**HINPW5，12-13 April 2019，Thessaloniki, Greece**

# Strongly Resonating Bosons in Hot Nuclei

S. Zhang   zsylt@imun.edu.cn
College of Physics and Electronics information, Inner Mongolia University for Nationalities, China.

**Collaborators:**

A. Bonasera, Z. Kohley , S.J. Yennello
Cyclotron Institute, Texas A&M University,  College Station, TX-77843, USA

M. Huang, J.C. Wang, L. Lu
College of Physics and Electronics information, Inner Mongolia University for Nationalities, China.

H. Zheng
School of Physics and Information Technology, Shaanxi Normal University, China

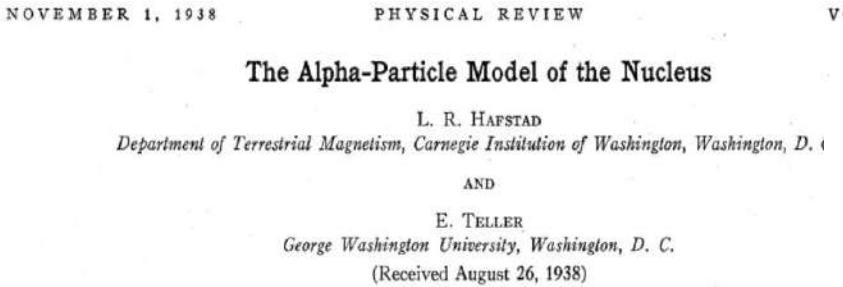
Y.G. Ma, G. Zhang
Shanghai Advanced Research Institute, Chinese Academy of Sciences, China

# Outline

- Introduction: α Cluster Structure in Nuclei
- Motivation: Efimov State and Hoyle State in $^{12}C$
- 3α Resonances in Heavy Ion Collisions
- Summary

# Introduction: α Cluster Structure in Nuclei

## Long History and Fruitful Subject



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.*

AND

E. TELLER
*George Washington University, Washington, D. C.*
(Received August 26, 1938)

Letter | Published: 18 July 2012

How atomic nuclei cluster

J.-P. Ebran, E. Khan, T. Nikšić & D. Vretenar

*Nature* **487**, 341–344 (19 July 2012) | Download Citation

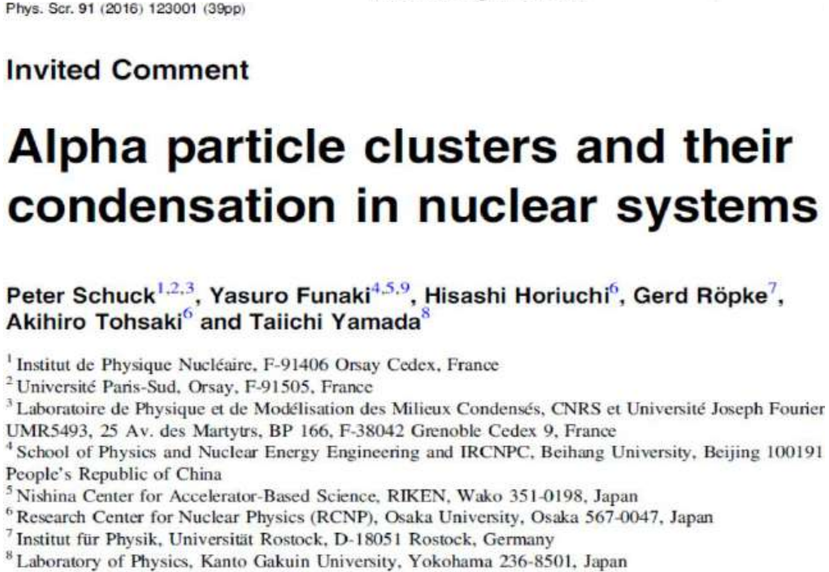
News & Views | Published: 18 July 2012

**Nuclear physics**

Nucleons come together

Martin Freer

*Nature* **487**, 309–310 (19 July 2012) | Download Citation



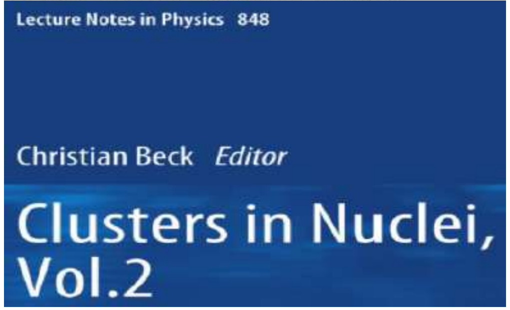
Phys. Scr. 91 (2016) 123001 (39pp)

**Invited Comment**

Alpha particle clusters and their condensation in nuclear systems

**Peter Schuck[1,2,3], Yasuro Funaki[4,5,9], Hisashi Horiuchi[6], Gerd Röpke[7], Akihiro Tohsaki[6] and Taiichi Yamada[8]**

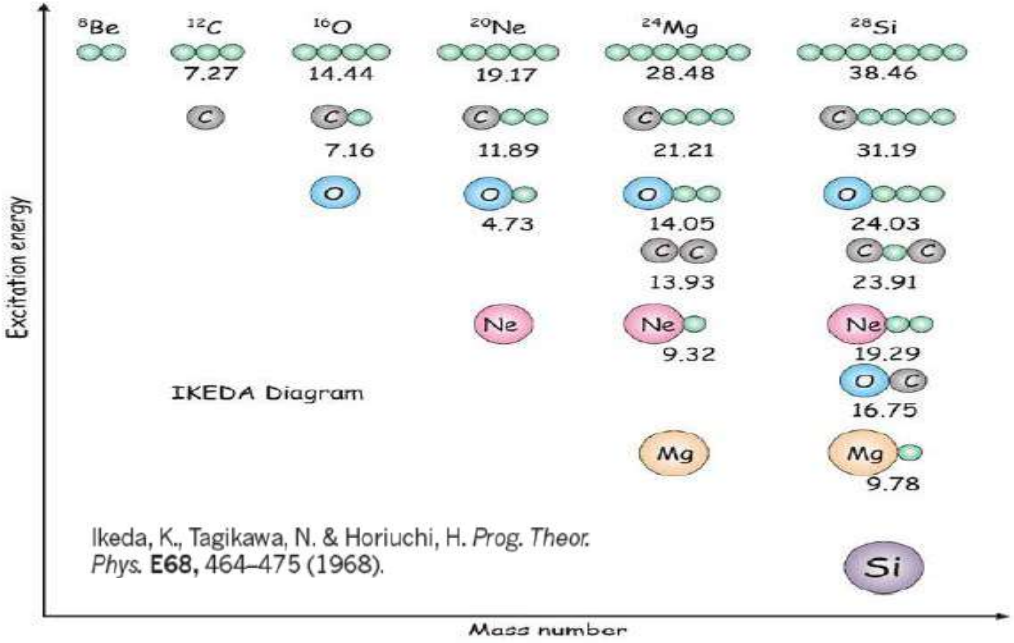
[1] Institut de Physique Nucléaire, F-91406 Orsay Cedex, France
[2] Université Paris-Sud, Orsay, F-91505, France
[3] Laboratoire de Physique et de Modélisation des Milieux Condensés, CNRS et Université Joseph Fourier UMR5493, 25 Av. des Martyrs, BP 166, F-38042 Grenoble Cedex 9, France
[4] School of Physics and Nuclear Energy Engineering and IRCNPC, Beihang University, Beijing 100191 People's Republic of China
[5] Nishina Center for Accelerator-Based Science, RIKEN, Wako 351-0198, Japan
[6] Research Center for Nuclear Physics (RCNP), Osaka University, Osaka 567-0047, Japan
[7] Institut für Physik, Universität Rostock, D-18051 Rostock, Germany
[8] Laboratory of Physics, Kanto Gakuin University, Yokohama 236-8501, Japan



Lecture Notes in Physics 848

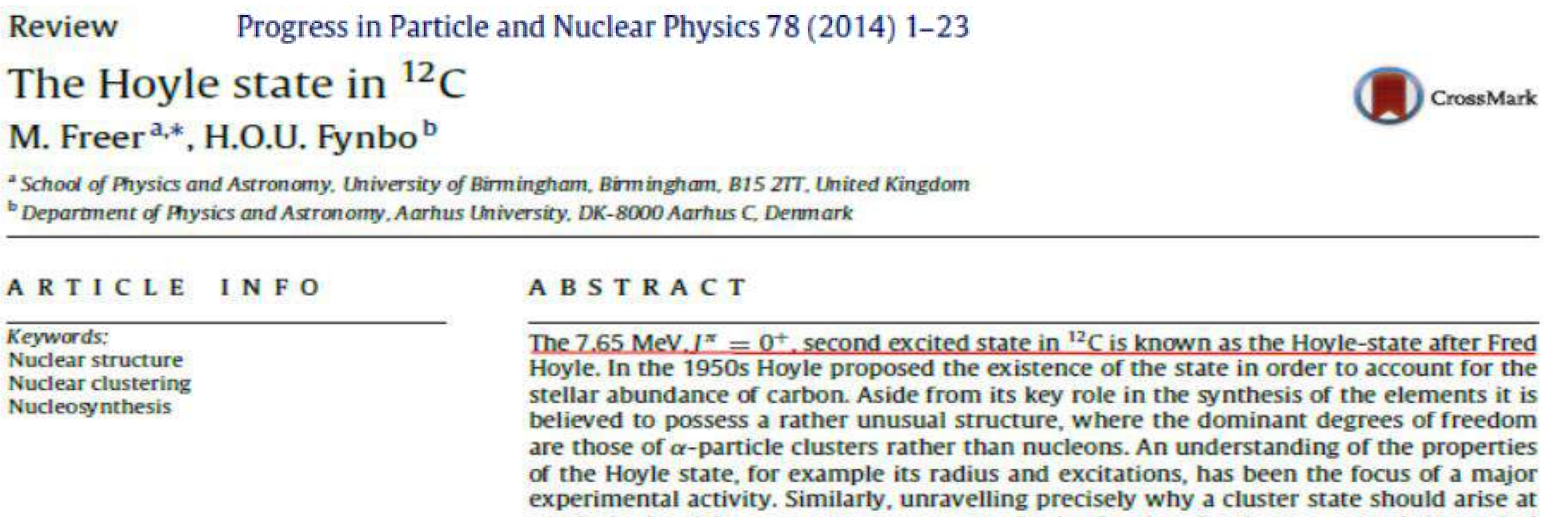
Christian Beck *Editor*

Clusters in Nuclei, Vol.2



Ikeda, K., Tagikawa, N. & Horiuchi, H. *Prog. Theor. Phys.* **E68**, 464–475 (1968).

# Motivation: Hoyle State and Efimov State in $^{12}$C



Review Progress in Particle and Nuclear Physics 78 (2014) 1–23

## The Hoyle state in $^{12}$C

M. Freer[a,*], H.O.U. Fynbo[b]

[a] School of Physics and Astronomy, University of Birmingham, Birmingham, B15 2TT, United Kingdom
[b] Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark

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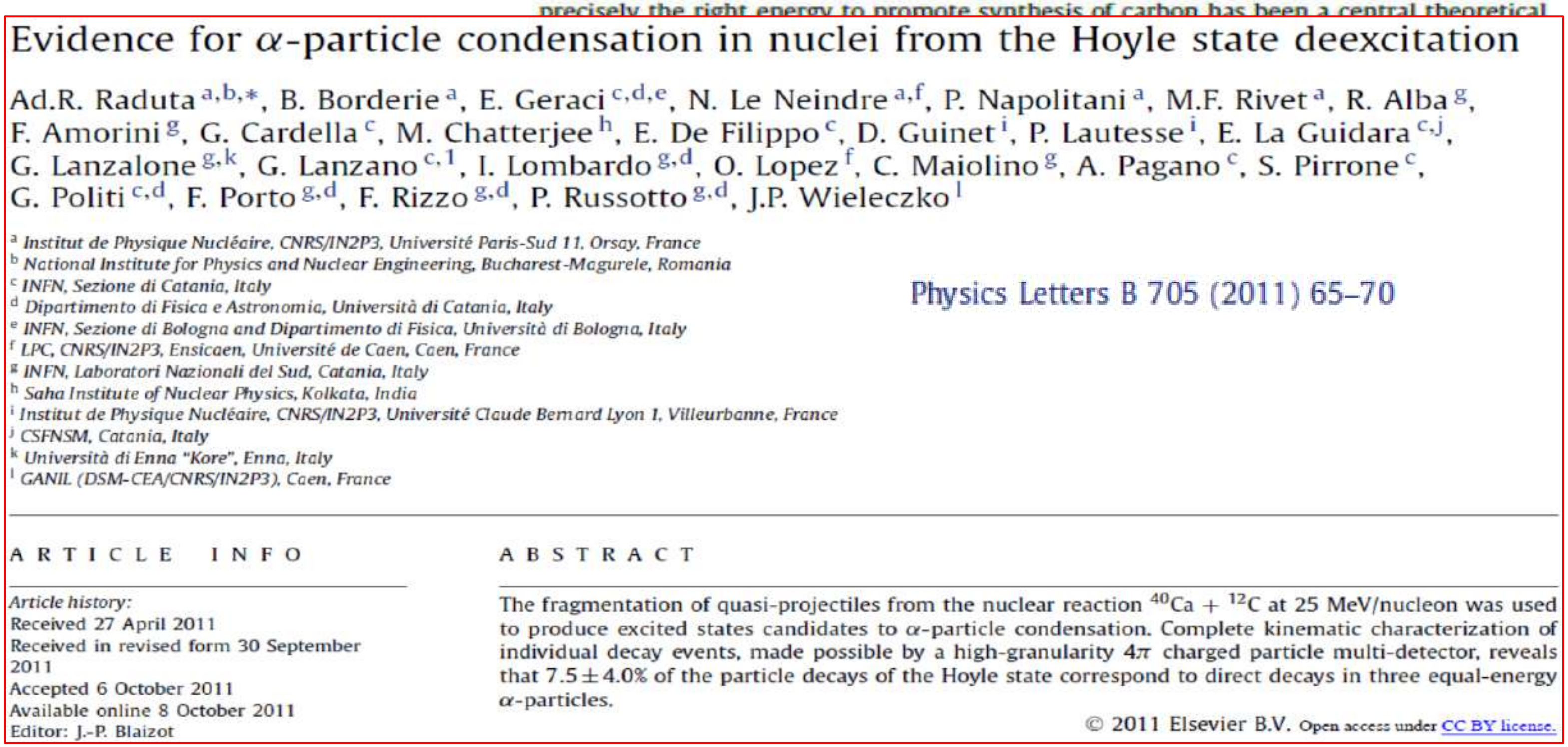
ABSTRACT

The 7.65 MeV, $J^\pi = 0^+$, second excited state in $^{12}$C is known as the Hoyle-state after Fred Hoyle. In the 1950s Hoyle proposed the existence of the state in order to account for the stellar abundance of carbon. Aside from its key role in the synthesis of the elements it is believed to possess a rather unusual structure, where the dominant degrees of freedom are those of $\alpha$-particle clusters rather than nucleons. An understanding of the properties of the Hoyle state, for example its radius and excitations, has been the focus of a major experimental activity. Similarly, unravelling precisely why a cluster state should arise at precisely the right energy to promote synthesis of carbon has been a central theoretical



## Evidence for $\alpha$-particle condensation in nuclei from the Hoyle state deexcitation

Ad.R. Raduta[a,b,*], B. Borderie[a], E. Geraci[c,d,e], N. Le Neindre[a,f], P. Napolitani[a], M.F. Rivet[a], R. Alba[g], F. Amorini[g], G. Cardella[c], M. Chatterjee[h], E. De Filippo[c], D. Guinet[i], P. Lautesse[i], E. La Guidara[c,j], G. Lanzalone[g,k], G. Lanzano[c,1], I. Lombardo[g,d], O. Lopez[f], C. Maiolino[g], A. Pagano[c], S. Pirrone[c], G. Politi[c,d], F. Porto[g,d], F. Rizzo[g,d], P. Russotto[g,d], J.P. Wieleczko[l]

[a] Institut de Physique Nucléaire, CNRS/IN2P3, Université Paris-Sud 11, Orsay, France
[b] National Institute for Physics and Nuclear Engineering, Bucharest-Magurele, Romania
[c] INFN, Sezione di Catania, Italy
[d] Dipartimento di Fisica e Astronomia, Università di Catania, Italy
[e] INFN, Sezione di Bologna and Dipartimento di Fisica, Università di Bologna, Italy
[f] LPC, CNRS/IN2P3, Ensicaen, Université de Caen, Caen, France
[g] INFN, Laboratori Nazionali del Sud, Catania, Italy
[h] Saha Institute of Nuclear Physics, Kolkata, India
[i] Institut de Physique Nucléaire, CNRS/IN2P3, Université Claude Bernard Lyon 1, Villeurbanne, France
[j] CSFNSM, Catania, Italy
[k] Università di Enna "Kore", Enna, Italy
[l] GANIL (DSM-CEA/CNRS/IN2P3), Caen, France

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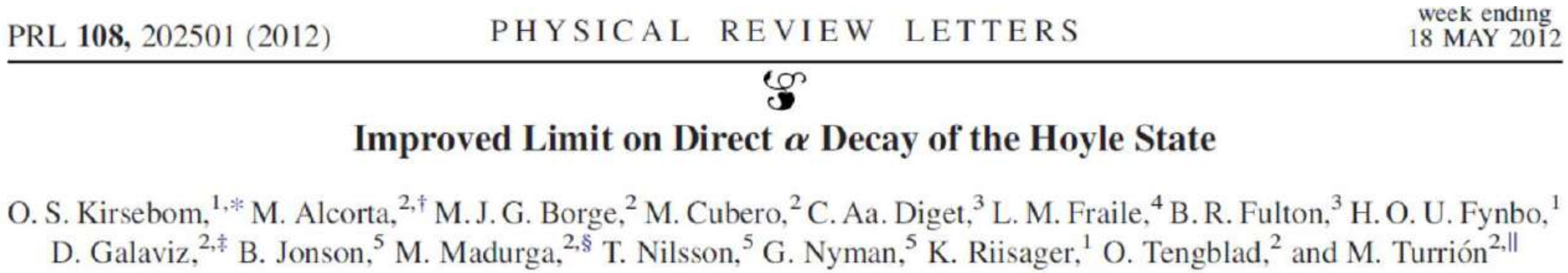
ABSTRACT

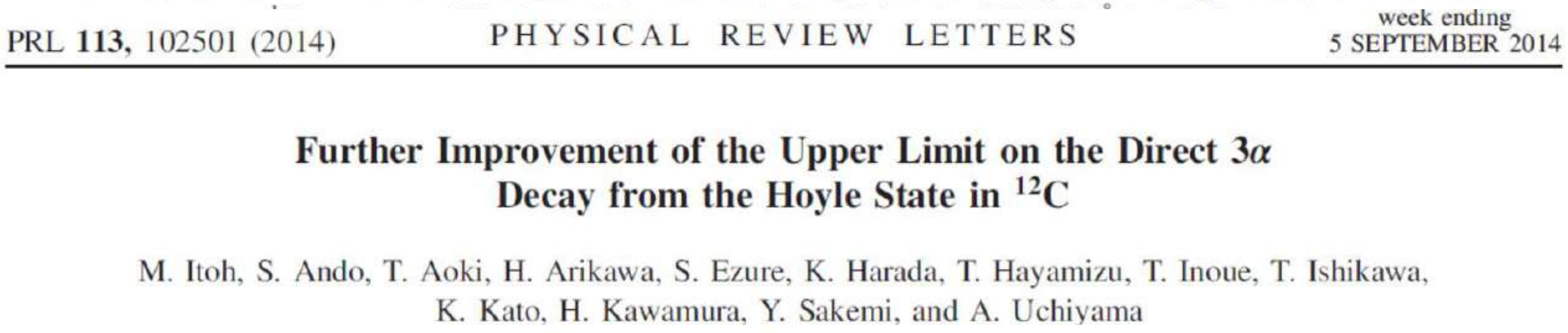
The fragmentation of quasi-projectiles from the nuclear reaction $^{40}$Ca + $^{12}$C at 25 MeV/nucleon was used to produce excited states candidates to $\alpha$-particle condensation. Complete kinematic characterization of individual decay events, made possible by a high-granularity $4\pi$ charged particle multi-detector, reveals that $7.5 \pm 4.0\%$ of the particle decays of the Hoyle state correspond to direct decays in three equal-energy $\alpha$-particles.



PRL 108, 202501 (2012) PHYSICAL REVIEW LETTERS week ending 18 MAY 2012

## Improved Limit on Direct $\alpha$ Decay of the Hoyle State

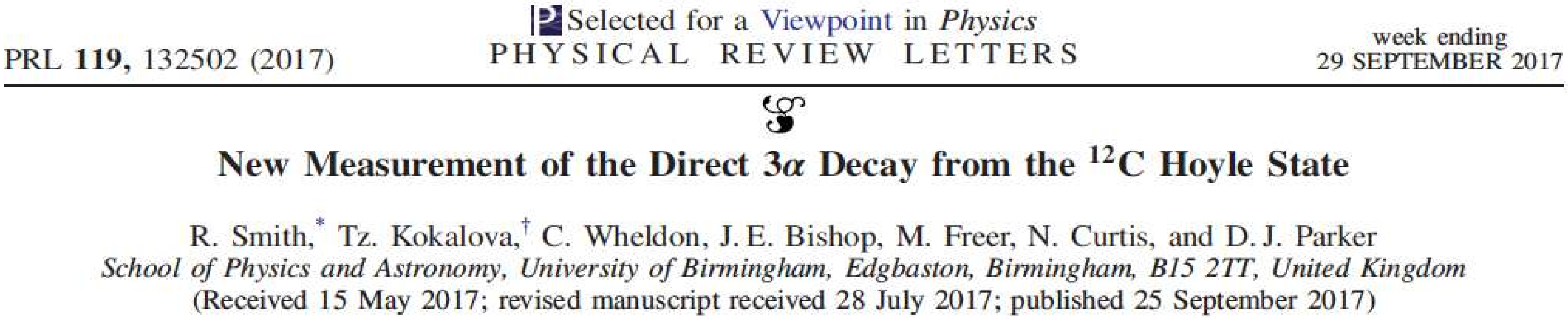
O. S. Kirsebom,[1,*] M. Alcorta,[2,†] M. J. G. Borge,[2] M. Cubero,[2] C. Aa. Diget,[3] L. M. Fraile,[4] B. R. Fulton,[3] H. O. U. Fynbo,[1]
D. Galaviz,[2,‡] B. Jonson,[5] M. Madurga,[2,§] T. Nilsson,[5] G. Nyman,[5] K. Riisager,[1] O. Tengblad,[2] and M. Turrión[2,∥]



PRL 113, 102501 (2014) PHYSICAL REVIEW LETTERS week ending 5 SEPTEMBER 2014

## Further Improvement of the Upper Limit on the Direct $3\alpha$ Decay from the Hoyle State in $^{12}$C

M. Itoh, S. Ando, T. Aoki, H. Arikawa, S. Ezure, K. Harada, T. Hayamizu, T. Inoue, T. Ishikawa,
K. Kato, H. Kawamura, Y. Sakemi, and A. Uchiyama



Selected for a Viewpoint in *Physics*

PRL 119, 132502 (2017) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2017

## New Measurement of the Direct $3\alpha$ Decay from the $^{12}$C Hoyle State

R. Smith,[*] Tz. Kokalova,[†] C. Wheldon, J. E. Bishop, M. Freer, N. Curtis, and D. J. Parker
*School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT, United Kingdom*

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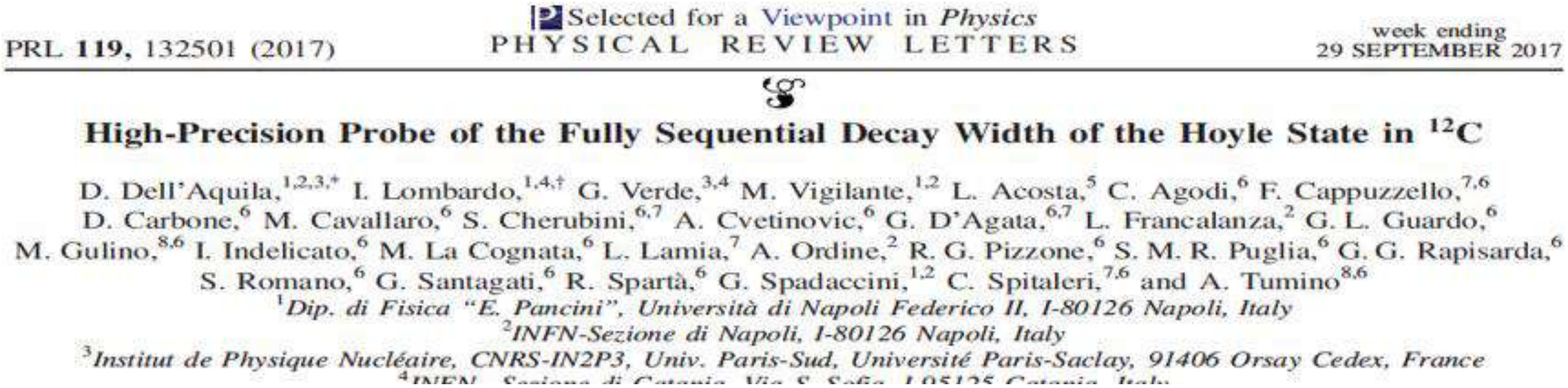


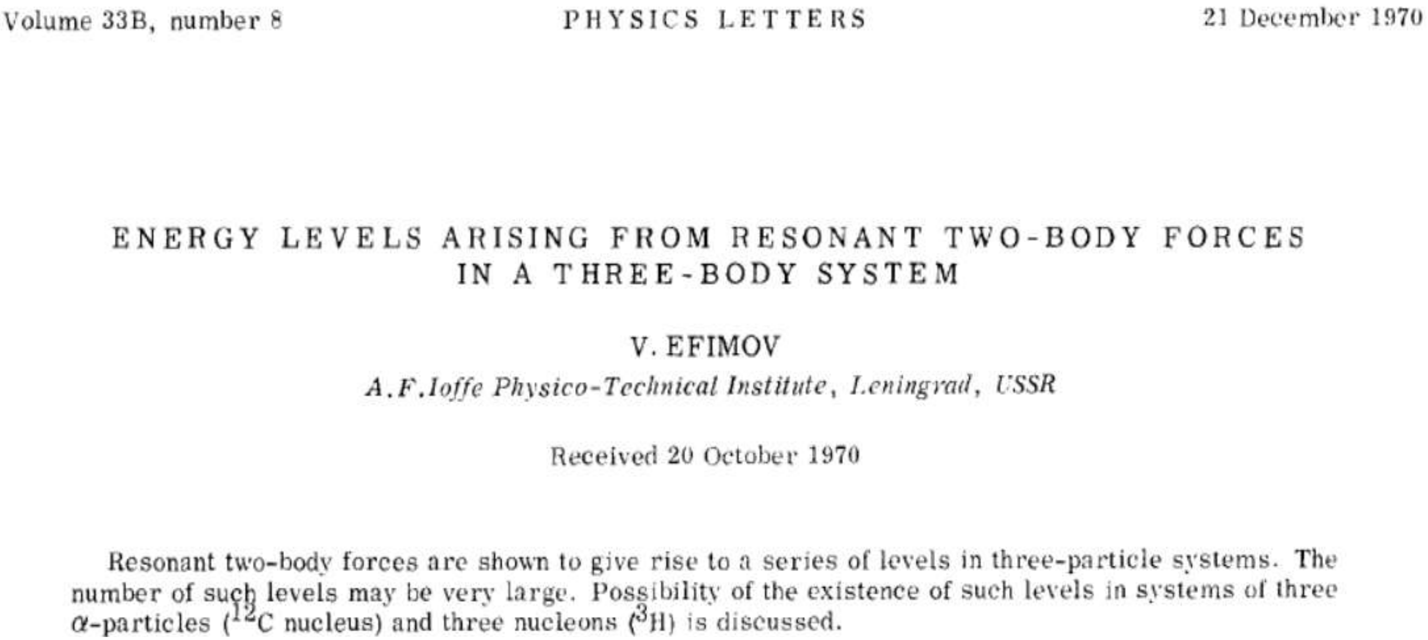
Selected for a Viewpoint in *Physics*

PRL 119, 132501 (2017) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2017

## High-Precision Probe of the Fully Sequential Decay Width of the Hoyle State in $^{12}$C

D. Dell'Aquila,[1,2,3,*] I. Lombardo,[1,4,†] G. Verde,[3,4] M. Vigilante,[1,2] L. Acosta,[5] C. Agodi,[6] F. Cappuzzello,[7,6]
D. Carbone,[6] M. Cavallaro,[6] S. Cherubini,[6,7] A. Cvetinovic,[6] G. D'Agata,[6,7] L. Francalanza,[2] G. L. Guardo,[6]
M. Gulino,[8,6] I. Indelicato,[6] M. La Cognata,[6] L. Lamia,[7] A. Ordine,[2] R. G. Pizzone,[6] S. M. R. Puglia,[6] G. G. Rapisarda,[6]
S. Romano,[6] G. Santagati,[6] R. Spartà,[6] G. Spadaccini,[1,2] C. Spitaleri,[7,6] and A. Tumino[8,6]
[1]*Dip. di Fisica "E. Pancini", Università di Napoli Federico II, I-80126 Napoli, Italy*
[2]*INFN-Sezione di Napoli, I-80126 Napoli, Italy*
[3]*Institut de Physique Nucléaire, CNRS-IN2P3, Univ. Paris-Sud, Université Paris-Saclay, 91406 Orsay Cedex, France*

# Motivation: Hoyle State and Efimov State in $^{12}$C



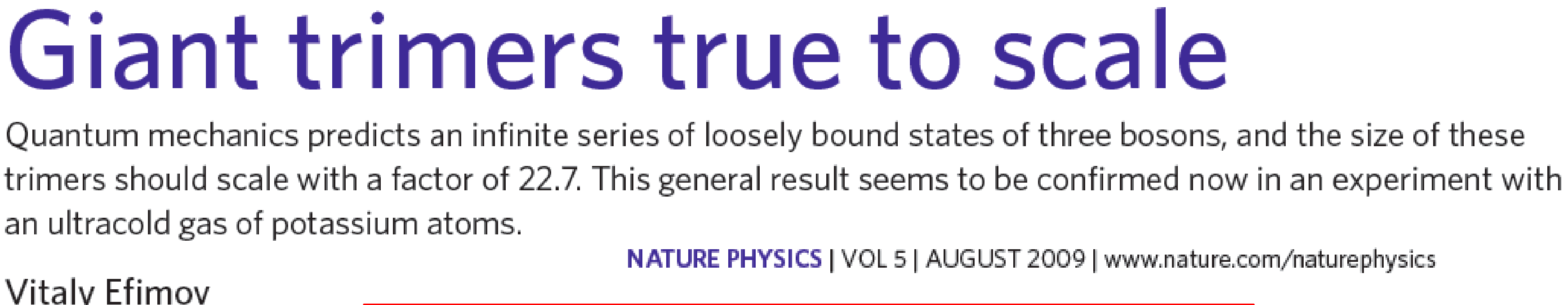
Volume 33B, number 8 PHYSICS LETTERS 21 December 1970

## ENERGY LEVELS ARISING FROM RESONANT TWO-BODY FORCES IN A THREE-BODY SYSTEM

V. EFIMOV
*A.F.Ioffe Physico-Technical Institute, Leningrad, USSR*

Received 20 October 1970

Resonant two-body forces are shown to give rise to a series of levels in three-particle systems. The number of such levels may be very large. Possibility of the existence of such levels in systems of three $\alpha$-particles ($^{12}$C nucleus) and three nucleons ($^{3}$H) is discussed.



## Giant trimers true to scale

Quantum mechanics predicts an infinite series of loosely bound states of three bosons, and the size of these trimers should scale with a factor of 22.7. This general result seems to be confirmed now in an experiment with an ultracold gas of potassium atoms.

**NATURE PHYSICS** | VOL 5 | AUGUST 2009 | www.nature.com/naturephysics

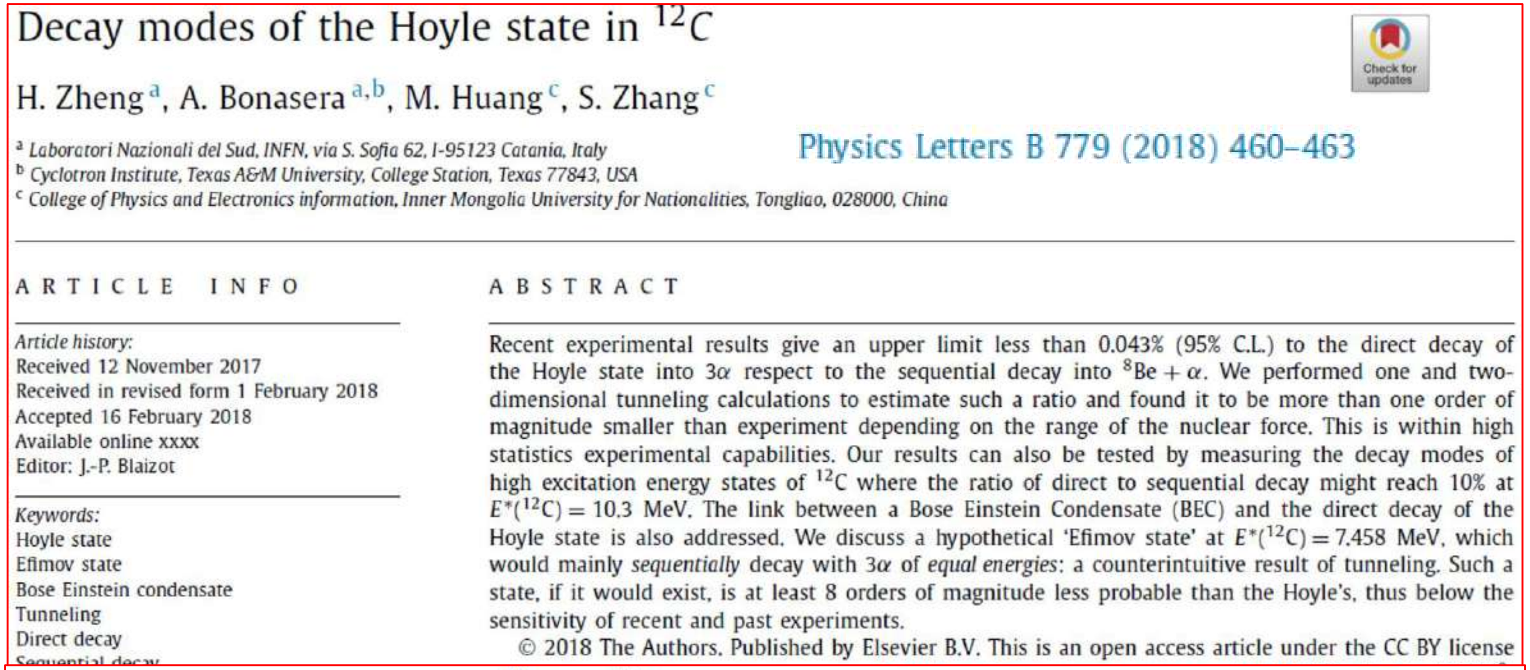
Vitaly Efimov

Letter | Published: 16 March 2006

## Evidence for Efimov quantum states in an ultracold gas of caesium atoms

T. Kraemer, M. Mark, P. Waldburger, J. G. Danzl, C. Chin, B. Engeser, A. D. Lange, K. Pilch, A. Jaakkola, H.-C. Nägerl & R. Grimm

*Nature* **440**, 315–318 (2006) | Download Citation



# Decay modes of the Hoyle state in $^{12}C$

H. Zheng[a], A. Bonasera[a,b], M. Huang[c], S. Zhang[c]

[a] Laboratori Nazionali del Sud, INFN, via S. Sofia 62, I-95123 Catania, Italy
[b] Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA
[c] College of Physics and Electronics information, Inner Mongolia University for Nationalities, Tongliao, 028000, China

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Sequential decay

ABSTRACT

Recent experimental results give an upper limit less than 0.043% (95% C.L.) to the direct decay of the Hoyle state into $3\alpha$ respect to the sequential decay into $^8\mathrm{Be}+\alpha$. We performed one and two-dimensional tunneling calculations to estimate such a ratio and found it to be more than one order of magnitude smaller than experiment depending on the range of the nuclear force. This is within high statistics experimental capabilities. Our results can also be tested by measuring the decay modes of high excitation energy states of $^{12}$C where the ratio of direct to sequential decay might reach 10% at $E^*(^{12}\mathrm{C}) = 10.3$ MeV. The link between a Bose Einstein Condensate (BEC) and the direct decay of the Hoyle state is also addressed. We discuss a hypothetical 'Efimov state' at $E^*(^{12}\mathrm{C}) = 7.458$ MeV, which would mainly *sequentially* decay with $3\alpha$ of *equal energies*: a counterintuitive result of tunneling. Such a state, if it would exist, is at least 8 orders of magnitude less probable than the Hoyle's, thus below the sensitivity of recent and past experiments.

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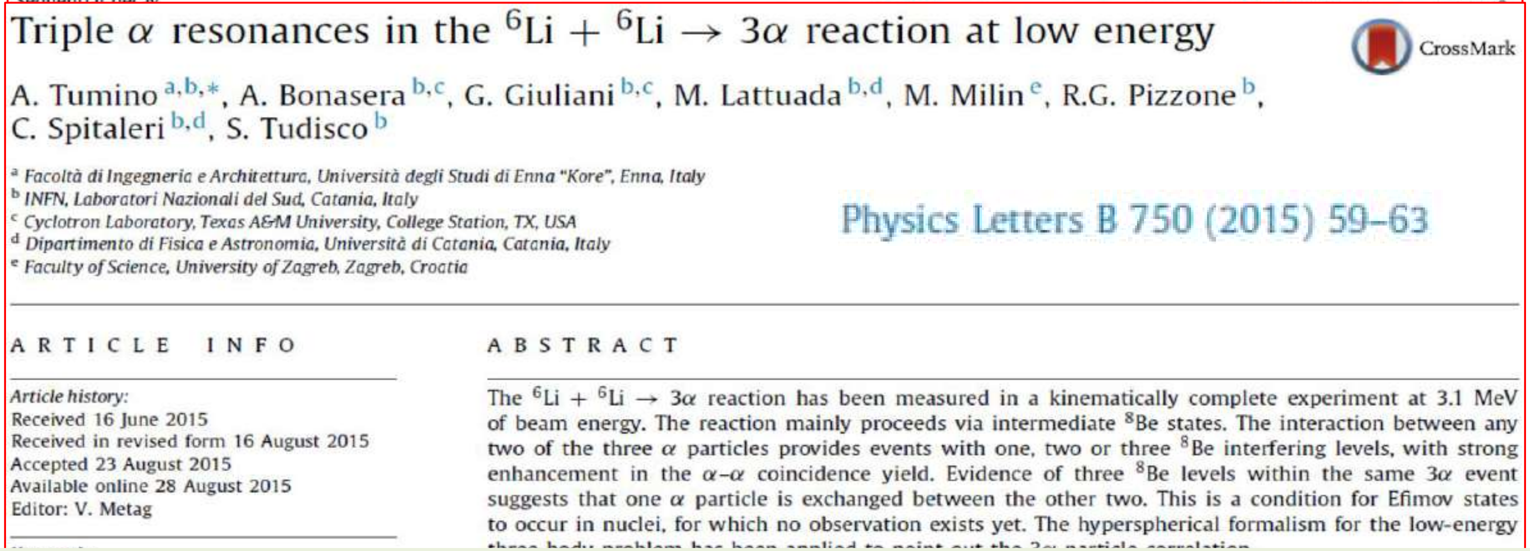

# Triple $\alpha$ resonances in the $^6\mathrm{Li}+{}^6\mathrm{Li}\rightarrow 3\alpha$ reaction at low energy

A. Tumino[a,b,*], A. Bonasera[b,c], G. Giuliani[b,c], M. Lattuada[b,d], M. Milin[e], R.G. Pizzone[b],
C. Spitaleri[b,d], S. Tudisco[b]

[a] Facoltà di Ingegneria e Architettura, Università degli Studi di Enna "Kore", Enna, Italy
[b] INFN, Laboratori Nazionali del Sud, Catania, Italy
[c] Cyclotron Laboratory, Texas A&M University, College Station, TX, USA
[d] Dipartimento di Fisica e Astronomia, Università di Catania, Catania, Italy
[e] Faculty of Science, University of Zagreb, Zagreb, Croatia

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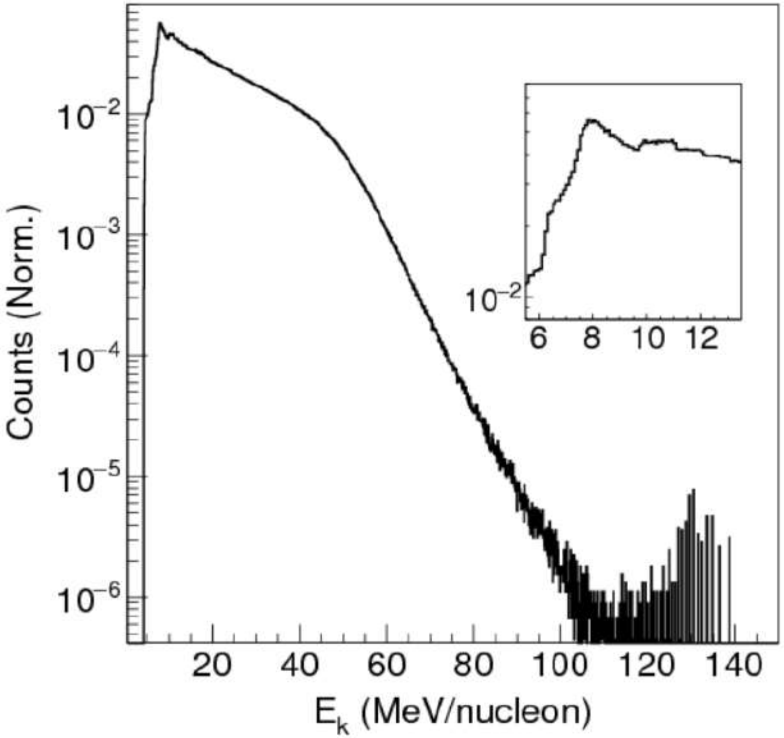
ABSTRACT

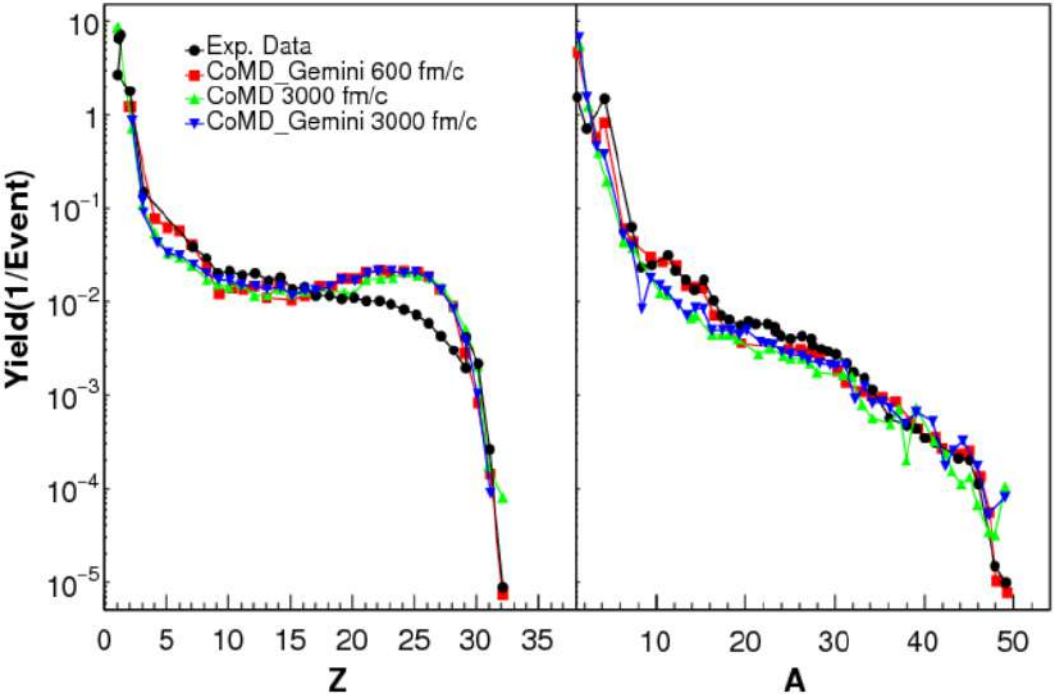
The $^6\mathrm{Li}+{}^6\mathrm{Li}\rightarrow 3\alpha$ reaction has been measured in a kinematically complete experiment at 3.1 MeV of beam energy. The reaction mainly proceeds via intermediate $^8$Be states. The interaction between any two of the three $\alpha$ particles provides events with one, two or three $^8$Be interfering levels, with strong enhancement in the $\alpha$–$\alpha$ coincidence yield. Evidence of three $^8$Be levels within the same $3\alpha$ event suggests that one $\alpha$ particle is exchanged between the other two. This is a condition for Efimov states to occur in nuclei, for which no observation exists yet. The hyperspherical formalism for the low-energy three-body problem has been applied to point out the $3\alpha$ particle correlation.

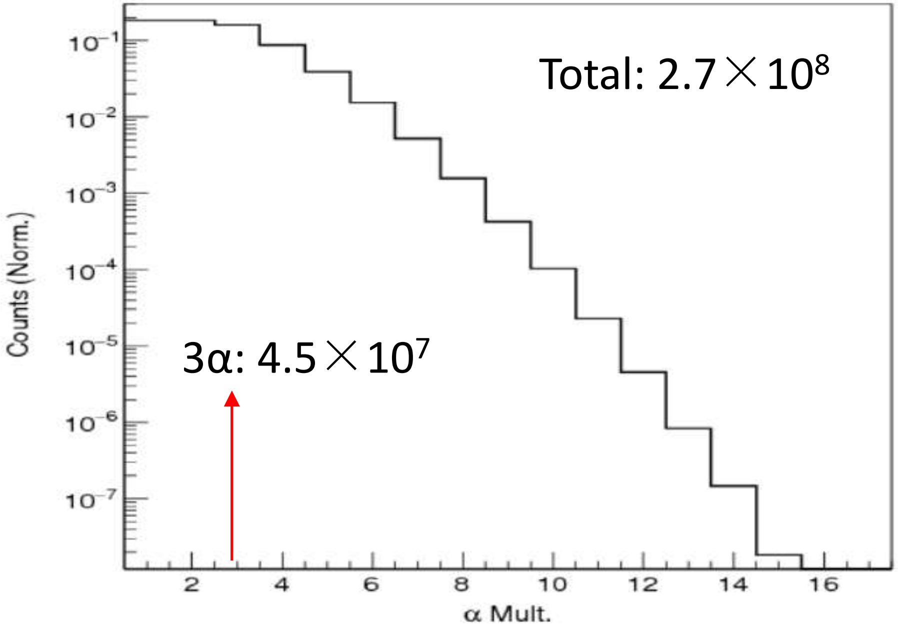
**While we are probably at the limit of the experimental sensitivity, higher-statistics experiments might be performed, or different strategies might be explored.**

# 3α Resonances in Heavy Ion Collisions

We analyzed the $^{70(64)}$Zn($^{64}$Ni)+$^{70(64)}$Zn($^{64}$Ni) reactions at E/A=35 MeV/nucleon data from the experiments performed at the Cyclotron Institute, Texas A&M University using the NIMROD 4π detector.







Total: 2.7×$10^8$

3α: 4.5×$10^7$

1) **S. Zhang, J.C. Wang, A. Bonasera, et al., Chinese Physics C 43(6), 064102 (2019).**
2) **S. Zhang, A. Bonasera, M. Huang, et al., Physical Review C 00, 004600 (2019).**
3) **Z. Kholey, 2010 PhD Thesis, Texas A &M University.**

# Method

If the two objects have the same mass $m$, $\mu = \frac{1}{2}m$ and

$$\begin{aligned} E_{12} &= \frac{p^2}{2\mu} \\ &= \frac{1}{4}\frac{(\mathbf{p}_1 - \mathbf{p}_2)^2}{2\mu} \end{aligned}$$

For a three body system with equal masses, we can define the excitation energy $E^*$ as:

$$E^* = \frac{2}{3}\sum_{i=1,j>i}^{3} E_{ij} - Q \qquad （1）$$

where $E_{ij}$ is the relative kinetic energy of two particles, and $Q$ is the $Q$-value. Note that the important ingredient entering Eq. (1) are the relative kinetic energies; since we have three indistinguishable bosons, we analyze the $E_{ij}$ distribution by cataloguing for each event the smallest relative kinetic energy, $E_{ij}^{\mathrm{Min.}}$, the middle relative kinetic energy, $E_{ij}^{\mathrm{Mid.}}$, and the largest relative kinetic energy, $E_{ij}^{\mathrm{Lar.}}$.

$$E_T^* = \frac{2}{3}\sum_{i=1,j>i}^{3} \frac{3}{2}(E_{ij}^X + E_{ij}^Y) - Q, \qquad （2）$$

where $E_{ij}^X$ and $E_{ij}^Y$ are the relative kinetic energy of $2\alpha$ in the $X$ and $Y$ directions ($Z$ is the beam axis direction).

In the N equal mass body system,

$$\begin{aligned} E_{ij} &= \frac{\boldsymbol{P}_{ij}^2}{2\mu} \\ &= \frac{1}{4}\frac{(\boldsymbol{P}_i - \boldsymbol{P}_j)^2}{2\mu} \end{aligned}$$

where $\boldsymbol{P}_i$ and $\boldsymbol{P}_j$ are the momenta of the i and j particles

$$\begin{aligned} \sum_{i=1}^{N} E_{ij} &= \frac{N}{4}\frac{\sum_{i=1}^{N} p_i'^2}{2\mu} \\ &= \frac{N}{2}\frac{\sum_{i=1}^{N} p_i'^2}{2m} \\ &= \frac{N}{2}(E^* + Q). \end{aligned}$$

In this work, we reconstruct the E*=7.458 MeV (ES) and E*=7.654 MeV (HS) of the $^{12}$C from 3α with Q=-7.275 MeV.

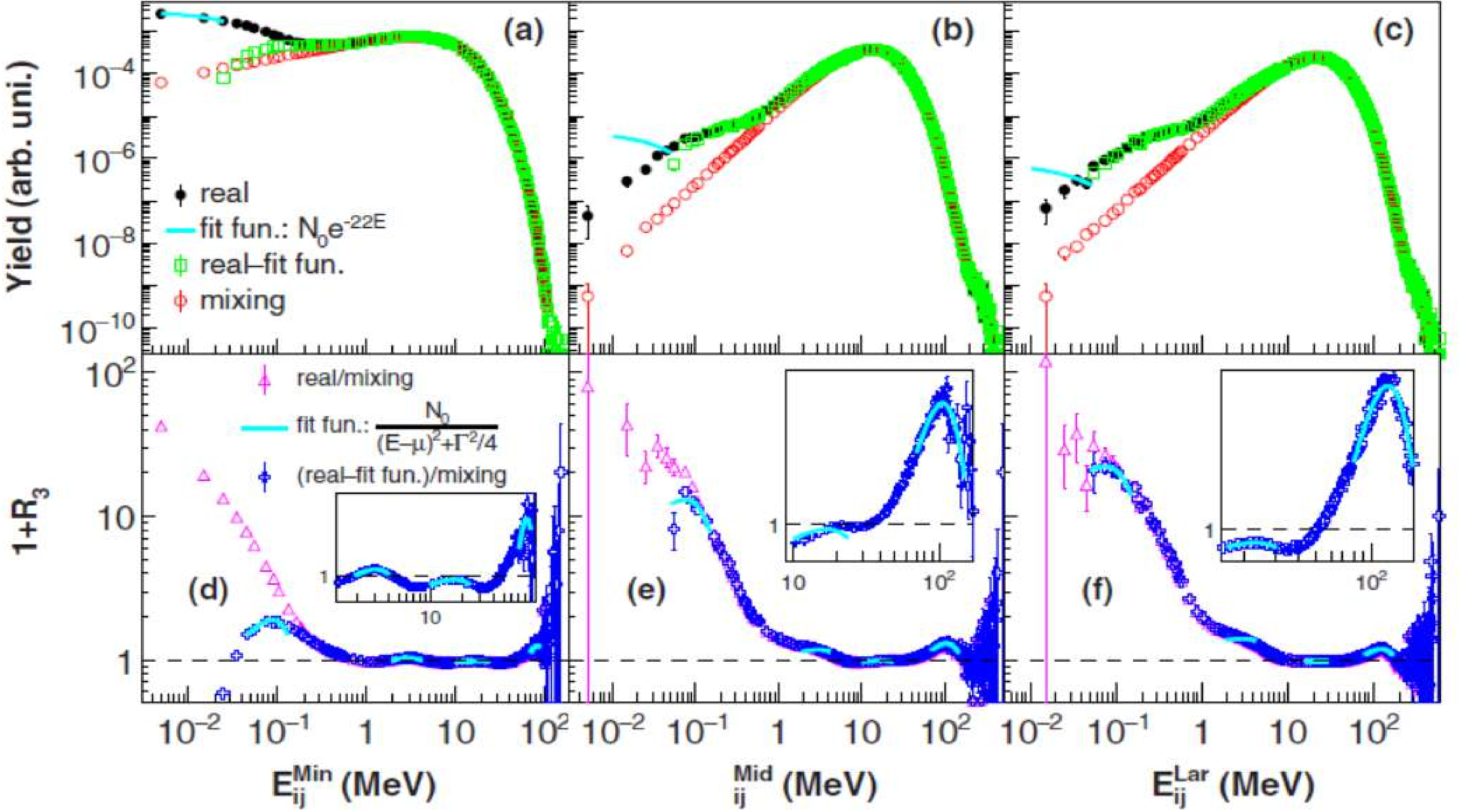


FIG. 1. Selected events from $^{70(64)}$Zn($^{64}$Ni) + $^{70(64)}$Zn($^{64}$Ni) at $E/A = 35$ MeV/nucleon with $\alpha$ multiplicity equal to three. Relative kinetic-energy distribution as a function of (a) the minimum relative kinetic energy, (b) the middle relative kinetic energy, and (c) the largest relative kinetic energy of 2$\alpha$s. The solid black circles represent data from real events, the red open circles are from mixing events, and the green open squares represent the difference between the real events and the exponential function (solid line), which takes into account the experimental error. The ratios of the real (pink open triangles) data and the real data minus the fitting function (blue crosses) divided by the mixing events are, respectively, a function of (d) the minimum relative kinetic energy, (e) the middle relative kinetic energy, and (f) the largest relative kinetic energy of 2$\alpha$s. The solid lines are Breit–Wigner fits.

| | $E_{ij}^{Min}$: $\mu$ (MeV) | $\hbar/\Gamma$ (fm/$c$) | $E_{ij}^{Mid}$: $\mu$ (MeV) | $\hbar/\Gamma$ (fm/$c$) | $E_{ij}^{Lar}$: $\mu$ (MeV) | $\hbar/\Gamma$ (fm/$c$) |
|---|---|---|---|---|---|---|
| Peak 1 | 0.088 ± 0.001 | 1192 ± 66 | 0.08 ± 0.02 | 1089 ± 288 | 0.08 ± 0.04 | 984 ± 540 |
| Peak 2 | 3.05 ± 0.01 | 14.2 ± 0.3 | | | | |
| Peak 3 | 17.0 ± 0.1 | 2.08 ± 0.04 | | | 22.9 ± 0.3 | 1.1 ± 0.1 |
| Peak 4 | 83 ± 3 | 2.8 ± 1.0 | 106 ± 1 | 0.95 ± 0.04 | 124.1 ± 0.9 | 0.70 ± 0.02 |

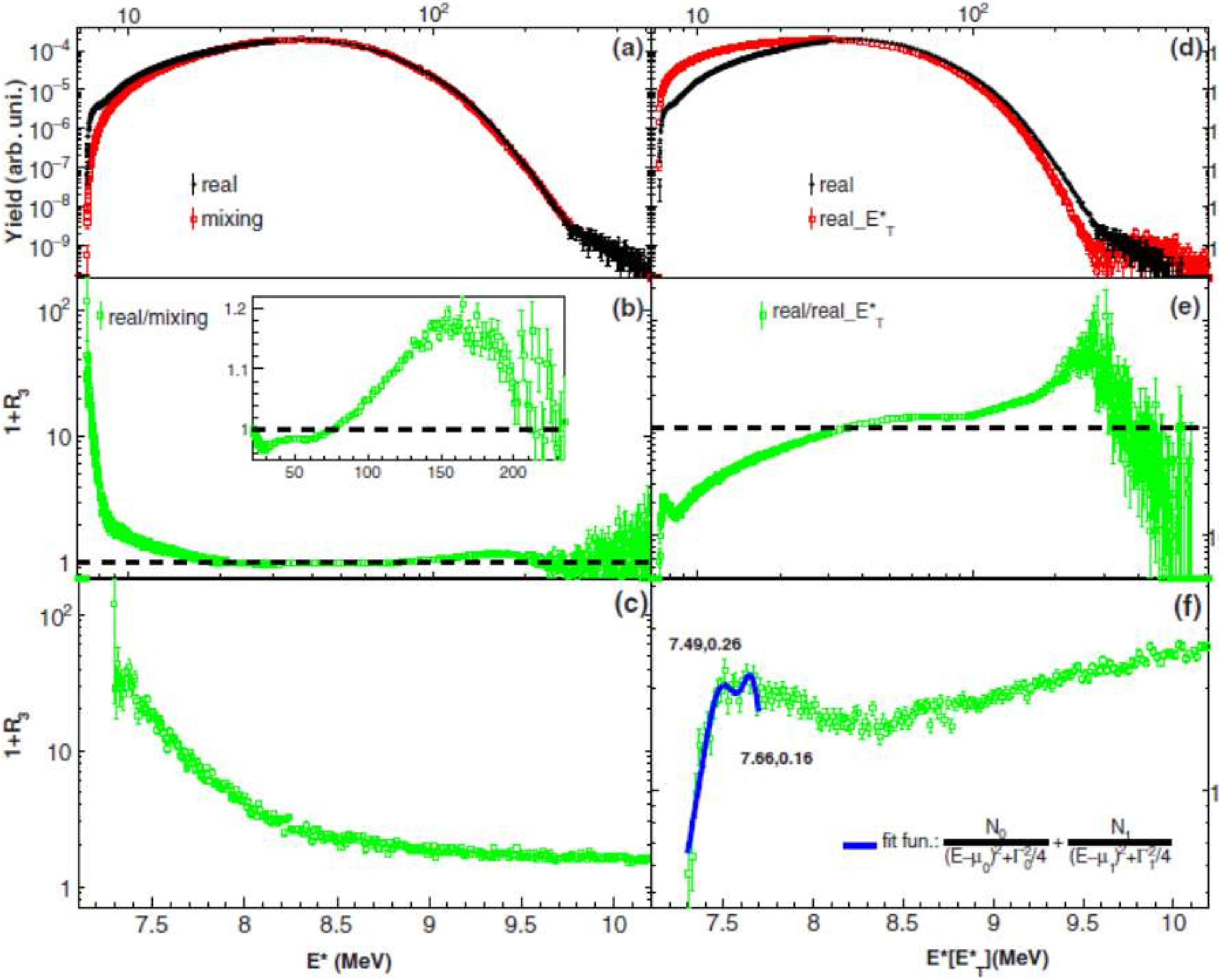


FIG. 2. The excitation-energy distributions of $^{12}$C from 3$\alpha$s. The solid black circles are the real events, red open squares are mixing events (or real transverse events), green open squares indicate the ratios of the real and mixing events (or real transverse events), and the blue solid line is the BW fit.

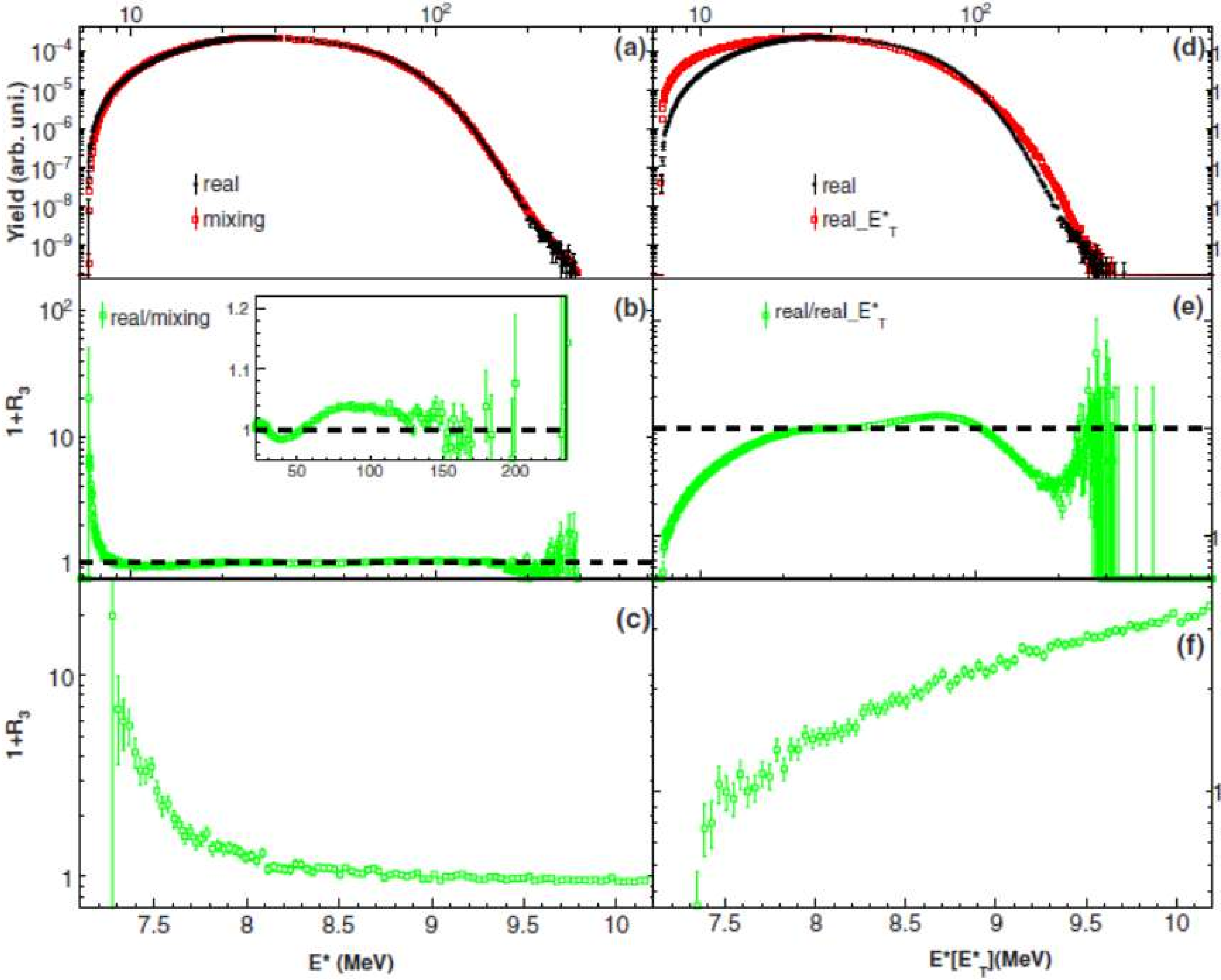


FIG. 3. The excitation-energy distributions of the $^3$Li from three proton events, where we have arbitrarily assigned $Q = -7.275$ MeV for easy comparison to Fig. 2. The solid black circles are the real events, red open squares are mixing events (or real transverse events), green open squares indicate the ratios of the real and mixing events (left panels) or real transverse events (right panels).

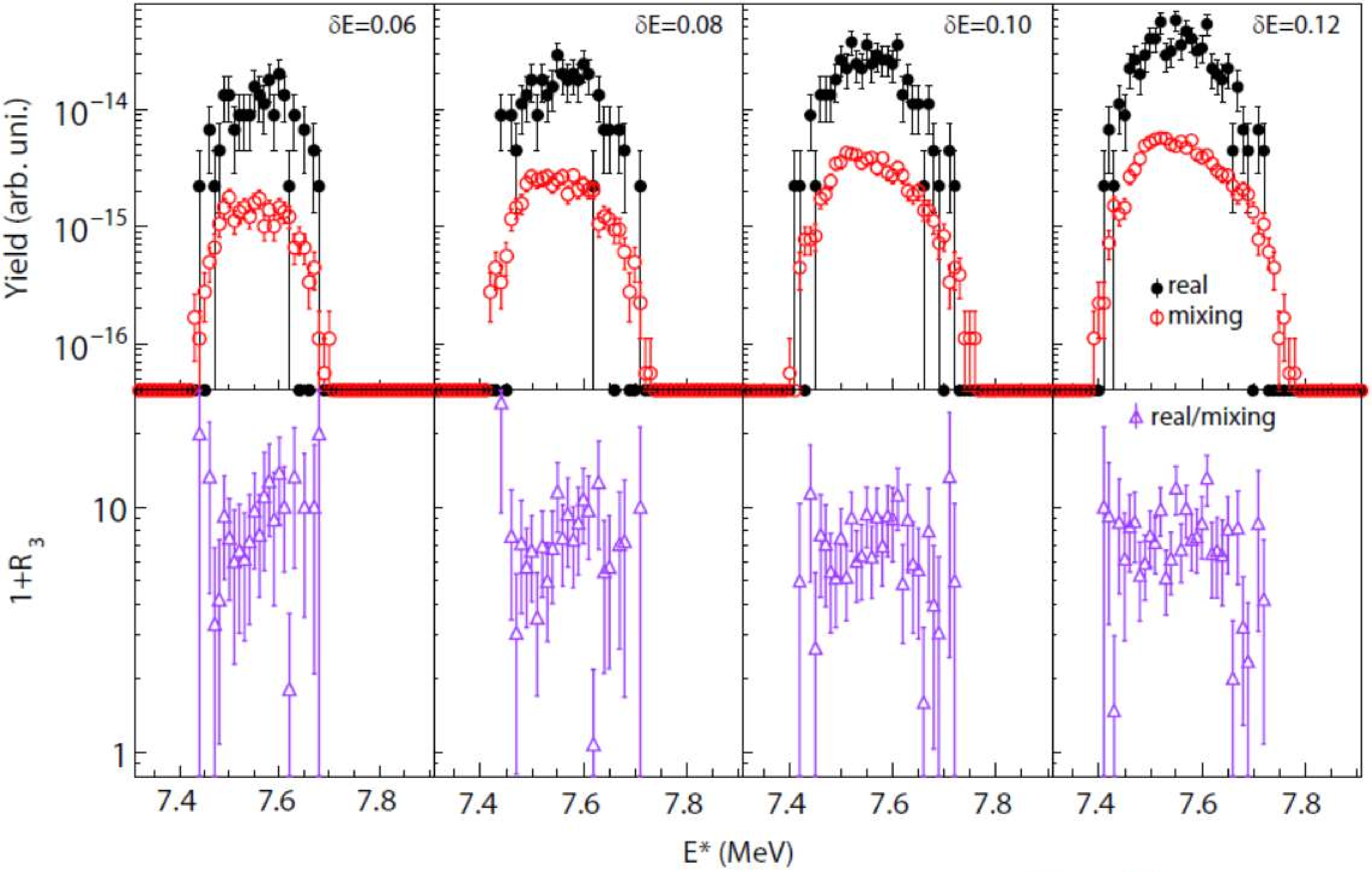


**FIG. 4** Reconstructed excitation energy distributions of $^{12}$C from 3 $\alpha$-particles with $E_{ij}^{\text{Min.}} = E_{ij}^{\text{Mid.}} = 0.092 \pm \frac{\delta E}{3}$ MeV. The solid black circles are from the real events, red open circles are the mixing events, pink open triangles indicate the ratios of the real events to the mixing events.

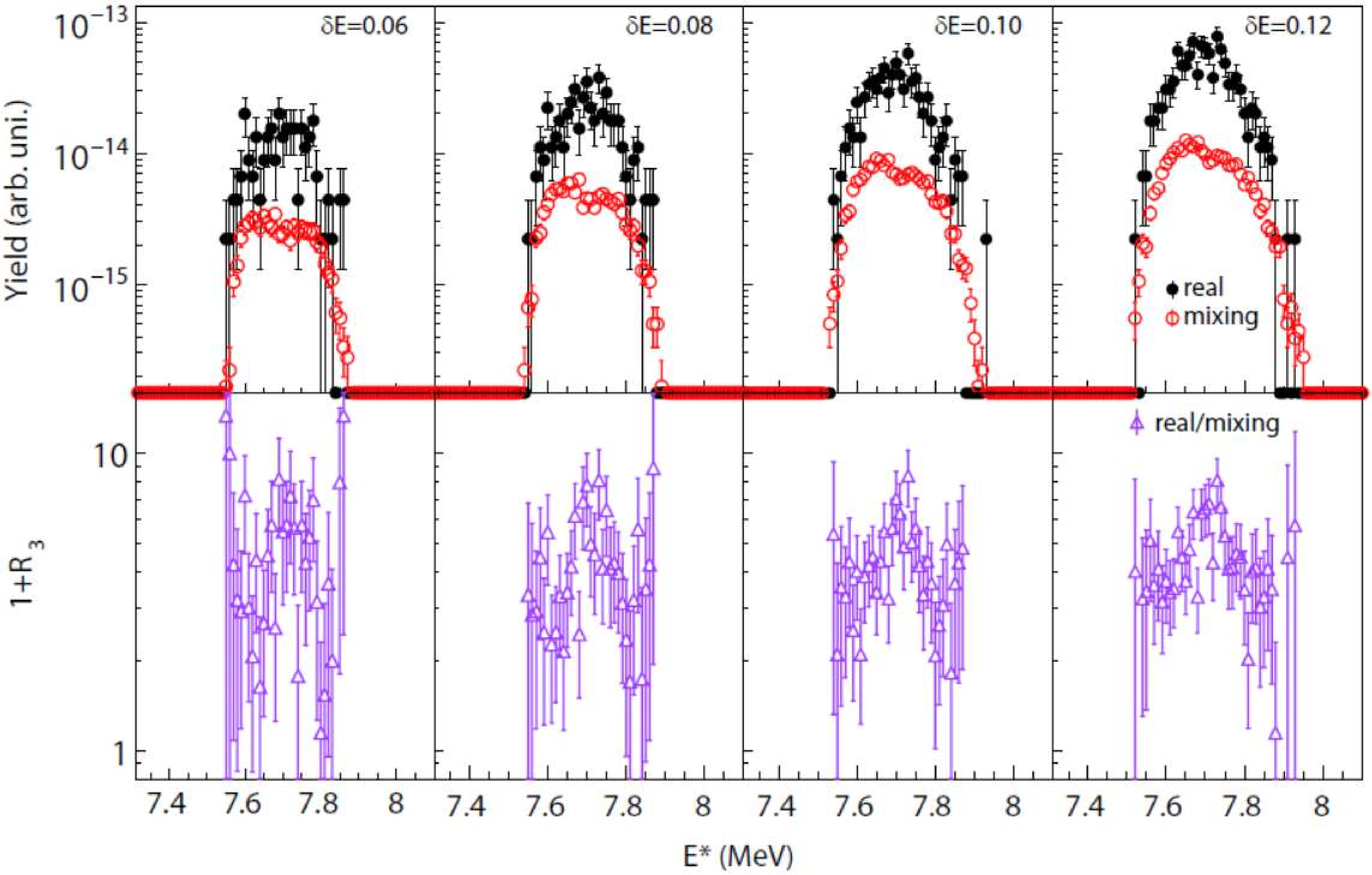
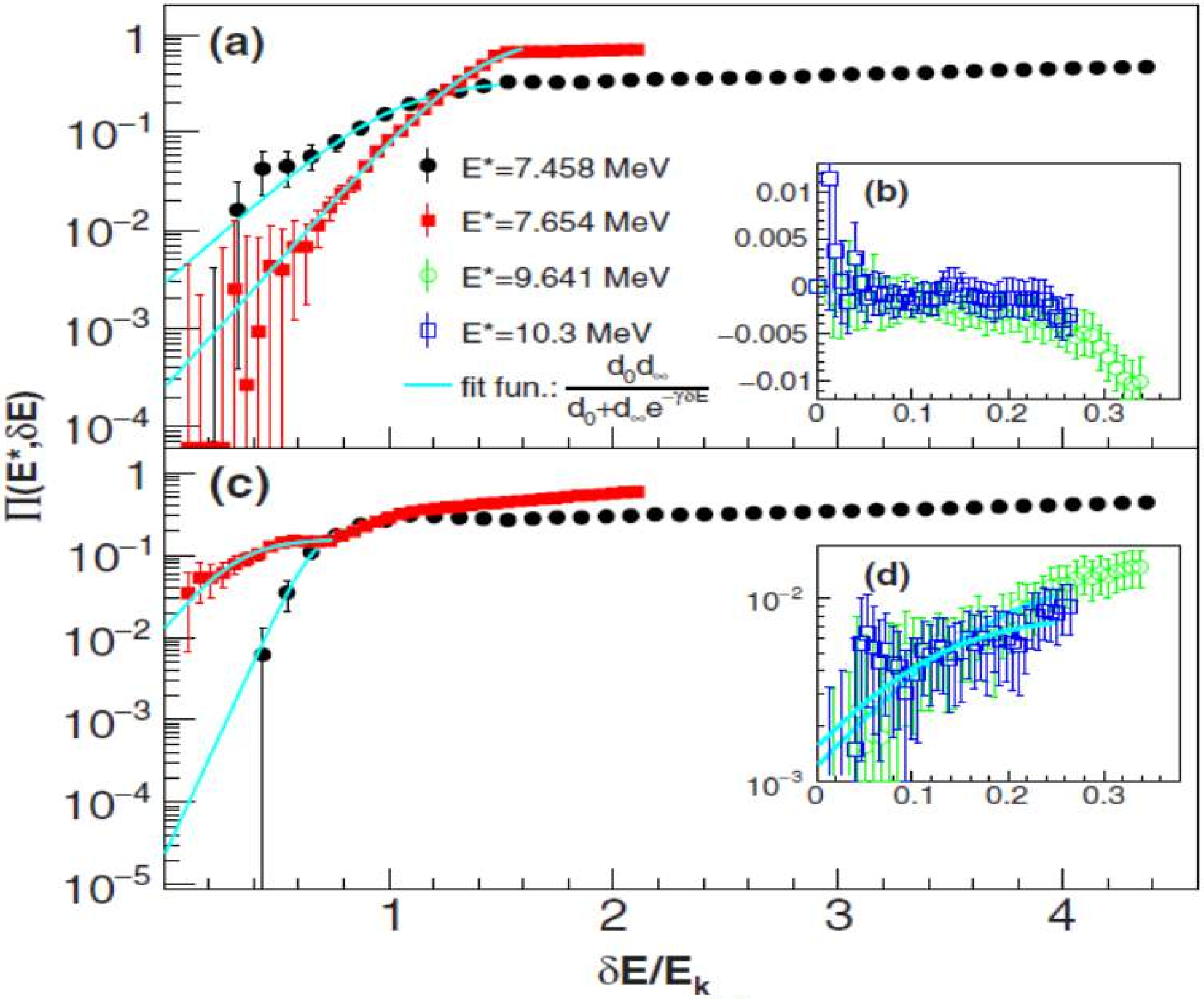


**FIG. 4** Reconstructed excitation energy distributions of $^{12}$C from 3 $\alpha$-particles with $E_{ij}^{\mathrm{Min.}} = 0.092 \pm \frac{\delta E}{3}$ MeV, $E_{ij}^{\mathrm{Mid.}} = 0.092 \times 2 \pm \frac{\delta E}{3}$ MeV. The solid black circles and the red open circles denote respectively the real events and the mixing events, pink open triangles indicate the ratios of the real events to the mixing events.

In order to strengthen the above results, we derived observables which give the probability of $^{12}$C decay into a particular mode (say the 3$\alpha$s relative kinetic energies are equal (DDE) or two energies are equal and the third one is twice the sum of the first two (LD)) with respect to SD. These probabilities have been discussed experimentally using different techniques [8–16]; thus, it is especially interesting to compare our results in a medium with conventional approaches. Notice that the effects in a medium might be present in Ref. [9] and this might explain the discrepancies from conventional approaches [8–16]. We define the decay probability as Eq.(3):

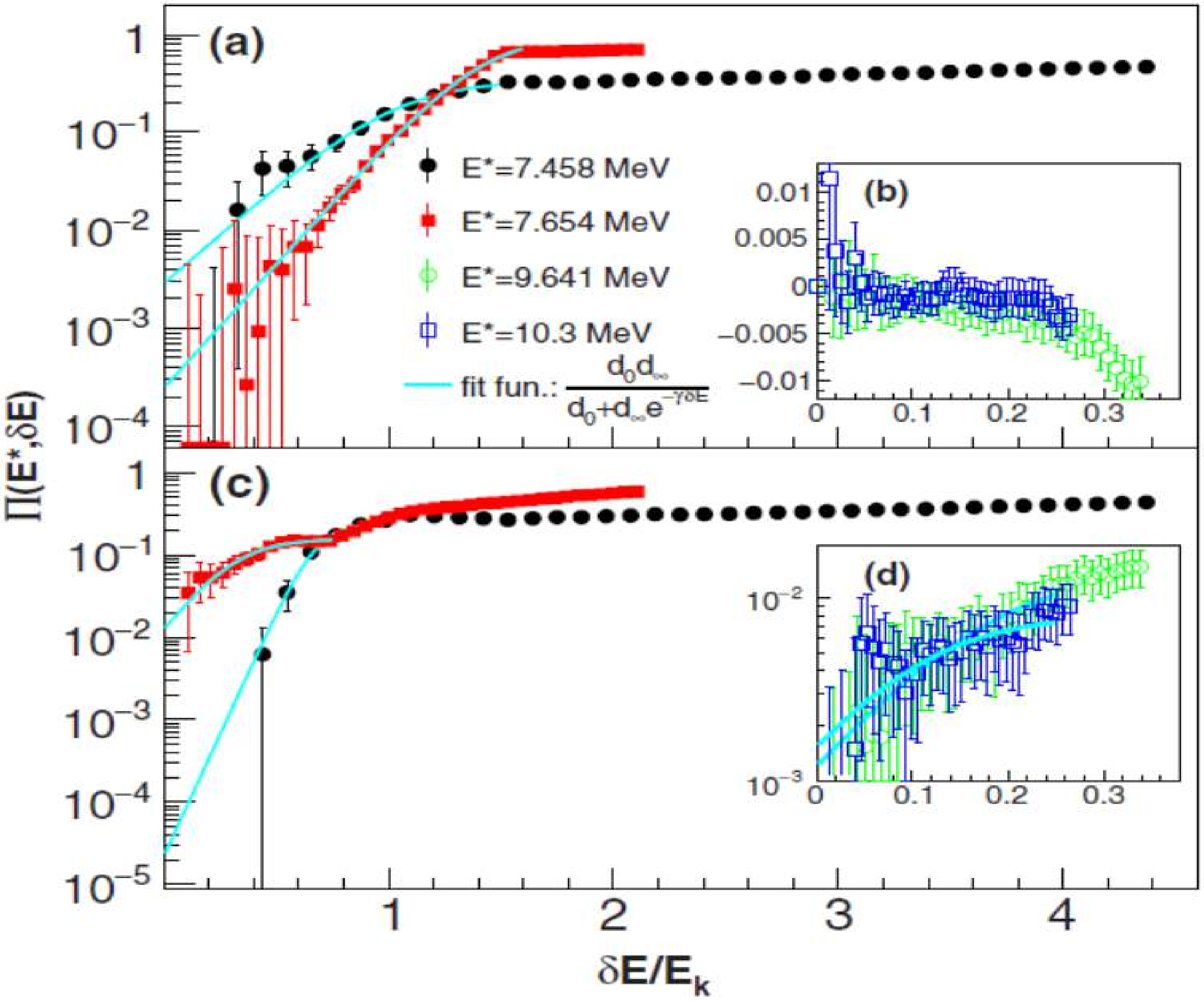
$$\prod(E^*,\delta E) = \frac{\sum_{ij}[Y_R(DDE\,or\,LD,E_{ij}) - Y_M(DDE\,or\,LD,E_{ij})]}{\sum_{ij}[Y_R(SD,E_{ij}) - Y_M(SD,E_{ij})]}, \tag{3}$$

where the sum is extended over all relative kinetic energies corresponding to a $^{12}$C level with excitation energy E$^*$ from Eq.(1) and variance $\delta$E, which we will vary to the smallest values allowed by the statistics. The Y$_R$(SD, E$_{ij}$) and Y$_M$(SD, E$_{ij}$) in the denominator are obtained by fixing the smallest relative kinetic energy to the $^8$Be$_{g.s.}$ ± $\delta$E/3 for the real (R) and mixing (M) events, respectively. The yields of DDE or LD are obtained by opportunely choosing the relative kinetic energies in the numerator. For example, the DDE case is obtained by choosing three equal relative kinetic energies (within $\delta$E/3 for each one). For a fixed excitation energy, we can estimate Eq.(3) from the data by changing $\delta$E in order to derive the limiting value of the ratio compatible with the experimental sensitivity.



$$\prod(E^*,\delta E) = \frac{d_0 d_\infty}{d_0 + d_\infty e^{-\gamma\delta E}}. \qquad (4)$$

The parameter $d_0$ (δE→0) gives the smallest possible physical value of the ratios or the experimental error, while the largest value $d_\infty$ (δE→∞) is connected to the available phase space [33]. The fit values of $d_0$ are reported in Table II and are compared to the data in literature. Since Ref. [9] might contain effects from within a medium as in our case, we argue that the difference is due to not properly subtracting the mixing events when calculating the ratios, as in Eq.(3). Another possibility is the contribution of the ES due to the experimental sensitivity. We can see that the LD contribution of the ES is compatible with zero, which is consistent with the definition of the ES. For the larger excitation energies considered here, the ratios are negative for the DDE case (see Fig. 4(b)) and compatible with zero for the LD case (see Fig. 4(d)).



| | ES : DDE (%) | ES : LD (%) | HS : DDE (%) | HS : LD (%) | 9.641 : DDE (%) | 9.641 : LD (%) | 10.3 : DDE (%) | 10.3 : LD (%) |
|---|---|---|---|---|---|---|---|---|
| Present | 0.3 ± 0.1 | 0.002 ± 0.004 | 0.025 ± 0.005 | 1 ± 1 | 0 | 0.1 ± 0.1 | 0 | 0.2 ± 0.2 |
| Ref. [9] | | | 7.5 ± 4.0 | 9.5 ± 4.0 | 0 | | | |
| Ref. [12] | | | 0.3 ± 0.1 | 0.1 | | | | |
| Ref. [11] | | | 0.45 | | | | | |
| Ref. [15] | | | 0.036 | 0.024 | | | | |
| Ref. [10] | | | 0.09 | 0.09 | | | | |
| Ref. [13] | | | 0.08 | | | | | |
| Ref. [5] | | | 0.005 | 0.03 | | | | |
| Ref. [31] | | | 0.0036 | | | | | |

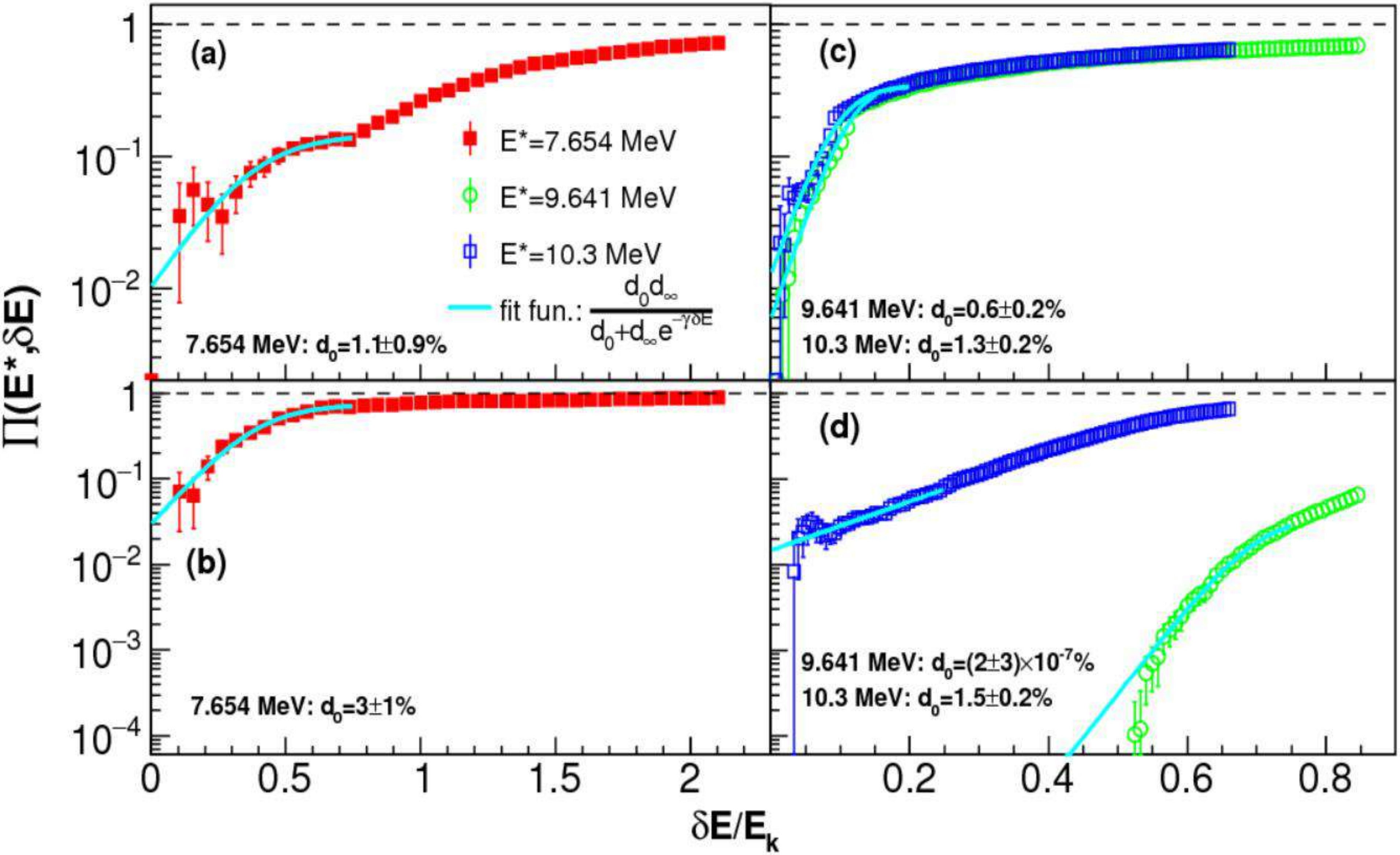
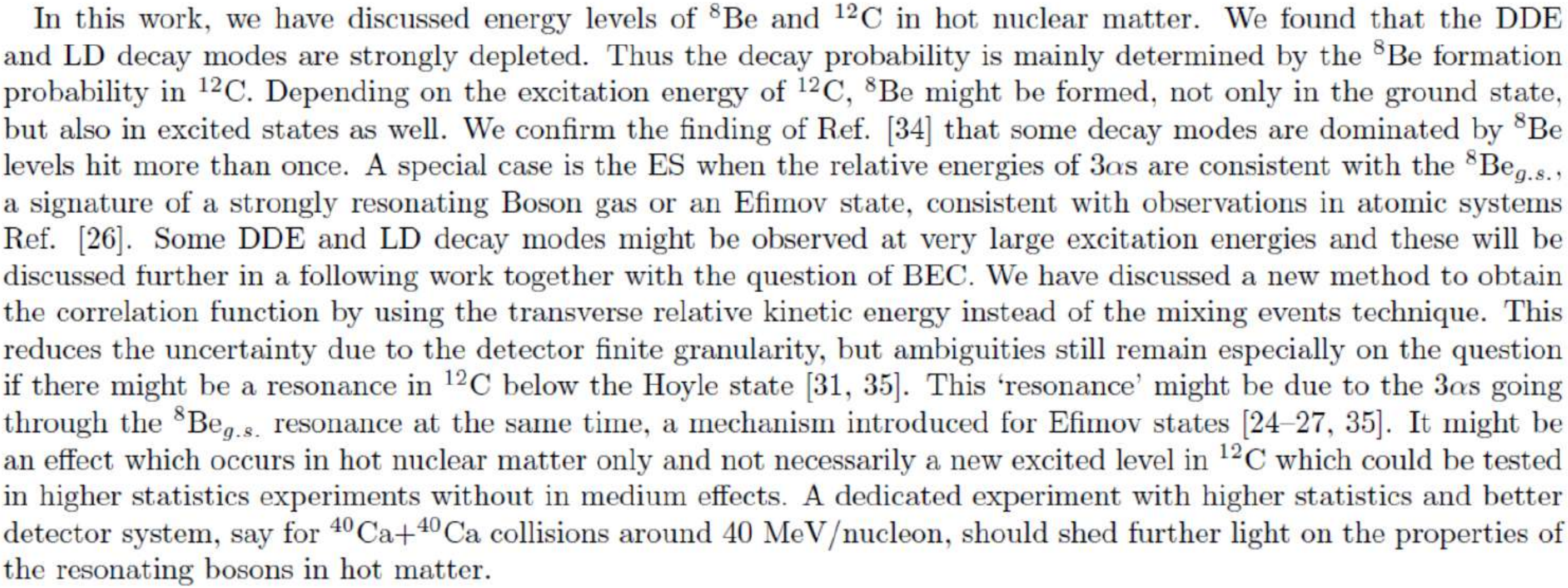


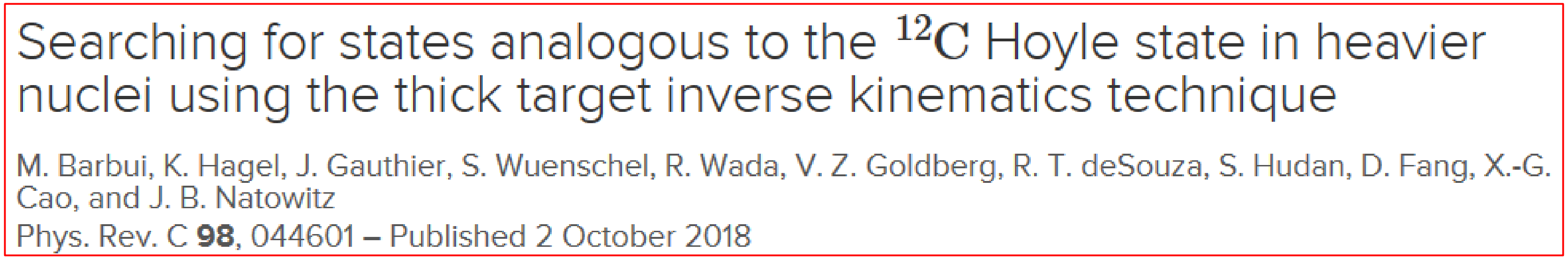
**FIG. 6** The probability ratios of the HS (a) when the $^8\mathrm{Be}_{g.s.}$ energy is consistent with two $\alpha$ relative kinetic energies, or (b) the second largest energy is twice of the $^8\mathrm{Be}_{g.s.}$ energy. The ratios are plotted for 9.641 MeV (green open circles) and 10.3 MeV (blue open squares), (c) when the $E_{ij}^{Min}$=0.092 MeV, $E_{ij}^{Mid}$=$E_{ij}^{Lar}$, or (d) the $E_{ij}^{Lar}$=3.03 MeV, $E_{ij}^{Min}$+$E_{ij}^{Mid}$=$\frac{3}{2}$×($E^*$ + Q) - $E_{ij}^{Lar}$.

# Summary



In this work, we have discussed energy levels of $^{8}$Be and $^{12}$C in hot nuclear matter. We found that the DDE and LD decay modes are strongly depleted. Thus the decay probability is mainly determined by the $^{8}$Be formation probability in $^{12}$C. Depending on the excitation energy of $^{12}$C, $^{8}$Be might be formed, not only in the ground state, but also in excited states as well. We confirm the finding of Ref. [34] that some decay modes are dominated by $^{8}$Be levels hit more than once. A special case is the ES when the relative energies of $3\alpha$s are consistent with the $^{8}$Be$_{g.s.}$, a signature of a strongly resonating Boson gas or an Efimov state, consistent with observations in atomic systems Ref. [26]. Some DDE and LD decay modes might be observed at very large excitation energies and these will be discussed further in a following work together with the question of BEC. We have discussed a new method to obtain the correlation function by using the transverse relative kinetic energy instead of the mixing events technique. This reduces the uncertainty due to the detector finite granularity, but ambiguities still remain especially on the question if there might be a resonance in $^{12}$C below the Hoyle state [31, 35]. This 'resonance' might be due to the $3\alpha$s going through the $^{8}$Be$_{g.s.}$ resonance at the same time, a mechanism introduced for Efimov states [24–27, 35]. It might be an effect which occurs in hot nuclear matter only and not necessarily a new excited level in $^{12}$C which could be tested in higher statistics experiments without in medium effects. A dedicated experiment with higher statistics and better detector system, say for $^{40}$Ca+$^{40}$Ca collisions around 40 MeV/nucleon, should shed further light on the properties of the resonating bosons in hot matter.

# We're thinking …



Searching for states analogous to the $^{12}$C Hoyle state in heavier nuclei using the thick target inverse kinematics technique

M. Barbui, K. Hagel, J. Gauthier, S. Wuenschel, R. Wada, V. Z. Goldberg, R. T. deSouza, S. Hudan, D. Fang, X.-G. Cao, and J. B. Natowitz

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**Warmly Welcome to Collaborate and Join us for Short, Long or Permanent Position at Inner Mongolia, China !**

# Thank you！