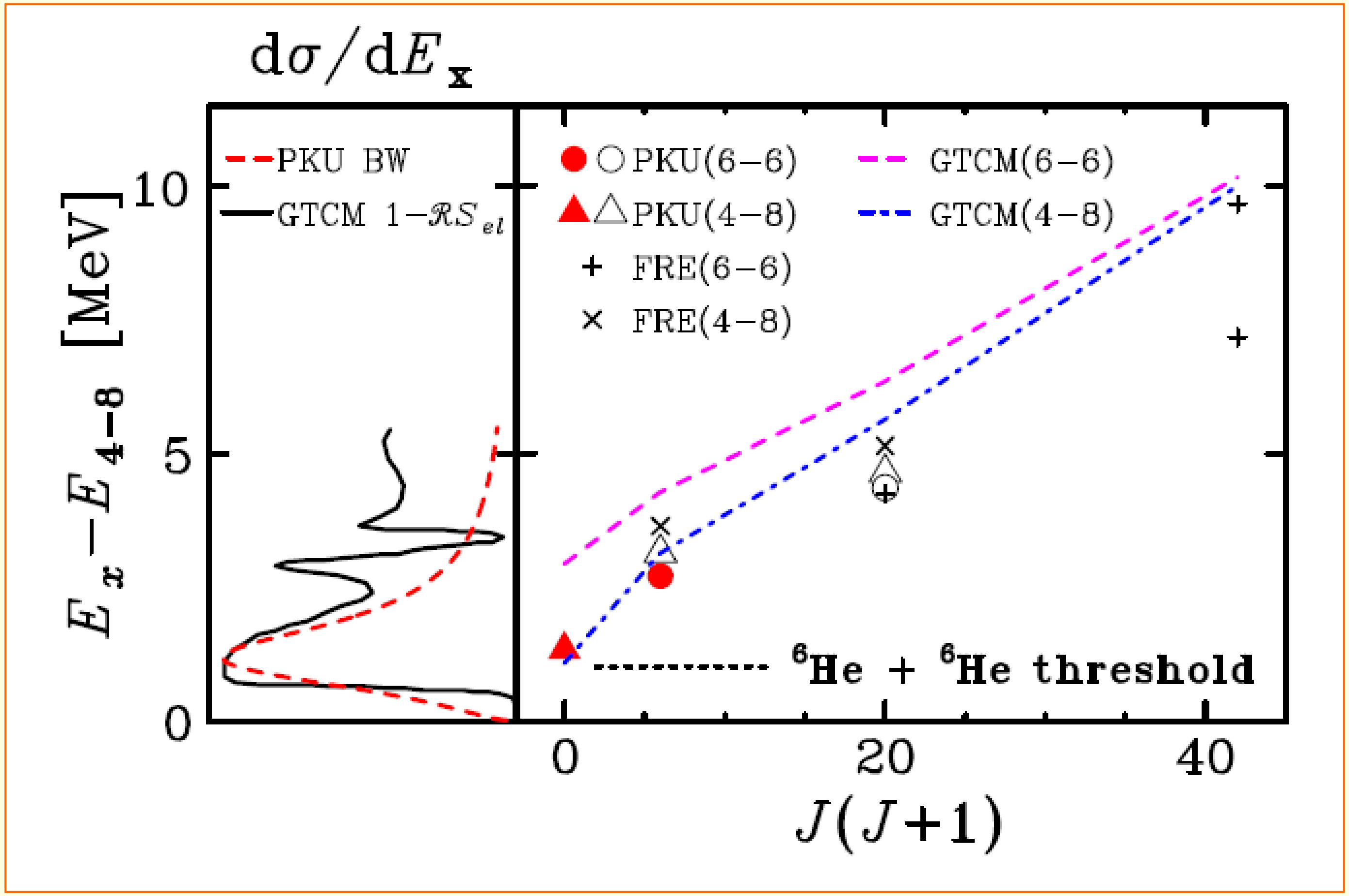
Determining the cluster decay width

10.3 MeV (0^+) state:

$$\sigma = \pi \lambda\!\!\!^{-2} \frac{\Gamma_a \Gamma_b}{(E' - E_0)^2 + (\Gamma/2)^2}$$

$$\Gamma = \sum_i \Gamma_i = 1.5(2)\ \text{MeV}$$

$$\Gamma = \Gamma_\gamma + \Gamma_n + \Gamma_p + \Gamma_\alpha + \cdots$$



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)**

- **For the first time a strong monopole strength has been determined in unstable nuclei, providing a clear evidence for cluster formation in ^{12}Be.**
- **Angular-correlation method is very sensitive to the spin of the resonance. MR band in ^{12}Be has been justified based on the E_x-spin systematics .**
- **A large cluster-decay width, and consequently a large cluster SF, are obtained for the 10.3 MeV state in ^{12}Be.**

All these findings demonstrate a dominating cluster structure in ^{12}Be just above the ^{4}He+^{8}He threshold.

Outline

I. Historical background

II. How to observe

III. ^{12}Be — an example

IV. Future perspectives

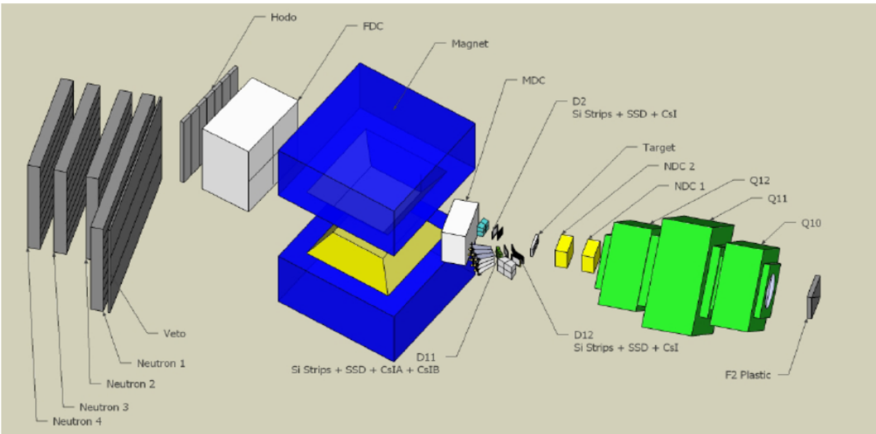
For clustering in ground state
— QFS at > 100 MeV/u

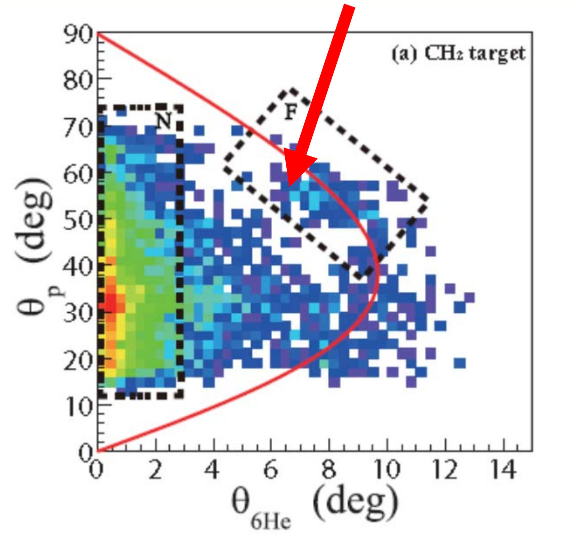
Ex: $^{8}He(p, p^{6}He)$ at RIPS

RIKEN-RIBF Exp. RRC48, ;

Z.X. Cao, Y.L.Ye et all, PLB707(2012)46

- 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), Empty





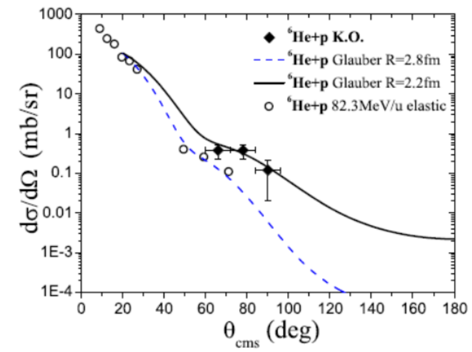
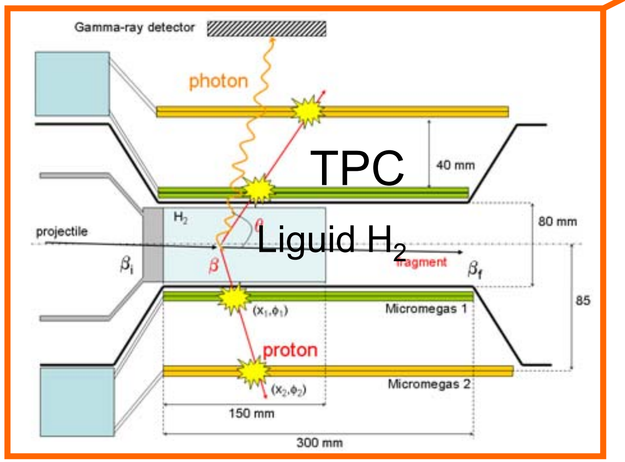
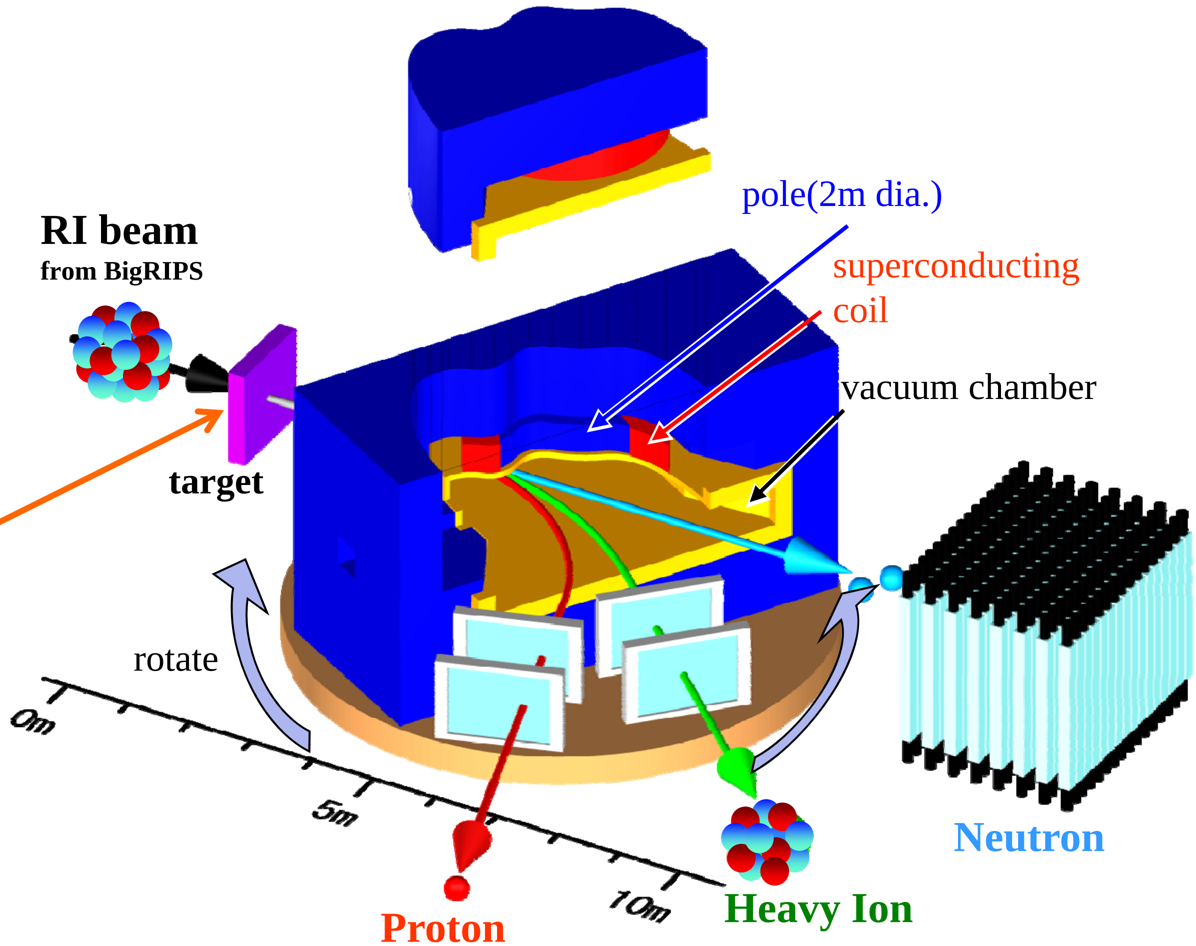


Figure 4: Differential cross sections of ^{6}He core fragments knocked out (K.O.) from ^{8}He projectiles at 82.3 MeV/u (the fulled diamonds). Data for elastic scattering of ^{6}He on proton target are also presented by the circles [22]. The dashed line represents the Glauber model calculation for elastic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

New proposals at BigRIPS + AMURAI ……

MINOS:
MagIc Numbers Off Stability
Δ x<3mm FWHM
Eff. >85%



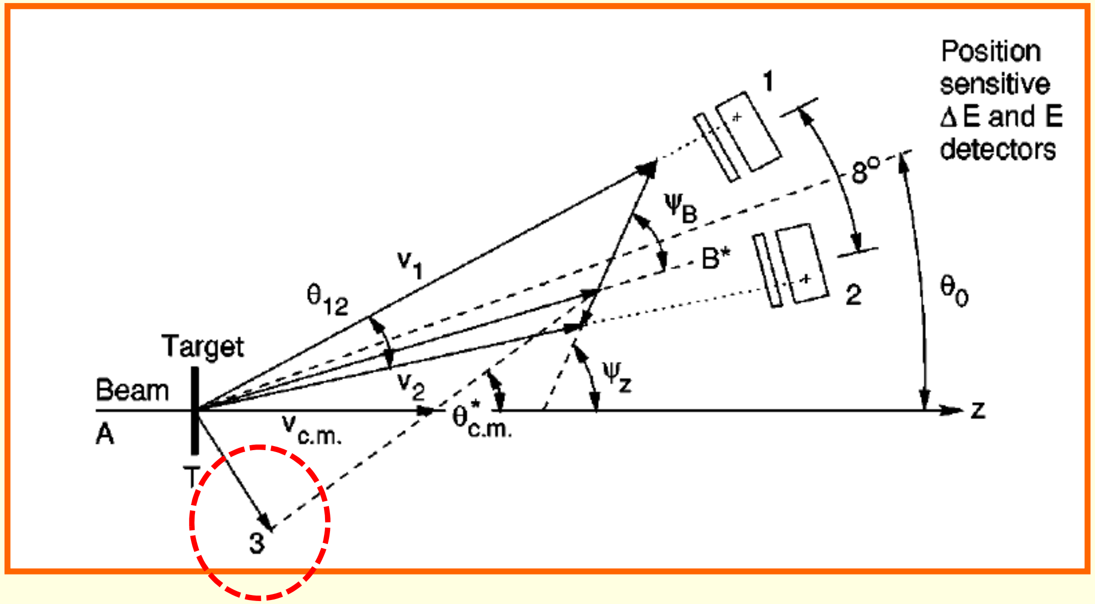


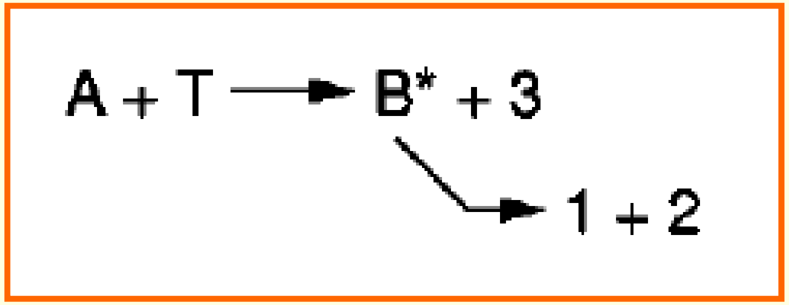
For clustering in resonant states — beams < 30 MeV/u

- peak position (band?)
- spin-parity (band?)
- area (cross section) as a function of angle
- shape and width (R-matrix analysis)
- decay branches (partial widths) and angular correlation

Need both missing mass (MM) and invarant mass (IM) measurements

missing mass (inelastic or transfer)



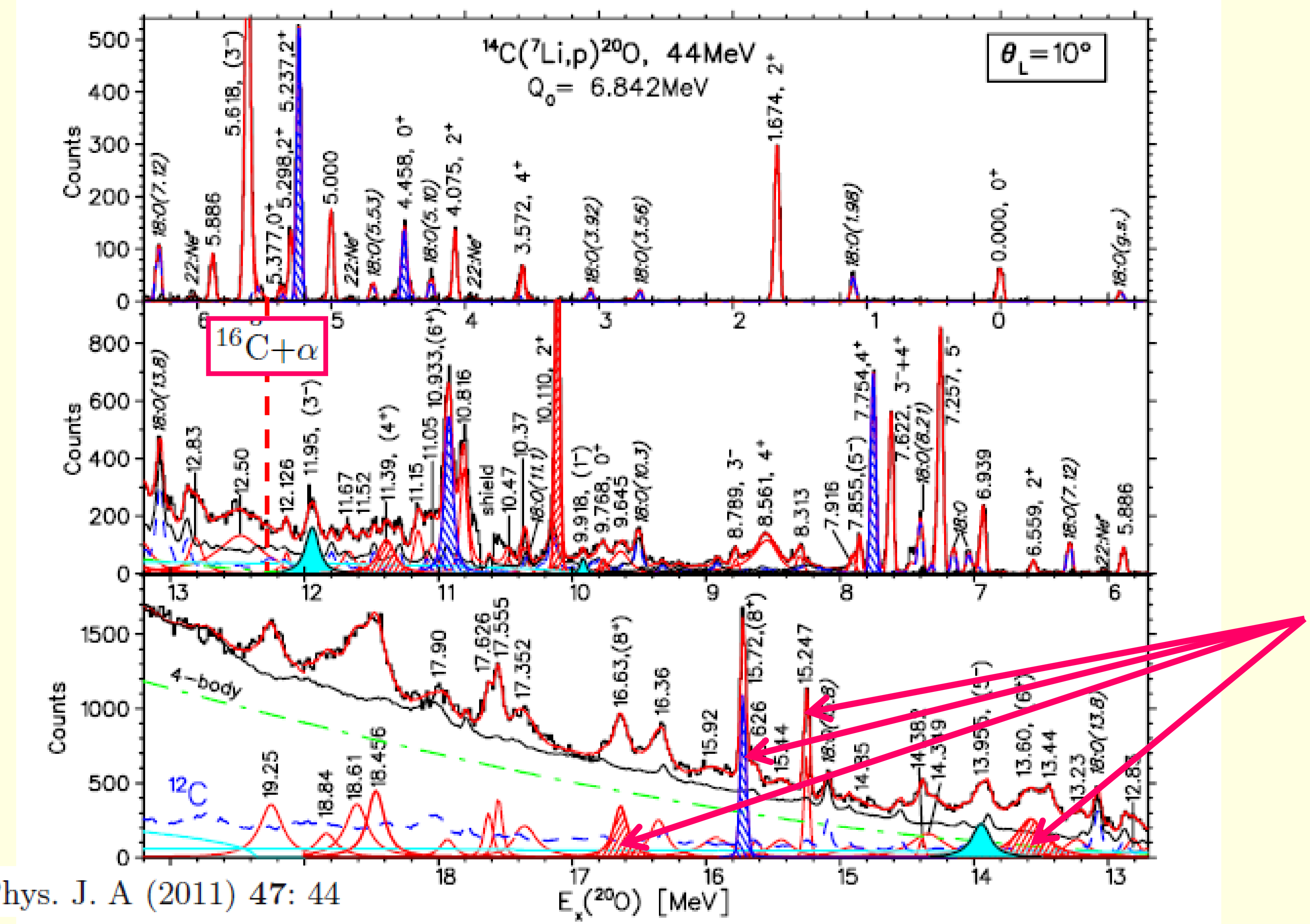


$$Q = T_3 + T_{B*} - T_A = m_T + m_A - m_3 - m_{B*}$$

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

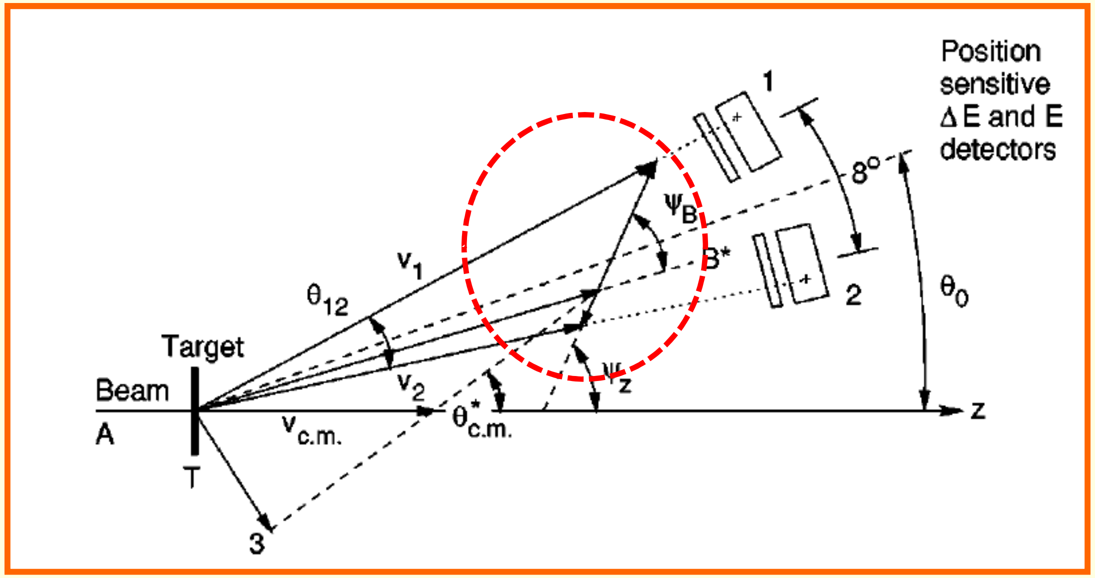
$$Q = \left(\frac{m_A}{m_B} - 1\right)T_A + \left(\frac{m_3}{m_B} + 1\right)E_3 - \frac{2\left(m_A m_3 T_A T_3\right)^{1/2}\cos\theta}{m_B}$$

Members of the $K = 0^+_2$, 1^-_2 , and 0^+_4 bands of ^{20}O (with tentative assignments) are marked by downward hatched (blue), filled (cyan), and upward hatched (red) areas, respectively.



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

invariant mass



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

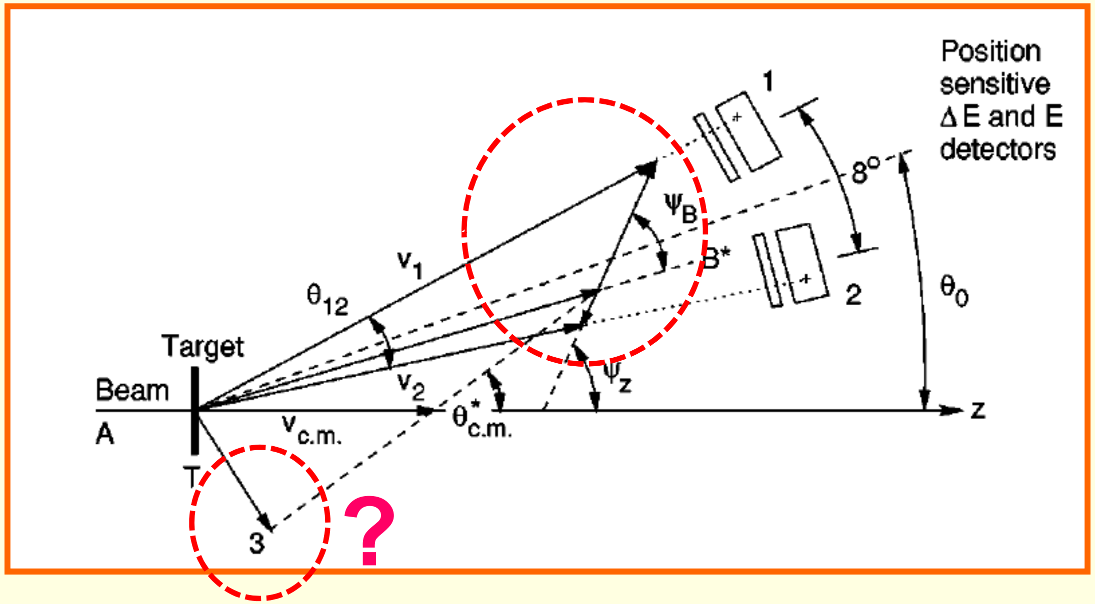
$$E_{B*} = E_1 + E_2, \qquad \vec{p}_{B*} = \vec{p}_1 + \vec{p}_2$$

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

$$E_S = (m_1 + m_1 - m_B)c^2$$

$$E_x = m_{B*}c^2 - m_B c^2 = E_S + E_{rel}$$

RI beam & recoil target: IM + MM



A + T → B* + 3

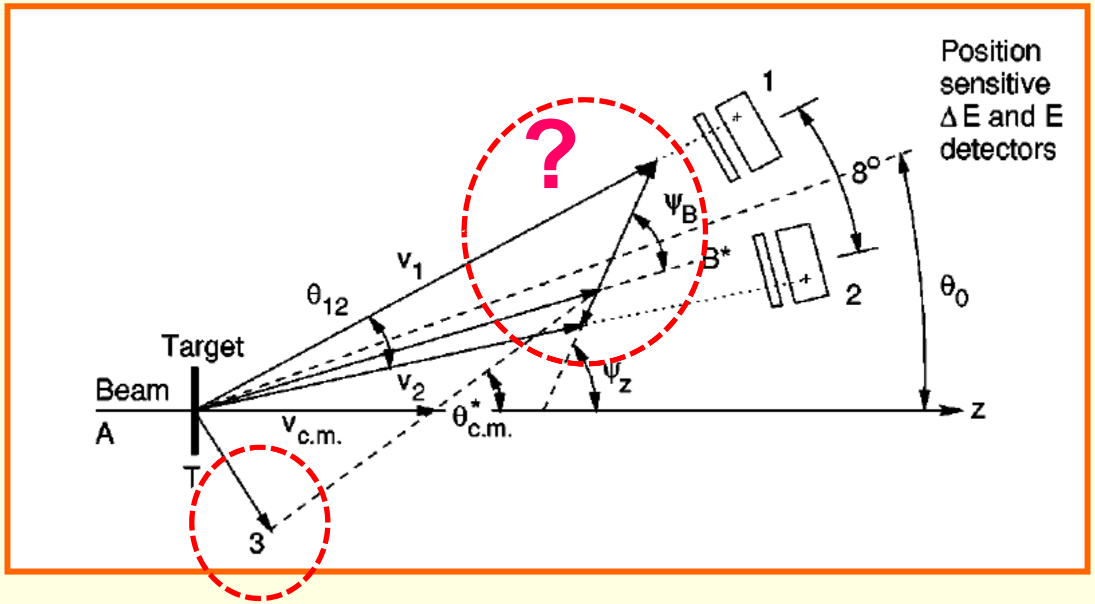
B* → 1 + 2

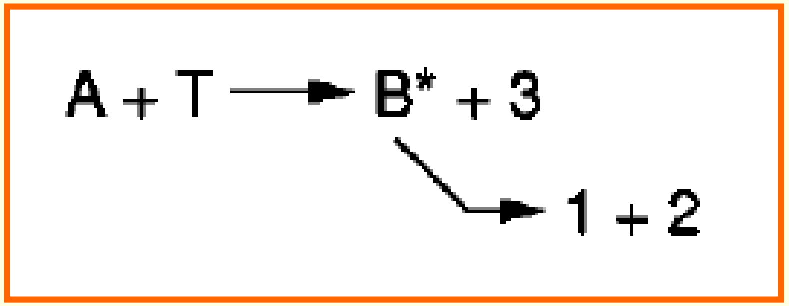
for RI beam excitation (IM) & recoil target (MM)

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

* one proposal made at HIRFL-RIBLL

Stable beam & excited target: MM + IM





for stable beam (MM) and target excitation (IM)

- good experiences on MM measurement
- IM at low recoil energies

* one proposal made at CIAE

Summary

- Clustering should be a general phenomenon in light unstable nuclei.
- Consistent evidences are needed to experimentally ping down a cluster state, such as large momentum of inertial, large cluster decay partial width and large selective excitation strength.
- QFS at higher energies and MM + IM measurements at lower energies are good ways to observe the evidences of clustering

Thank you for your attention

TABLE VI. The theoretical values of the partial decay widths and the reduced widths for the $^6He+^6He$ and $^8He+^4He$ decays from excited states of ^{12}Be. The channel radius is chosen to be $a=5$ fm.

	$^6He+^6He$		$^8He+^4He$	
J_n^+	$\gamma^2_{^6He}(a)$	$\Gamma_{^6He}$ (keV)	$\gamma^2_{^4He}(a)$	$\Gamma_{^4He}$ (keV)
0_3^+	2.5×10^{-1}	7×10^2	1.3×10^{-2}	4×10^1
2_4^+	8.3×10^{-2}	1	3.5×10^{-3}	3
4_2^+	1.3×10^{-1}	7	1.7×10^{-2}	5
6_2^+	4.3×10^{-2}	16	2.2×10^{-3}	1
8_1^+			1.6×10^{-2}	1

Impact on the nuclear-astrophysics

Progress of Theoretical Physics Supplement No. 196, 2012

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

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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]

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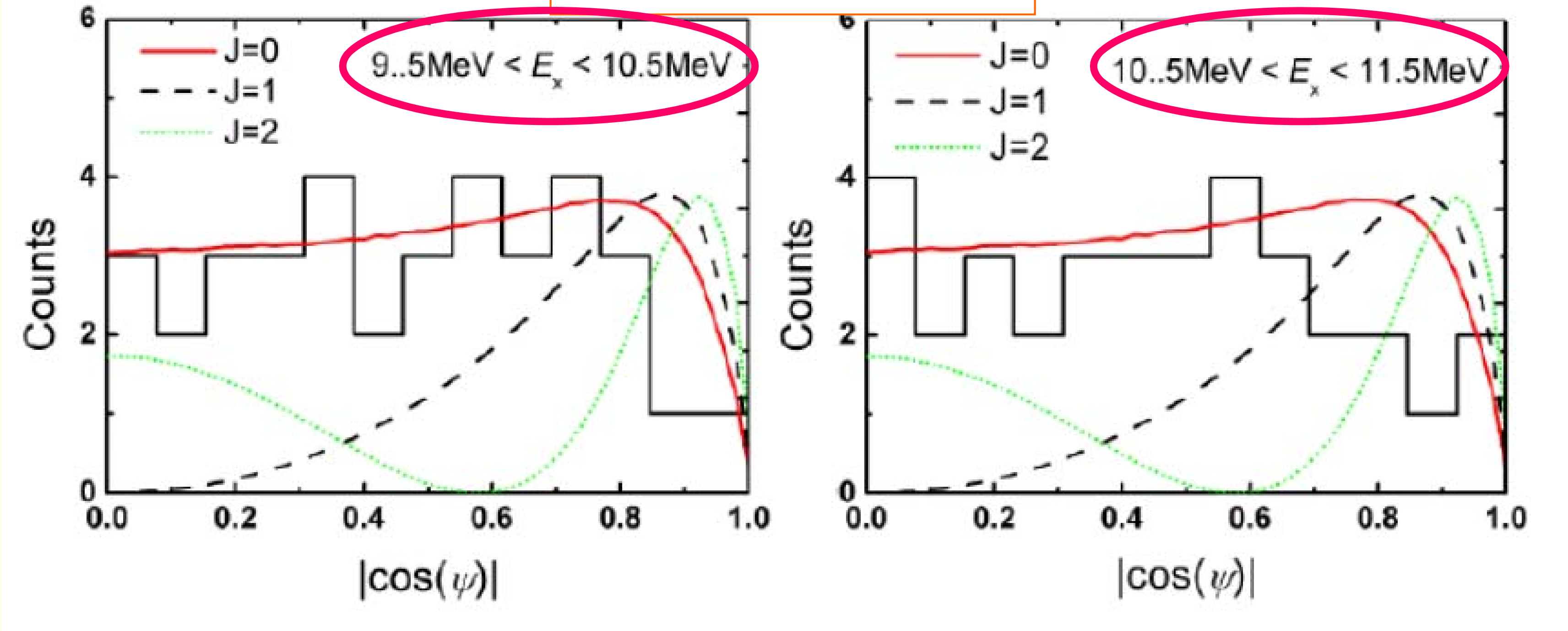
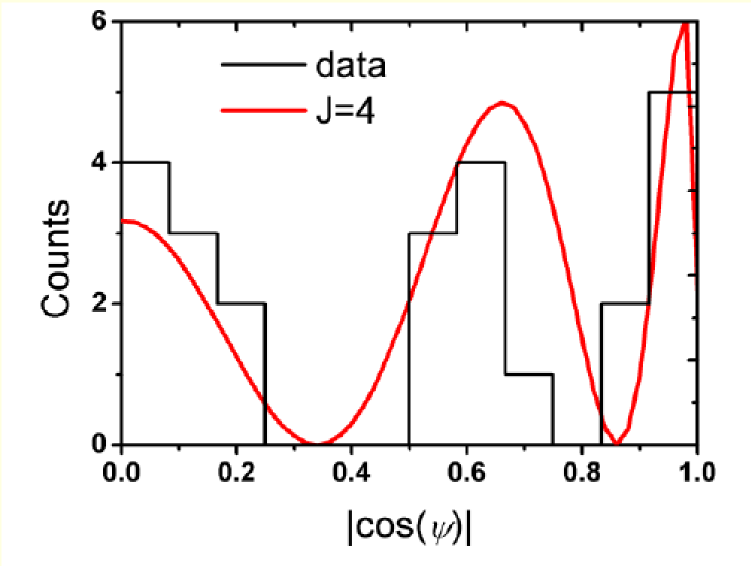
Nucleosynthesis by alpha particles and heavier 4n nuclei are of great interest as they would involve nuclear cluster resonances. The role of nuclear clustering is discussed for nucleosynthesis with the Cluster Nucleosynthesis Diagram (CND) proposed before, especially those involving alpha induced reactions, 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.

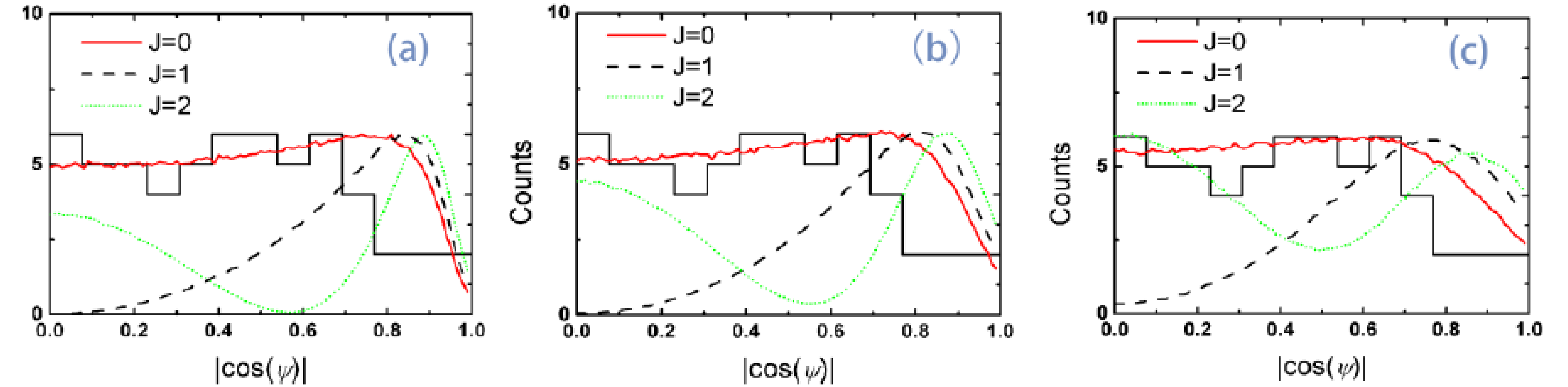
10.3 MeV state





13.6 MeV state

10.3 MeV state



|cosΨ| resolution

0.1 **0.2** **0.4**

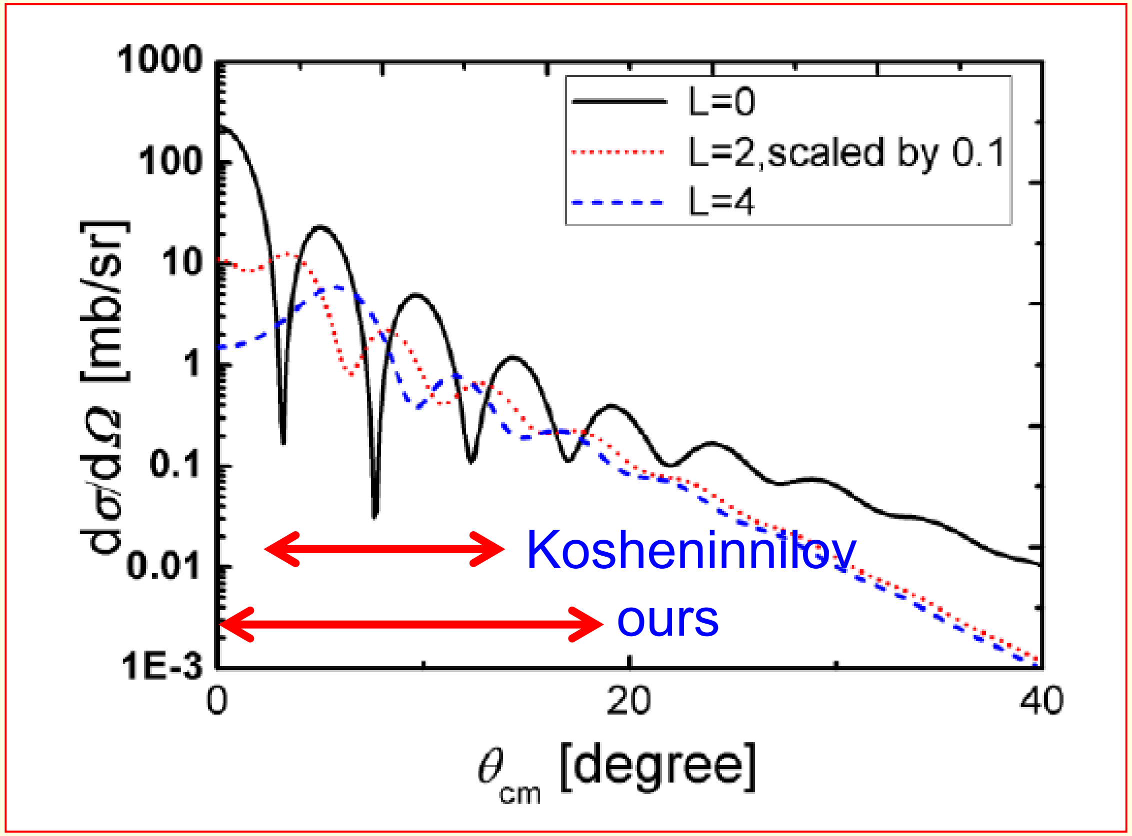
All possible decay channels

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]
$^4He+^8He$	9.6	39%	27.6 %	36 %
$^6He+^6He$	10.1	21%	13.1%	19.3 %
$^4He+^6He+2n$	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 %
$^9Be+3n$	10.48	0.098%	2.1E-3 %	0.028 %
$^8Be+4n$	12.06	6.9E-5 %	----------	3.4E-6 %

Overall dominance of the 0^+ state



DWBA calculations for the excitation of 12Be from its ground state to the 10.3 MeV excited state, when interacting with a C target.