On the breakup of ^{12}C resonances into three α particles

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Erice, October 2011

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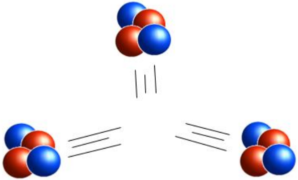
Graphical illustration



α clustering in nuclei

(historical introduction)

Very early days of nuclear physics

At that time* one was tempted to consider alpha particles as basic building blocks of nuclei. However, from those days a warning from Schrödinger still persists in my mind. During the late twenties he chided the participants in a Berlin seminar for their lack of imagination. In his impulsive manner he said: **"Just because you see alpha particles coming out of the nucleus, you should not necessarily conclude that inside they exist as such."**

(J. Hans D. Jensen, Nobel lecture 1963)

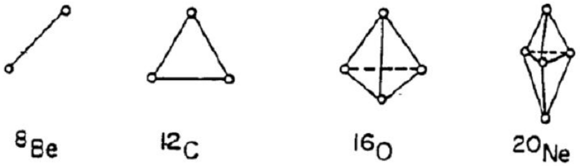
* Late 1920s

J. Hans D. Jensen

E. Schrödinger

Birth of the α-cluster model

Bethe and Bacher (1936)
Wefelmeier (1937)
Wheeler (1937)
von Weizsäcker (1938)



Constant per-bond energy?

Example: ^{12}C

7.28 MeV / 3 bonds = 2.4 MeV per bond

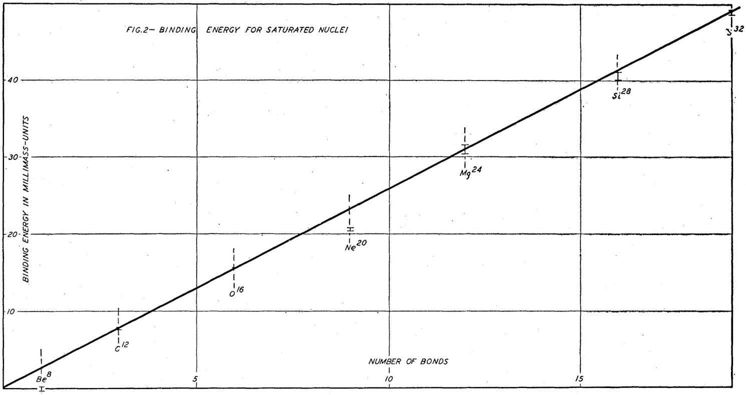


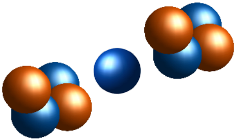
FIG. 2. Binding energy for saturated nuclei.

Valence nucleon/hole

Hafstad and Teller (1938)

The alpha cluster model is extended to cases where one additional nucleon is present or missing from the complete $N\alpha$ structure

$$^{9}\text{Be} = n + \alpha + \alpha$$



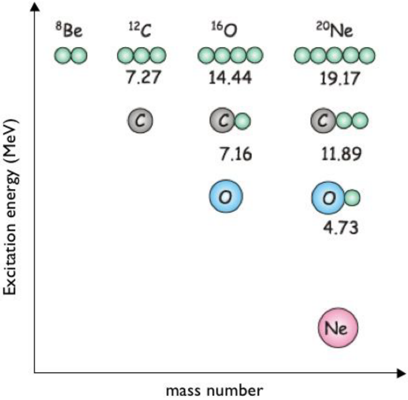
binding $\approx$ 1.6 MeV

E. Teller

New understanding

"The alpha particle loses its identity in the compact nucleus"

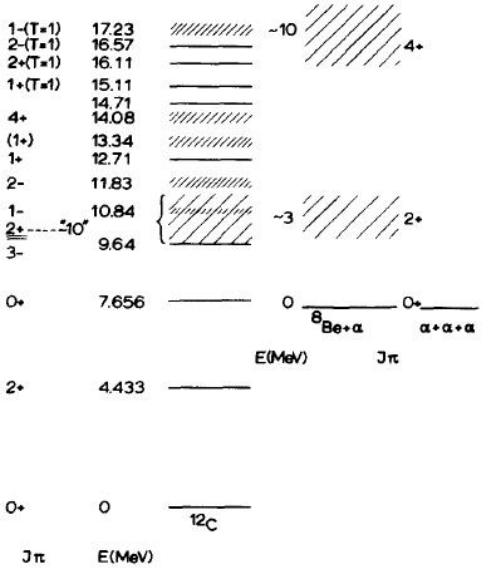
Ikeda, Takigawa, Horiuchi (1968)



α clustering in ^{12}C

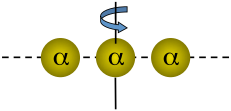
F. Hoyle

1953



H. Morinaga

1956



Claims of observation

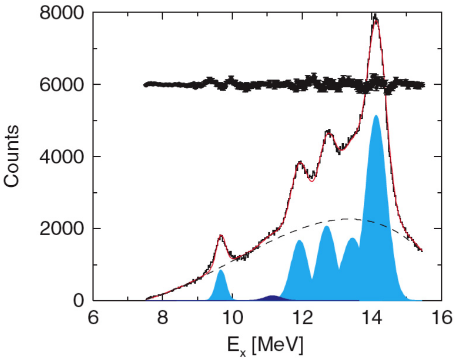
Table: Claims of observation of the 2^+ rotational excitation of the Hoyle state

Ref.	Exp. method	E (MeV)	Γ (MeV)
John *et al.* (2003)	$^{12}C(\alpha, \alpha')$	11.46	0.43
Itoh *et al.* (2004)	$^{12}C(\alpha, \alpha')$	9.9	1.0
Freer *et al.* (2007)	$^{12}C(^{12}C, 3\alpha)^{12}C$	11.16	$\cdots$
Freer *et al.* (2009)	$^{12}C(p, p')$	9.6	0.6
Hyldegaard *et al.* (2010)	$^{12}B(, \beta^-)^{12}C(, 3\alpha)$ $^{12}N(, \beta^+)^{12}C(, 3\alpha)$	~ 11	$\cdots$
Freer *et al.* (2011)	$^{12}C(\alpha, 3\alpha)\alpha$ and $^{9}Be(\alpha, 3\alpha)n$	9.4^*	$\cdots$
Gai (2011)	$^{12}C(\gamma, 3\alpha)$	9.63	1.91
Zimmerman *et al.* (2011)	$^{12}C(p, p')$	9.6	0.5

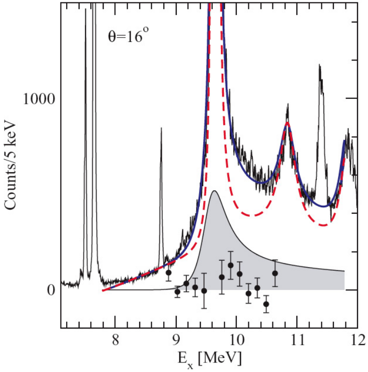
* Inferred from the observation of a possible 4^+ state at 13.3 MeV.

Claims of observation

Freer *et al.* 2007



Freer *et al.* 2009



Characteristics of α-cluster states

- large spatial extension
- large decay width (α preformation factor ~ 1)
- momentum distribution of decay products? *

*only for N-body decays with $N \geq 3$

α decay and nuclear structure

It is remarkable that very little information about nuclear structure could be gained from the study of alpha decay. Max von Laue has pointed this out very clearly in a letter to Gamow in 1926; he congratulated Gamow on his explanation of the Geiger-Nuttal law in terms of the tunneling effect and then went on: **"however, if the alpha decay is dominated by quantum phenomena in the region outside the nucleus, we obviously cannot learn much about nuclear structure from it."**

(J. Hans D. Jensen, Nobel lecture 1963)

J. Hans D. Jensen

G. Gamow

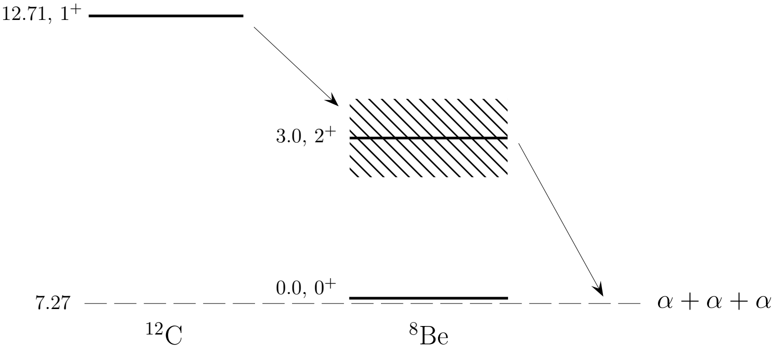
M. von Laue

Theoretical models

Theoretical models

- sequential
- democratic (direct)
- three-body

Sequential



Sequential

Physical ingredients:

- *R*-matrix parametrization of α-α resonance ($^8\mathrm{Be}_{2^+}$)
- angular correlations due to spin-parity conservation
- symmetrization of decay amplitude

$$f = \sum_{m_b} (\ell\ m_a - m_b\ j_b m_b | j_a m_a) Y_\ell^{m_a - m_b}(\Theta_1, \Phi_1) Y_{\ell'}^{m_b}(\theta_2, \phi_2) \times \frac{\sqrt{\Gamma_1 \Gamma_2 / \sqrt{E_1 E_{23}}}\, e^{i(\omega_\ell - \phi_\ell)} e^{i(\omega_{\ell'} - \phi_{\ell'})}}{E_0 - \gamma_2^2 [S_{\ell'}(E_{23}) - S_{\ell'}(E_0)] - E_{23} - i\frac{1}{2}\Gamma_2}$$

D. P. Balamuth *et al.*, Phys. Rev. C **10** (1974) 975
H. O. U. Fynbo *et al.*, Phys. Rev. Lett. **91** (2003) 082502

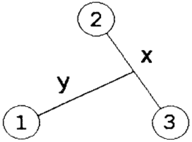
Democratic

- five variables $\{E_1, \Omega_x, \Omega_y\}$
- expand decay amplitude in hyperspherical harmonics

$$f^{JM} = \sum_n B_n \, \Phi_n^{JM}(E_1, \Omega_x, \Omega_y)$$

- hypermomentum $K = \ell_x + \ell_y + 2n$
- three-body centrifugal barrier

$$V_{c.b.} \sim (K + \tfrac{3}{2})(K + \tfrac{5}{2})/\rho^2$$



$$\rho = \sqrt{x^2 + y^2}$$

- only retain lowest-order term allowed by symmetries
- expected to work best for low excitation energies

A. A. Korsheninnikov, Sov. J. Nucl. Phys. **52** (1990) 827

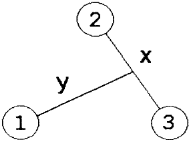
Three-body

- hyperspherical variables $\{\rho, \alpha, \Omega_x, \Omega_y\}$
- expand wave function in hyperspherical harmonics

$\Omega = \{\alpha, \Omega_x, \Omega_y\}$

$$\Psi^{JM} = \rho^{-5/2} \sum_n f_n(\rho)\, \Phi_n^{JM}(\rho, \Omega)$$

- solve Faddeev equations in coordinate space
- phenomenological Ali-Bodmer α-α potential
- three-body short-range potential
- complex scaling method used to compute resonances



$$x = \rho \sin\alpha$$
$$y = \rho \cos\alpha$$

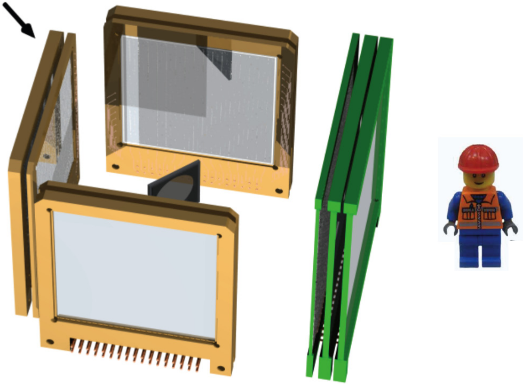
R. Álvarez-Rodríguez *et al.*, Eur. Phys. J. A **31** (2007) 303
and references therein

Experiment

Experimental method and setup

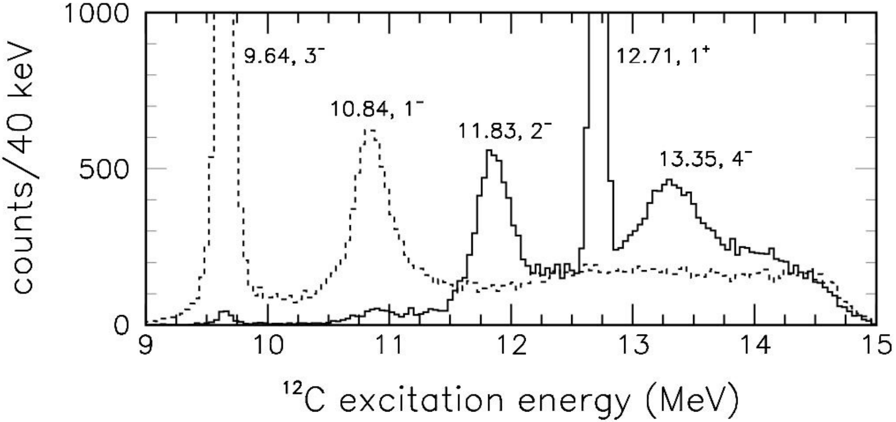
$$^{3}\text{He} + {}^{10}\text{B} \to p + 3\alpha \quad \text{at 4.9 MeV}$$

$$^{3}\text{He} + {}^{11}\text{B} \to d + 3\alpha \quad \text{at 8.5 MeV}$$



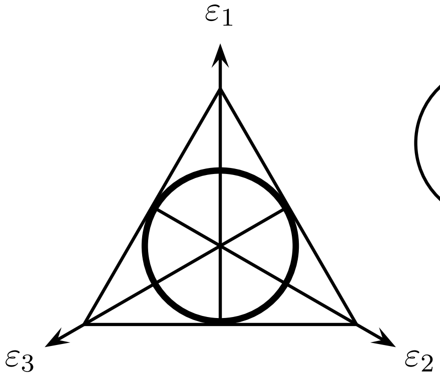
M. Alcorta *et al.*, Nucl. Instr. Meth. A **605** (2009) 318

Excitation spectrum in $^{3}He + ^{11}B \rightarrow d + ^{12}C^{*}$



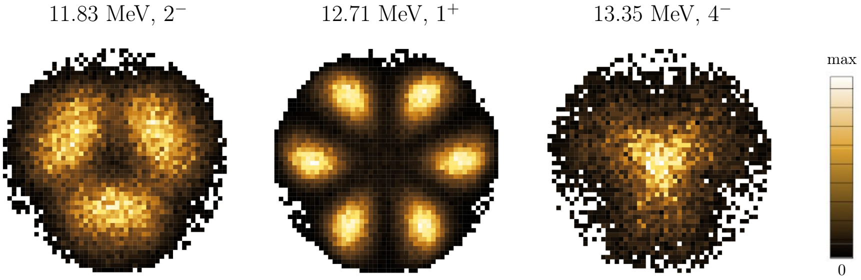
Dalitz-plot analysis technique

Dalitz plot



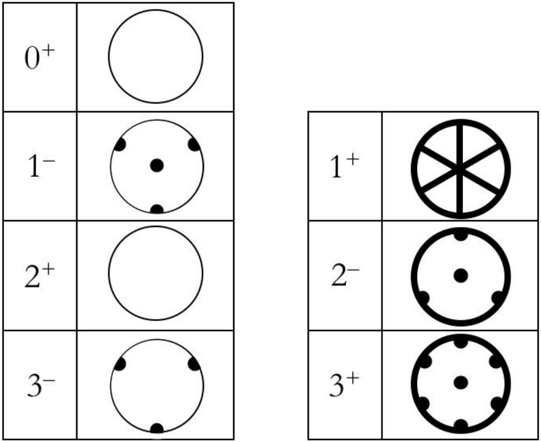
Experimental Dalitz plots

Experimental Dalitz plots for three selected states



What is the origin of the observed structures?

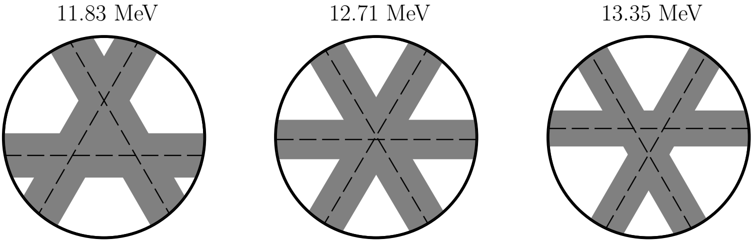
"Forbidden regions" owing to spin-parity conservation and Bose symmetry



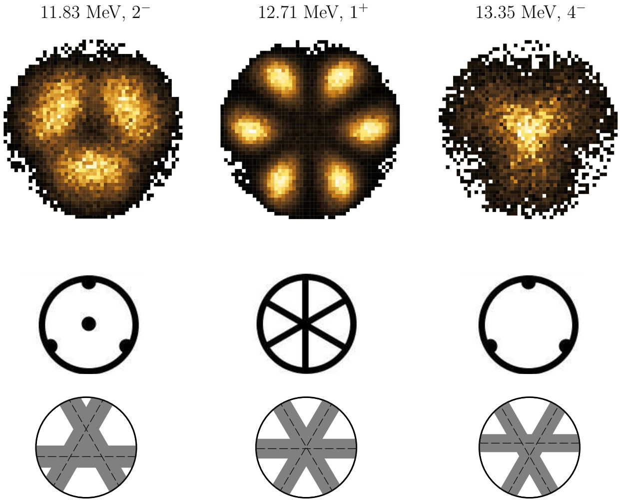
C. Zemach, Phys. Rev. 133 (1964) B1201

Final-state interactions

Bands of increased intensity owing to the $^{8}Be_{2^{+}}$ resonance

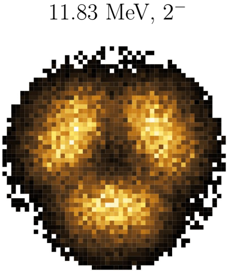


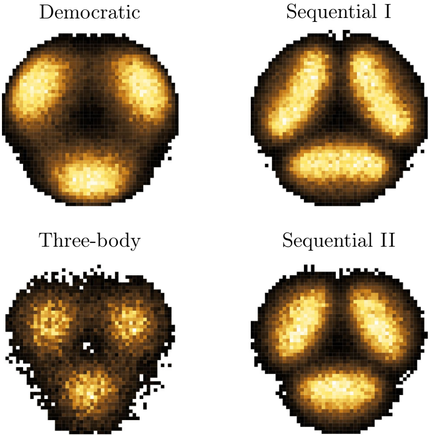
Qualitative analysis



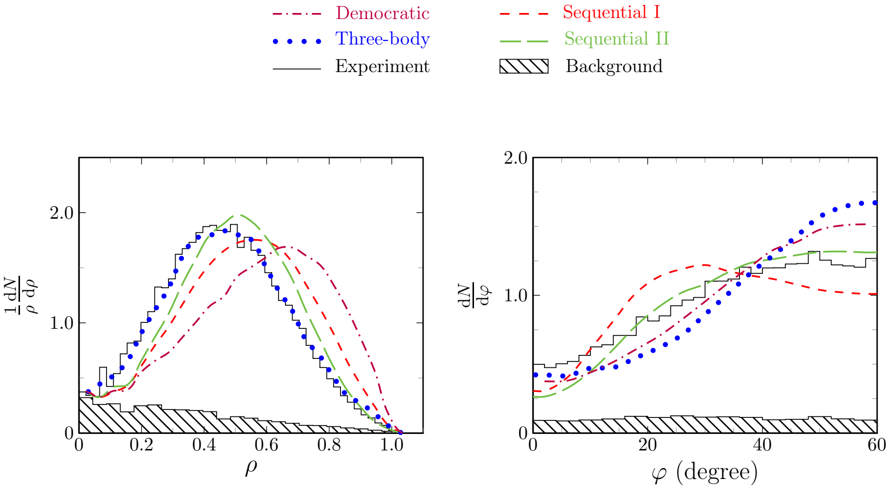
Comparison to models

Quantitave analysis 11.83 MeV, 2^-



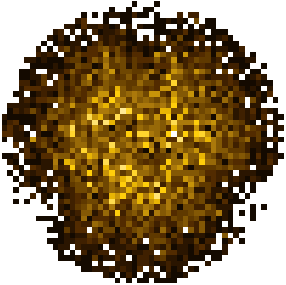


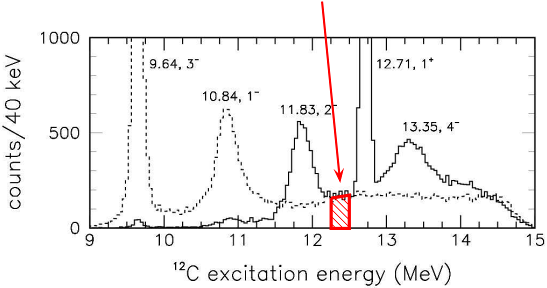
Quantitave analysis 11.83 MeV, 2^-



Broad states

Example of Dalitz plot





Complications

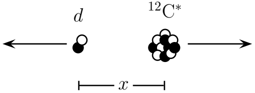
Possible background from

1. $^{3}\text{He} + {}^{11}\text{B} \;\rightarrow\; {}^{8}\text{Be} + {}^{6}\text{Li}^{*} \;\rightarrow\; d + \alpha + \alpha + \alpha$
2. $^{3}\text{He} + {}^{11}\text{B} \;\rightarrow\; \alpha + {}^{10}\text{B}^{*} \;\rightarrow\; d + \alpha + \alpha + \alpha$

Complications

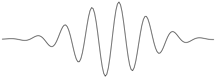
Four-body problem?

- distance separating d and $^{12}C^*$ at time of 3α breakup:
$$x = v\tau = v\hbar/\Gamma$$



- Coulomb energy:
$$E_C = \frac{1.4\, Z_1 Z_2}{x} \text{ fm MeV}$$

- $\Gamma = 0.6\text{–}1$ MeV $\Rightarrow$ $E_C \sim 10\%$ of the decay energy



- $\Gamma = 1\text{–}2$ MeV $\Rightarrow$ $\lambda = h/p \sim x$

Summary

- **Question**

  Is the α momentum distribution sensitive to short-range structure?

- **Methods**

  - Complete kinematics measurement
  - Dalitz-plot analysis (symmetries and final-state interactions)

- **Results**

  Full three-body calculation reproduces the gross structures of the Dalitz distribution, but fails to reproduce the detailed shape
  (effect of short-range structure?)

- **Future**

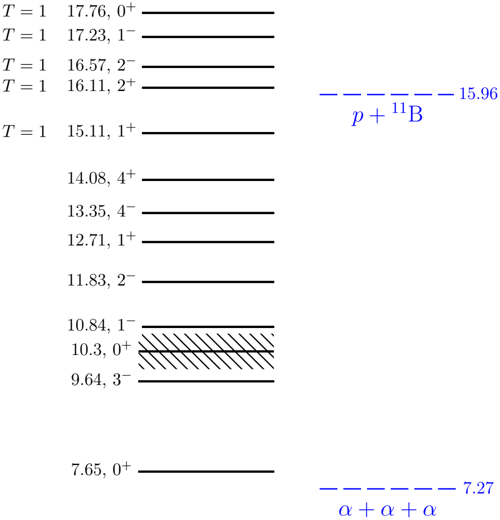
  Apply similar analysis to very broad states

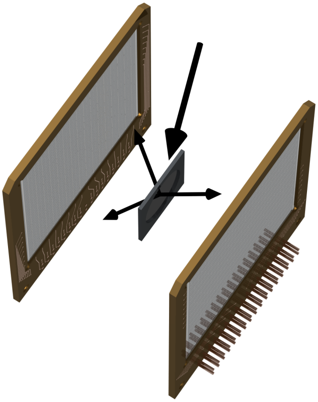
O. S. Kirsebom *et al.*, Phys. Rev. C **81** (2010) 064313

New experiment

(more Dalitz plots)

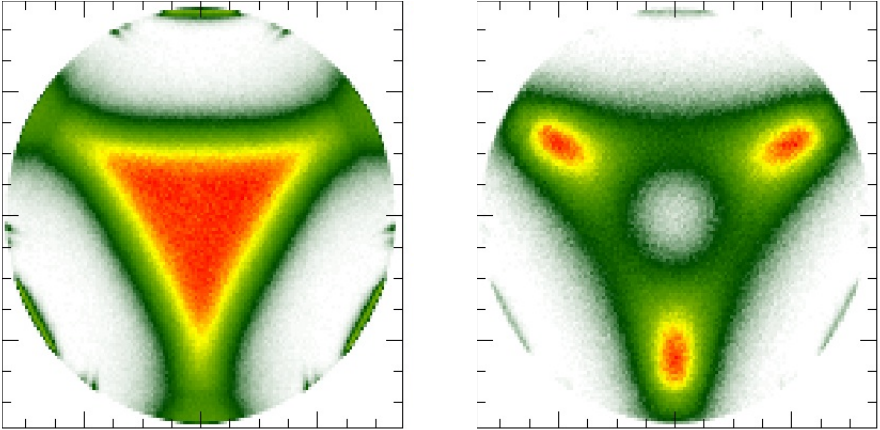
Reaction: $p + {}^{11}\text{B} \rightarrow {}^{12}\text{C}^* \rightarrow 3\alpha$





Dalitz plots

16.11, 2^+ 16.57, 2^-

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Collaboration

O. S. Kirsebom[1], M. Alcorta[2], M. J. G. Borge[2], M. Cubero[2], C. Aa. Diget[3], R. Dominguez-Reyes[2], L. M. Fraile[4], B. R. Fulton[3], H. O. U. Fynbo[1], D. Galaviz[2], S. Hyldegaard[1], K. L. Jensen[1], B. Jonson[5], M. Madurga[2], A. Muñoz Martin[6], T. Nilsson[5], G. Nyman[5], A. Perea[2], K. Riisager[1], O. Tengblad[2] and M. Turrion[2]

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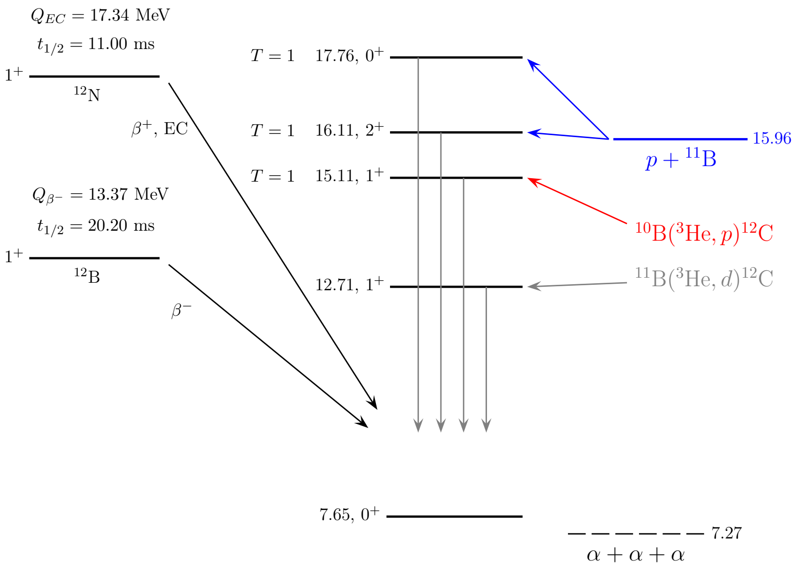
Selective searches for the 2^+ state

(β and γ decay)

β and γ decay in the $A = 12$ system



β and γ decay in the $A = 12$ system