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Evidence for the statistical and sequential nature of ^{16}O breakup into four alphas

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The relation between the folding angle distributions observed in the decay of ^{16}O into four alphas and the final alpha-alpha interactions is discussed and inferred from model calculations. Likewise, the excitation energy dependence of the four-alpha decay channel probability is studied. A lack of alpha-alpha interactions is deduced from the analysis and the observed energy dependence is found to be characteristic of a statistical decay. This reveals the statistical nature of the disassembly and suggests a sequential breakup as the decay method.

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The recent studies [1–4] of the multiple breakup of ^{16}O projectiles excited in peripheral collisions in a wide range of incident energies (25–70 MeV per nucleon) have illustrated the interest and the difficulties of understanding the underlying breakup mechanism(s). Although the decay of ^{16}O into four alphas and other channels shows a clear agreement with the kinematical signatures predicted for a sequential binary decay [1–3,5], Suro *et al.* [4] have discussed the validity of some of these signatures, in particular, that of the folding angle distribution. In all cases, however, the experimental results rule out the predictions of a prompt scenario [5]. In this Brief Report, we discuss the relationship between the folding angle distributions and the alpha-alpha correlations and present new experimental evidence supporting a statistical breakup of ^{16}O into four alpha particles.

In the study of Ref. [1], experimental information coming from the decay of ^{16}O into four alphas was successfully compared to simulated events based on a sequential production of alphas. The successive emissions used in that study were made, by construction, totally independent from one another. This long time scale assumption effectively washed out most alpha-alpha interactions. In a different approach, Suro *et al.* [4] used a molecular dynamical model [6] and compared the predictions to the results for the breakup of ^{16}O into the four-alpha channel at 32.5 MeV per nucleon [1,7]. In this classical dynamical model (CDM), the ^{16}O projectile is treated as an ensemble of four alphas, and the collision between the ^{16}O and the target is simulated via classical dynamics using alpha-alpha and alpha-nucleus potentials. A study of the most peripheral simulations, properly filtered for detection efficiency, showed a fair agreement between the model and the data when comparing the folding angle distributions and the average sphericity-coplanarity values. But perhaps more important, the filtered and unfiltered results of the CDM were shown to be very different both qualitatively and quantitatively. This brought the authors [4] to suggest that the detector filtering had a large effect on both of these observables.

The work of Refs. [1–4] can help to assess the importance of the alpha-alpha correlations in the breakup of light projectiles. This is important as this correlation is the main distinguishing feature between a prompt and a slow breakup mechanism. The breakup mechanisms are characterized by the degree of particle-particle interactions that take place during the breakup. A slow sequential decay, that has only mother-daughter interactions and almost no interactions between the emitted particles, could be classified as a minimum-correlation breakup method. On the other hand, a prompt decay method, in which all the produced particles feel the presence of the other particles, could be called a maximum-correlation method. There is a clear connection between the presence of final particle-particle interactions and some experimentally observable kinematical signatures (such as the folding angle distribution) as was made clear in the work of Ref. [5].

Using this nomenclature then, the sequential decay models of Refs. [1–3,5] (that do not use any interactions between the emitted particles other than mother-daughter Coulomb interactions) must be labeled as minimum-correlation models. And along these lines, one can see that the powerful classical dynamical model can produce fragmentation events with varying degrees of correlation: a rapid production of particles would necessarily introduce interactions between the emitted particles to produce a high-correlation event, while a slow production of particles would limit the interactions to mother-daughter interactions only thus producing a low-correlation event.

The importance of the particle-particle correlations in the breakup of light projectiles comes clear when the exercises of Refs. [1–4] are classified according to the degree of particle-particle interactions. Several of these simulations have reproduced successfully the folding angle distributions of the different experimental data. For instance, the study of Ref. [1] found a good agreement between the predictions of a sequential binary decay model, a minimum-correlation model, and the experimental distribution of the decay of ^{16}O into four alphas at 32.5 MeV per nucleon. Likewise, similar experimental distributions obtained for the same reaction at 50 and 70 MeV per nucleon were also correctly fitted by the simulations of the

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minimum correlation sequential emission codes EDMON [8] and LILITA [9] used in Ref. [2]. Alternatively, in the same studies [1,2] predictions from the maximum-correlation simultaneous decay model of Ref. [5] were unable to correctly compare to the experimental results.

The CDM calculations of Ref. [4] provide further evidence of the lack of correlations in the experimental data. By gathering the results of this study, we see that the unfiltered CDM results, that could presumably contain high- and low-correlation events, were far from reproducing the experimental folding angle distribution, while the filtered events, that contained only a selected subset of the total results, fitted the experimental results adequately. On the surface, this suggests that the detector filtering could have a large effect on the folding angle distribution and that it thus could not be used to distinguish between a prompt and slow breakup mechanisms.

The effect of the correlations was made transparent when new artificial events without any correlation were created by randomly combining alphas from real experimental data and bona fide CDM simulations events in the Suro *et al.* work [4]. The folding angle distributions obtained from these totally uncorrelated fake events were practically indistinguishable from the experimental curves. Furthermore, a similar randomization of the simultaneous-breakup simulations of Ref. [1] was also found to yield a similar folding angle distribution [4].

These observations show that there is a direct connection between the observed folding angle distribution and the absence of alpha-alpha correlation in the particle emission process. It is important to notice that, although the detector indeed selects a preferred subset of events, the filtering alone cannot be responsible for the observed folding angle distribution. Effectively, it has been shown in several studies [1–3] that the filtering effect was small on sequential or prompt simulated events. Furthermore, the filtering itself does not wash out any potential correlation, as it is attested by the fact that the filtered simulations obtained with the simultaneous-breakup model of Refs. [1–3] did not reproduce the experimental curves (that is, not until all the correlations were eliminated by the randomization done in Ref. [4]). The clear agreement found between the predictions of low-correlation models and the experimental results seems to suggest an interaction-free production of particles, such as an independent emission of alphas in a statistical breakup of the decaying oxygen.

One can also emphasize the statistical nature of the ^{16}O breakup by looking at the excitation energy (E) dependence of the production yield, which has been recently used as an experimental signature for statistical multifragmentation [10]. More precisely, the logarithms of the ratio of n-fold to the multiplicity-2 yield as a function of $E^{-1/2}$ is expected to show a linear dependence for branching ratios determined statistically by the available phase space. This can be written as follows:

$$\ln[P(n)/P(2)] \propto E^{-1/2} . \qquad (1)$$

The theoretical dependence predicted by Eq. (1) has been experimentally observed in several occasions, for instance, in the case of electron-induced fission probability [11], and has recently been applied to the fragment production of heavy ions [10]. We now use this approach to study the nature of ^{16}O projectile breakup.

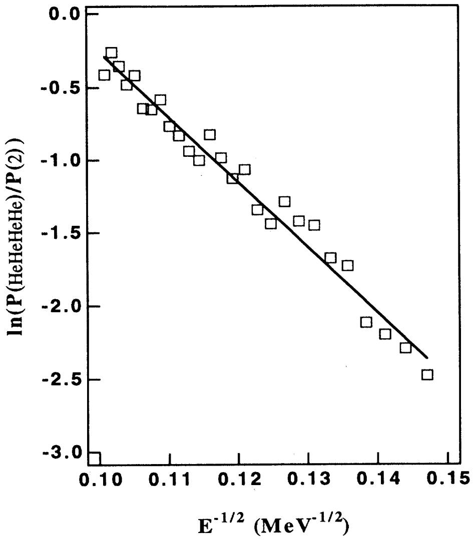

FIG. 1. The natural logarithm of the ratio of the four alpha channel to the twofold yield as a function of $E^{-1/2}$, where E is the projectile excitation energy, for the reaction ^{16}O+^{197}Au at 50 MeV per nucleon. The data are presented by the symbols and the straight line is the result of a least-squares fit.

The data of the multiple breakup of ^{16}O on a gold target at 50 MeV per nucleon [2] have been reanalyzed in the frame of Eq. (1). Figure 1 shows the natural logarithms of ratio of the excitation energy distributions for the four alpha P(HeHeHeHe) and the twofold P(2) channels plotted as a function of $E^{-1/2}$. Here, $P(2)$ represents the yields for the breakup of ^{16}O into two charged fragments. Only four breakup channels contribute to P(2), namely, N+H, C+He, B+Li, and Be+Be. For all these channels, the detected charge is 100% of the charge of the projectile. The fact that Eq. (1) involves the ratio of the yields for different multiplicities represent an advantageous feature. Effectively, the detection efficiency has been shown to be a function of E and almost insensitive to the multiplicity [12]. Thus the correction factors for the detection efficiency will be canceled out by taking the ratio. The size of the symbols on Fig. 1 approximately represents the statistical error. The linear dependence predicted by Eq. (1) and, hence, the statistical nature of the breakup, are clearly seen, as confirmed by the best fit (solid line).

In conclusion, we have presented several arguments that relate the observed folding angle distributions to correlation-free emission processes. Likewise, we have used a new signature to show that the experimental results have an excitation energy dependence characteristic of statistical breakups. All this, along with the previous folding angle and sphericity-coplanarity analyses [1–3,5], conclusively reveals the statistical nature of the disassembly of excited ^{16}O into four alpha particles, and strongly suggests a sequential breakup as the decay method, thus reducing the possibility of producing alphas through other highly correlated mechanisms such as a simultaneous breakup.

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