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Disentangling unclear nuclear breakup channels of beryllium-9 using the three-axis Dalitz plot

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Abstract. The three-axis Dalitz plot has been applied to the breakup of a nucleus into unequal mass fragments for the first time. The Dalitz plot allows clear identification of the various breakup channels of ^{9}Be $\rightarrow 2\alpha + n$ process. The method has allowed the branching ratio for the 6.38 MeV level in ^{9}Be to be provisionally calculated when examining the ^{9}Be(^{4}He,α)$\alpha\alpha n$ reaction. The effects of non-uniform angular distributions on the Dalitz plot must still be properly investigated along with the effects of contaminant reaction channels. It is proposed that this method could be used to determine the breakup branching ratio of a newly-measured level in this nucleus.

1. Introduction

A *ternary plot* is a barycentric plot of three quantities, which sum to a constant value [1]. Using the ternary plot representation, the three quantities are visualised simultaneously by a two-dimensional position on an equilateral triangle. While working at the University of Birmingham in 1953, R. H. Dalitz was the first person to apply the ternary plot technique to visualising the three-body decay of sub-atomic particles [2]. Therefore, the ternary plot will henceforth be referred to as a *Dalitz plot* in this context. In the centre of mass (CoM) of a decay $X \rightarrow a+b+c$, the energies of a, b and c must sum to the decay Q value (in the non-relativistic limit). The Dalitz plot technique is widely used in high energy physics [3].

Only in recent years has the technique been applied in nuclear physics. Such Dalitz plots are used to determine if the Hoyle state in ^{12}C decays through a ^{8}Be$_{g.s.}$ intermediate level or through a direct three-body process [4]. Further, interference patterns in these Dalitz plots are used to determine the angular momentum and parity of ^{12}C resonances [5]. There is no reason why it cannot also be applied to breakups into unequal mass fragments such as ^{9}Be $\rightarrow \alpha+\alpha+n$.

Measuring the breakup branching ratios for states in ^{9}Be is important, since the breakup through particular channels is correlated with the strength of the corresponding cluster

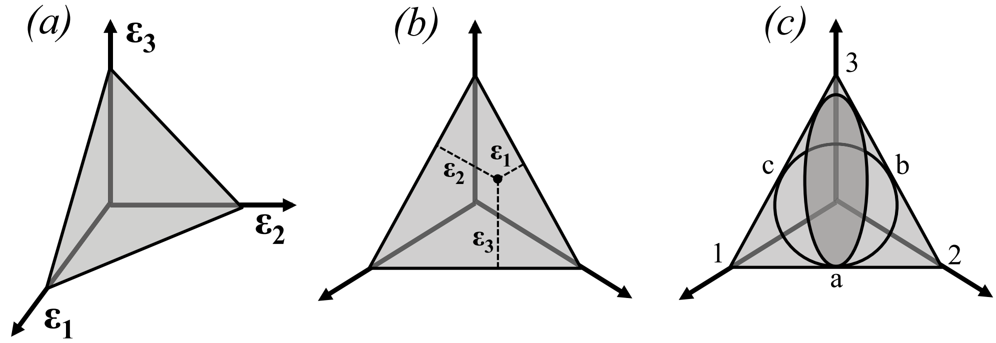

Figure 1. Construction of the Dalitz plot for a decay of a nucleus into three particles. ϵ_i corresponds to the fractional energy of particle i in the CoM of the decaying system. (a) illustrates that if $\sum \epsilon_i$ = constant then points must lie on the shaded triangle. (b) shows the same plot from a different perspective and (c) illustrates how the allowed area changes from a circle to an ellipse for decays into unequal mass fragments (see text for details).

configurations in the wave functions, which can have implications for astrophysical reaction rates [6,7]. The n + ^{8}Be$_{g.s}$, n + ^{8}Be$_{2+}$, α + ^{5}He$_{g.s}$ and $\alpha + \alpha + \alpha$ channels are expected to dominate for the low-lying levels. This paper demonstrates, through the use of Monte-Carlo simulations and experimental data, that the three-axis Dalitz plot can be applied to analyse the breakup systematics of the ^{9}Be $\rightarrow \alpha + \alpha + n$ system.

2. The Dalitz plot

Figure 1 illustrates how to plot three quantities (which sum to a constant) on a single 2D plot. In this case, ϵ_i corresponds to the fractional energy of particle i in the CoM of the decaying system ($\epsilon_i = E_i/\sum_{j=1}^{3} E_j$). Figure 1 ($a$) shows that by plotting three quantities in 3D cartesian coordinates, the resulting point must lie on the shaded triangle. By shifting the viewing perspective along a line normal to the plane of the triangle and passing through the origin, figure 1 (b) is extracted. A point on the triangle is uniquely defined by ϵ_1, ϵ_2 and ϵ_3 which are the distances of each point from each edge of the triangle. If particles 1, 2 and 3 are of equal mass, conservation of linear momentum ensures that points can only lie within the circle of figure 1 (c). For unequal mass fragments, the circle becomes an inscribed ellipse. The points where the circle or ellipse touch the edge of the triangle are denoted by a, b and c and are fixed such that 2b:b3 equals m_2:m_3 (and cyclical for sides 12 and 31). The x, y coordinates of a point on this triangle are related to ϵ_i by $x = \sqrt{3}(\epsilon_2\text{-}\epsilon_1)/2$ and $y = (2\epsilon_3\text{-}\epsilon_2\text{-}\epsilon_1)/2$.

3. Application to beryllium-9 breakup

An experiment was performed to measure the ^{9}Be(^{4}He,α)$\alpha\alpha n$ reaction, at 22 and 26 MeV beam energies (detailed in Ref. [8]). A new resonance was recorded at 3.8 MeV, and the necessity for reliable branching ratio measurements in order to determine the angular momentum of the state, was highlighted. The Dalitz plot method was applied to this experimental data in order to test if it was a valid method of calculating reliable branching ratios. The $7/2^-$ state at 6.38 MeV was chosen as a test subject because branching ratios are already well constrained [6]. The experimental analysis is similar to that of Ref. [8], however, the specific condition that decays proceeded via the ^{8}Be ground state was not required. Hence, ^{9}Be excitation spectra were reconstructed for events which break up via any of the open channels. Events in the excitation region between 6.1 and 6.7 MeV were selected to consider breakups of the 6.38 MeV level.

It was possible to select which final state α particles arise from the breakup of ^{9}Be. The

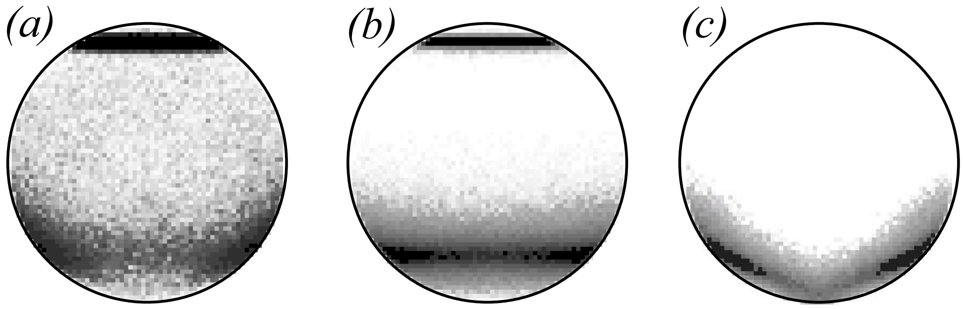

Figure 2. Dalitz plots for the breakup of the 6.38 MeV level in ^{9}Be. Darker regions indicate more counts. (a) depicts the experimental data within an excitation cut of $6.1 < E_x < 6.7$, (b) depicts a simulation of the $^{8}\mathrm{Be}_{g.s}$ (upper line) and $^{8}\mathrm{Be}_{2+}$ (lower line) channels and (c) shows the simulation of decays through the $^{5}\mathrm{He}_{g.s}$ channel. In the case of decays through $^{8}\mathrm{Be}_{g.s}/^{5}\mathrm{He}_{g.s}$, the first emitted n/α takes the majority of the decay energy, hence the event concentrations in these regions (top centre/ bottom left and right, respectively). Sequential decays through the broad $^{8}\mathrm{Be}_{2+}$ state lead to a more even distribution of energies.

energy and momentum of the undetected neutron was calculated from momentum conservation. The momenta of the breakup particles were converted into the CoM frame of the decaying ^{9}Be. Their fractional energies in this frame (ϵ_i) were used as the axes of a Dalitz plot. To force the Dalitz plot into a circular, rather than elliptical, shape, the axes were chosen to be ($4\epsilon_{\alpha_1}$, $4\epsilon_{\alpha_2}$, ϵ_n). The resulting Dalitz plot is shown in figure 2 (a). Simulations of the three decay processes with proper threshold dependencies, experimental resolution, but assuming isotropic particle emission, are shown in figures 2 (b) and 2 (c).

4. Conclusions

Figure 2 (a) shows contributions from all three sequential breakup channels as simulated in figures 2 (b) and 2 (c). Each decay contribution is well separated when compared with similar studies using other types of Dalitz plots [6]. One-dimensional projections of the Dalitz plot permitted a quantitative comparison between simulation and experiment. Provisional branching ratios were extracted which are comparable with previous measurements [6]. The effects of non-uniform angular correlations on each breakup stage and contaminant reaction channels need to be considered in order to be confident of these values. Lower levels in ^{9}Be such as the new 3.8 MeV state are much closer to the decay thresholds and it is predicted that the signatures from each channel will strongly overlap on the Dalitz plot. Their exact manifestations will depend on the angular distributions and it remains to be seen how separable each channel will be.

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