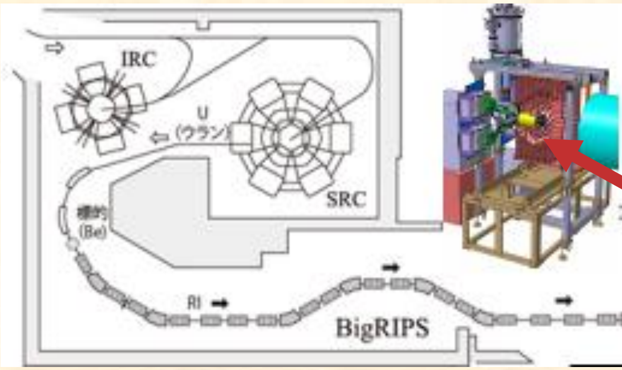
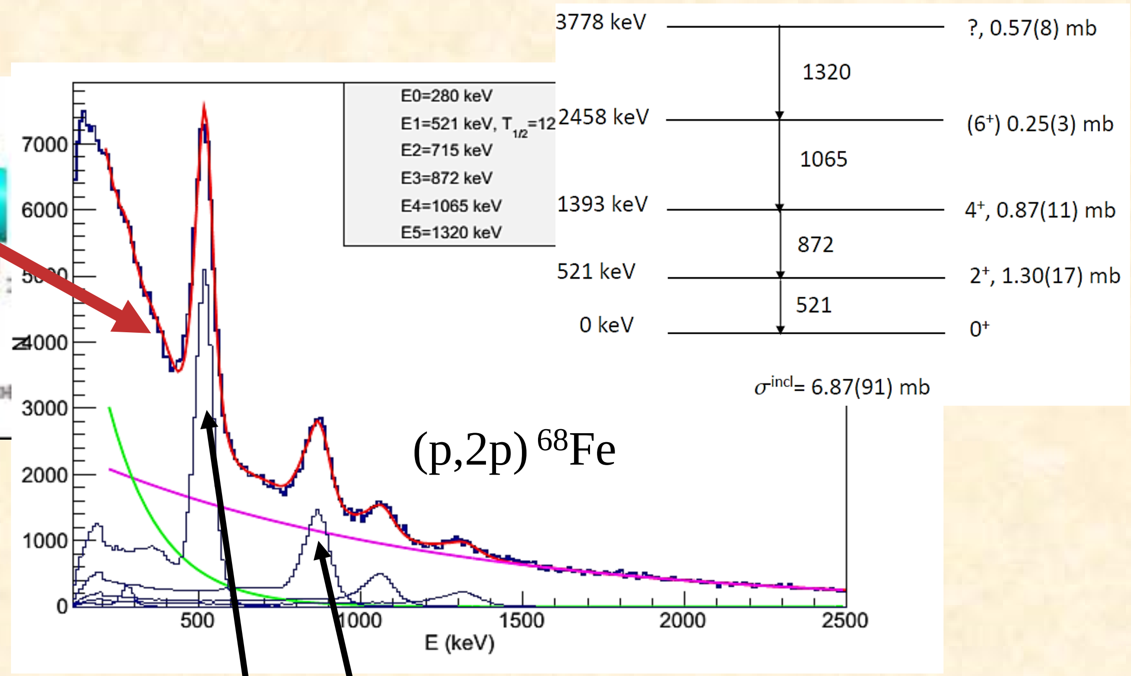
Nuclear physics activities in Vietnam
(highlight from NHEP2016 conference)

- **Experimental nuclear physics (INST Hanoi, INR Da Lat, IOP Hanoi): mainly through the international collaboration projects (nuclear structure of unstable nuclei) by about 10% of manpower, the rest 90% in the radiation technique and reactor research.**
- **Theoretical nuclear physics (INST Hanoi): both in international collaborations and pure VN research (direct nuclear reactions, nuclear cluster, and EOS of the neutron star and proto-neutron star matter).**

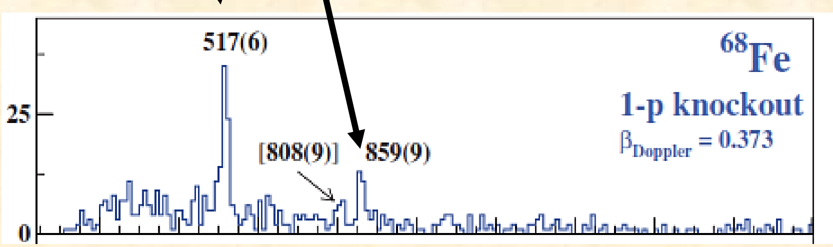
Spectroscopy of ^{68}Fe from SEASTAR project: prompt coincidences

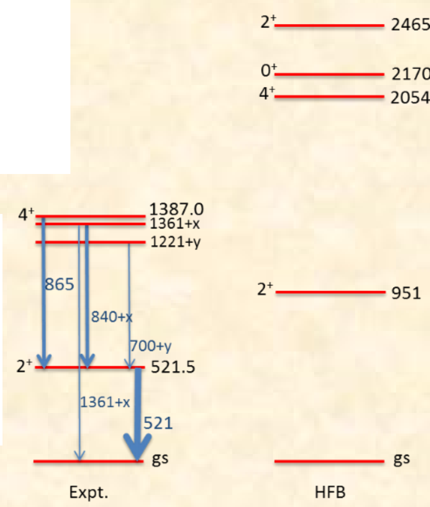
L.X. Chung, B.D. Linh et al. (VINATOM) in collaboration with CEA-Saclay and RIKEN





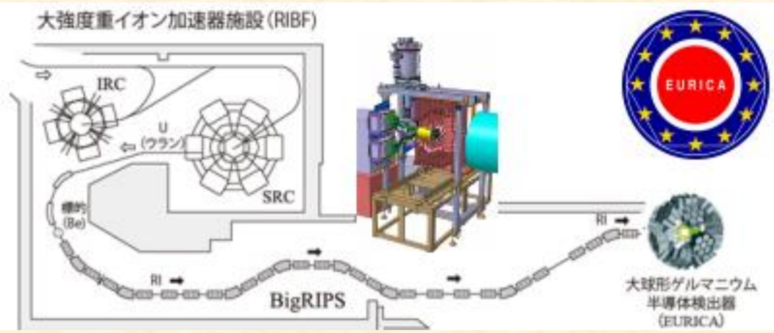
- 6 transitions have been observed: 280, 521, 715, 872, 1065 and 1320 keV.
- The exclusive cross sections of 4 transitions can be extracted: 521, 872, 1065 and 1320 keV. (the strengths of 280, 715 keV transitions are week)

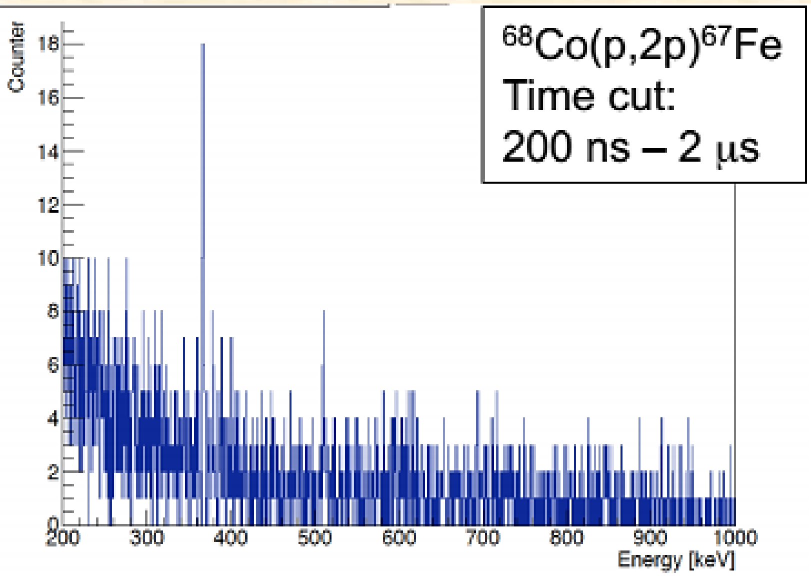


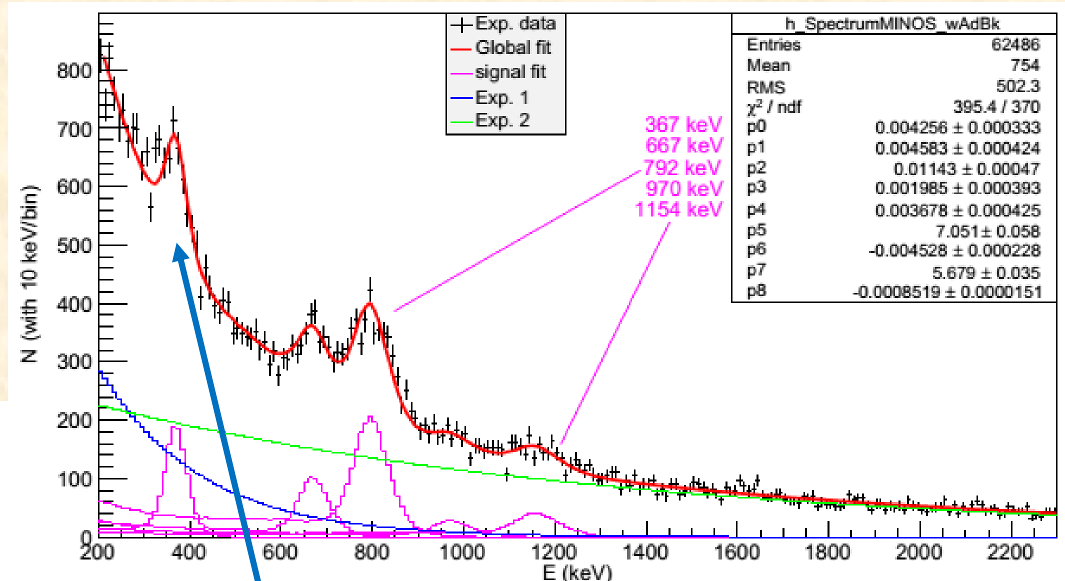


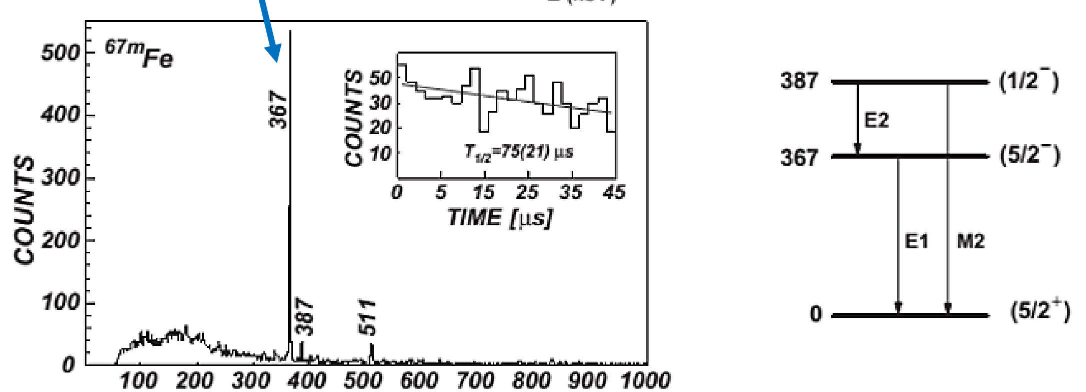
P. Adrich et al., PRC 77, 054306 (2007)

Spectroscopy of ^{67}Fe from SEASTAR project: isomer coincidences





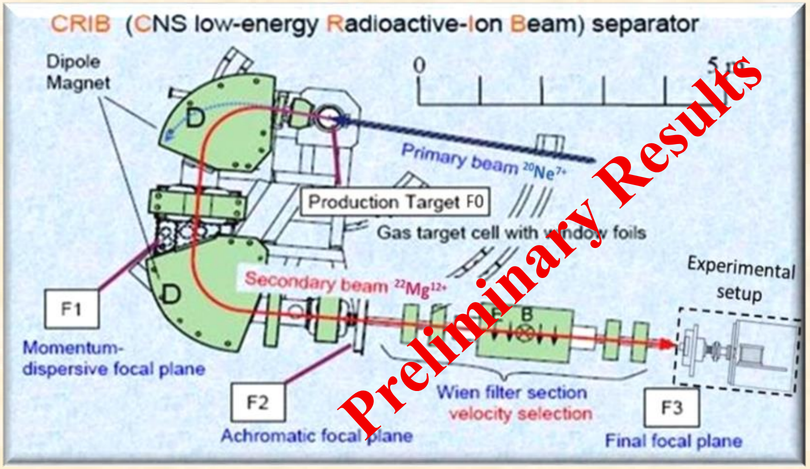




Eur. Phys. J. A **16**, 51–54 (2003)

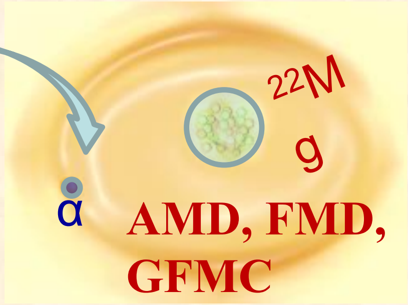
RESONANT STATES IN ^{26}Si VIA SCATTERING OF $^{22}Mg+\alpha$

N. N. Duy, L.H. Khiem et al (IOP) in collaboration with CNS & RIKEN



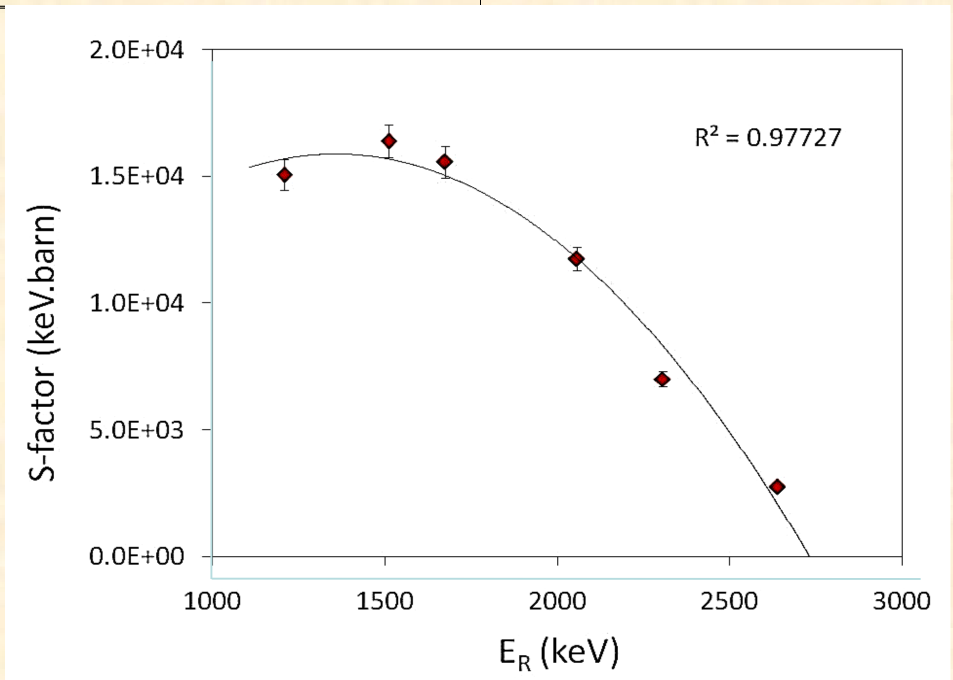
Plane view of CRIB facility of the University of Tokyo at RIKEN, Japan

Level	$^{22}Mg(\alpha,\alpha)^{22}Mg$		
	E_r (MeV)	Γ (MeV)	J^{π}
1	**10.325 ± 0.071**	0.218 ± 0.011	**(2^+, 1^-)**
2	**10.678 ± 0.016**	0.194 ± 0.006	**0^+**
3	**10.831 ± 0.113**	0.186 ± 0.013	**1^-**
4	**11.245 ± 0.028**	**0.208± 0.027**	**4^+**
5	**11.493 ± 0.216**	**0.292 ± 0.010**	**3^-**
6	**11.807 ± 0.117**	**0.156 ± 0.032**	**(0^+, 2^+)**



AMD, FMD, GFMC

s-wave or p-wave resonances?

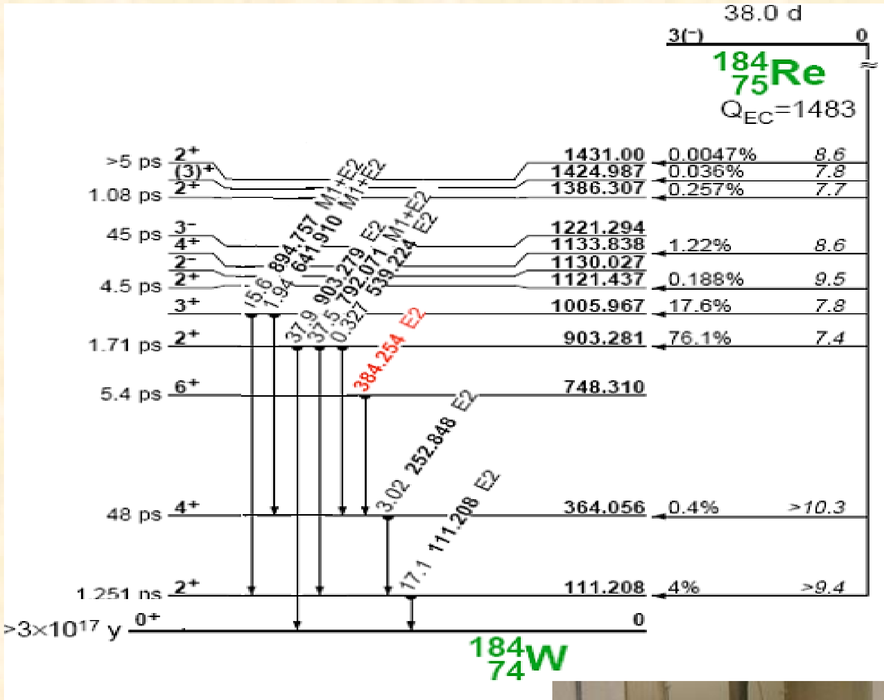


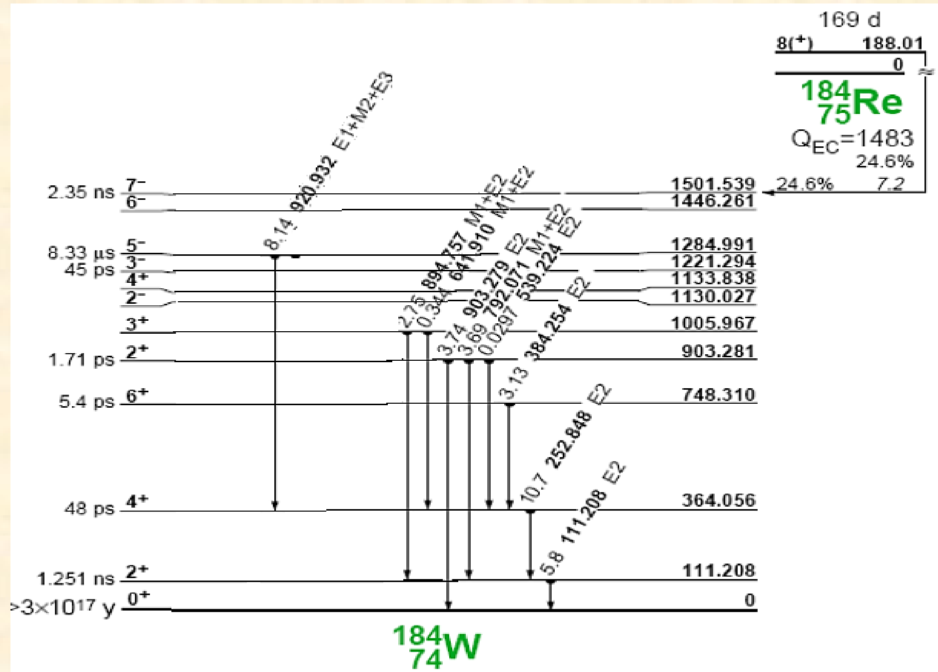
Six resonances in ^{26}Si obtained via $^{22}Mg(\alpha,\alpha)^{22}Mg$ was used to calculate the reaction rate of $^{22}Mg(\alpha,p)^{25}Al$.

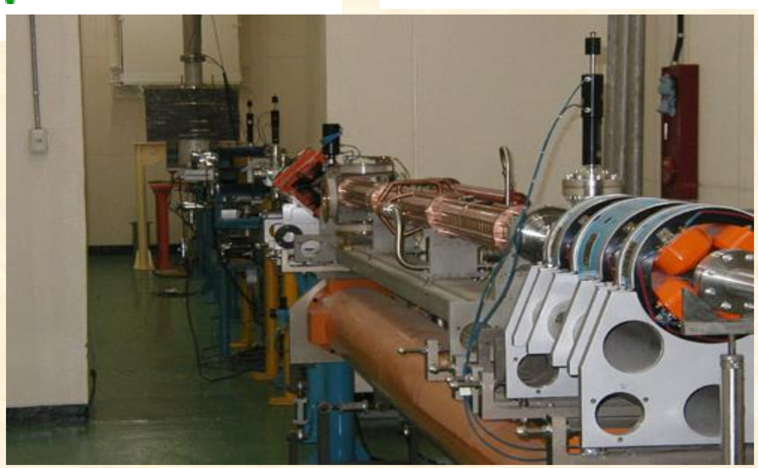
The speed of $^{22}Mg(p,\gamma)$ is fastest with ^{22}Mg nucleus

Isomeric yield ratios of the $^{nat}Re(\gamma,xn)^{184m,g}Re$ photonuclear reaction induced by 50-, 60-, and 70- MeV Bremsstrahlung

P. D. Khue et al. (IOP) in collaboration with Korean colleagues @ Pohang (Korea)



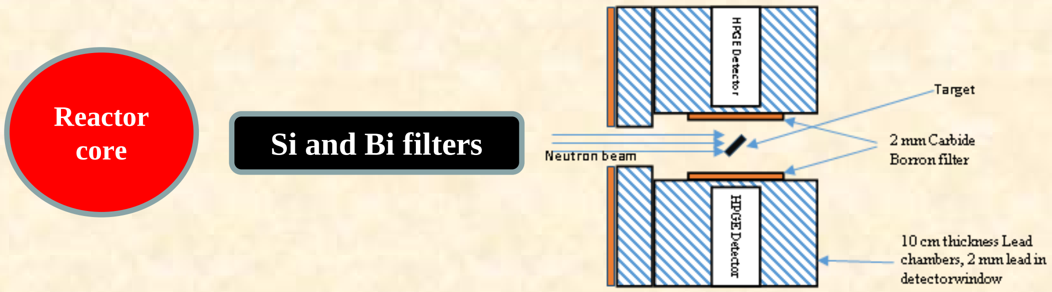




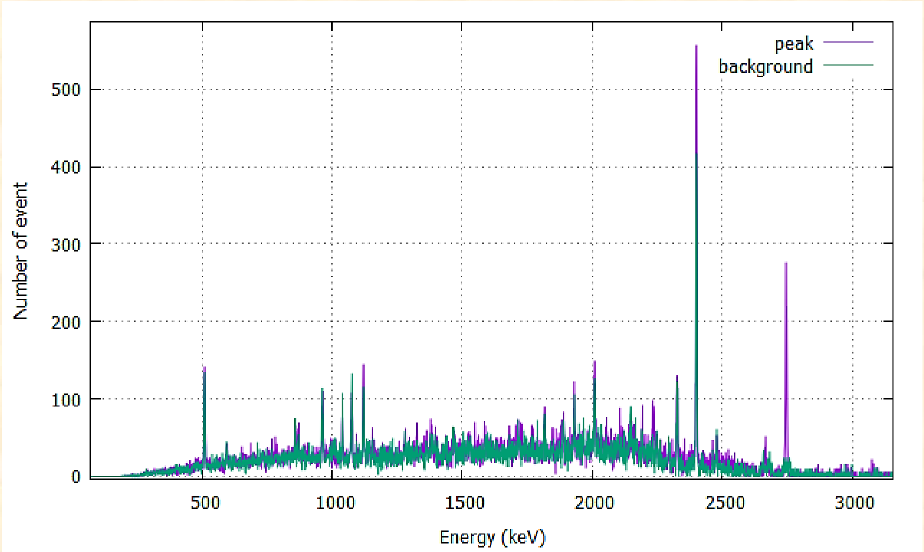
The 100 MeV Electron Linac, PAL, Korea

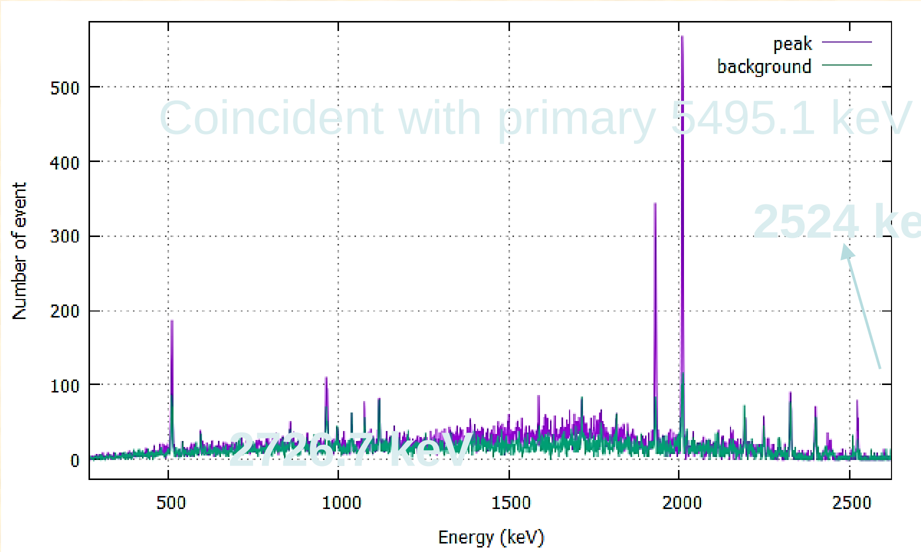
Study of level scheme for ^{172}Yb

N. N. Anh et al (Dalat Nuclear Research Institute, VINATOM)



^{171}Yb(n$_{th}$,γ)^{172}Yb

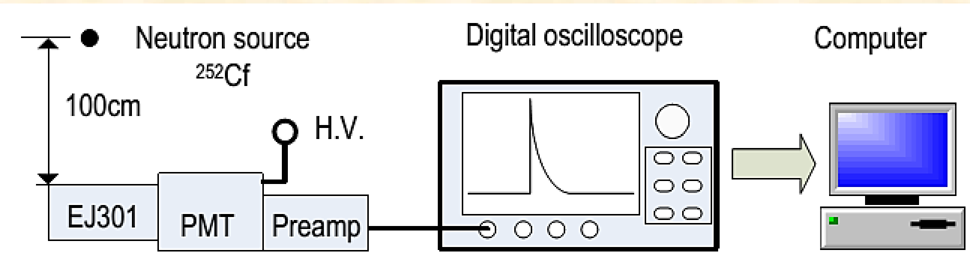




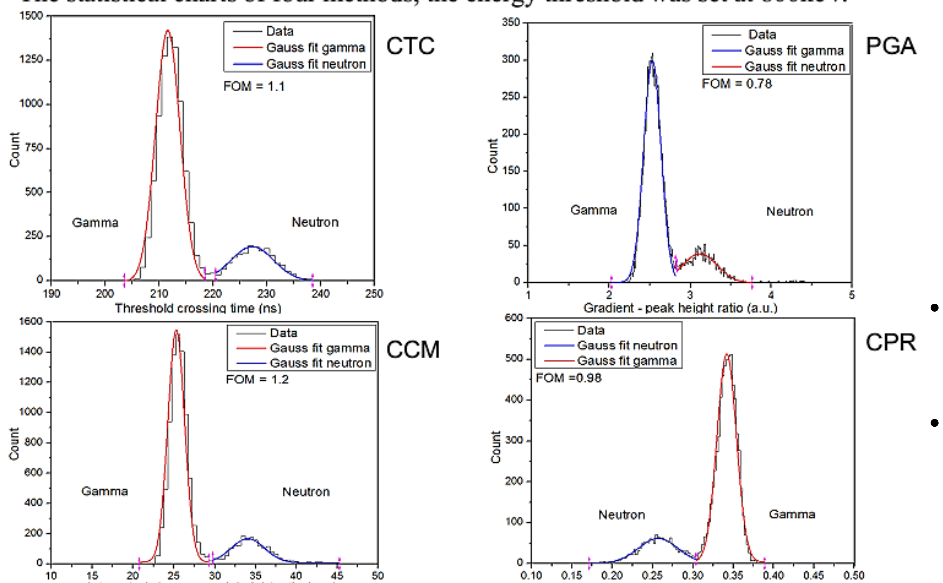
Three transitions (2249, 2524, 2746.7 keV), which are not presented in ENSDF library, are detected in this experiment.

The efficient discrimination of neutron-gamma pulse with small active scintillation detector

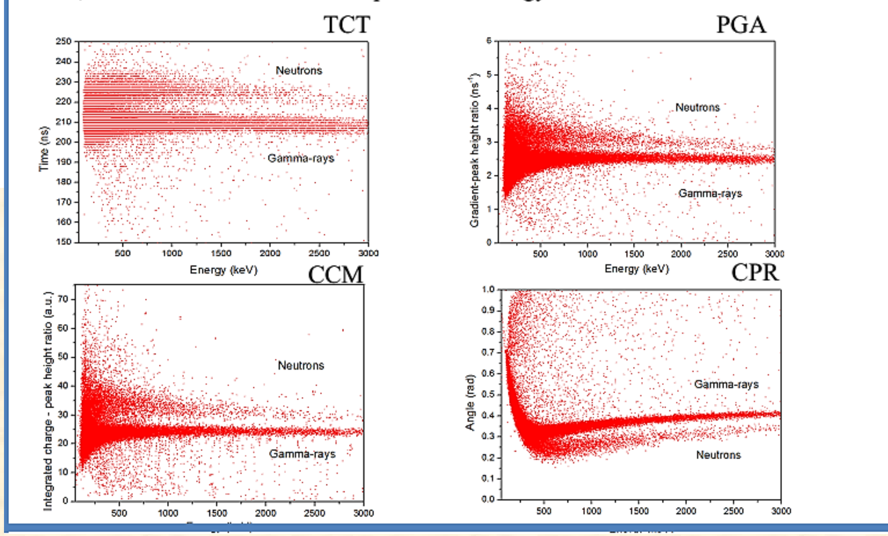
P. V. Chuan et al (Dalat Nuclear Research Institute, VINATOM)



The statistical charts of four methods, the energy threshold was set at 800keV.



The measured data with a neutron source ^{252}Cf were analyzed by methods of TCT, PGA, CCM and CPR. The scatter plots with energy threshold of 100keVee



- This study surveyed the distinguished efficiency of neutron-gamma pulses of a small scintillation detector which was used EJ-301 liquid scintillation
- These results are the basis for building the neutron detection systems using the EJ-301 liquid scintillation detector which are small active volume and combination with digital signal processing DSP and FPGA field programmable gate array techniques.

Threshold crossing time (TCT)

Charge Comparison Method (CCM)

Pulse gradient analysis (PGA)

Correlation pattern recognition (CPR)

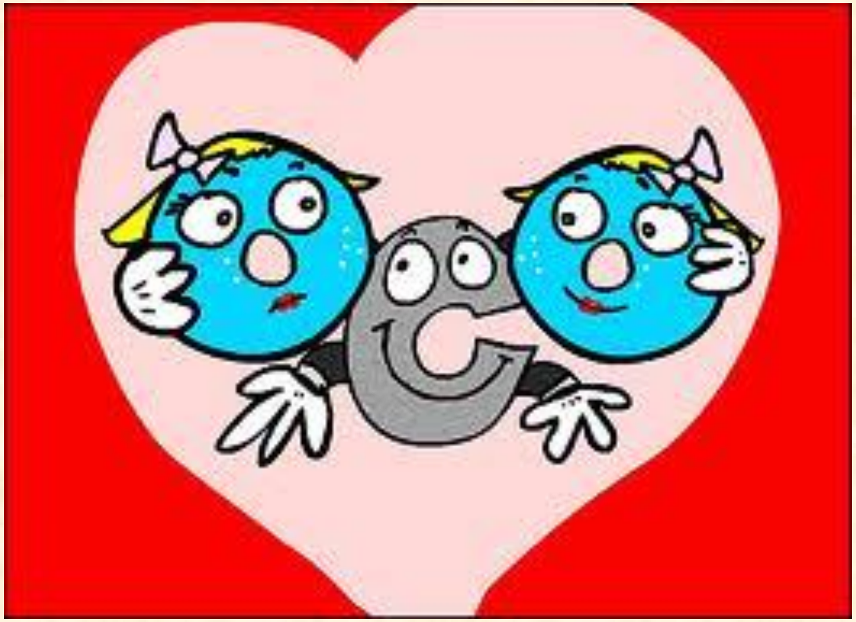
Pelletron at Hanoi University of Nat. Science

N.T. Nghia et al (HUS VIETNAM) in collaboration with CNS Tokyo (Prof. S. Kubono)

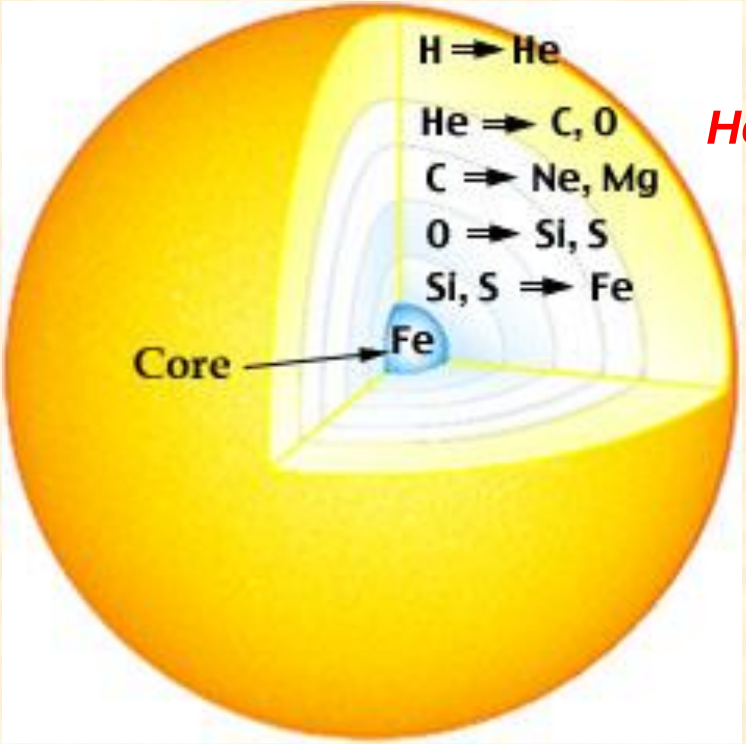
- Nuclear Reaction Analysis (NRA) and Particle Induced X-ray Emission (PIXE)
- Preparation for the exp. on $^{10}B(p,\alpha)$ reaction !

Excitation of the Hoyle state and transition strengths of cluster states in ^{12}C

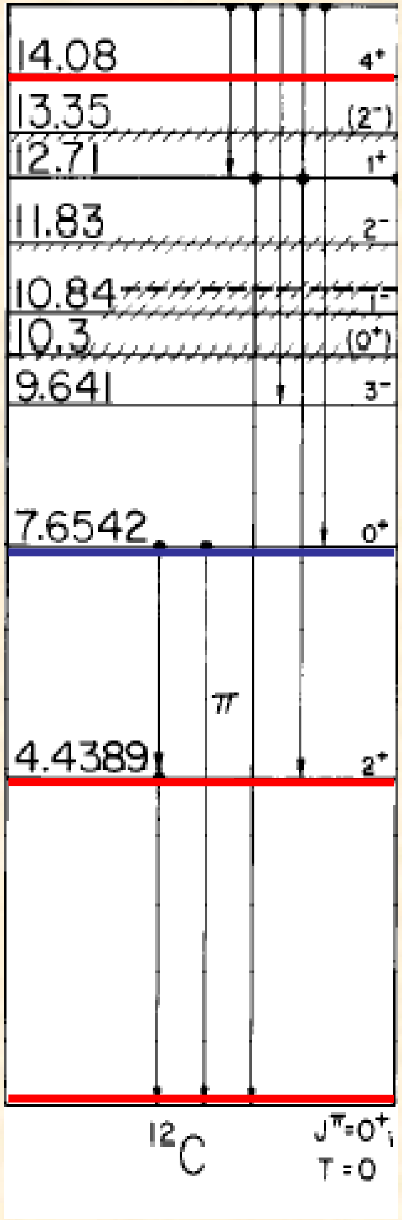
DAO TIEN KHOA
Nuclear Physics Center, INST Hanoi, VINATOM.

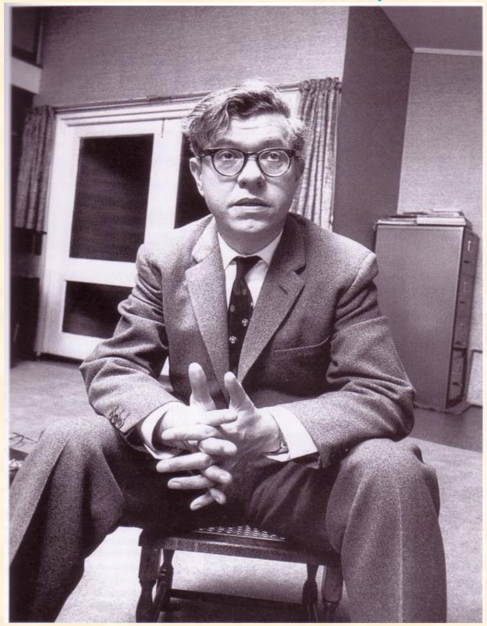


Carbon - Life's backbone



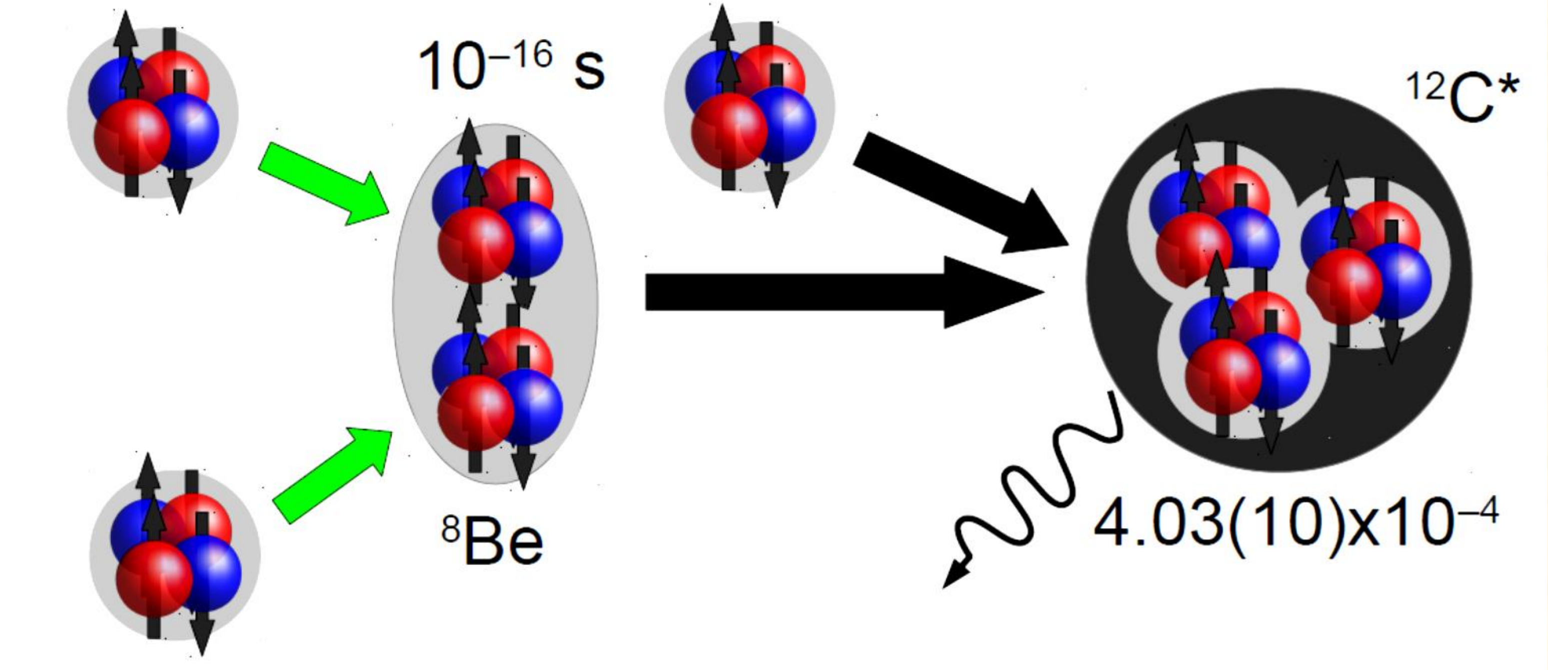
Helium burning





Fred Hoyle

Carbon synthesis in the Universe



Schematic of the triple alpha process at T~10^8 K.

$\alpha + \alpha$ → ^8Be – 0.092 MeV; ^8Be is unstable with $\tau_{1/2} \sim 10^{-16}$ s and decays quickly into two α - particles ! Carbon production is possible only via a resonance reaction $\alpha + \alpha + \alpha$ → $^{12}C^*$ → $^{12}C + 2\gamma$ + 7.37 MeV

$J^\pi=0^+$, E_x=7.654 MeV

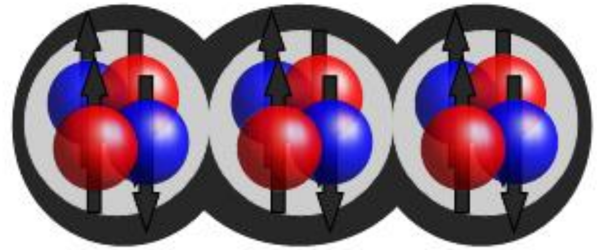
Predicted : F. Hoyle, D. N. F. Dunbar, W. A. Wenzel, *Phys. Rev.* **92**, 1095 (1953)

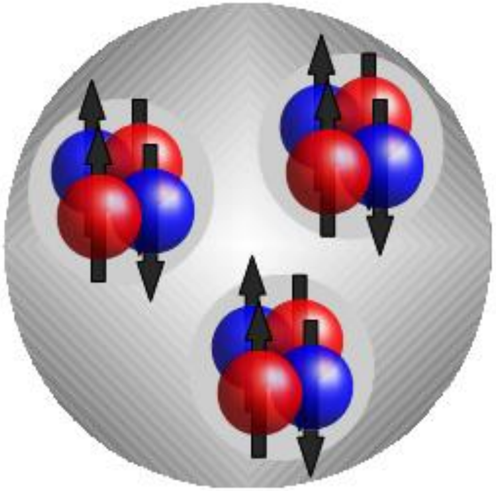
Observed: C. W. Cook, W. A. Fowler, T. Lauritsen, *Phys. Rev.* **107**, 508 (1957)

Three-alpha structure of the Hoyle state

– **Three α cluster – Linear chain**

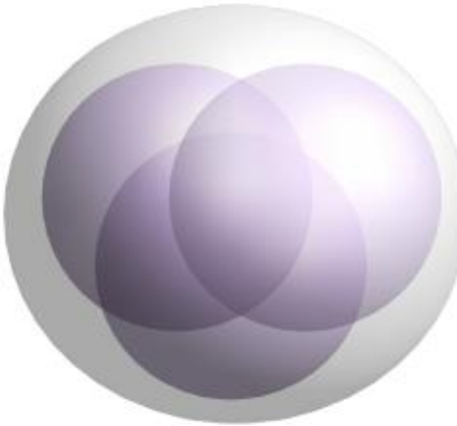
Cluster model: large moment of inertia
H. Morinaga, Phys. Rev. 101 (1956) 254.





– **Gas-like state of three α particles**

Large radius, see *e.g.* H. Horiuchi, Prog. Theor. Phys. **51** (1974) 1266.



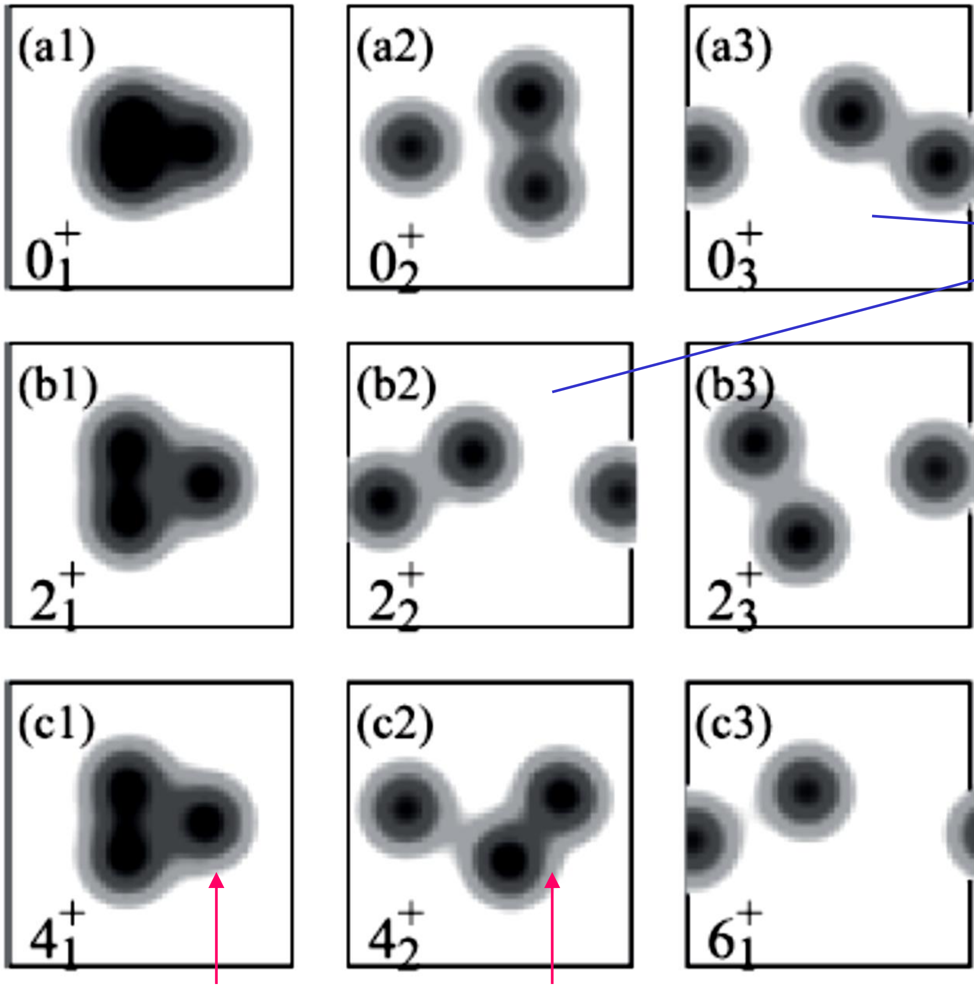
– **Three α condensate**

A. Tohsaki *et al.*, Phys. Rev. Lett. **87** (2001) 19250.

Progress of Theoretical Physics, Vol. 117, No. 4, April 2007

Y. Kanada-En'yo

AMD calculation



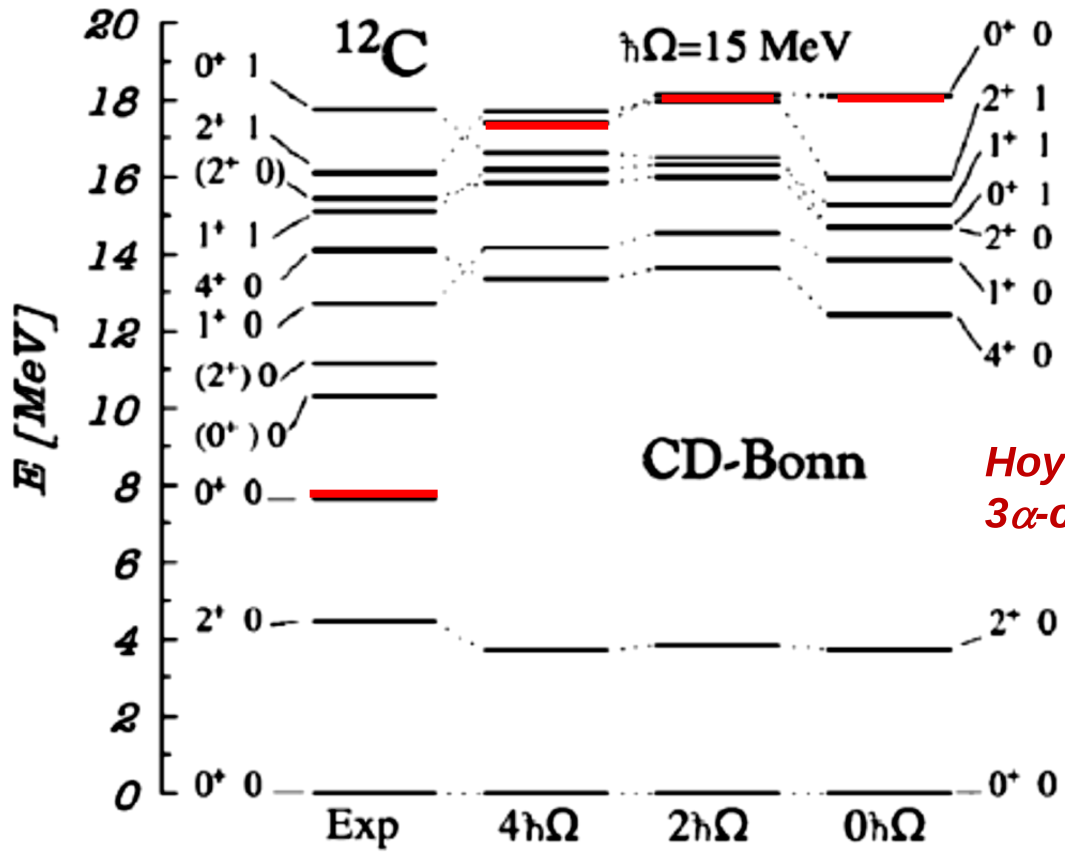
Degenerate at $E_x \sim 10$ MeV

Well clusterized $^8Be_{g.s.} + \alpha$ states

g.s. rot. band   *exc. rot. band*

No core shell model calculations

Navratil P, Vary J P and Barrett B R 2000 *Phys. Rev. Lett.* **84** 5728



Hoyle state - "anthropic"
3α-cluster state ?

Figure 27. The no core shell-model calculations for the nucleus ^{12}C. The left hand part of the figure shows the experimental results. The calculations using the CD Bonn $N-N$ interaction with increasing numbers of oscillator orbits are shown on the right [94].

PRL 109, 252501 (2012) PHYSICAL REVIEW LETTERS week ending 21 DECEMBER 2012

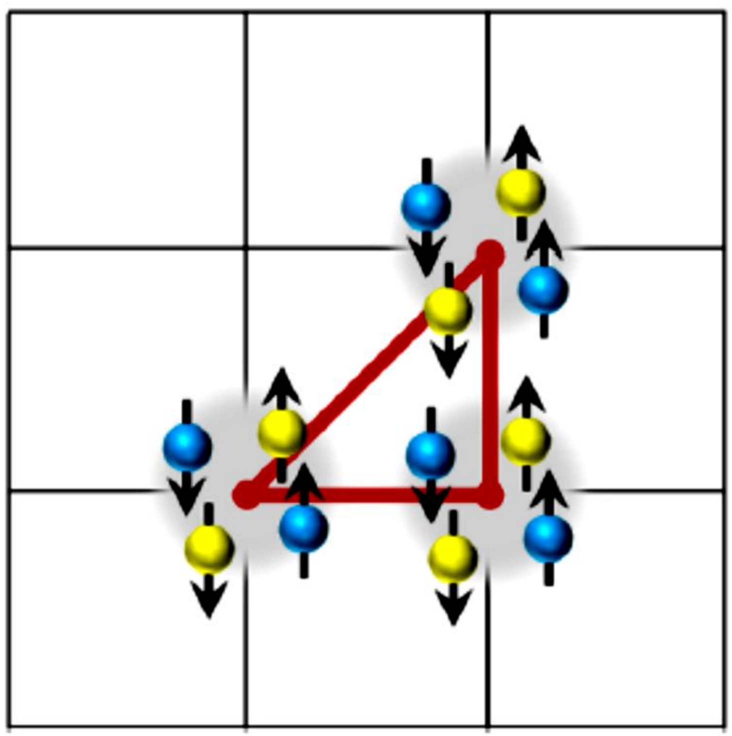
Structure and Rotations of the Hoyle State

Evgeny Epelbaum,[1] Hermann Krebs,[1] Timo A. Lähde,[2] Dean Lee,[4] and Ulf-G. Meißner[5,2,3]

[1]*Institut für Theoretische Physik II, Ruhr-Universität Bochum, D-44870 Bochum, Germany*
[2]*Institut für Kernphysik, Institute for Advanced Simulation, Jülich Center for Hadron Physics, Forschungszentrum Jülich, D-52425 Jülich, Germany*
[3]*JARA—High Performance Computing, Forschungszentrum Jülich, D-52425 Jülich, Germany*
[4]*Department of Physics, North Carolina State University, Raleigh, North Carolina 27695, USA*
[5]*Helmholtz-Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics, Universität Bonn, D-53115 Bonn, Germany*

TABLE II. Lattice and experimental results for the energies of the low-lying even-parity states of ^{12}C, in units of MeV.

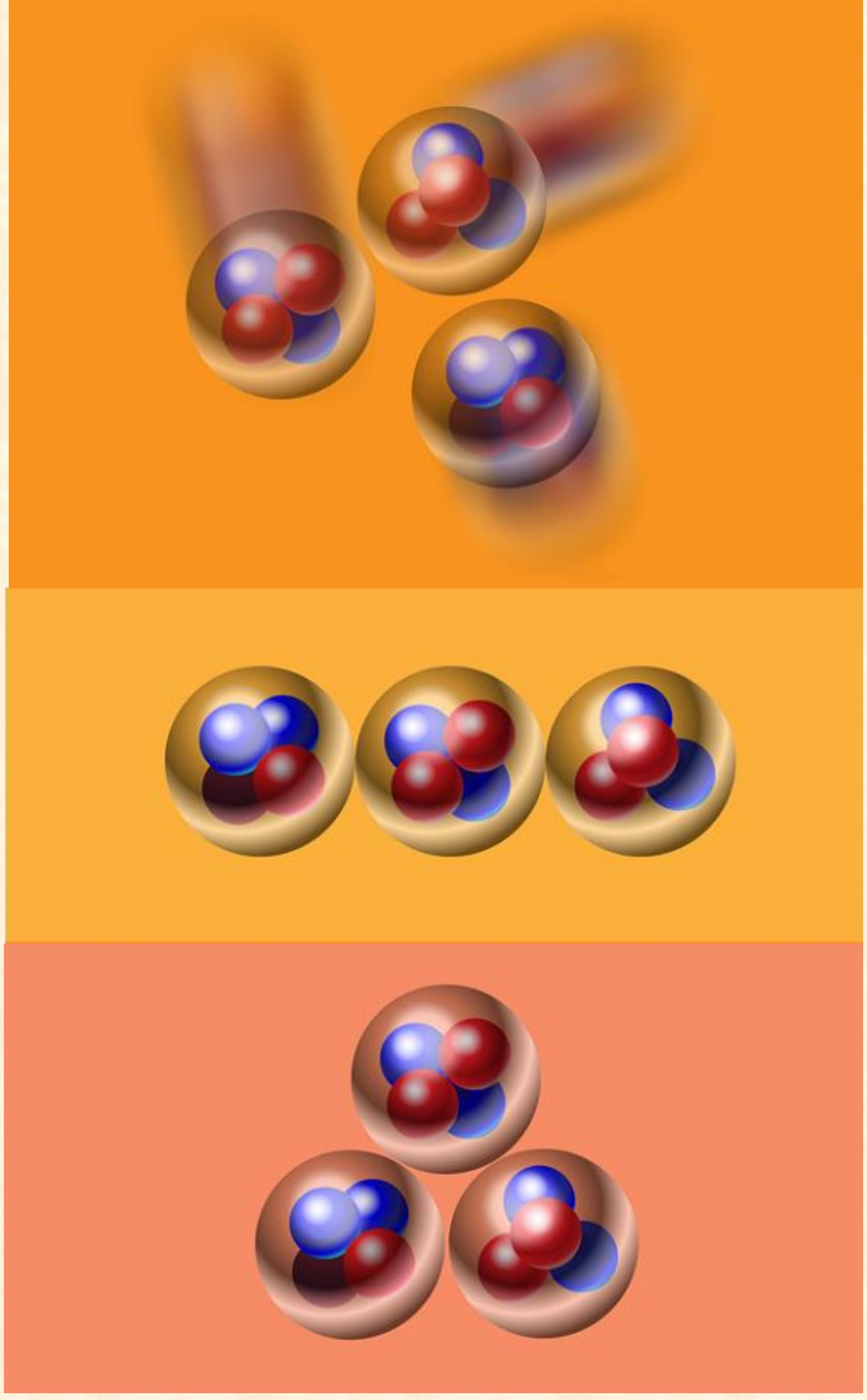
	0_1^+	$2_1^+(E^+)$	0_2^+	$2_2^+(E^+)$
LO	−96(2)	−94(2)	−89(2)	−88(2)
NLO	−77(3)	−74(3)	−72(3)	−70(3)
NNLO	−92(3)	−89(3)	−85(3)	−83(3)
Expt.	−92.16	−87.72	−84.51	−82.6(1) [8,10]
				−81.1(3) [9]
				−82.32(6) [11]



Hoyle state finally explained in ab-initio calculation, no more an "anthropic" 3α-cluster state !

Excitation of the Hoyle state

A puzzle and challenge for the (experimental) nuclear physics



$^{12}C^*$, $J^\pi=2^+$, $E_x\sim$ 10 MeV

rotation of the Hoyle state

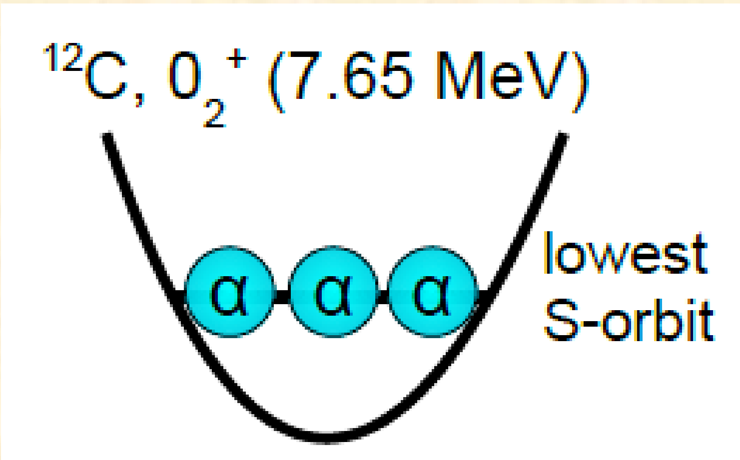
$^{12}C^*$, $J^\pi=0^+$, E_x=7.65 MeV

H. Morinaga, *Phys. Rev*. **101** (1956) 254

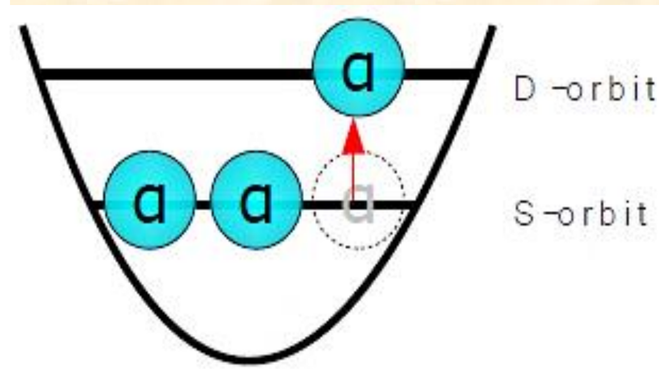
^{12}C, $J^\pi=0^+$, E_x=0

ground state

<u>BEC scenario</u>: Y. Funaki et al., *Eur. Phys. J. A* **28** (2006) 259

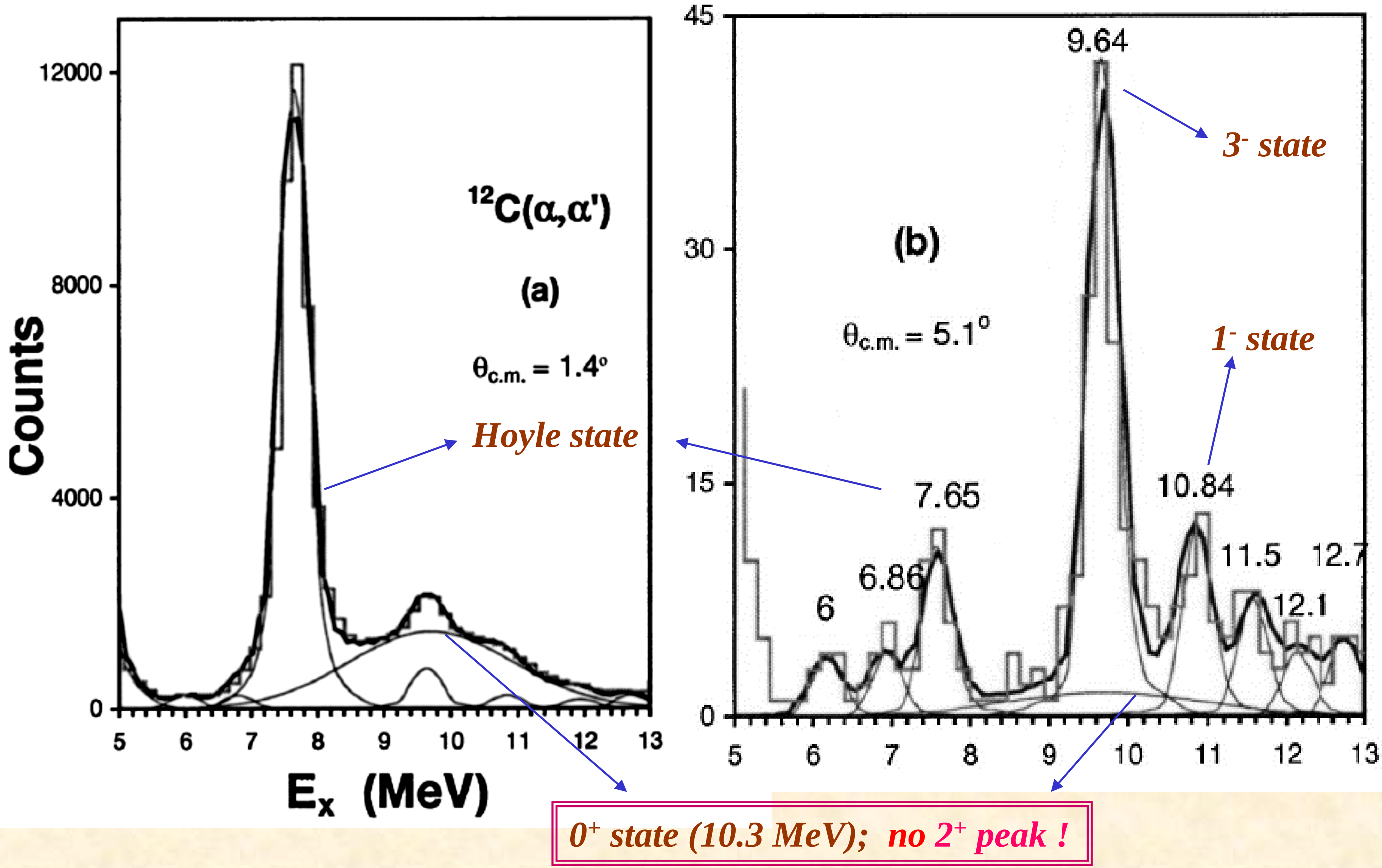


^{12}C, 2_2^+ (~10 MeV)



3α condensate

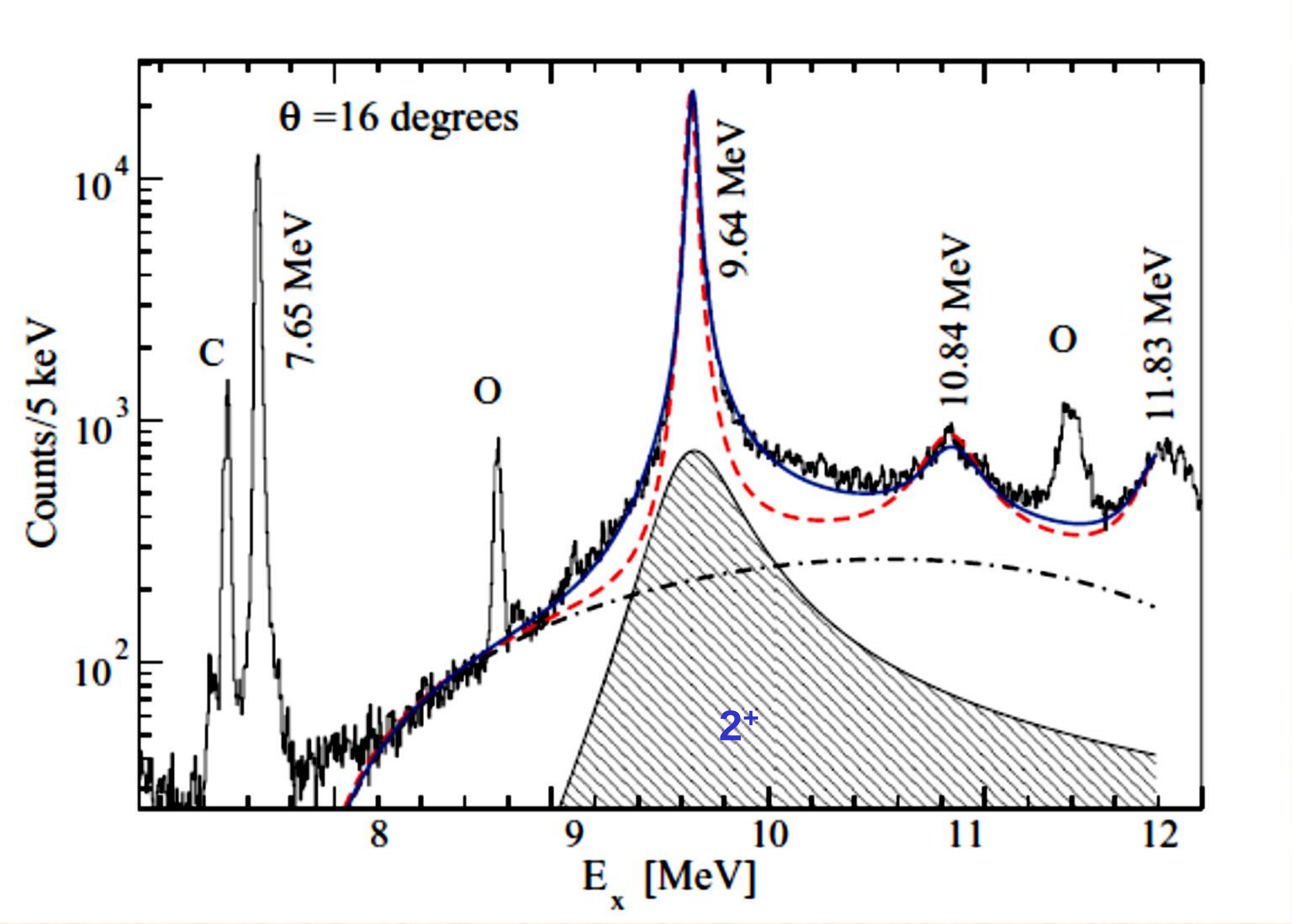
Inelastic α + ^{12}C or ^{12}C + ^{12}C scattering => isoscalar excitation of ^{12}C target



PHYSICAL REVIEW C **68**, 014305 (2003)

Bency John,* Y. Tokimoto, Y.-W. Lui, H. L. Clark, X. Chen, and D. H. Youngblood
Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA

12C(p,p')@66 MeV, M. Freer et al., *Phys. Rev*. C **86**, 034320 (2012)



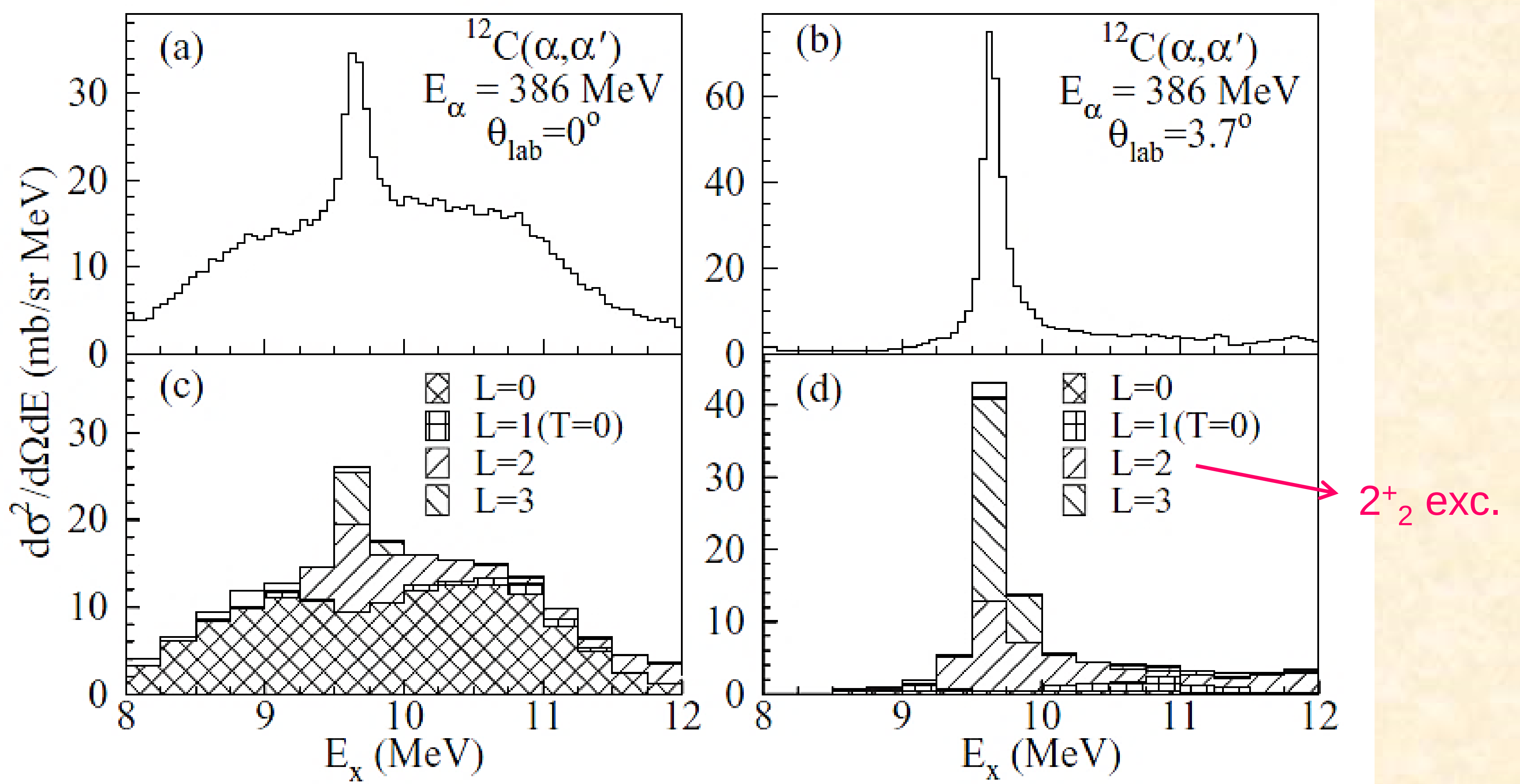
Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW C **84**, 054308 (2011)

Candidate for the 2^+ excited Hoyle state at $E_x \sim 10$ MeV in ^{12}C

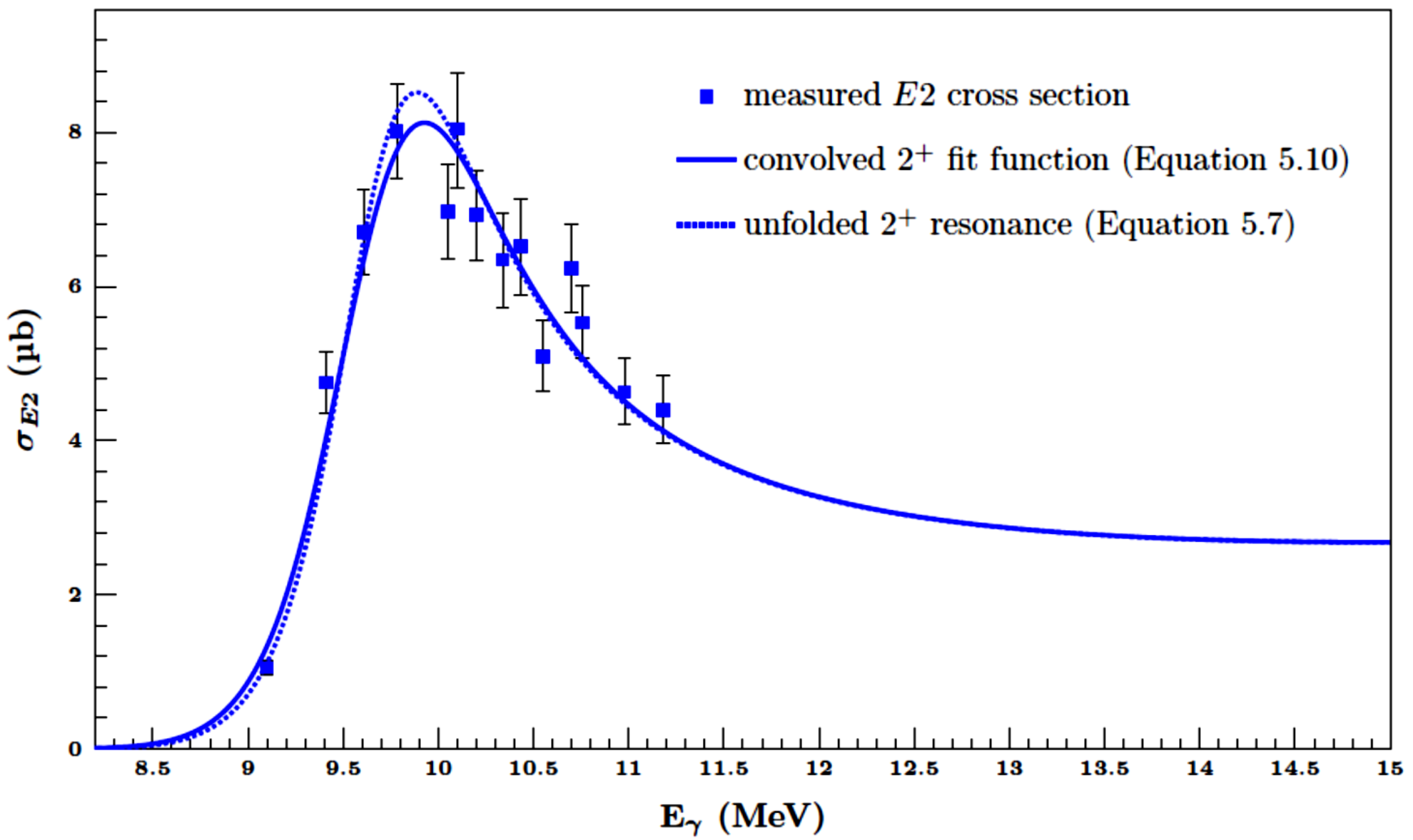
M. Itoh,[1] H. Akimune,[2] M. Fujiwara,[3] U. Garg,[4] N. Hashimoto,[3] T. Kawabata,[5] K. Kawase,[3] S. Kishi,[5] T. Murakami,[5] K. Nakanishi,[3] Y. Nakatsugawa,[5] B. K. Nayak,[4] S. Okumura,[3] H. Sakaguchi,[3] H. Takeda,[6] S. Terashima,[5] M. Uchida,[7] Y. Yasuda,[3] M. Yosoi,[3] and J. Zenihiro[3]

Measured with Grand Raiden spectrometer



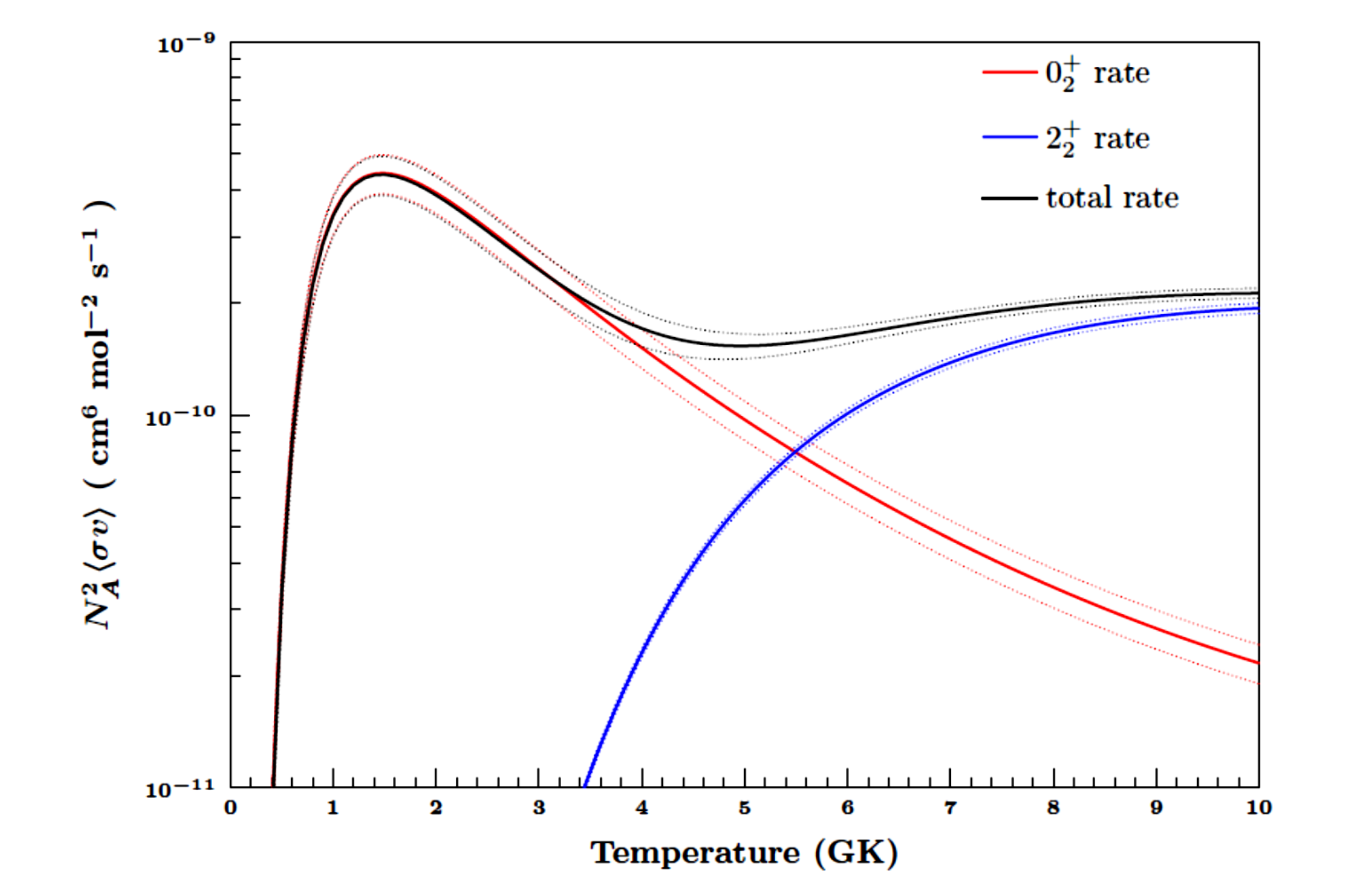
First observation of 2_2^+ state from the $^{12}C(\gamma,\alpha)^8Be$ reaction

Zimmerman *et al. Phys. Rev. Lett.* 110, 152502 (2013).



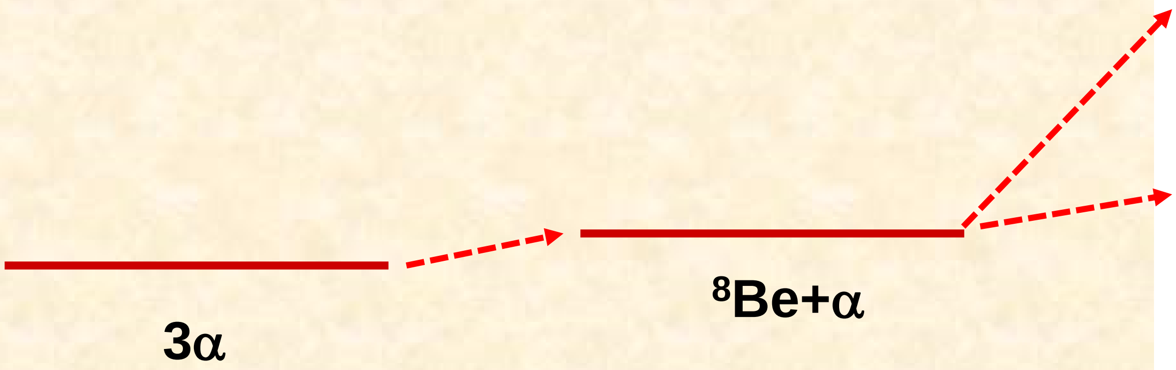
Why is the 2+ excitation of the Hoyle state so important ?

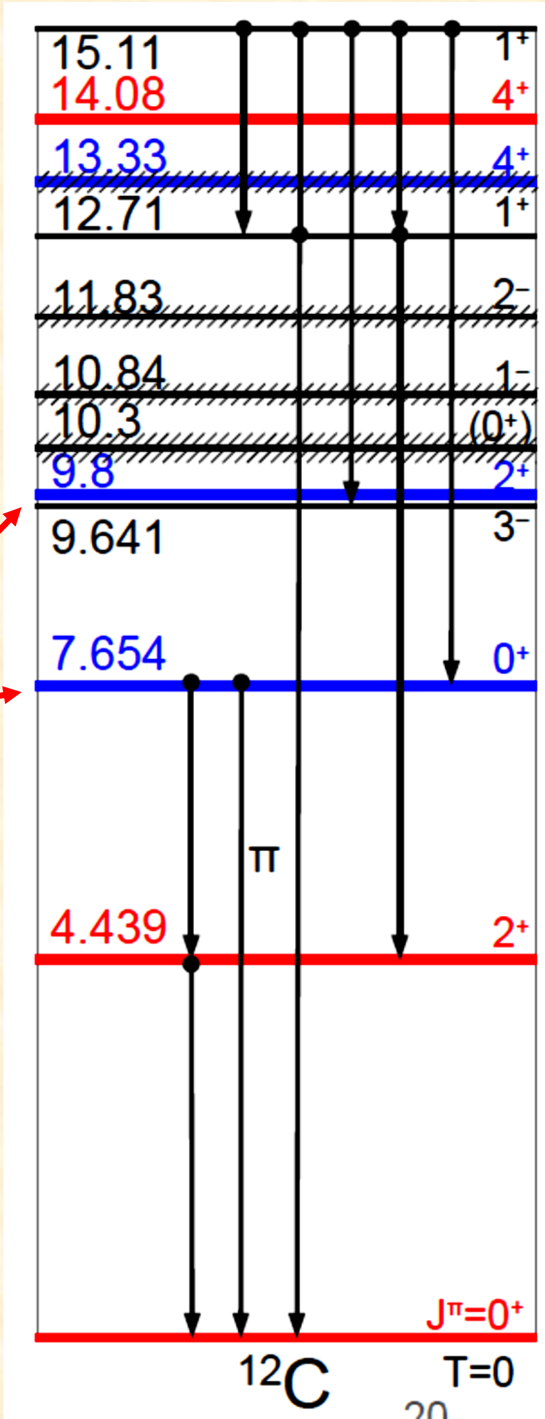
Triple-alpha reaction rates



W.R. Zimmerman, PhD Thesis, Univ. of Connecticut, 2014.

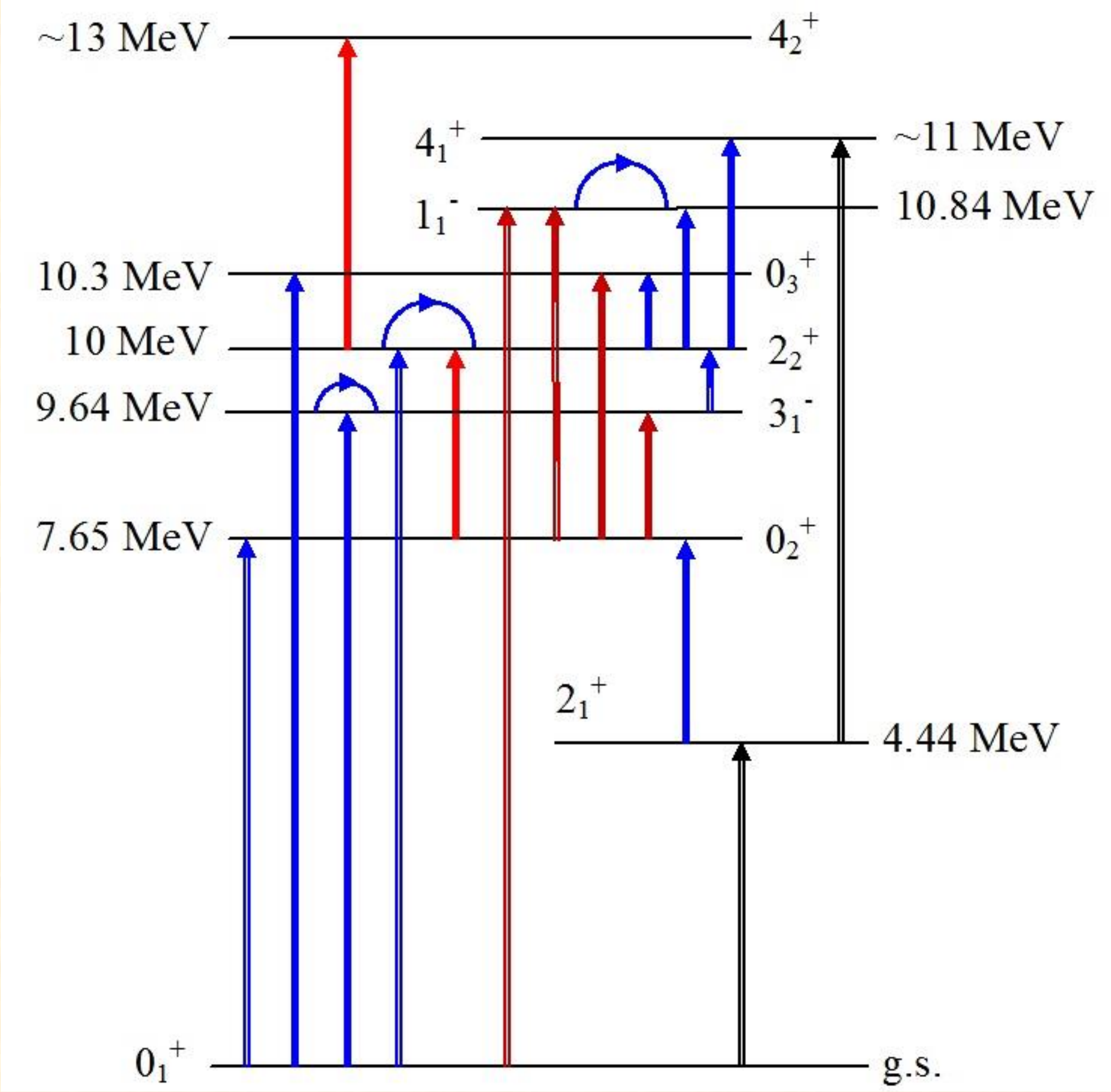
Strong coupling between the α cluster states





- ***Enhanced cross section of triple-α reaction***
- ***Coupling effects in the inelastic α scattering***

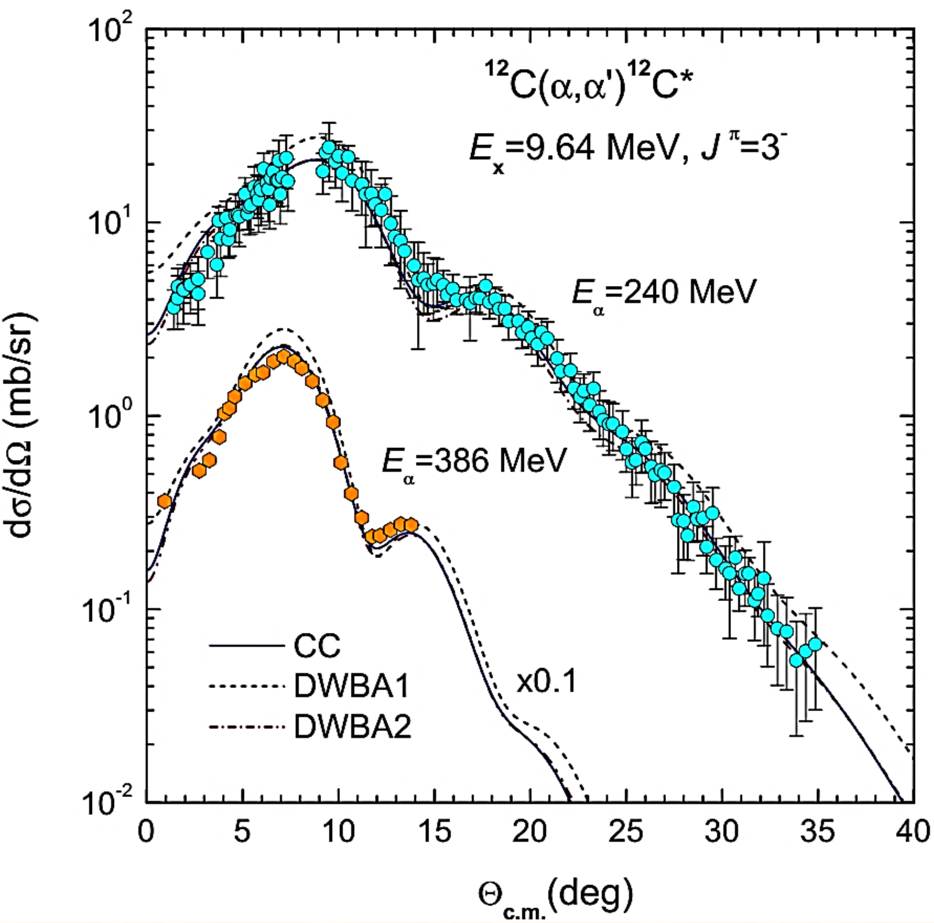
D.C. Cuong, D.T. Khoa, Y. Kanada-En'yo, *Phys. Lett.* B **695**, 469 (2011);
Phys. Rev. C **88**, 064317 (2013).



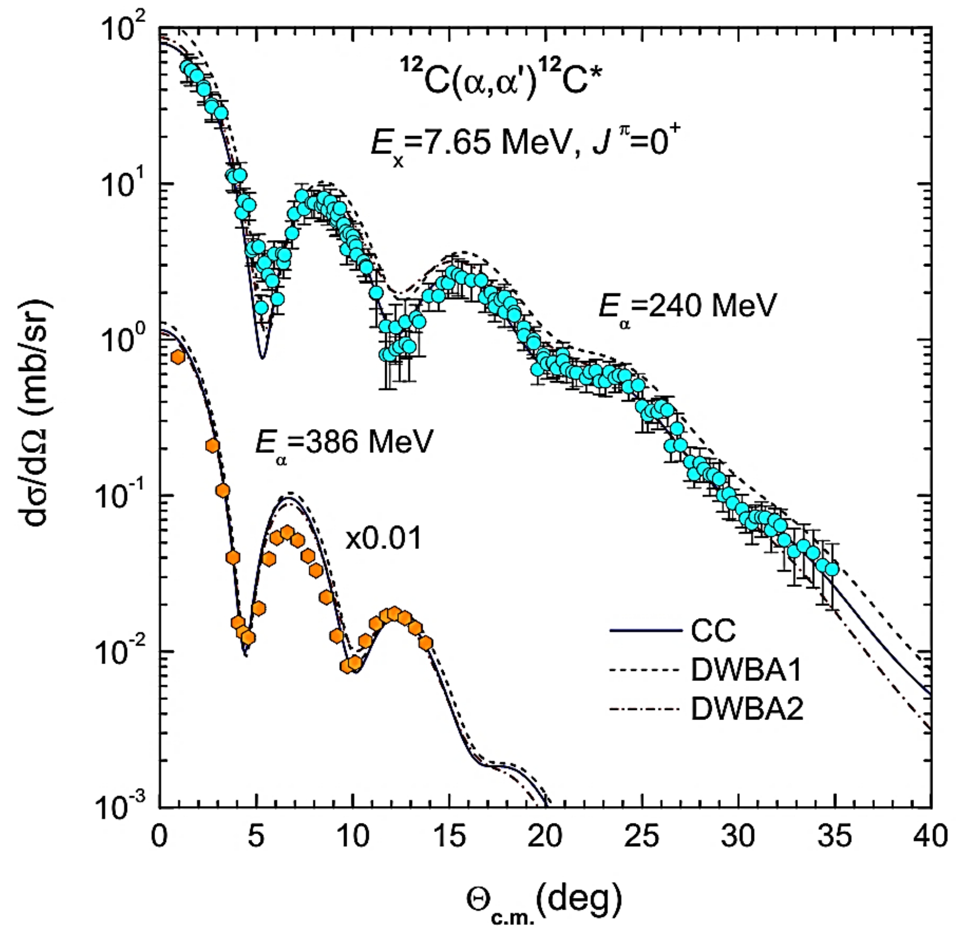
Comprehensive CC analysis of (α,α') data.

$< nJ_A||V_\lambda(R)||nJ_A >$ $< n'J'_A||V_\lambda(R)||nJ_A >$ **were calculated using the AMD diagonal and transition densities**

J^π	$\langle r^2\rangle^{1/2}_{calc}$ (fm)	E_{calc} (MeV)	E_{exp} (MeV)	Transition	Calc. (e^2 fm$^{2\lambda}$)	Best-fit (e^2 fm$^{2\lambda}$)	Exp. (e^2 fm$^{2\lambda}$)
2_1^+	2.668	4.5	4.44	$B(E2;2_1^+\to 0_1^+)$	8.4	8.4 ± 1.5	7.4 ± 0.2
							7.7 ± 1.0
							8.0 ± 0.8
				$B(E2;2_1^+\to 4_1^+)$	28.5		
0_2^+	3.277	8.1	7.65	$M(E0;0_2^+\to 0_1^+)$	6.6	4.5 ± 0.5	3.7 ± 0.2
							5.4 ± 0.2
				$B(E2;0_2^+\to 2_1^+)$	25.5		13.0 ± 2.0
				$B(E3;0_2^+\to 3_1^-)$	3122		
				$M(E0;0_2^+\to 0_3^+)$	16.7		
				$M(E1;0_2^+\to 1_1^-)$	12.5		
3_1^-	3.139	10.8	9.64	$B(E3;3_1^-\to 0_1^+)$	74.4	59.5 ± 3.2	35.9 ± 1.4
							34.3 ± 5.7
							87.1 ± 1.3
				$B(E3;3_1^-\to 2_2^+)$	136.7		
				$M(E1;3_1^-\to 2_2^+)$	3.71		
0_3^+	3.985	10.7	10.3	$M(E0;0_3^+\to 0_1^+)$	2.3	2.9 ± 0.3	3.0 ± 0.2
				$B(E2;0_3^+\to 2_2^+)$	1553		
2_2^+	3.993	10.6	9.84	$B(E2;2_2^+\to 0_1^+)$	0.4	0.6 ± 0.1	0.37 ± 0.02
			10.13				1.57 ± 0.14
				$B(E2;2_2^+\to 0_2^+)$	102		
				$B(E2;2_2^+\to 4_1^+)$	13.5		
				$B(E2;2_2^+\to 4_2^+)$	1071		
1_1^-	3.424	12.6	10.84	$M(E1;1_1^-\to 0_1^+)$	1.58	0.34 ± 0.04	0.31 ± 0.04
				$M(E1;1_1^-\to 2_2^+)$	3.73		
				$B(E3;1_1^-\to 2_2^+)$	1679		



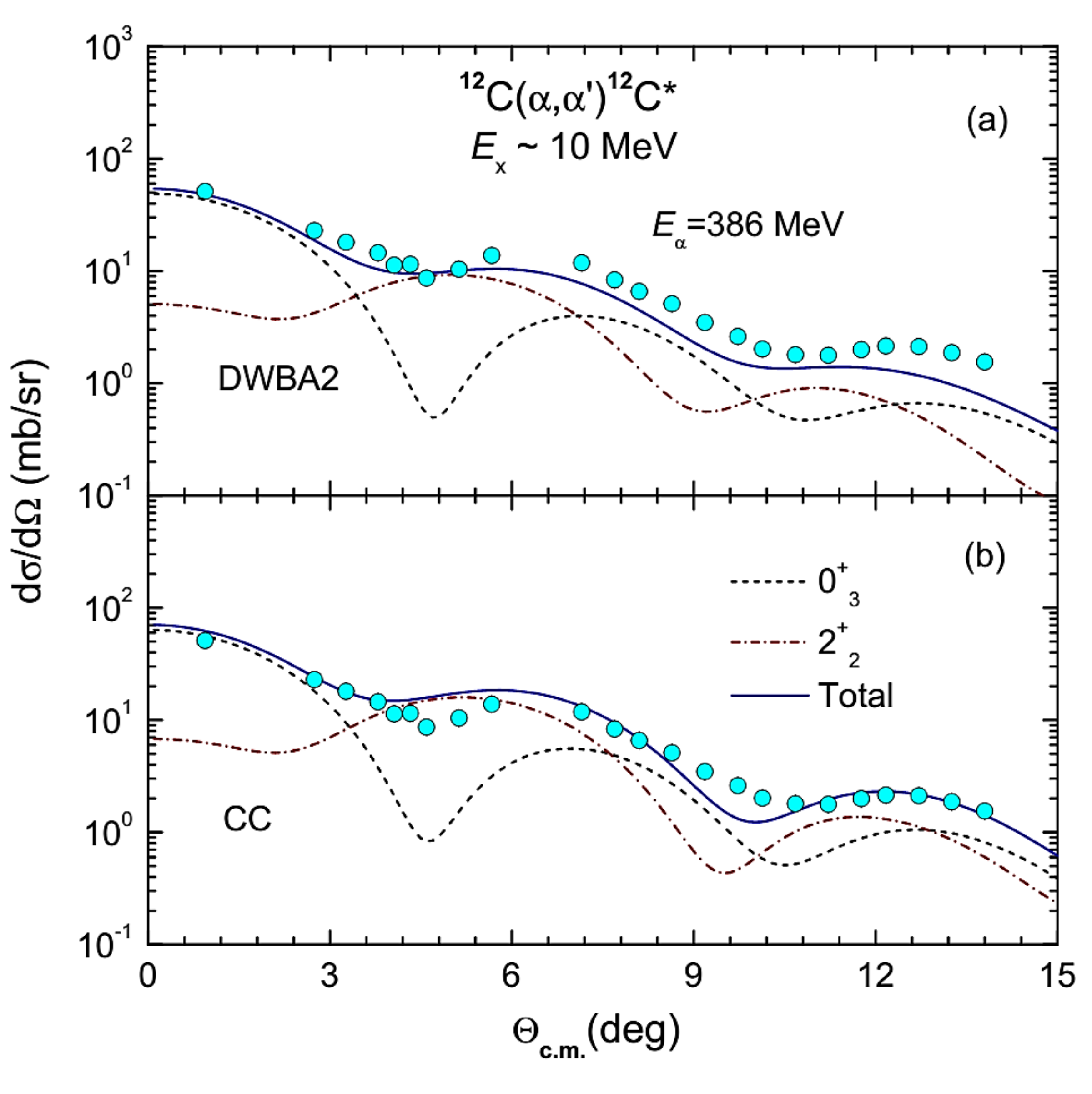
DWBA1 calculation uses the same OP in the entrance and the exit channels; DWBA2 and CC calculations use the OP of the exit channel computed separately at the energy $E_\alpha - Q$, with the AMD diagonal density of $^{12}C^*$



$M(E0; 0^+_2 \rightarrow$ g.s.$) = 4.5\ e\ fm^2$

$B(E3; 3^-_1 \rightarrow$ g.s.$) = 59.5\ e^2\ fm^6$

D.C. Cuong, D.T. Khoa, Y. Kanada-En'yo, *Phys. Rev.* C **88**, 064317 (2013)

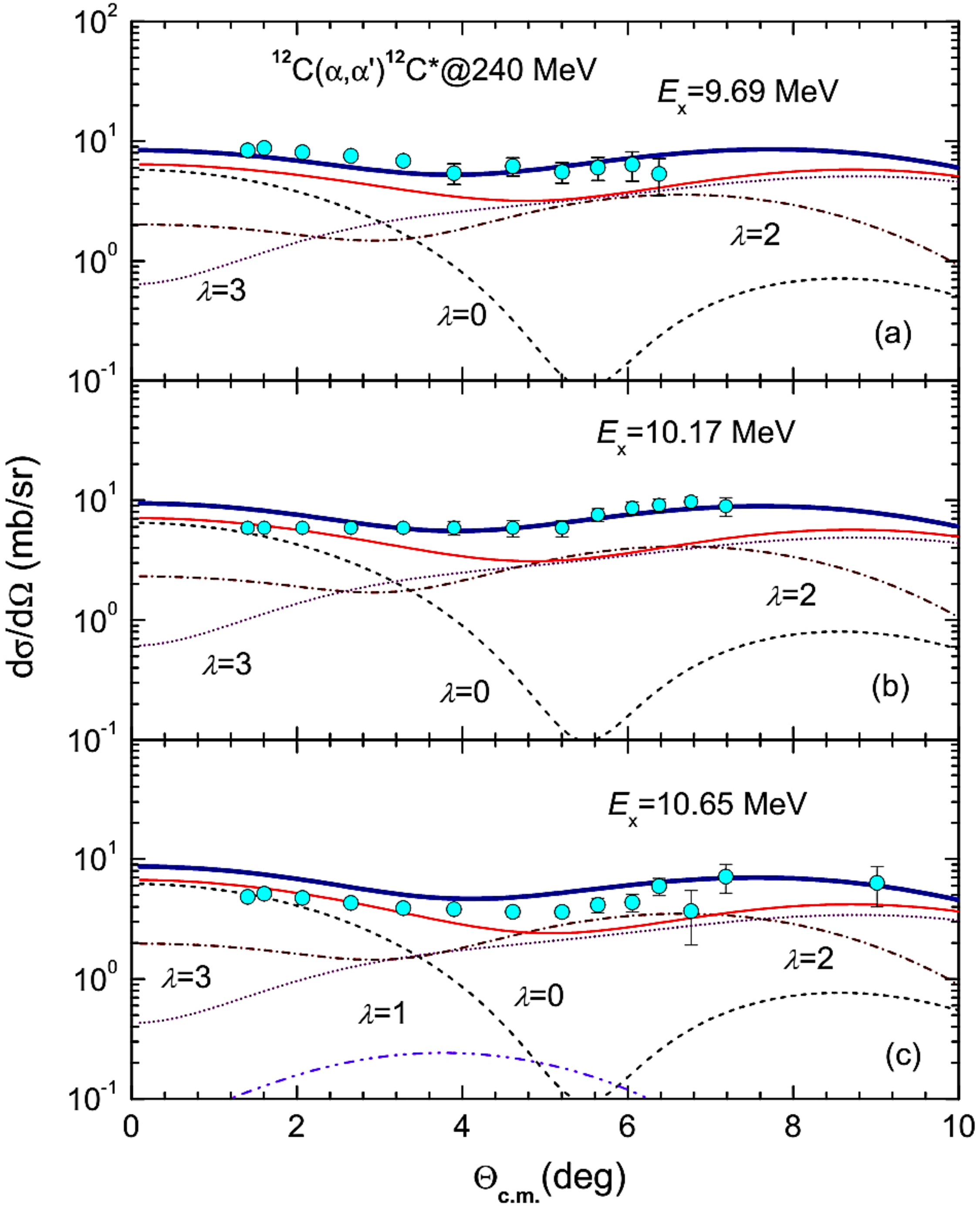


Best fit transition strength
B(E2; 2^+_2→ g.s.)=0.6 e^2 fm^4

⇕

~ 0.4 e^2 fm^4 by Itoh et al.
~ 1.57 e^2 fm^4 determined from $^{12}C(\gamma,\alpha)^8Be$ reaction
W.R. Zimmerman PhD Thesis; W.R. Zimmerman *et al. Phys. Rev. Lett.* **110**, 152502 (2013);

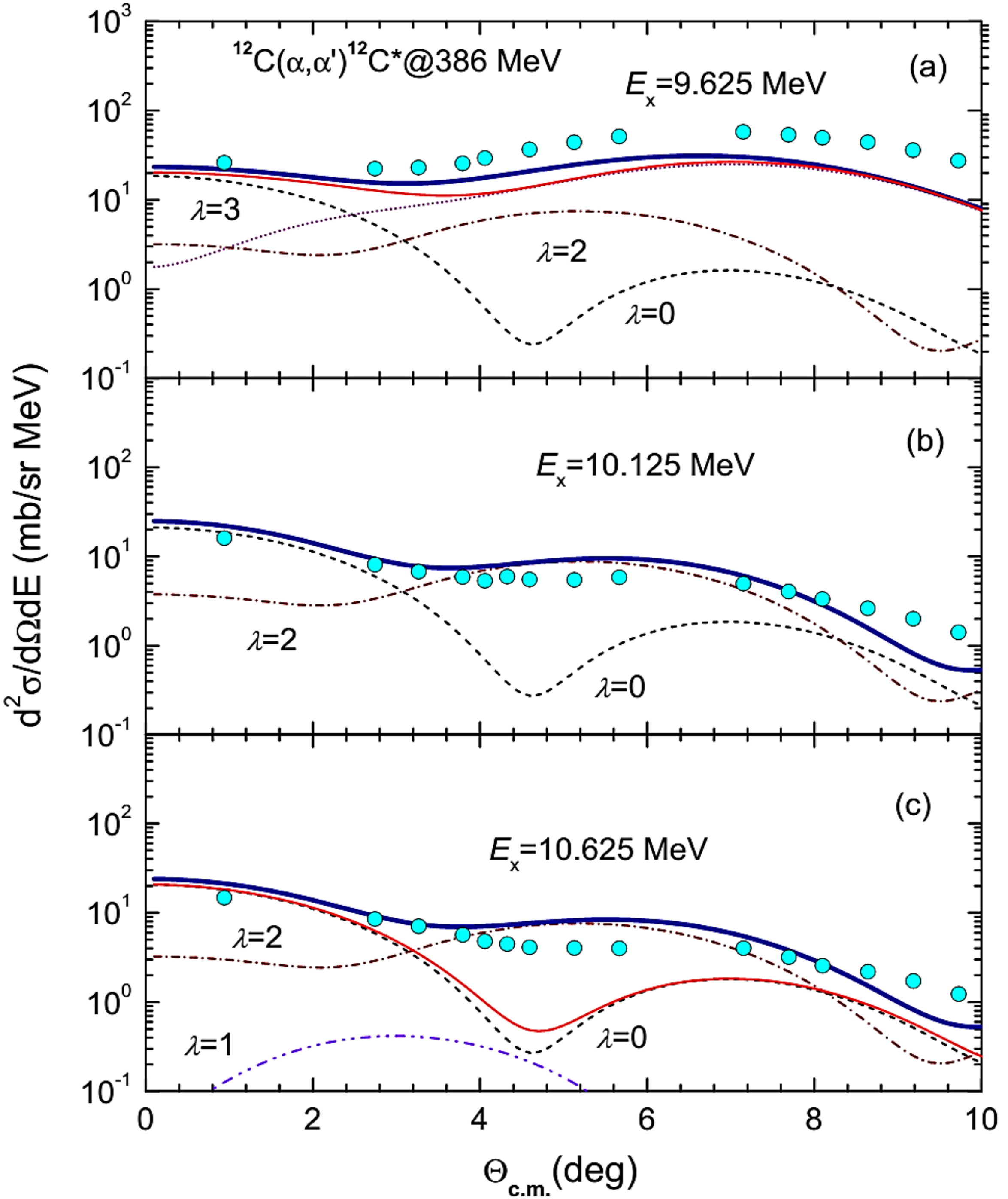
Data: M. Itoh *et al., Phys. Rev.* C **84,** 054308 (2011)



D.C. Cuong, *et al*.,
Phys. Rev. C **88**, 064317 (2013)

Multipole decomposition of the CC results, compared with the data at 240 MeV. The total cross sections obtained with and without the contribution from the 2^+_2 state are shown as the blue and red solid lines, respectively.

Data: B. John, *et al*.,
Phys. Rev. C **68**, 104315 (2003);
Private communication.



Data: M. Itoh *et al.*, *Phys. Rev.* C **84,** 054308 (2011)

CC results compared with data at 386 MeV. The 2^+_2 state is fragmented over the total width Γ=2.1 MeV, determined from ^{12}C (γ,α) ^8Be reaction (W.R. Zimmerman, PhD Thesis, Univ. Connecticut 2014).

Conclusion

- *A clear presence of the 2^+_2 state of ^{12}C at E_x~10 MeV has been confirmed consistently by the CC analysis of the inelastic $\alpha + ^{12}C$ scattering data measured at 240 and 386 MeV → End of the puzzle of the Hoyle state.*
- *Given strong $E\lambda$ transition strengths predicted for transitions between the 2^+_2 state and other cluster states of ^{12}C, a high-precision (α,α') measurement at lower energies should be of interest for a probe of the indirect (two-step) excitation of this state.*
- *Some difference between the $E\lambda$ transition strengths of the 0^+_2, 0^+_3, 3^-_1, and 2^+_2 states given by the folding + CC analysis of (α,α') data and those given by the MDA of the same data has been shown to be due to the strong coupling between cluster states.*

The International Symposium on Physics of Unstable Nuclei 2017 (ISPUN17)

Halong City, Vietnam, September 25 – 30, 2017

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