Three-Body Decays of Many-Body Resonances

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Contents

Introduction

Three-body decay is important for studying different decay mechanisms: direct vs. sequential.

Direct decay: all 3 particles leave simultaneously their interaction regions.

Sequential decay: proceeds via an intermediate 2-body configuration.

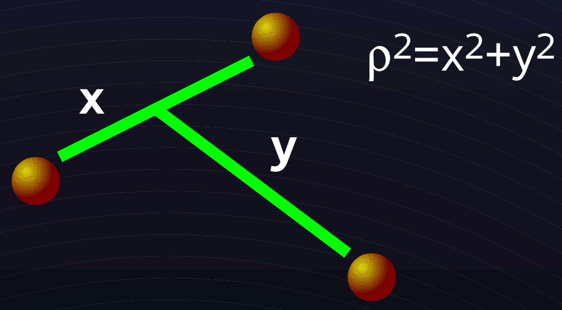
Experimentally energy and momenta of the fragments after the decay carry all the information.

Theoretical Framework

Faddeev equations and complex scaling

The resonances decay into 3 bodies → 3-body problem

We use Faddeev equations and solve them by means of the hyperspherical adiabatic expansion method with complex scaling



We include:

- Short-range potential (Ali-Bodmer between α's)
- Coulomb potential
- Phenomenological 3-body potential corrects the energy of the resonance

Ref. Nielsen et al. Phys. Rep. 347 (2001) 373

Faddeev equations

Faddeev equations describe a 3-body system.

The wave function is written as a sum of three components referred to the three Jacobi coordinates systems

$$\Psi = \sum_{i=1}^{3} \Psi_i$$

Each component satisfies the Faddeev equations

$$(T - E)\Psi_i + V_i(\Psi_i + \Psi_j + \Psi_k) = 0$$

The sum of the 3 Faddeev equations is the Schrödinger equation

Hyperspherical adiabatic expansion method

Coordinates: hyperspherical coordinates $\{\rho,\alpha,\Omega_x,\Omega_y\}$

ρ varies slowly: we fix ρ and solve the angular part:

$$(T_\Omega - \lambda_n)\Phi^{(i)}_{nJM} + \frac{2m}{\hbar^2}\rho^2 V_i \Phi_{nJM} = 0 \qquad i = 1, 2, 3$$

The total wave function is expanded on the hyper-angular eigenfunctions

$$\Psi^{JM} = \frac{1}{\rho^{5/2}} \sum_n f_n(\rho) \Phi_{nJM}(\rho, \Omega)$$

f_n are the hyper-radial wave functions

3-body decay

- ***Energy distributions***: the only experimental information one can get, which allows us to study the decay path

  ❀ The information is contained in the large-distance part of the wave function

  ❀ We integrate the absolute square of the wave function for a large value of ρ

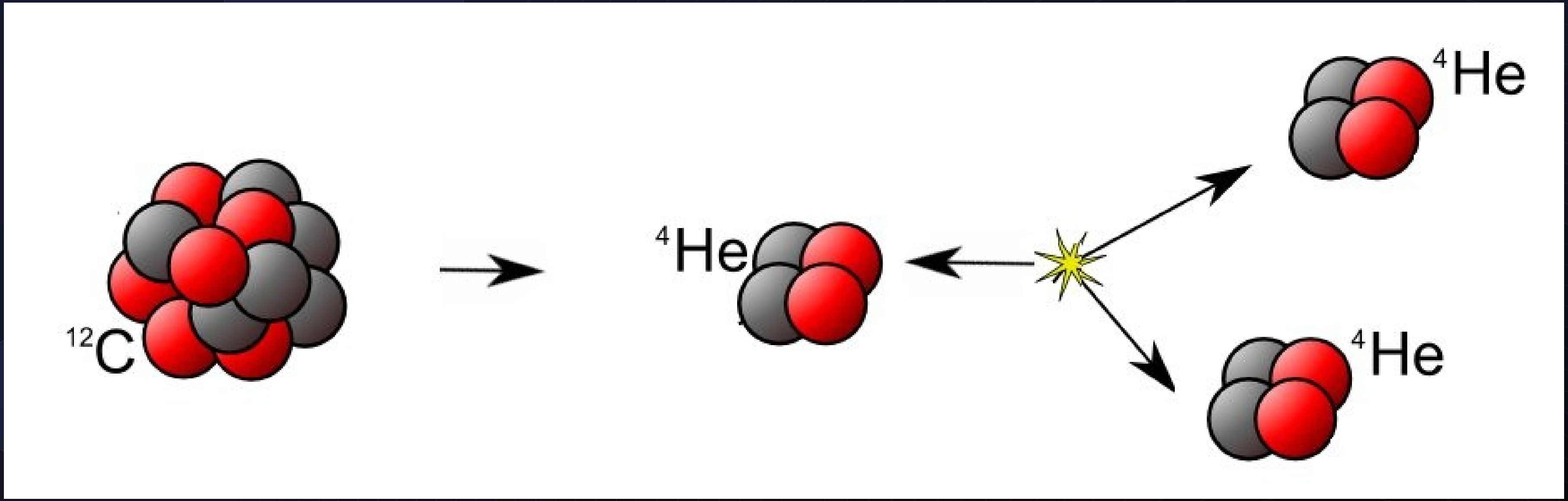
$$\Psi = \sum_{i=1}^{3} \Psi_i$$

- ***Dalitz plots***: contain more information than single energy distributions

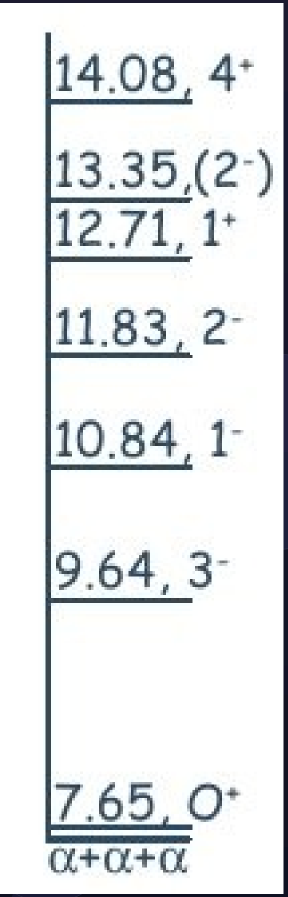
  ❀ This is an easy way to see how the 3 particles share the energy

- ***Angular correlations***: important to assign spin and parity

Part I: ^{12}C



Why ^{12}C?



I.- 3α decay is the time reverse process of triple α reaction in stars.

II.- The low-lying resonance states of ^{12}C have been studied over many years but...

...there are still unanswered questions: what are their energies, angular momenta and decay properties.

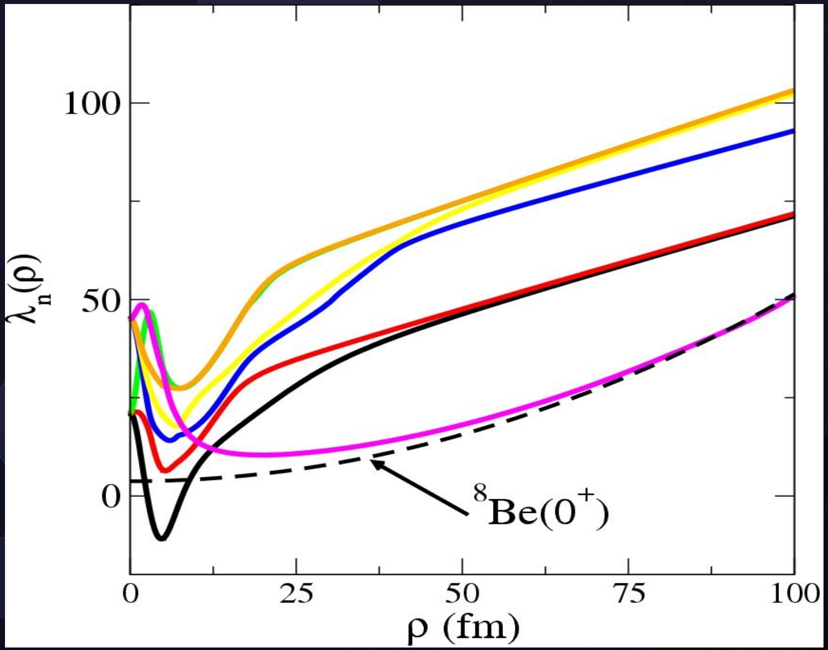
III.- Completely open questions on the 2^+ resonance: its existence as a rotational band member was conjectured in the 1950s: no agreement for the position and width of the first 2^+ resonance.

Ref. Morinaga Phys. Rev. 101 (1956) 254

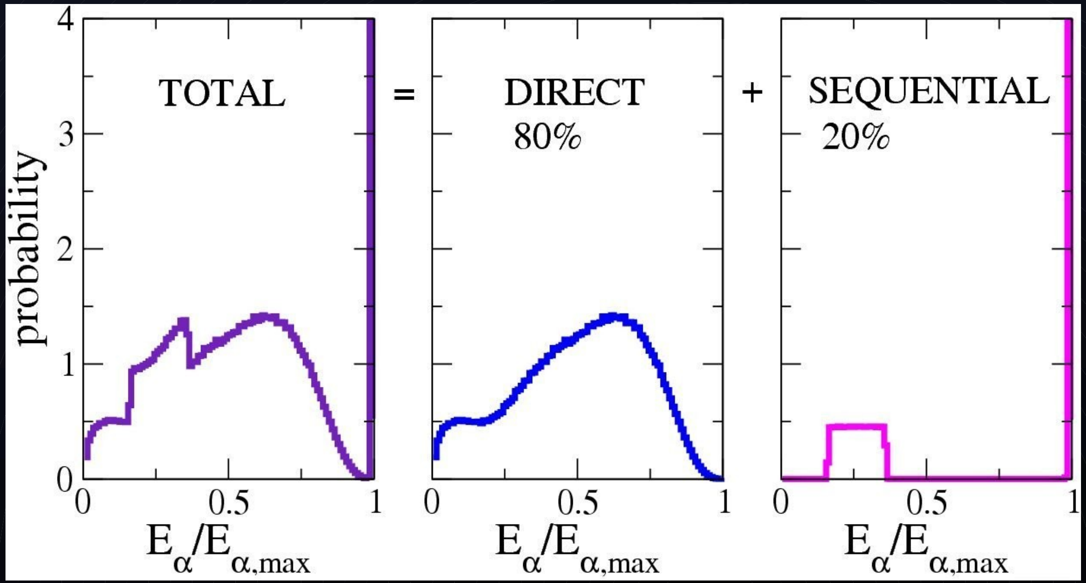
Decay via $^{8}Be(0^{+})$

Natural-parity states (0^+, 1^-, 2^+, 3^-, 4^+): they can decay sequentially via the ^{8}Be ground state

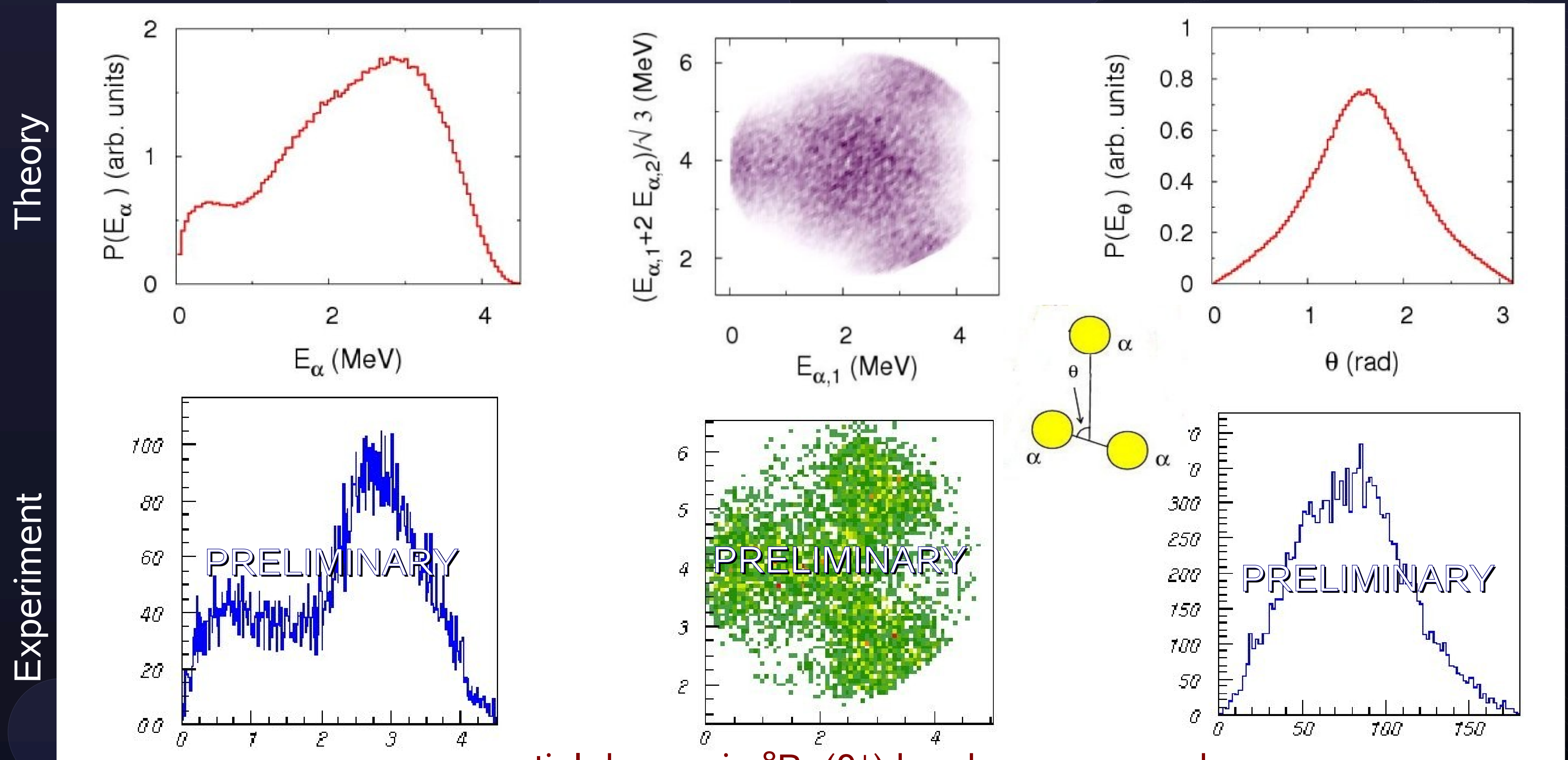
Unnatural-parity states (1^+, 2^-, 4^-): angular momentum conservation forbids the decay through $^{8}Be(0^{+})$



$^{12}C(4^{+})$ at 14.08 MeV



Energy distributions: $^{12}C(4^+)$ at 14.1 MeV

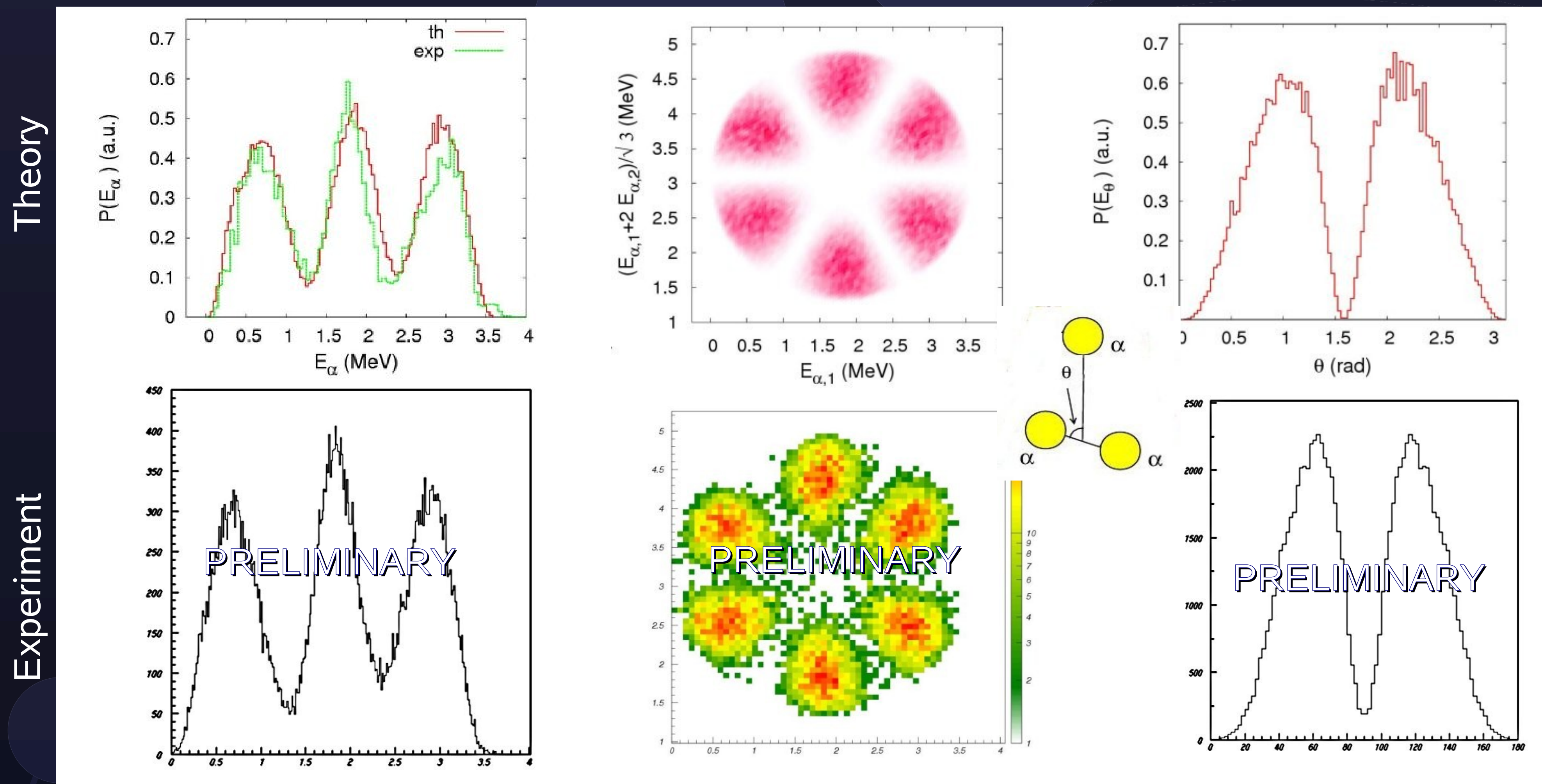


sequential decay via $^8Be(0^+)$ has been removed

Refs. R. Alvarez-Rodriguez et al. PRC 77(2008)064305

Experimental data by M. Alcorta, O. Tengblad et al. CMAM, Madrid 2008

Energy distributions: $^{12}C(1^+)$ at 12.7 MeV



Refs. R. Alvarez-Rodriguez et al. PRL 99(2007)072503, PRC 77(2008)064305

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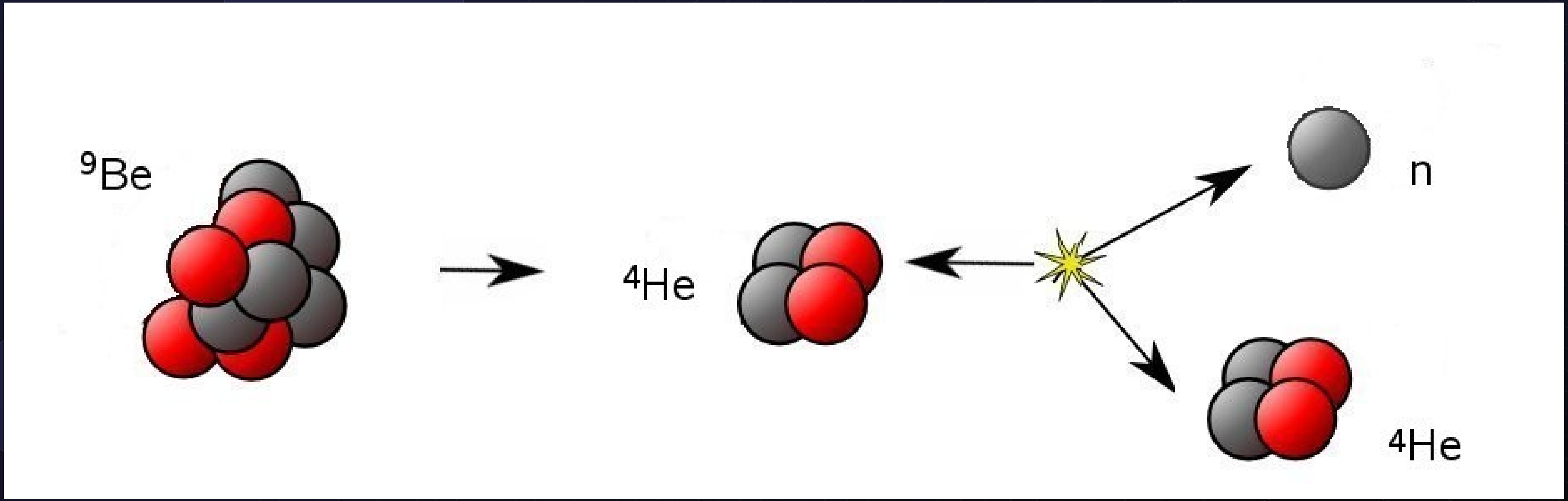
Part II: ^{9}Be



Why ^{9}Be?

Experimentalists discuss with no agreement the decay of $5/2^{-}$ resonance of $^{9}Be \rightarrow \alpha\,\alpha\,n$ as sequential via ^{8}Be or ^{5}He

- R-Marix analyses assume sequential decay via intermediate 2-body configurations

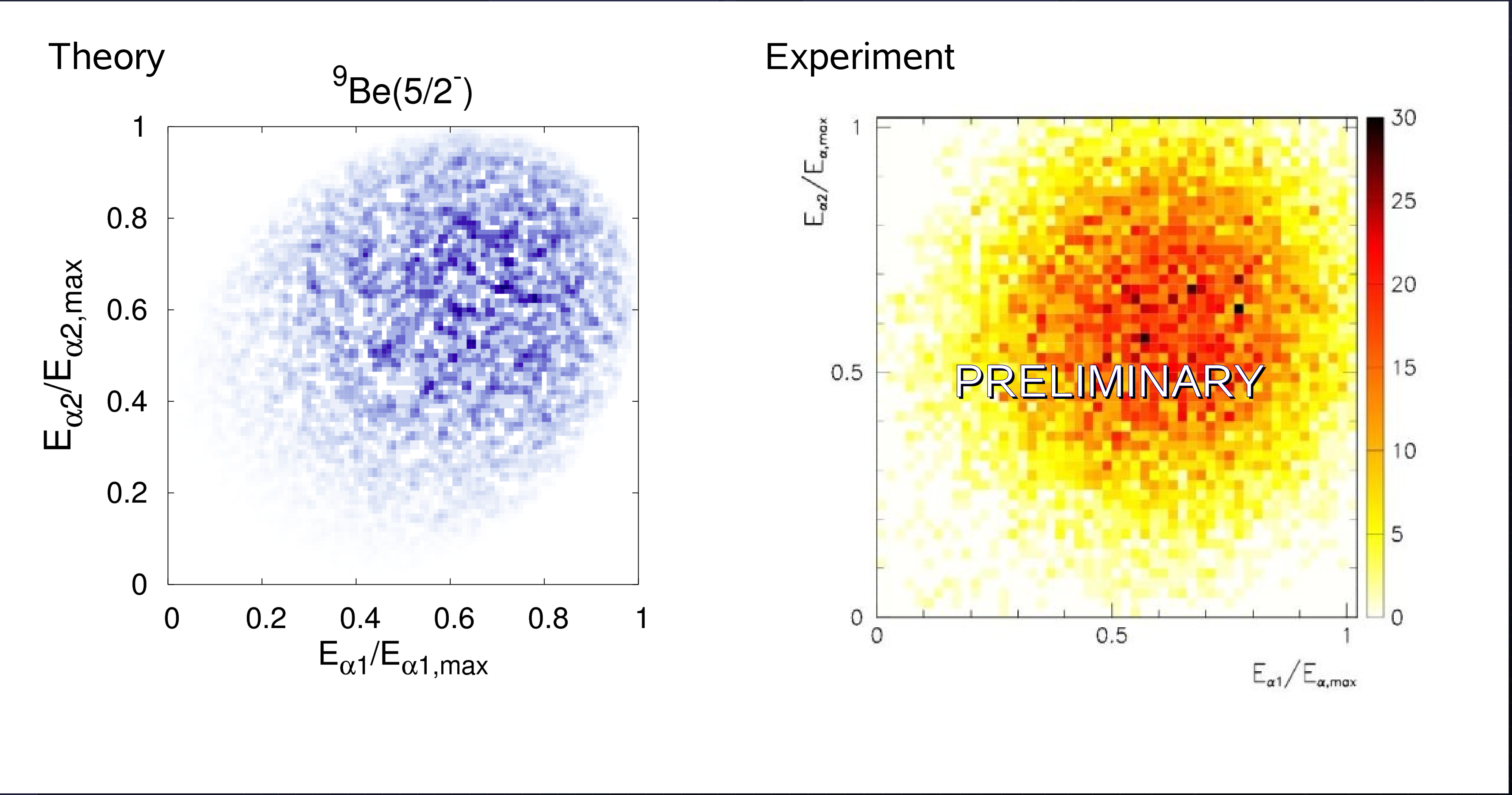
The interpretations of the data are used to derive the reaction rates of the inverse process

- The absorption process is important in astrophysics

The intermediate decay path is not observable in quantum mechanics

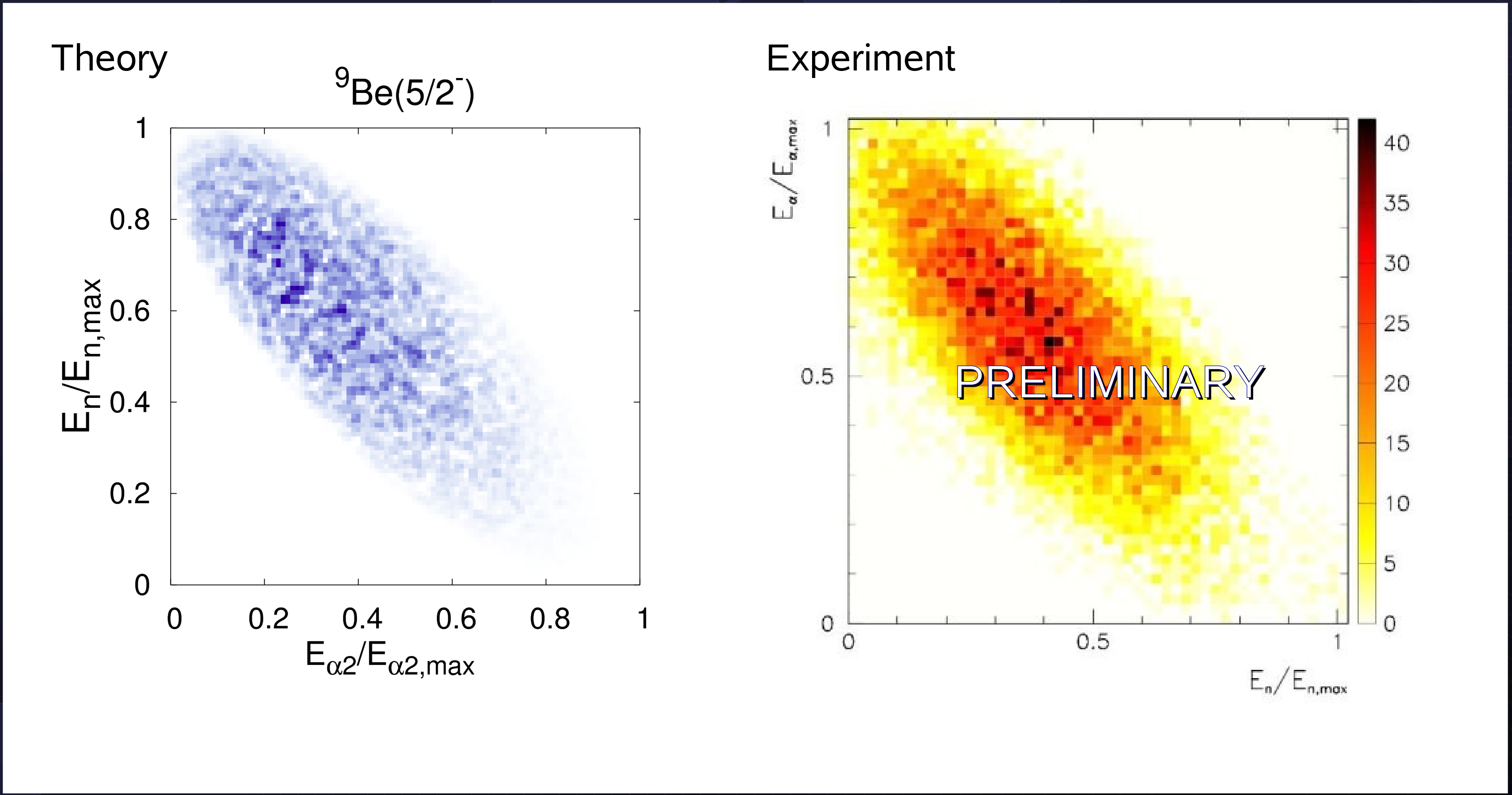
- Classification into decay modes are the results of interpretation or model computations

Dalitz plots: ^{9}Be(5/2^{-}) at 2.4 MeV



Refs. R. Alvarez-Rodriguez et al. PRL 100(2008)192501,
A.S. Jensen et al. Journal of Physics: Conference Series 111(2008)012035
Experimental data by O.Kirsebom et al. CMAM, Madrid 2008

Dalitz plots: ^{9}Be(5/2$^-$) at 2.4 MeV



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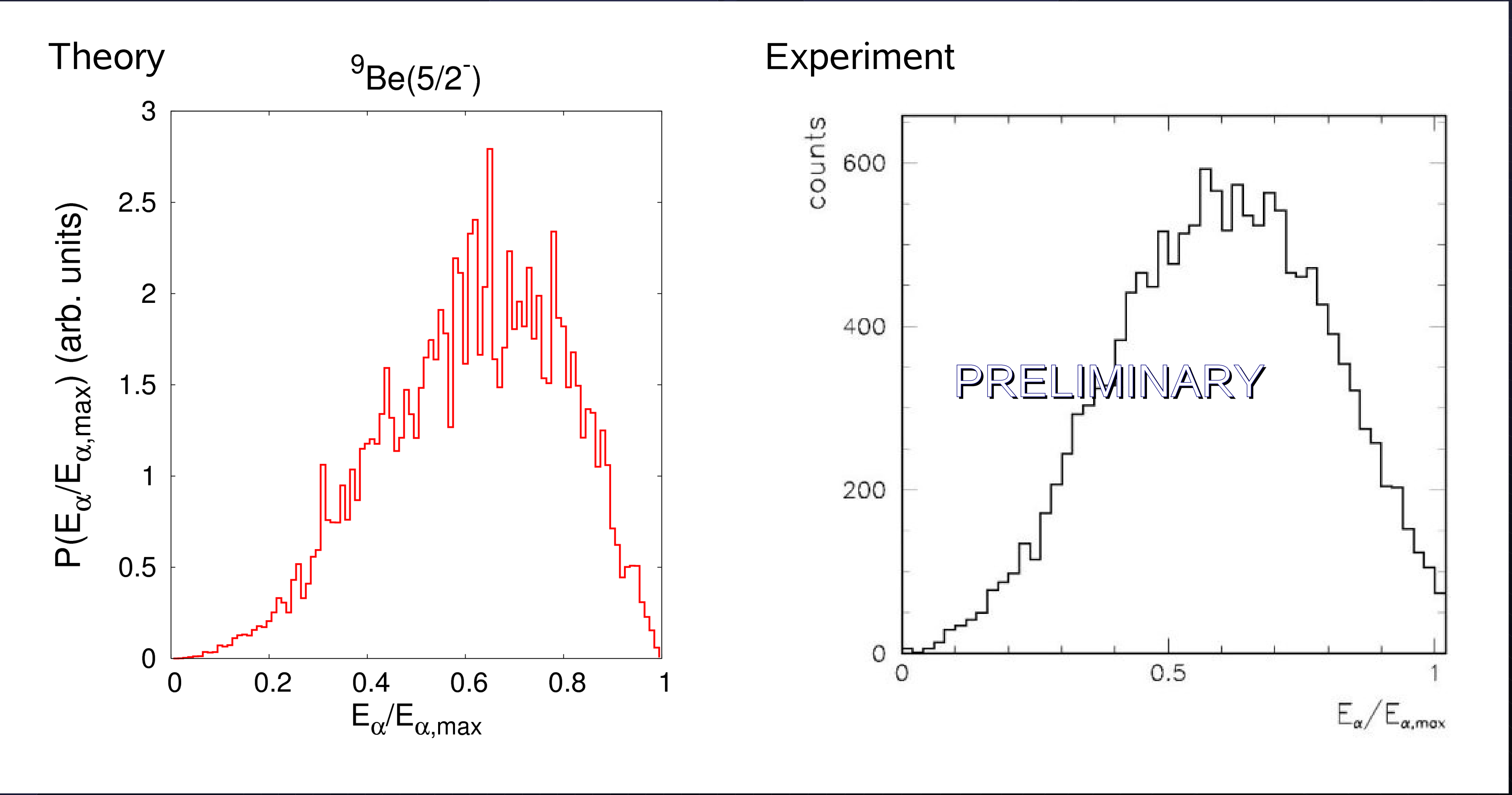
Energy distributions: $^9Be(5/2^-)$ at 2.4 MeV



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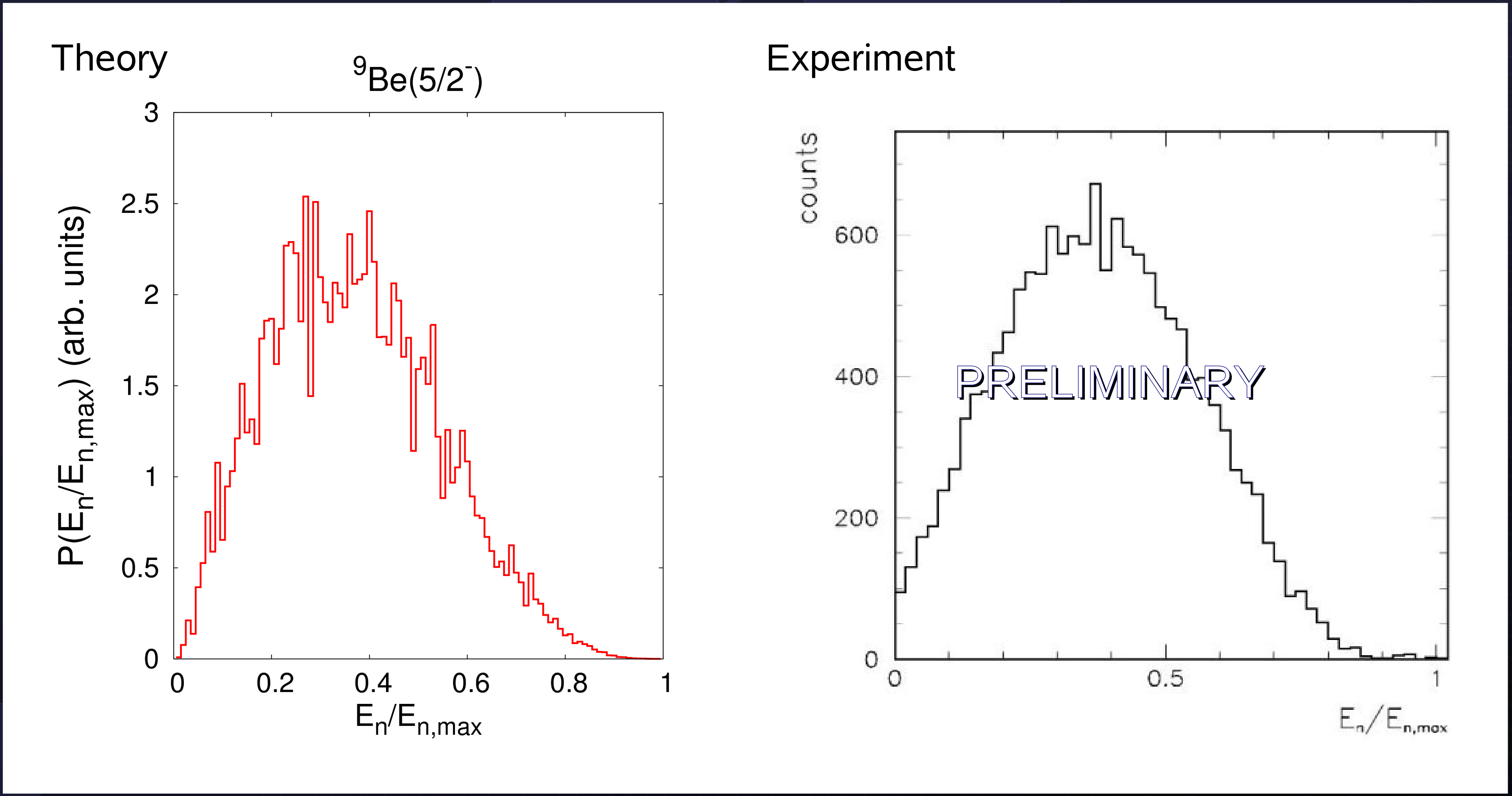

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Spatial energy distributions

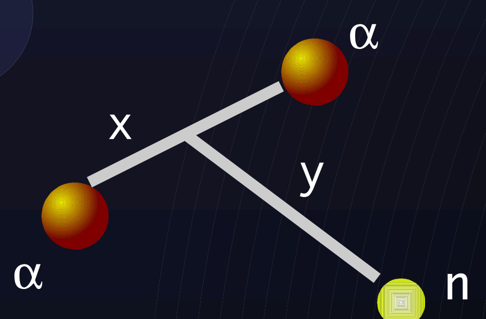
We integrate the absolute square of the wave function for a large value of ρ:

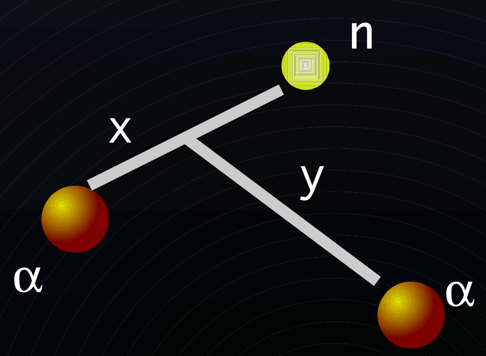
$$P(k_y^2) \propto P(\cos^2\alpha) \propto \sin(2\alpha) \int d\Omega_x d\Omega_y |\Psi(\rho, \alpha, \Omega_x, \Omega_y)|^2$$

Considering:

$$x^2 = \rho^2 \cos^2\alpha \qquad\qquad y^2 = \rho^2 \sin^2\alpha$$

we can get the spatial energy distribution: $P(\cos^2\alpha) \to P(x/y)$





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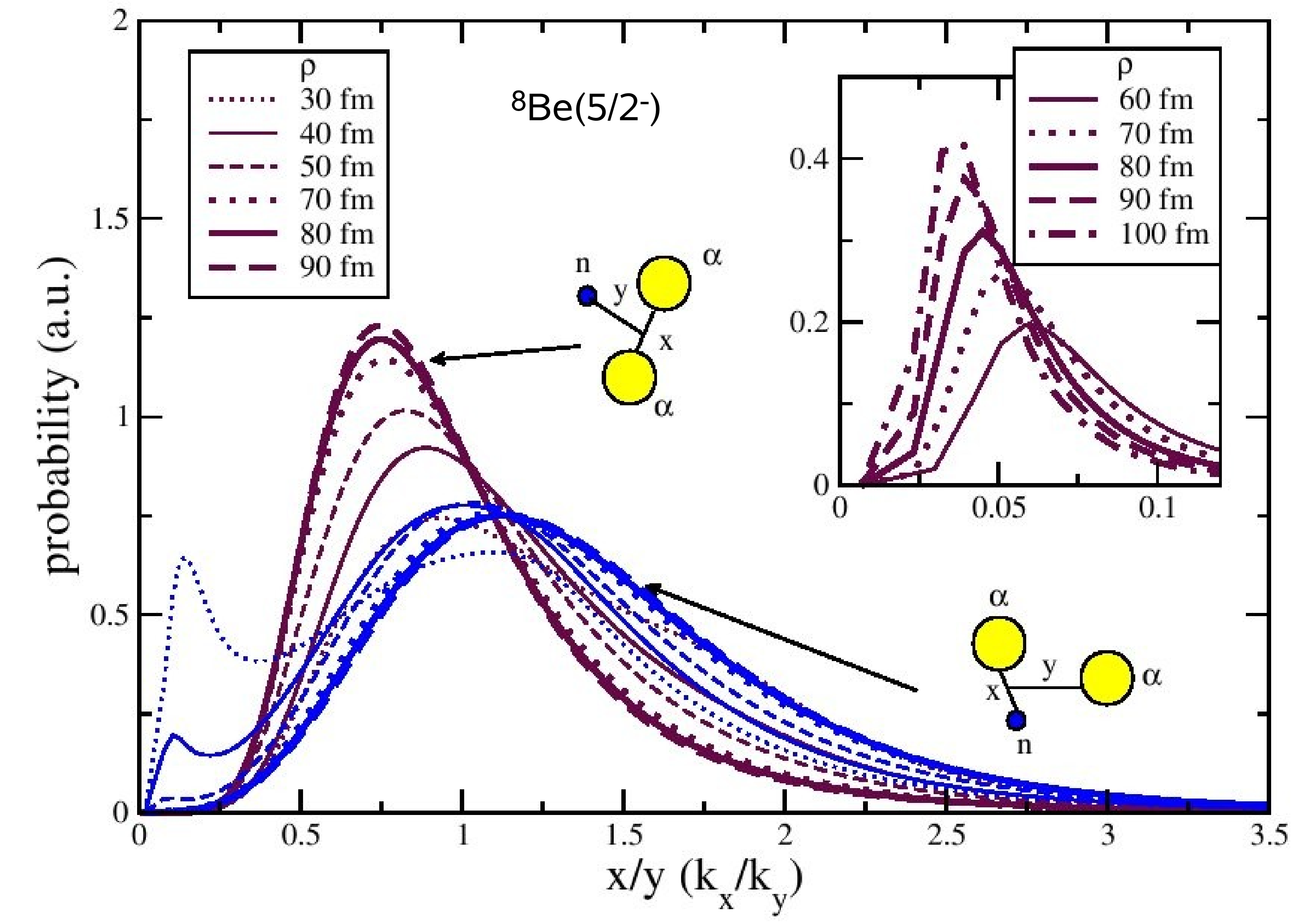
Spatial energy distributions



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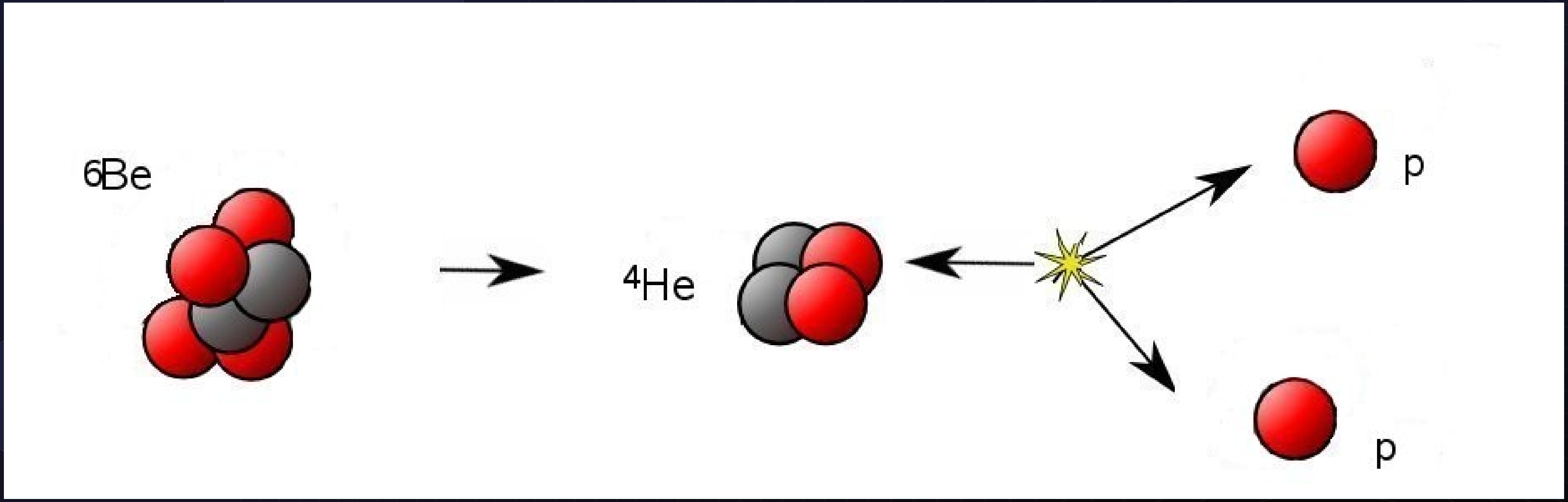
Part III: ^{6}Be



Why ^{6}Be?

^{6}Be is an example of 2 proton radioactivity

The decay of ^{6}Be is discussed to be:

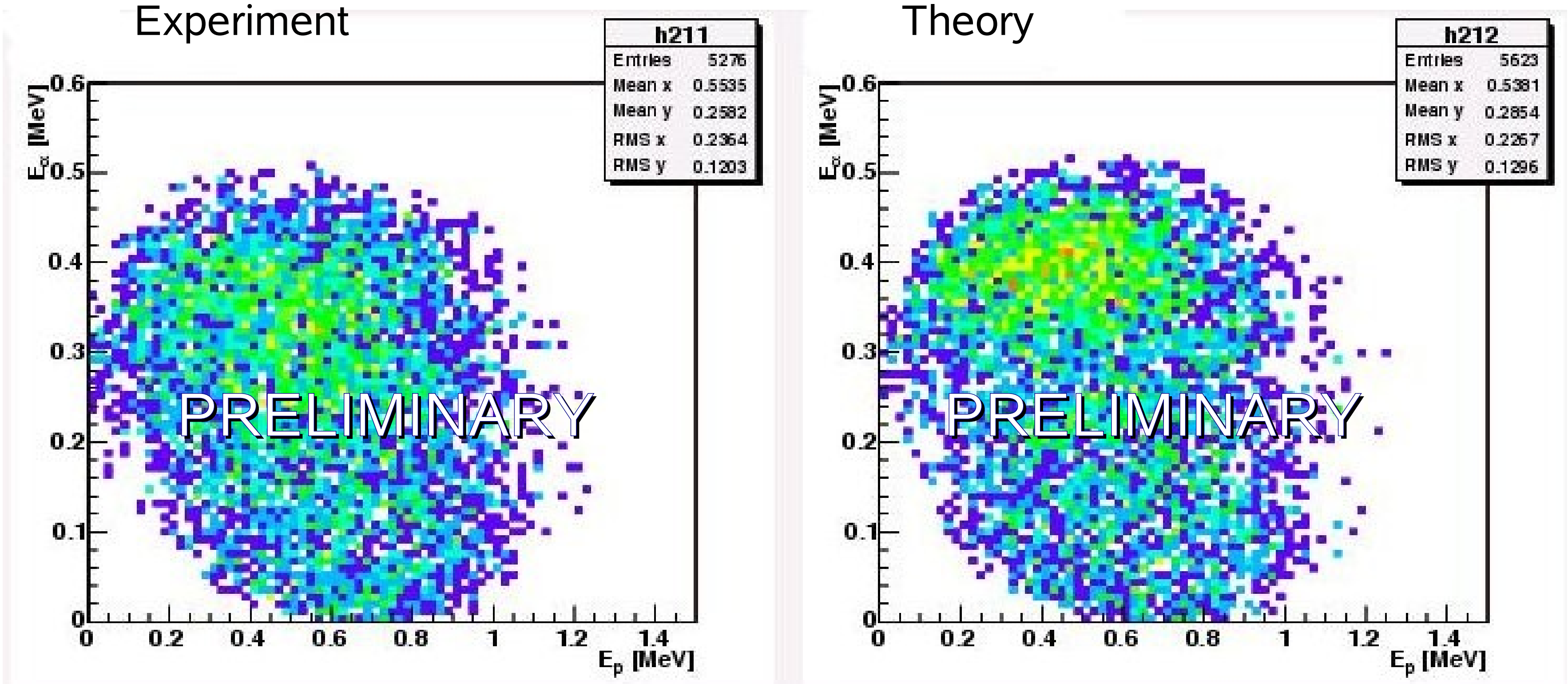
- Diproton emission
- Sequential emission of the 2 protons through the low-energy tail of ^{5}Li g.s.

The reverse reaction is important in Astrophysics since it is invoked to bridge the A=5,8 masses.

- A good knowledge of this mechanism is required for reaction rates calculations in nucleosynthesis environments

Refs. D.F. Gesaman et al. PRC 15(1977)1835, O.V. Bochkarev et al. NPA 505(1989)215

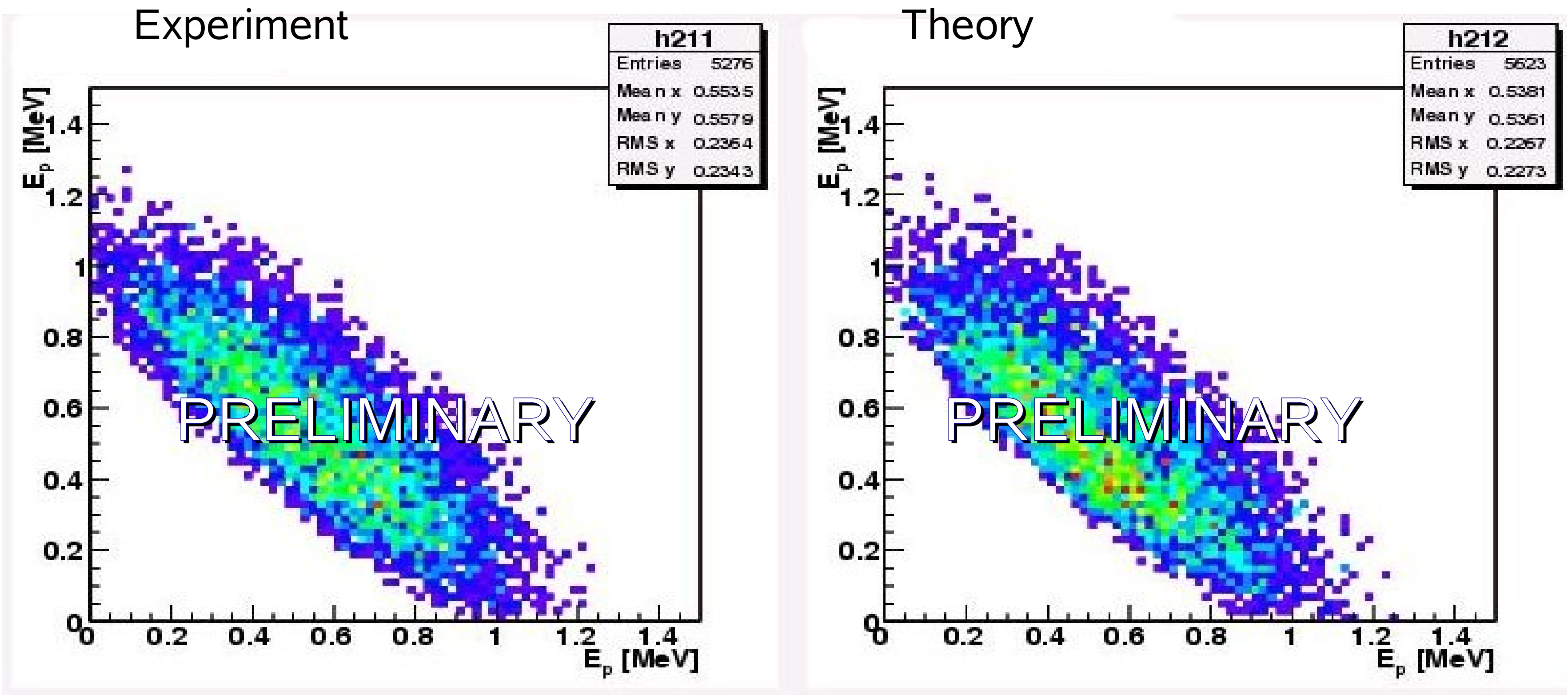
Dalitz plots: $^6Be(0^+)$ g.s.



Figures by Paul Papka

Experimental data by P. Papka et al. iTHEMBA, South Africa 2007

Dalitz plots: $^{6}Be(0^{+})$ g.s.



Figures by Paul Papka

Experimental data by P. Papka et al. iTHEMBA, South Africa 2007

Summary

- We have developed a formalism to deal with 3-body decays of many-body resonances.
- We use short-range and Coulomb potentials. A 3-body potential is used to mock-up the many-body effects.
- We compute energy distributions after the decay of ^{12}C, ^{9}Be and ^{6}Be resonances into 3 particles.
- Preliminary experimental results are in good agreement with our predictions.

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