The Triangular $\mathcal{D}_{3h}$ Symmetry of ^{12}C

Moshe Gai
University of Connecticut
http://astro.uconn.edu, moshe.gai@uconn.edu

1. Why ^{12}C? Why now?
2. The Cluster Model
   The Triangular Spinning Top:
   U(7), $\mathcal{D}_{3h}$ Symmetry
3. The HIγS and ELI-NP facilities
4. The O-TPC and eTPC Detectors
5. Birmingham: Evidence for D_{3h} Symmetry
6. Outlook/ Future

Nuclear Structure 2016, Knoxville, July 29, 2016

Why ^{12}C? Why now?

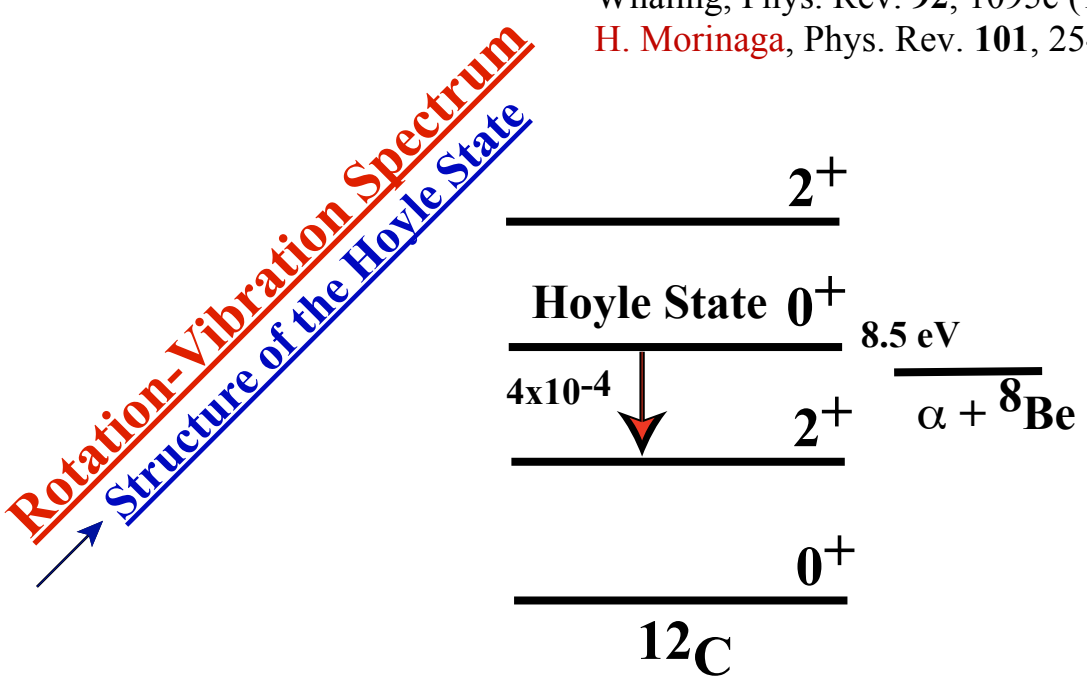
Ab-initio Shell Model:	R. Roth, J. Langhammer, A. Calci, S. Binder, P. Navratil, Phys. Rev. Lett. **107**, 072501 (2011).
EFT on the Lattice:	E. Epelbaum, H. Krebs, T. A. Lahde, D. Lee, U.-G. Meissner, Phys. Rev. Lett. **109**, 252501 (2012)
FMD model:	M. Chernykh, H. Feldmeier, T. Neff, P. von Neumann-Cosel, and A. Richter, Phys. Rev. Lett. **98**, 032501 (2007).
No core NCSpM:	A.C. Dreyfuss, K.D. Launey, T. Dytrych, J.P. Draayer, C.Bahri, Phys. Lett. B **727**, 511 (2013).
AMD model:	Yoshiko Kanada-Enyo, Prog. Theo. Phys. **117**, 655 (2007).
BEC cluster model:	Y. Funaki, H. Horiuchi, W. von Oertzen, G. Ropke, P. Schuck, A. Tohsaki, and T. Yamada, Phys. Rev. C **80**, 64326 (2009).

and

D_{3h} U(7) model:	R. Bijker and F. Iachello, Phys. Rev. C **61**, 067305 (2000).

But

F. Hoyle, D. N. F. Dunbar, W.A. Wenzel, and W. Whaling, Phys. Rev. **92**, 1095c (1953).
H. Morinaga, Phys. Rev. **101**, 254 (1956).



Viability of Carbon-Based Life as a Function of the Light Quark Mass

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

[1]*Institut für Theoretische Physik II, Ruhr-Universität Bochum, D-44870 Bochum, Germany*

[2]*Institut für Kernphysik, Institute for Advanced Simulation, and Jülich Center for Hadron Physics, Forschungszentrum Jülich, D-52425 Jülich, Germany*

[3]*Department of Physics, North Carolina State University, Raleigh, North Carolina 27695, USA*

[4]*Helmholtz-Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics, Universität Bonn, D-53115 Bonn, Germany*

[5]*JARA—High Performance Computing, Forschungszentrum Jülich, D-52425 Jülich, Germany*

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The Hoyle state plays a crucial role in the helium burning of stars that have reached the red giant stage. The close proximity of this state to the triple-alpha threshold is needed for the production of carbon, oxygen, and other elements necessary for life. We investigate whether this life-essential condition is robust or delicately fine-tuned by measuring its dependence on the fundamental constants of nature, specifically the light quark mass and the strength of the electromagnetic interaction. We show that there exist strong correlations between the alpha-particle binding energy and the various energies relevant to the triple-alpha process. We derive limits on the variation of these fundamental parameters from the requirement that sufficient amounts of carbon and oxygen be generated in stars. We also discuss the implications of our results for an anthropic view of the Universe.

DOI: 10.1103/PhysRevLett.110.112502 PACS numbers: 21.10.Dr, 21.30.−x, 21.60.De

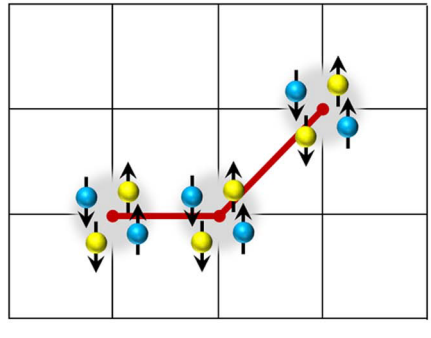
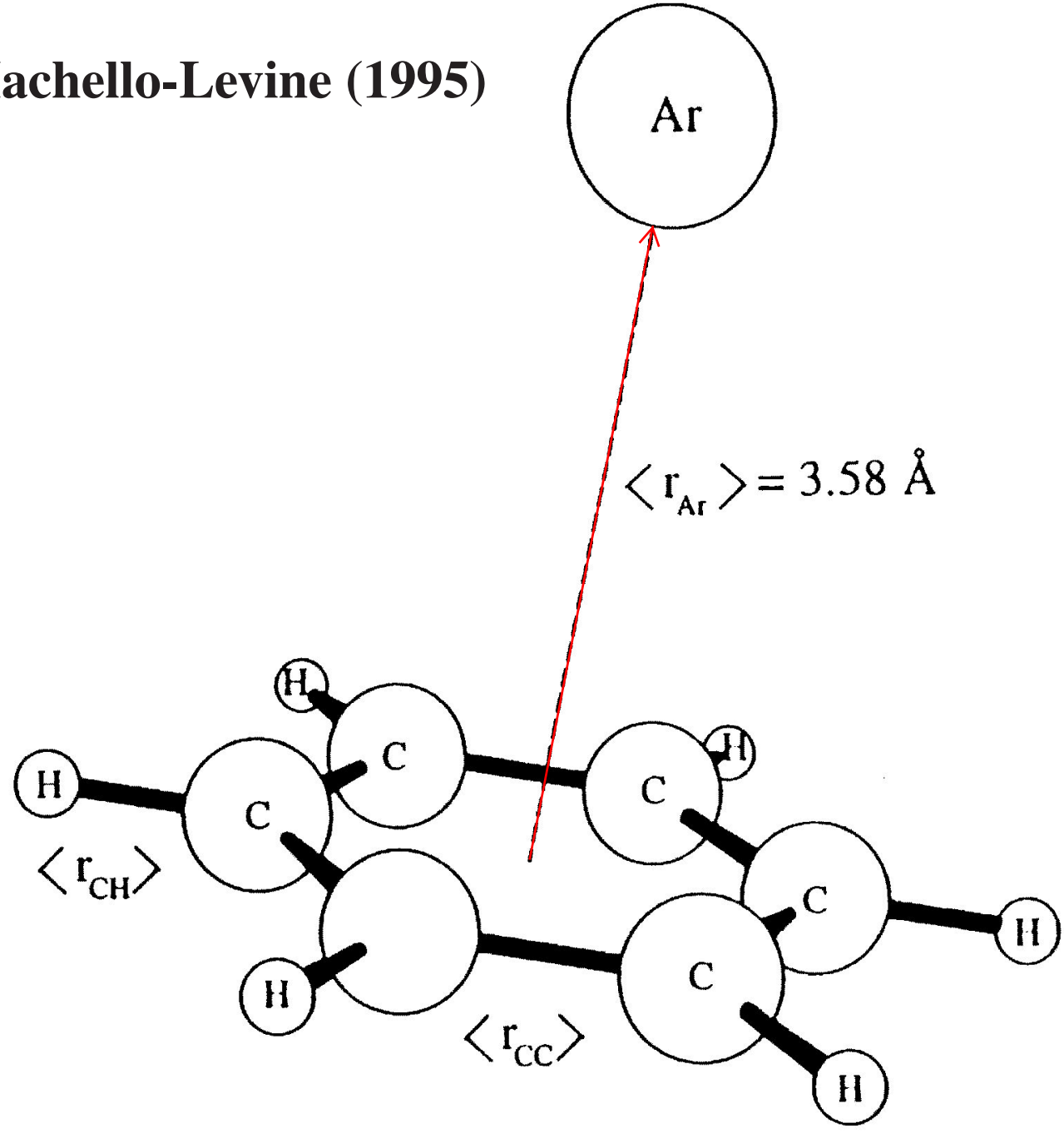
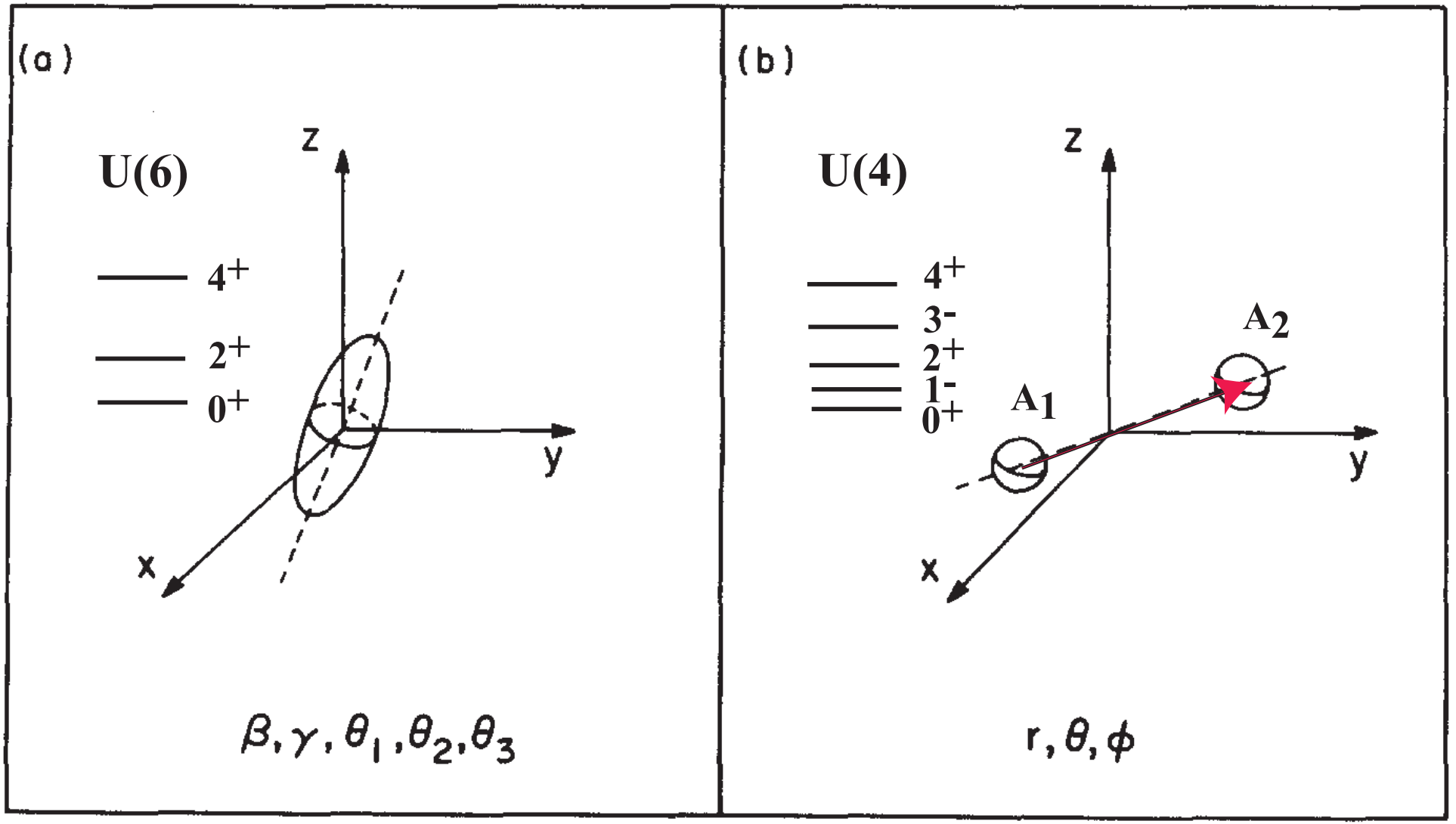


FIG. 3 (color online). Illustration of the initial state Λ. There are 24 equivalent orientations of this bent-arm or obtuse triangular configuration.

Iachello-Levine (1995)



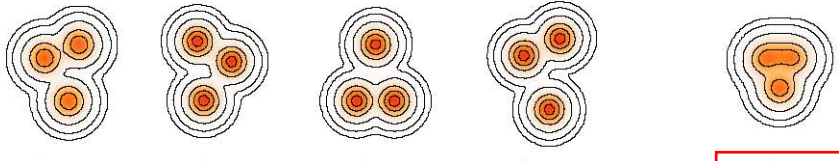


J. Chem. Phys., Vol. 77, No. 6, 15 September 1982

M. Chernykh, H. Feldmeier, T. Neff, P. von Neumann-Cosel, and A. Richter
Fermionic Molecular Dynamic Model (FMD), Phys. Rev. lett. 98, 032501 (2007)

PRL **98,** 032501 (2007) PHYSICAL REVIEW LETTERS week ending 19 JANUARY 2007

^{12}C



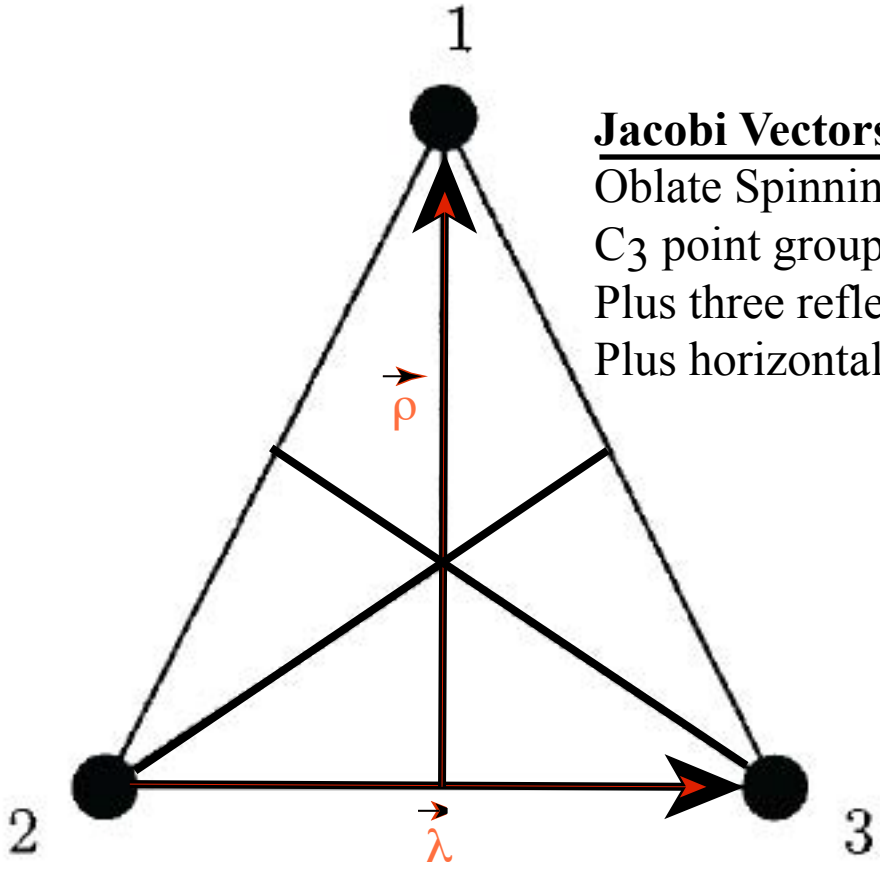
ground state:	$\lvert\langle 1\lvert 0_1^+\rangle\rvert = 0.30$	$\lvert\langle 2\lvert 0_1^+\rangle\rvert = 0.25$	$\lvert\langle 3\lvert 0_1^+\rangle\rvert = 0.15$	$\lvert\langle 4\lvert 0_1^+\rangle\rvert = 0.08$	$\lvert\langle 5\lvert 0_1^+\rangle\rvert = 0.94$
Hoyle state:	$\lvert\langle 1\lvert 0_2^+\rangle\rvert = 0.72$	$\lvert\langle 2\lvert 0_2^+\rangle\rvert = 0.71$	$\lvert\langle 3\lvert 0_2^+\rangle\rvert = 0.61$	$\lvert\langle 4\lvert 0_2^+\rangle\rvert = 0.61$	$\lvert\langle 5\lvert 0_2^+\rangle\rvert = 0.04$

Spectrum of the (Symmetric) Triangular Spinning Top:

Molecular Physics: H_3^+ Molecule

Hadron Structure: Three Quark Model

Nuclear Structure: ^{12}C Three Alpha-Particles



Jacobi Vectors: $\vec{\lambda}, \vec{\rho}$

Oblate Spinning Top: U(6+1)

C_3 point group symmetry

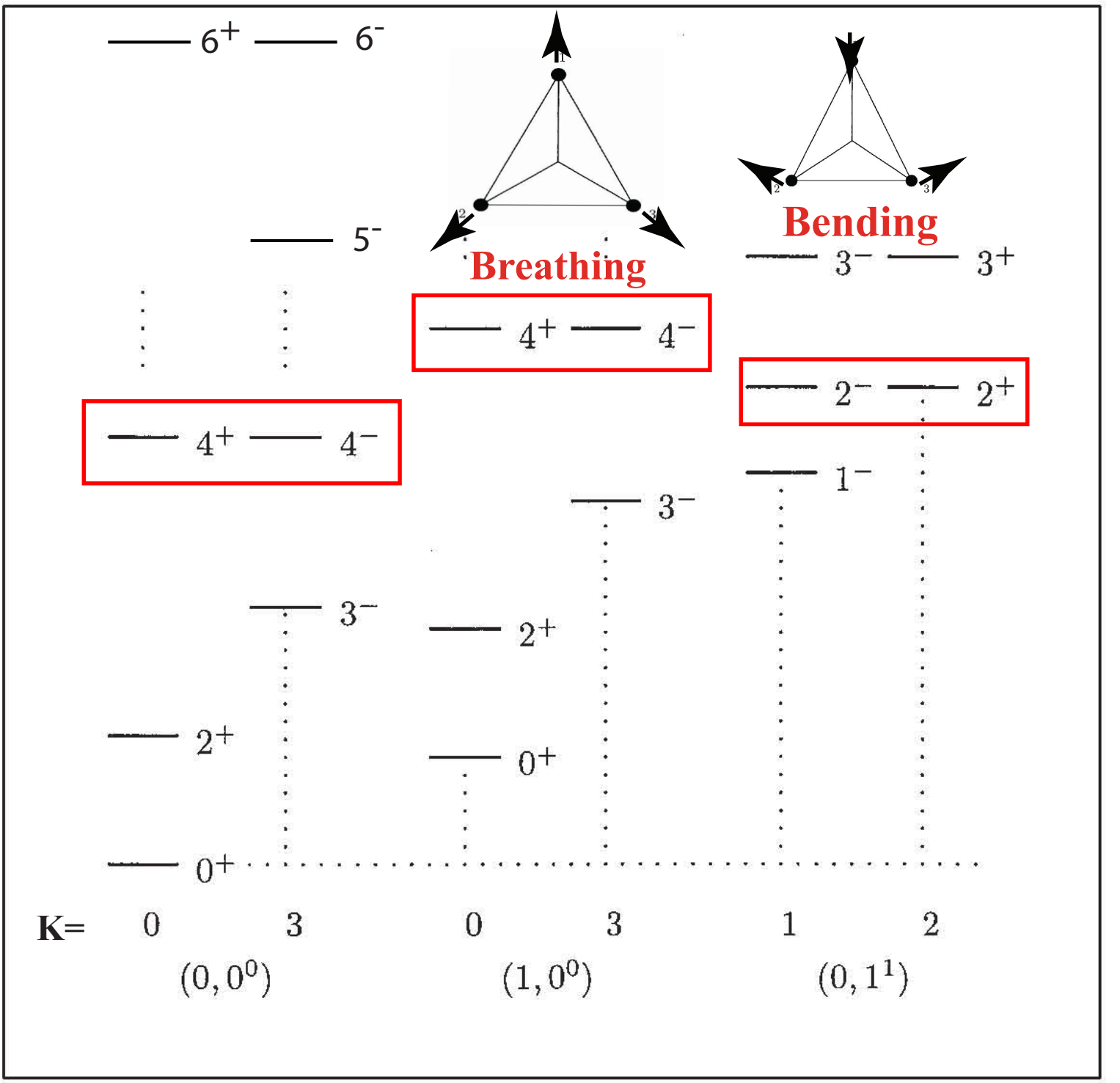
Plus three reflections

Plus horizontal: D_{3h} Symmetry

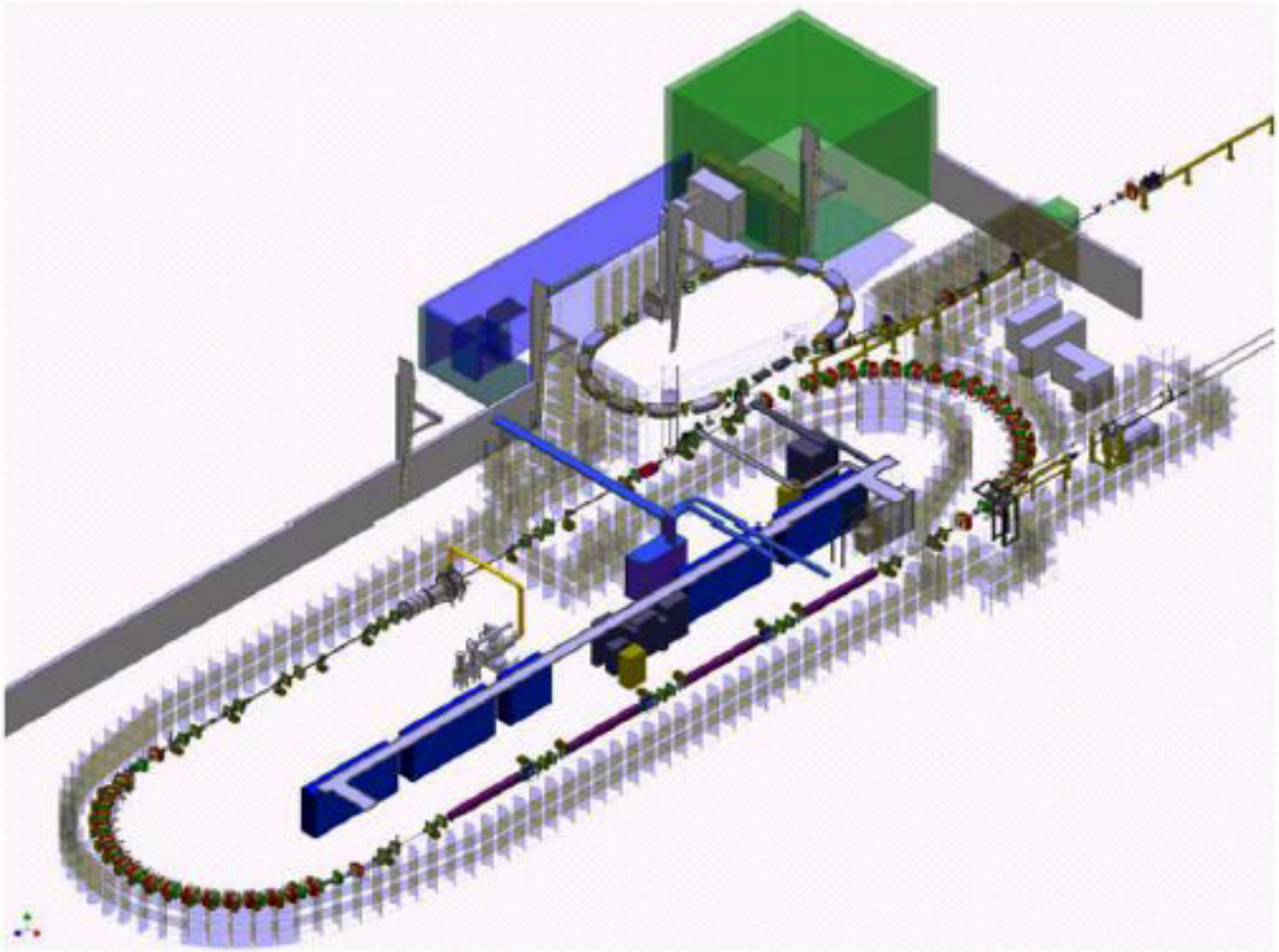
Rotation-Vibration Spectrum of the Three Alpha Triangular Spinning Top

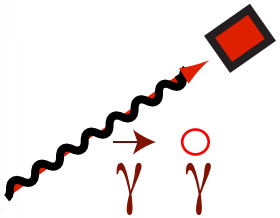
U(7) Model/ D_{3h} Symmetry

R. Bijker and F. Iachello; Ann. Phys. **298**(2002)334

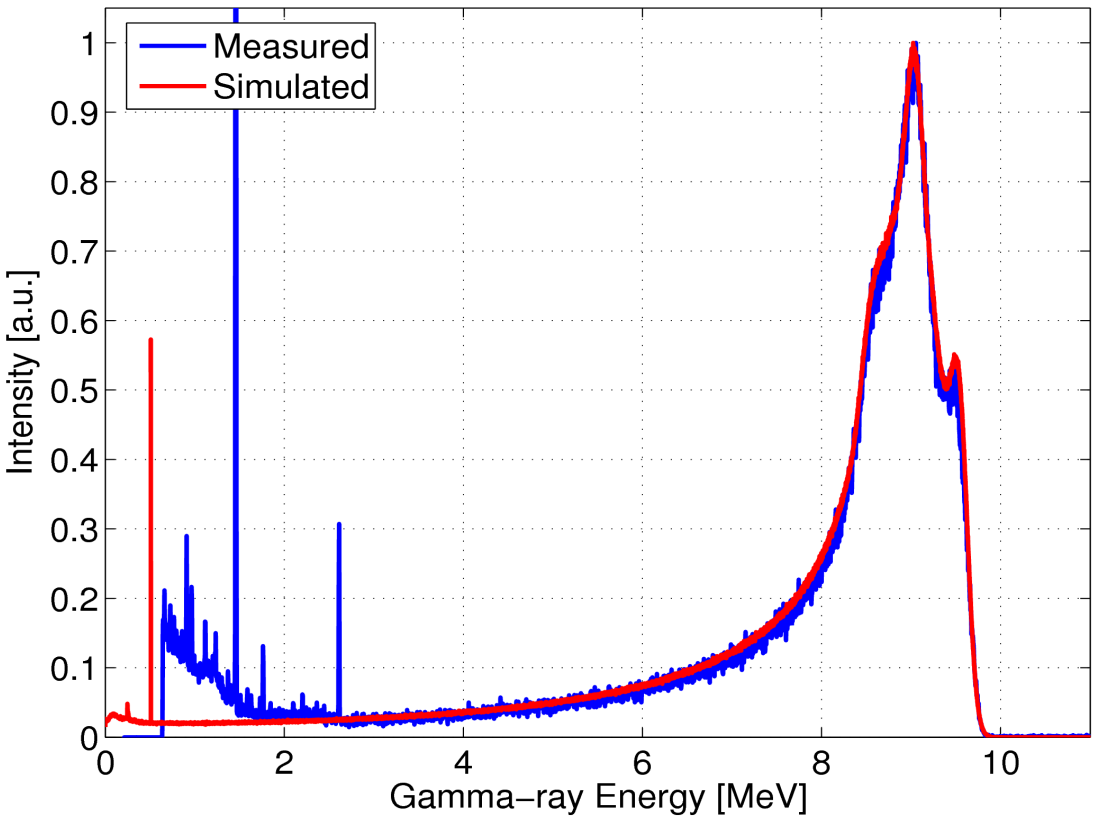


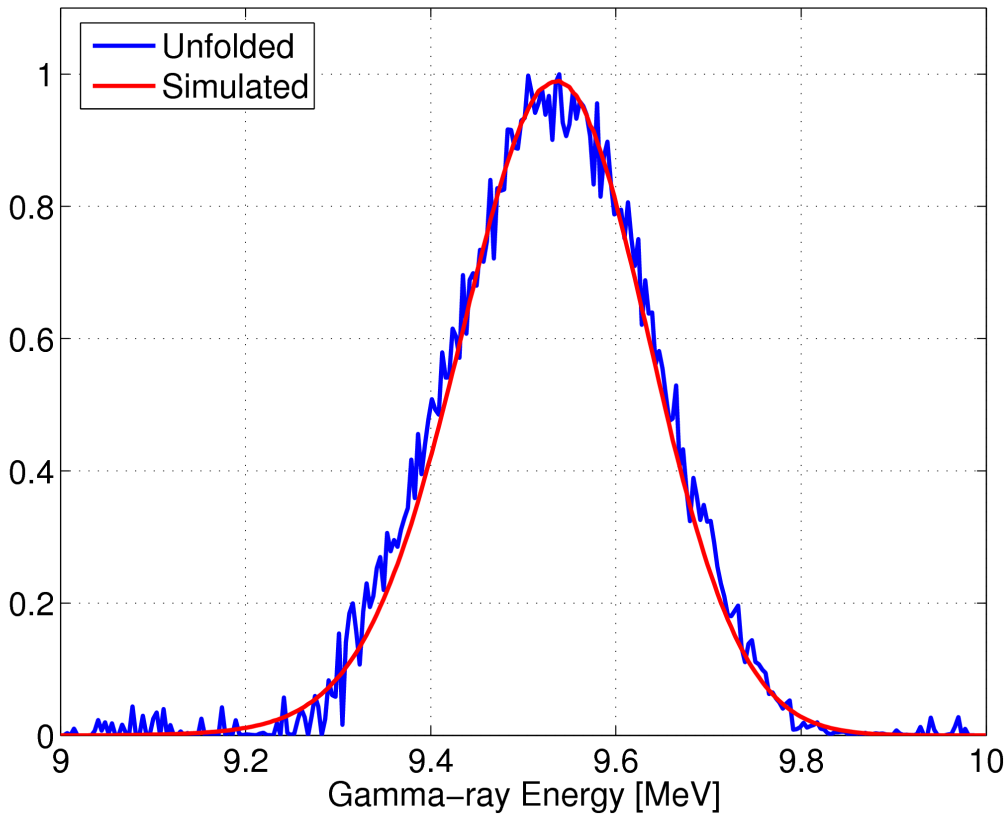
DFELL & HIGS





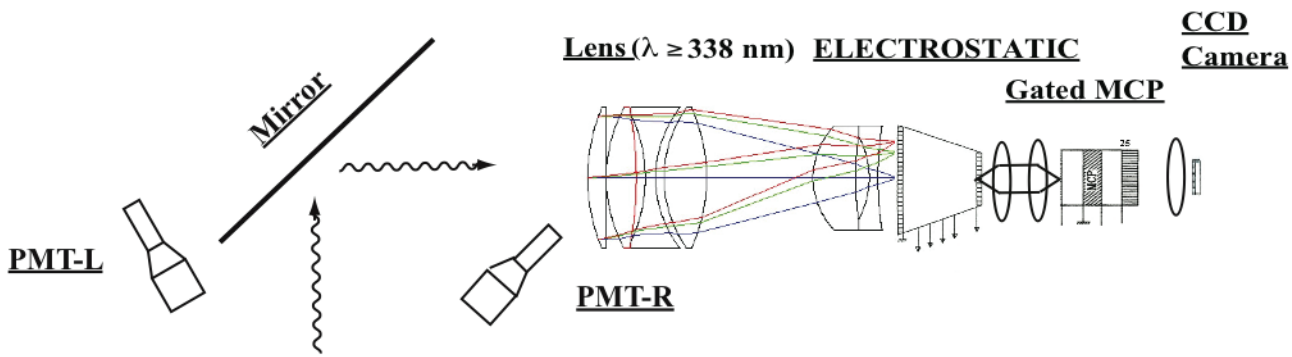
9.55 MeV

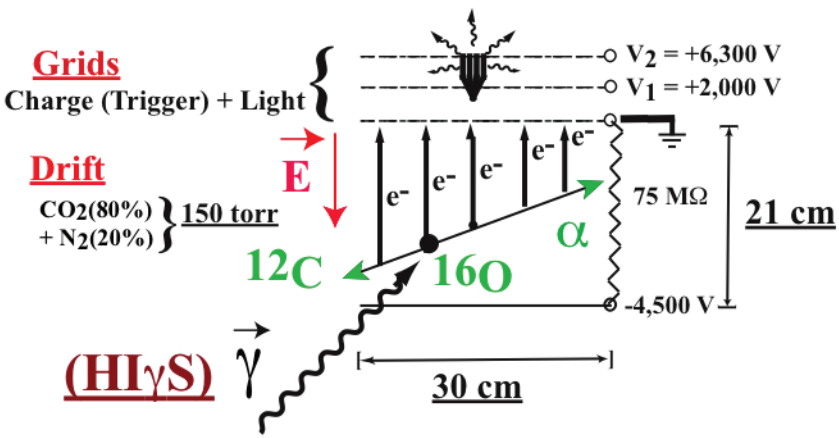

Measured
Simulated
Intensity [a.u.]
Gamma−ray Energy [MeV]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
2
4
6
8
10


Unfolded
Simulated
Gamma−ray Energy [MeV]
0
0.2
0.4
0.6
0.8
1
9
9.2
9.4
9.6
9.8
10

Optical Readout TPC (O-TPC)

Opto-Electronic Chain



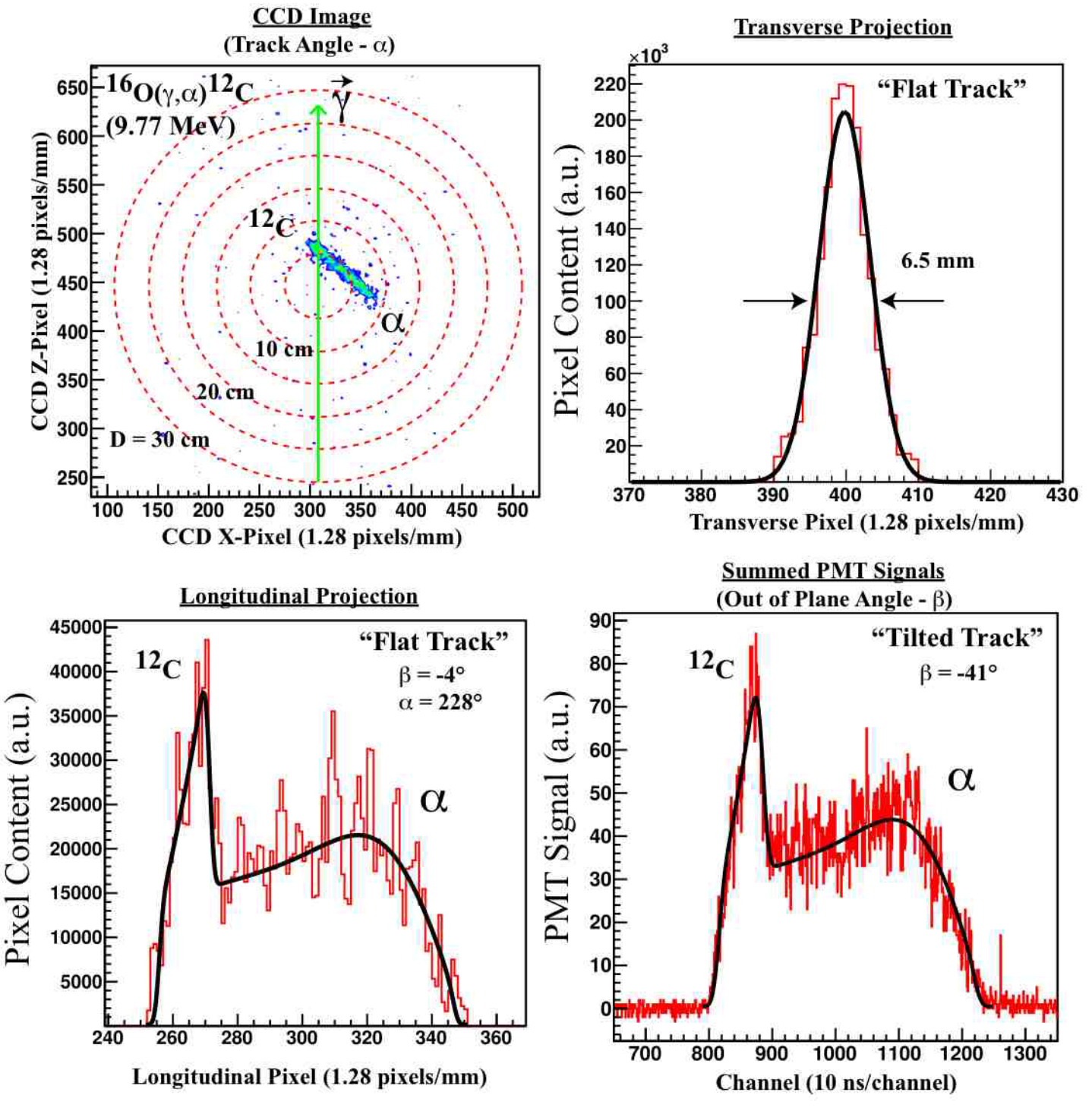


Multiplication

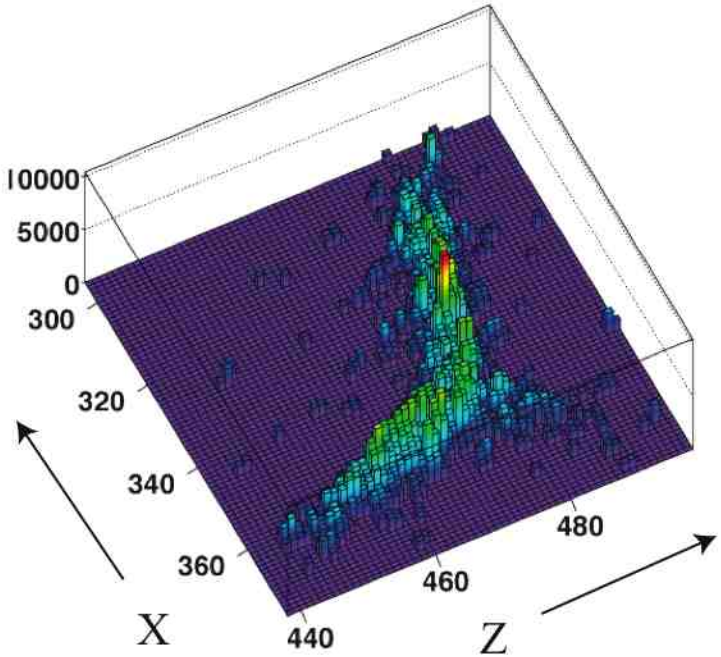
Drift

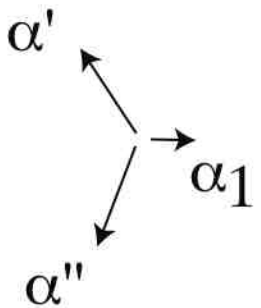
O-TPC at HIγS at TUNL/ Duke

M. Gai *et al.;* JINST 5(2010)12004

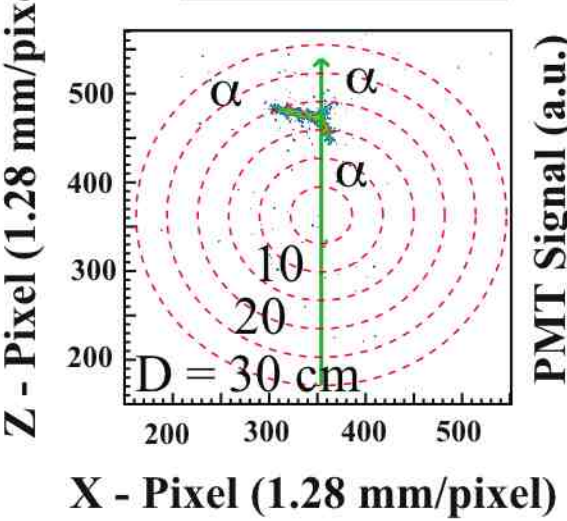


$$10.84\ \text{MeV}\ \vec{\gamma} + {}^{12}\text{C} \longrightarrow {}^{12}\text{C}^*(1^-) \longrightarrow \alpha_1 + {}^{8}\text{Be}^*(3.05)$$

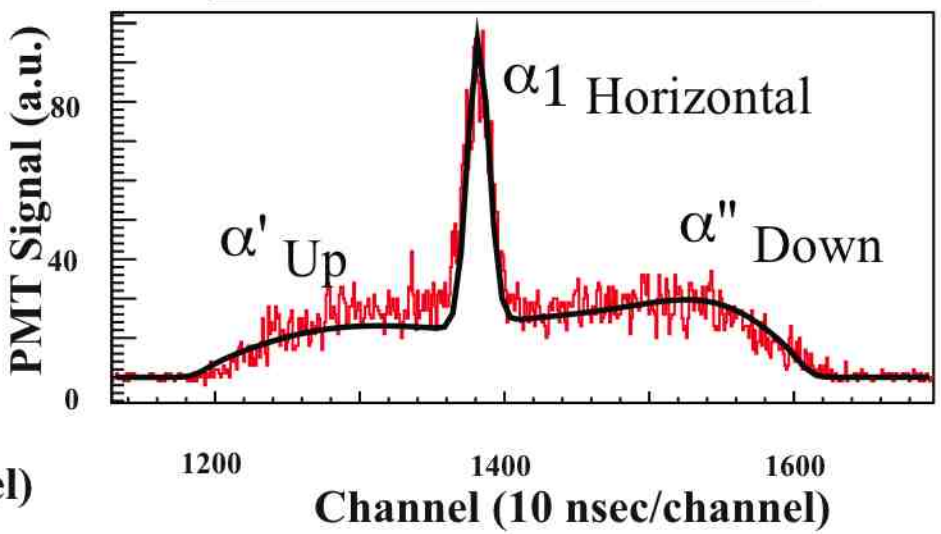




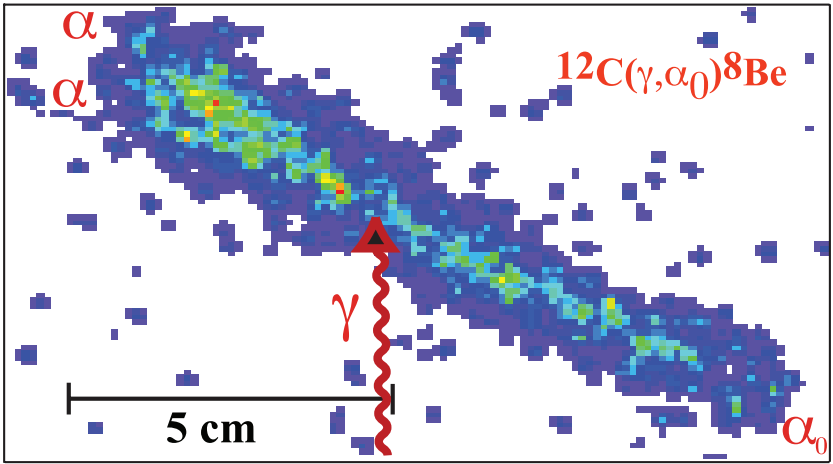
CCD Image

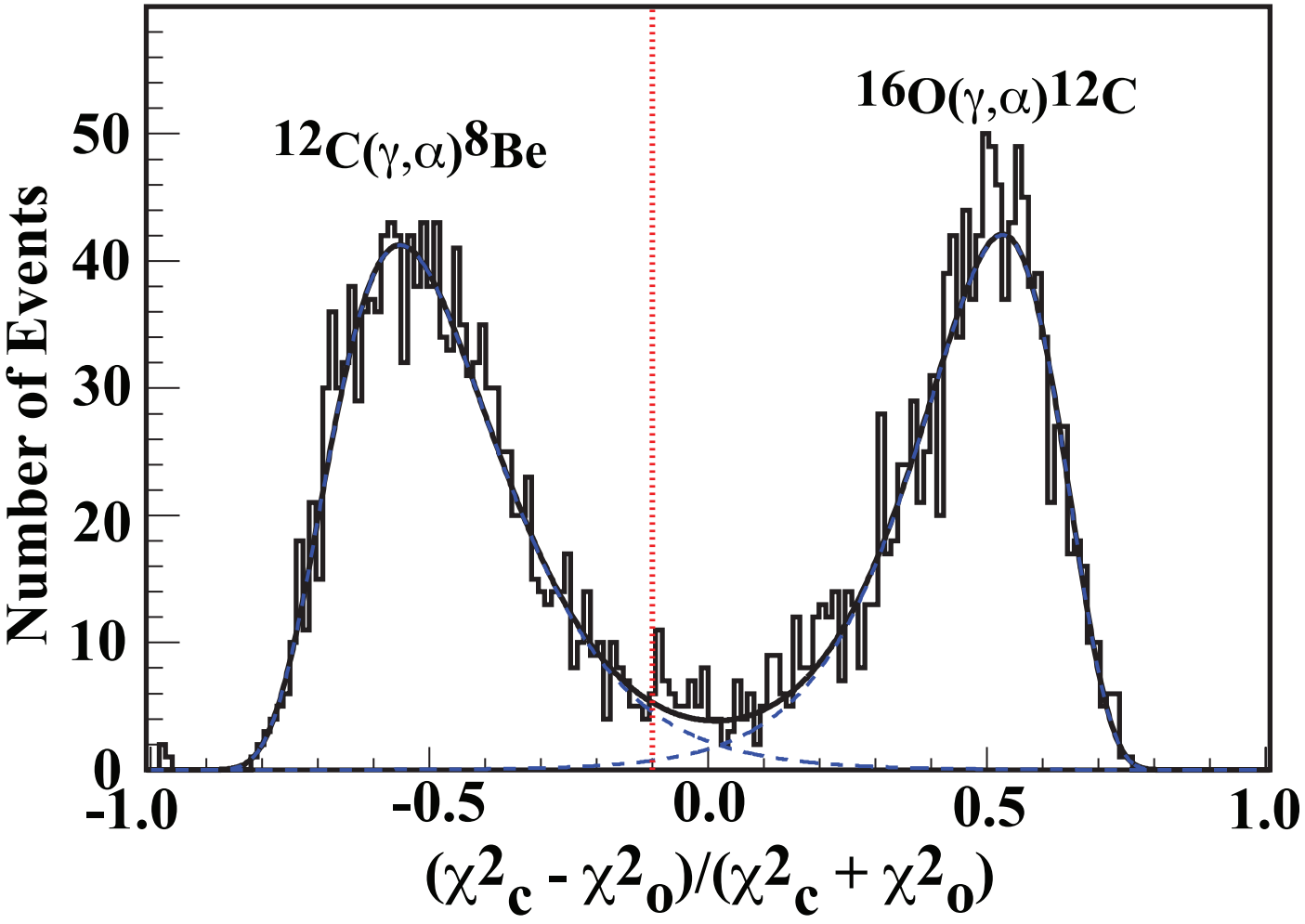


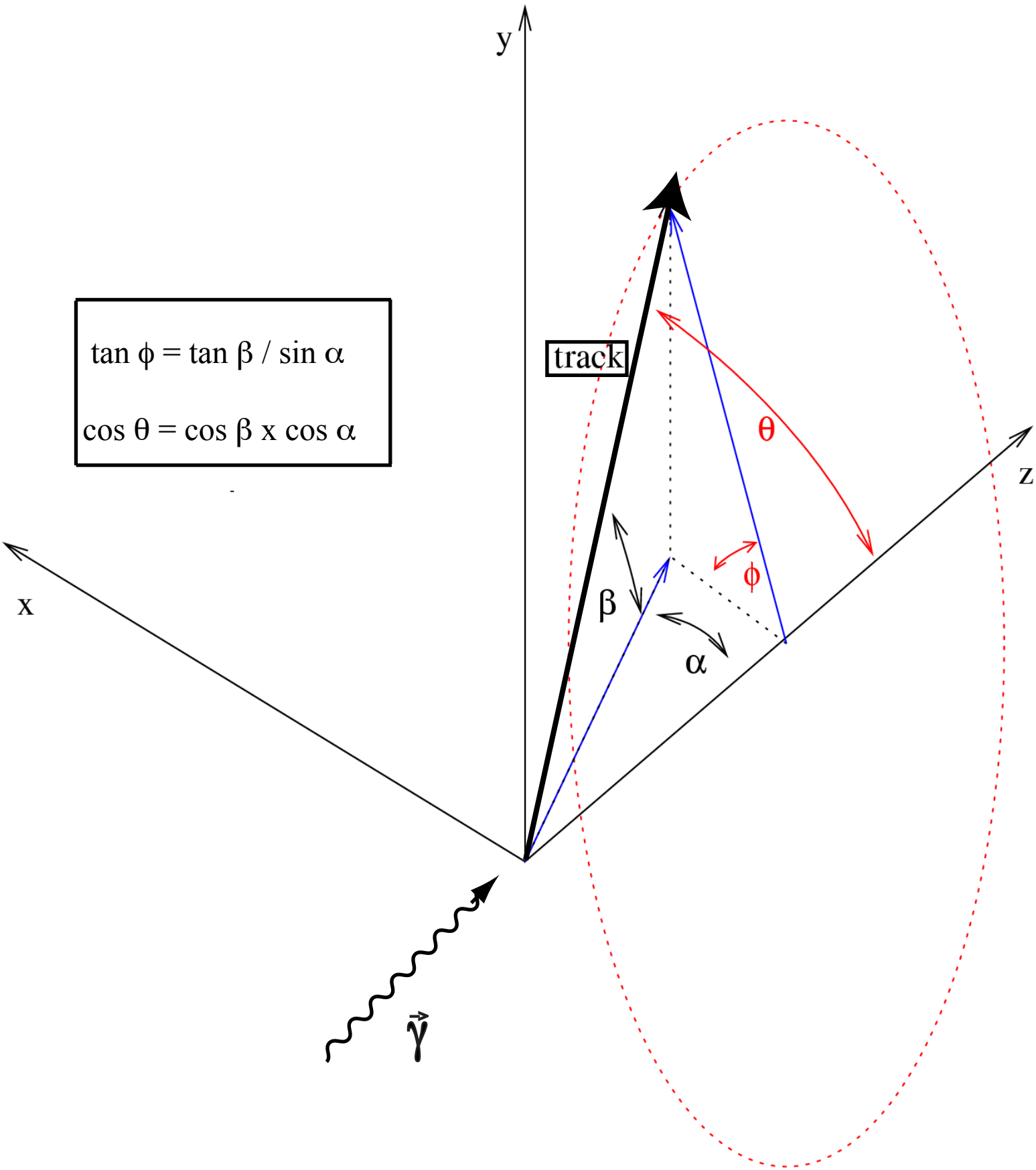
PMT (Time Projection)



W.R. Zimmerman *et al.*; Phys. Rev. Lett. 110(2013)152502



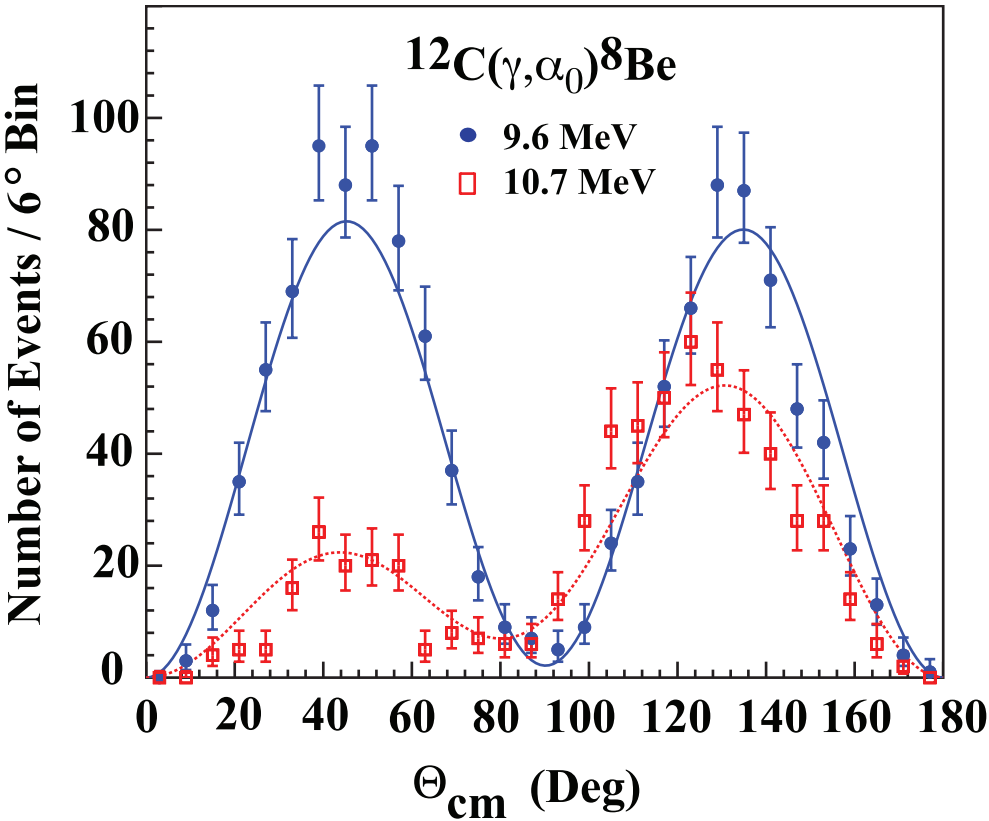

$^{12}C(\gamma,\alpha)^{8}Be$
$^{16}O(\gamma,\alpha)^{12}C$
Number of Events
0
10
20
30
40
50
-1.0
-0.5
0.0
0.5
1.0
$(\chi^2_c - \chi^2_o)/(\chi^2_c + \chi^2_o)$

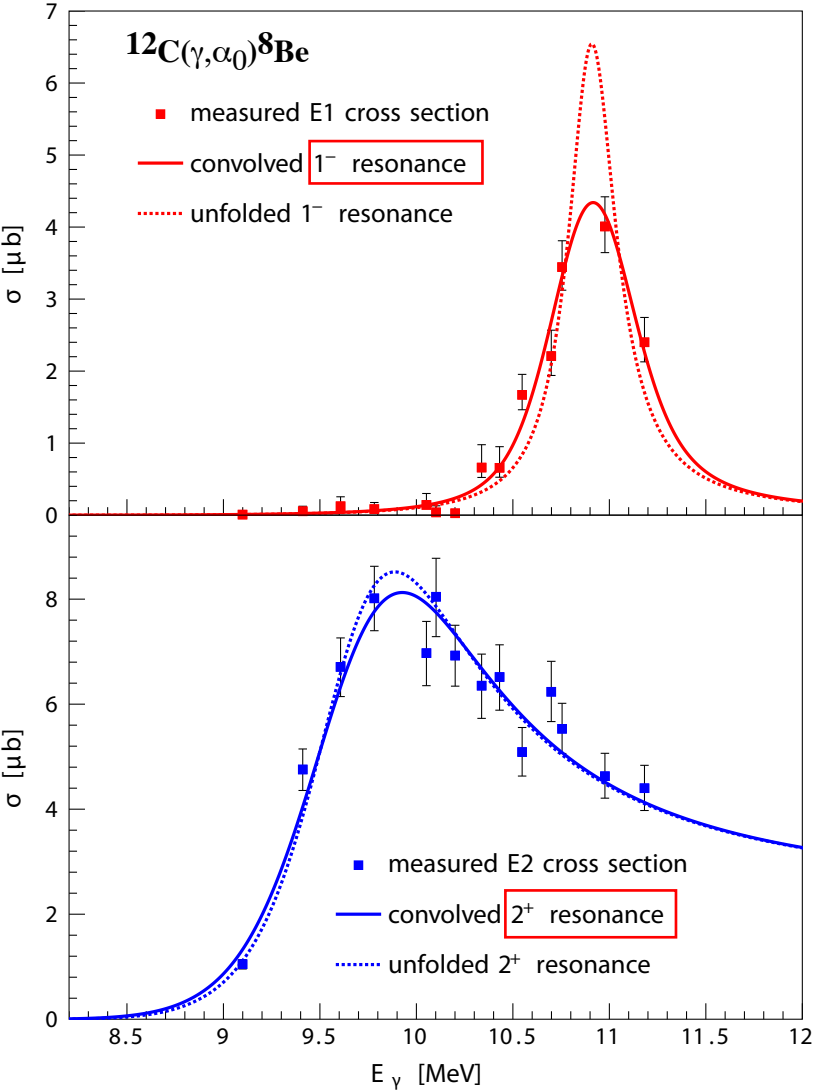


$$\tan \phi = \tan \beta / \sin \alpha$$

$$\cos \theta = \cos \beta \times \cos \alpha$$

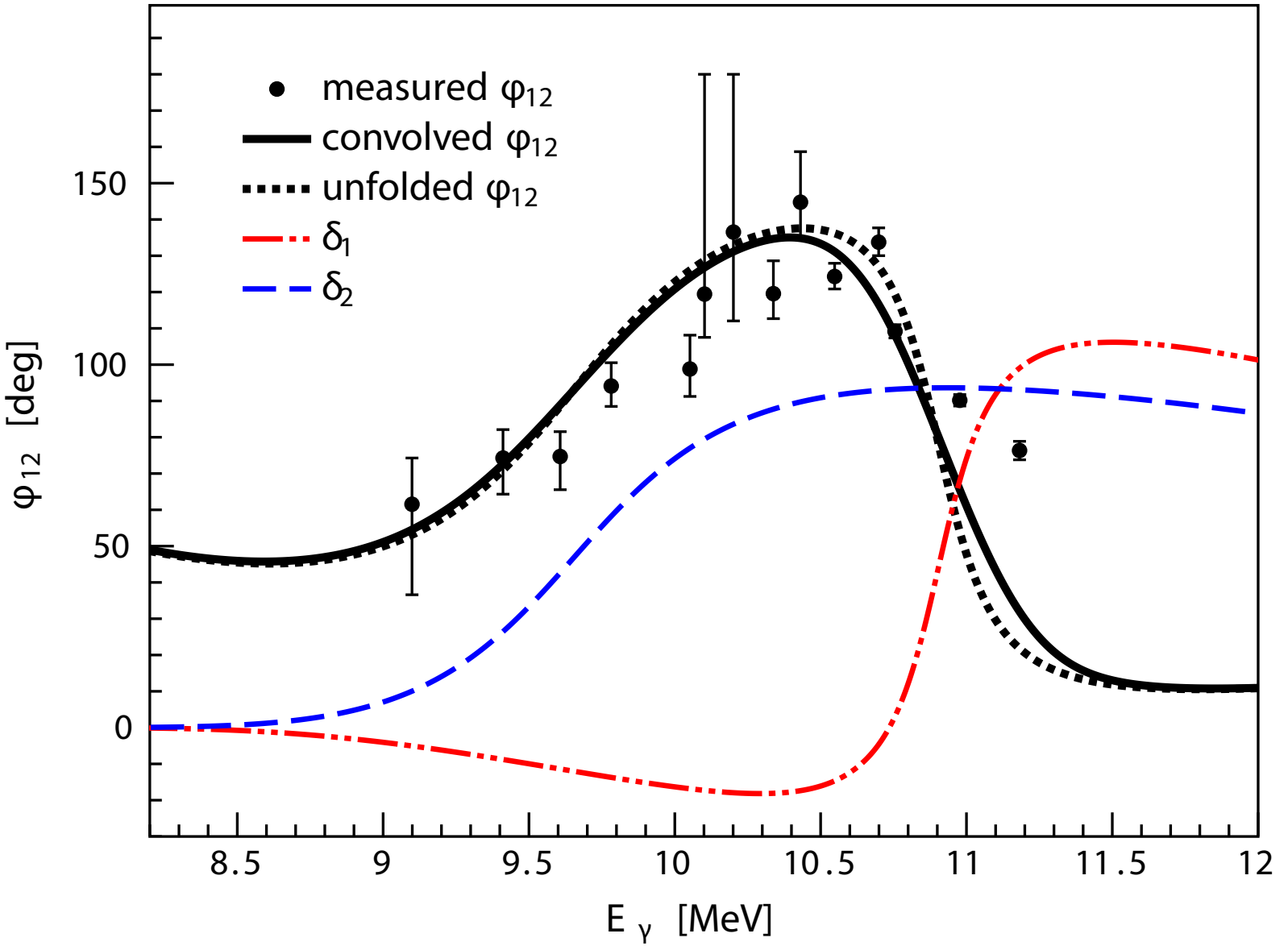
	9.6 MeV	10.7 MeV
E2/(E1+E2) =	0.97 ± 0.02	0.71 ± 0.05
ϕ_{12} =	80 ± 6°	132 ± 5°




$^{12}C(\gamma,\alpha_0)^8Be$
measured E1 cross section
convolved 1⁻ resonance
unfolded 1⁻ resonance
σ [μb]
measured E2 cross section
convolved 2⁺ resonance
unfolded 2⁺ resonance
σ [μb]
E γ [MeV]

W.R. Zimmerman *et al.*; Phys. Rev. Lett. 110(2013)152502

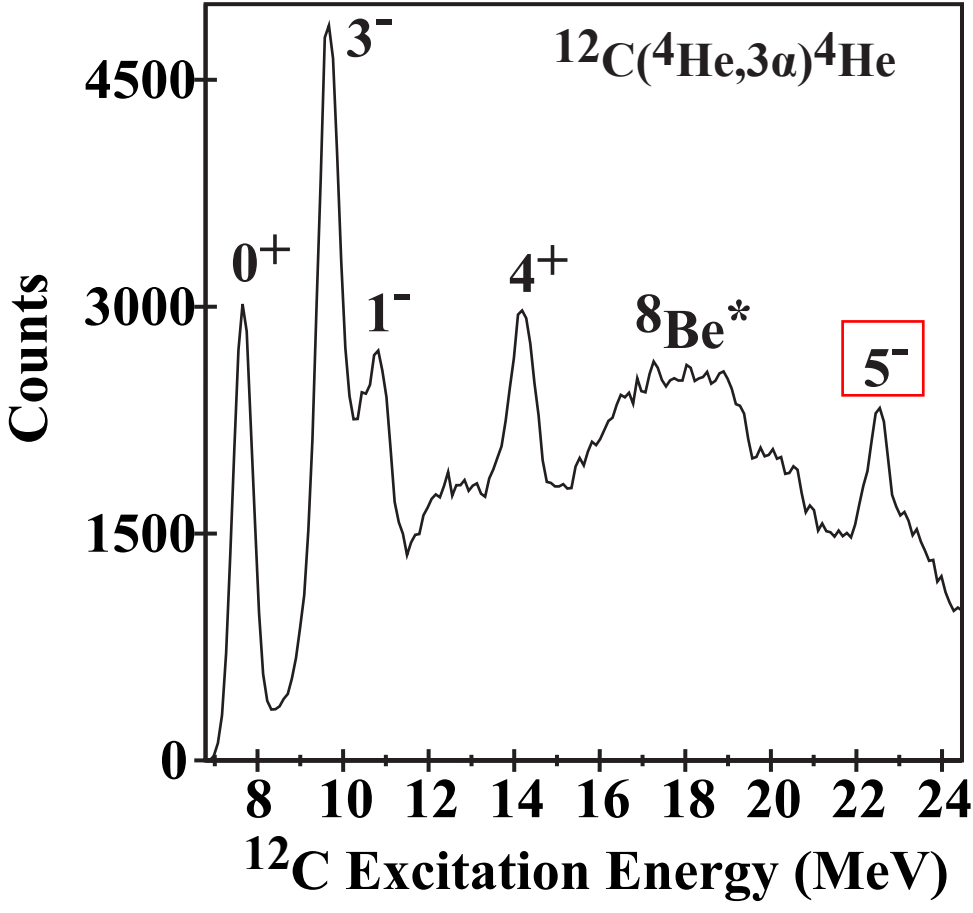
$$\phi_{12} = \delta_2 - \delta_1 + \arctan(\eta/2)$$



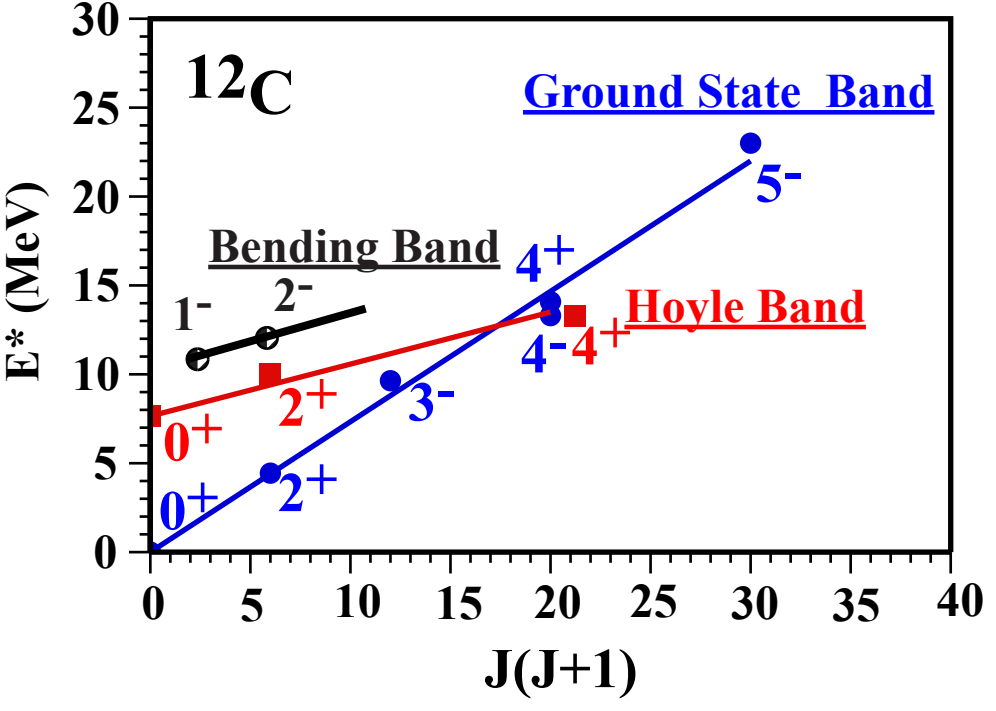
Birmingham Measurement:

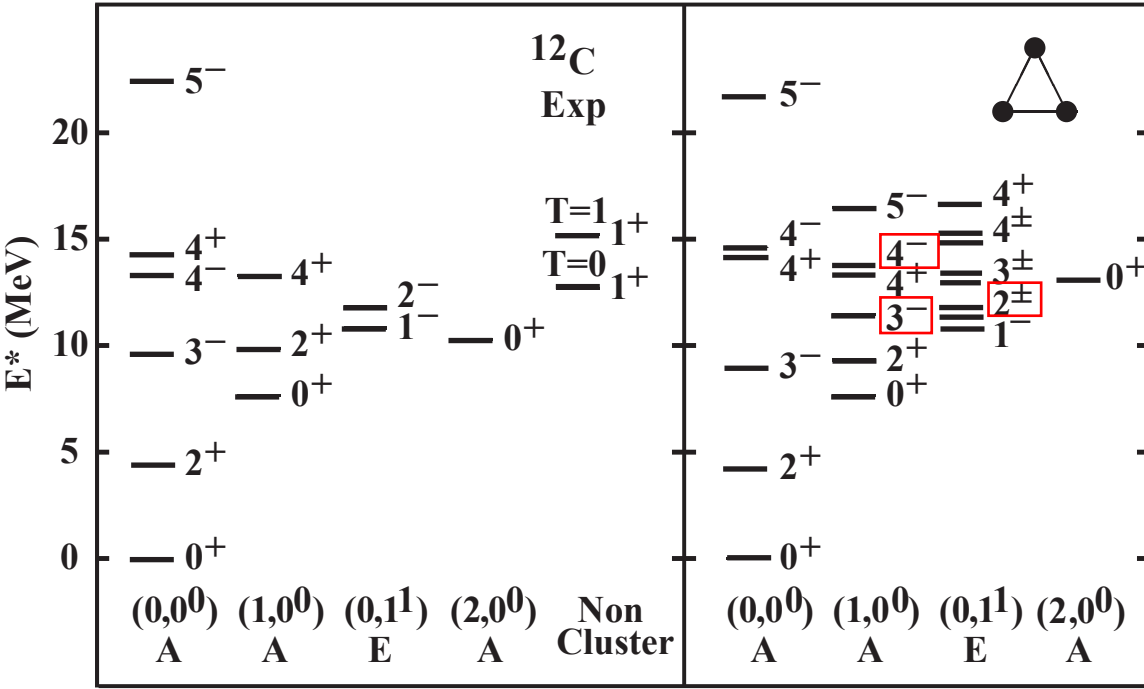
D.J. Marin-Lambarri, R. Bijker, M. Freer, M. Gai, Tz. Kokalova, D.J. Parker, C. Wheldon

Phy. Rev. Lett. 113, 012502 (2014)



D.J. Marin-Lambarri, R. Bijker, M. Freer, M. Gai, Tz. Kokalova, D.J. Parker, C. Wheldon, Phys. Rev. Lett. 113, 012502 (2014)




12C
Exp
E* (MeV)
20
15
10
5
0
5−
4+
4−
3−
2+
0+
4+
2+
0+
2−
1−
0+
T=1
1+
T=0
1+
(0,00)
A
(1,00)
A
(0,11)
E
(2,00)
A
Non
Cluster
5−
4−
4+
3−
2+
0+
5−
4−
4+
3−
2+
0+
4+
4±
3±
2±
1−
0+
(0,00)
A
(1,00)
A
(0,11)
E
(2,00)
A

PHYSICAL REVIEW C **76**, 034320 (2007)

Reexamination of the excited states of ^{12}C

M. Freer,[1] I. Boztosun,[2,*] C. A. Bremner,[2] S. P. G. Chappell,[2] R. L. Cowin,[3] G. K. Dillon,[3] B. R. Fulton,[3] B. J. Greenhalgh,[3] T. Munoz-Britton,[1] M. P. Nicoli,[1] W. D. M. Rae,[2] S. M. Singer,[1] N. Sparks,[1] D. L. Watson,[3] and D. C. Weisser[4]

[1]*School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom*

[2]*Nuclear and Astrophysics Laboratory, University of Oxford, Keble Road, Oxford OX1 3RH, United Kingdom*

[3]*Department of Physics, University of York, Heslington, York YO10 5DD, United Kingdom*

[4]*Department of Nuclear Physics, The Australian National University, Canberra ACT 0200, Australia*

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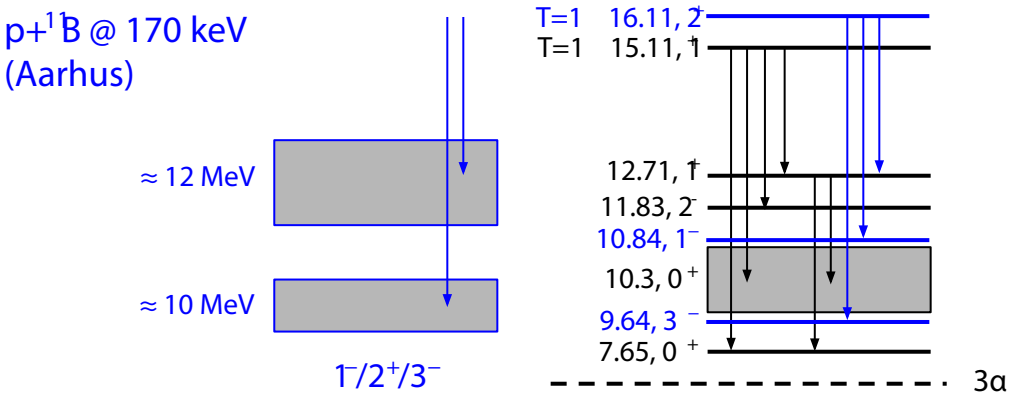
An analysis of the ^{12}C(^{12}C, 3α)^{12}C reaction was made at beam energies between 82 and 106 MeV. Decays to both the ground state and the excited states of ^{8}Be were isolated, allowing states of different characters to be identified. In particular, evidence was found for a previously observed state at 11.16 MeV. An analysis of the angular distributions of the unnatural parity states at 11.83 and 13.35 MeV, previously assigned $J^{\pi} = 2^{-}$, calls into question the validity of these assignments, suggesting that at least one of the states may correspond to $J^{\pi} = 4^{-}$. Evidence is also found for 1^{-} and 3^{-} strengths associated with broad states between 11 and 14 MeV.

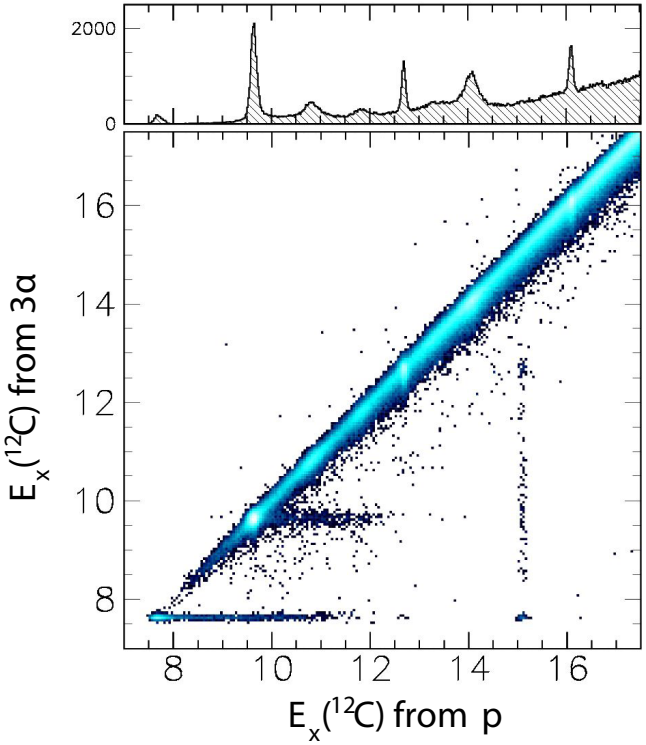
DOI: 10.1103/PhysRevC.76.034320 PACS number(s): 25.70.Ef, 25.70.Mn, 27.20.+n

What can we do with these data?

Example 4:

Indirectly observe gamma transitions between unbound states





Laursen et al. J. Phys. Conf. Ser. 569 (2014) 012073

Kirsebom et al. PLB 680 (2009) 44-49

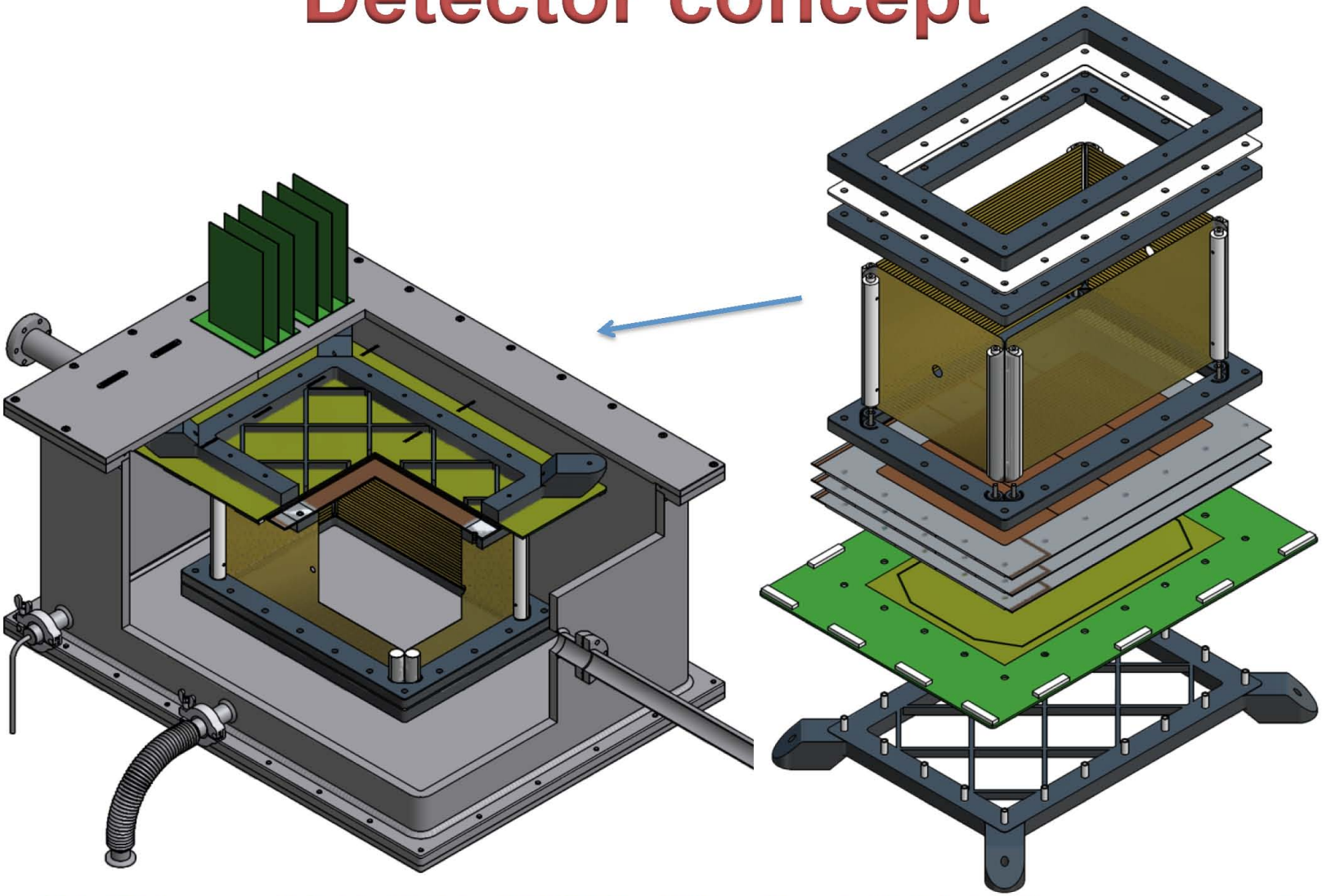
ELI-NP, July 18, 2014, Magurele, Bucharest, Romania

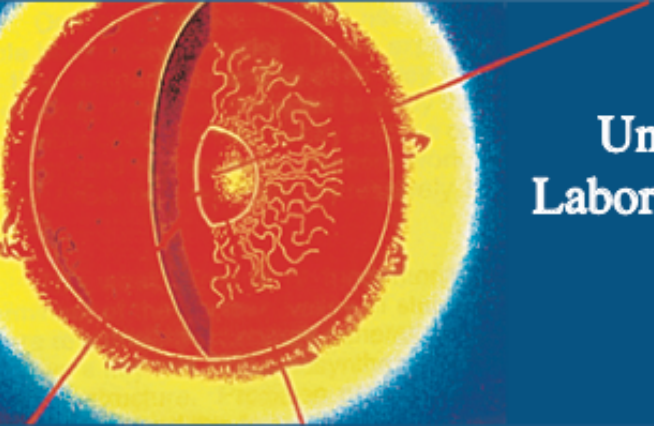
ELI-NP December 24, 2015

Warsaw-UConn-ELI eTPC

W. Dominik, M. Cwiok (Warsaw) *et al.*
(Charged Particle Working Group: GB-TDR#4)

Detector concept





University of Connecticut
Laboratory for Nuclear Science
at Avery Point

Conclusions and Outlook/ Future

The Equi-Lateral Triangle Configuration $\mathcal{D}_{3h}$ Symmetry:

All states below ~15 MeV in ^{12}C are accounted for.
(Except for non-cluster 1^+ states)
Confirmed the Ground State Rotational Band:
$J^\pi = 0^+, 2^+, 3^-, 4^\pm, 5^-$

Hoyle Rotational Band: 3^- and 4^-?
Will determine geometry of Hoyle State
(equilateral, obtuse, etc.)

New Chapter of the Cluster Model

We Still Do Not Fully Understand the Hoyle State
(Our Very Existence… Anthropic View…).

Great Future for ELI-NP and HIγS
$^{12}C(e,e')$ Measurement at the S-DALINAC
B(E2), B(E3), B(E4), missing 2^-, 3^-, 4^-