Energy Correlations in the Reaction $^9Be(d, t\alpha)^4He$ at 26.3 MeV

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The three-body reaction $^9Be+d \to t+\alpha+\alpha$ has been studied in a kinematically complete way at $E_d=26.3$ MeV. The data are represented in terms of projections for selected parts of the Dalitz plot, emphasizing the two-body resonance structure. Excitation energies and widths for the broad resonances are deduced. Although the reaction mechanism is shown to be predominantly sequential, we have observed a significant three-body breakup contribution (about 19% over the entire three-body phase space).

Studies of three-body reactions have delivered valuable information on reaction dynamics and on nuclear spectroscopy, especially in the region of light nuclei,[1] in spite of great complexity in both measuring technique and analysis. Particularly, work done[1,2] at relatively low energies has shown that three-body reactions tend to proceed in sequential steps, provided that well-defined resonance states may be formed in any of the two-body subsystems.

In this Letter, we present results on $^9Be+d \to t+\alpha+\alpha$ at 26.3 ± 0.1 MeV, obtained with the Instituut voor Kernphysisch Onderzoek synchrocyclotron and the BOL[3] multidetector coincidence system (64 detectors in spherical geomometry). The measurements are kinematically complete and cover a major fraction of the three-body phase space. The angular range was 10°–170° in the lab system. The beam had an energy spread below 100 keV, the total energy resolution was 200 keV, and the angular resolution 1.5°. The contribution of accidental coincidences was less than 1%. The $t\alpha\alpha$ events were selected in the subsequent off-line analysis on the basis of (a) identification of tritons and (b) use of three-body kinematical constraints. The events were calibrated and expressed in terms of kinematic invariants. The accumulated data were then "normalized" with respect to (i.e., divided by) a three-body phase-space prediction obtained by a Monte Carlo method accounting for beam energy spread and instrumental effects. A general description of the standard analysis procedures has been given in Ref. 3. Details of the selection procedures and the physical analysis will be published shortly. Information is obtained about the interplay of different reaction modes through both broad and narrow resonance states in the subsystems ^7Li and ^8Be.

Figure 1 shows the data as a function of the final-state relative energies $T_{t\alpha}$ and $T_{\alpha\alpha}$ for the corresponding pairs of clusters, $t\alpha$ and $\alpha\alpha$. Resonances in the two-body subsystems (^7Li, ^8Be) show up in the Dalitz plot as enhancements with respect to the flat phase-space prediction along straight lines corresponding to a constant relative energy. The Dalitz plot allows the following conclusions: (1) The reaction is predominantly sequential. (2) Different reaction modes strongly involve levels in ^8Be as well as in ^7Li, the ^8Be resonances being more pronounced. (3) No order-of-emission interference effects at the intersection of resonance bands are observed in this integrated representation.

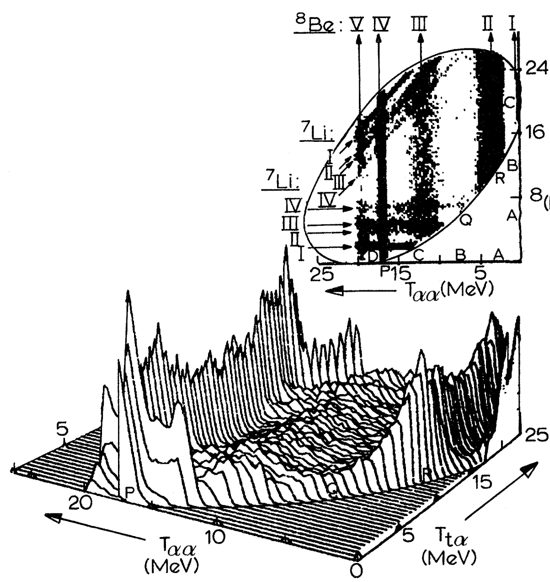

FIG. 1. Isometric representation of the Dalitz plot for $d+{}^9Be \to t+\alpha+\alpha$ showing the normalized yield versus $T_{t\alpha}$ and $T_{\alpha\alpha}$. A top-view plot is inserted for identification of the structure. The letters P, Q, and R clarify the correspondence of the contours. The notation ^8Be: I–V indicates resolved intermediate states in ^8Be at 0, 2.9, 11.4, 16.9, and ~19.9 MeV; ^7Li: I–IV correspond to levels in ^7Li at 4.6, 6.6, 7.5, and 9.4 MeV, respectively.

In order to obtain a more quantitative analysis of the intermediate states of ^{8}Be, we show in Fig. 2 normalized projections on the $T_{\alpha\alpha}$ axis for 8-MeV-broad slices along the $T_{t\alpha}$ axis of the Dalitz plot (see top, Fig. 1). These curves display predominantly the continuum excitation structure of ^{8}Be in various regions of phase space, corresponding to different parts of the ^{7}Li excitation spectrum: Curve A, in particular, contains significant contributions of ^{7}Li resonances (see also Fig. 3); curve B covers the region where no strong ^{7}Li resonances occur; curve C again incorporates the ^{7}Li resonance structure, but now for the alternative t-α pair; and curve D shows the $T_{\alpha\alpha}$ spectrum integrated over the entire Dalitz plot, again divided by the phase-space prediction. Analysis of these continuum spectra yields the following information:

(a) Strong peaks in the ^{8}Be excitation spectrum are observed at 0, 3.2, 11.7, 16.9, and 19.6 MeV. These α-particle-decaying states, with even J and positive parity, correspond to known levels[4] with excitation energies (and J^π values) 0 (0^+), 2.9 (2^+), 11.4 (4^+), 16.9 (2^+), and ~19.9 MeV (2^+), respectively. A 4^+ resonance found at ~19.8 MeV in a recent phase-shift analysis of α-α scattering at higher energies[5] may also contribute to the peak observed at 19.6 MeV. The 16.6-MeV 2^+ level (strongly mixed with the 16.9-MeV 2^+ level) has not been resolved completely. This level is populated with a relative probability of ≈ 17% compared to the 16.9-MeV level, and gives roughly the same angular distribution as deduced from a peak-unfolding procedure. This strongly supports the single-particle character of this doublet as proposed by Marion.[6]

(b) The widths of the two broad rotational states at 2.9 and 11.4 MeV are remarkably constant over the Dalitz plot. The $T_{\alpha\alpha}$ spectrum in the region where no ^{7}Li states contribute (Fig. 2, curve B) has been analyzed with a standard peak-fitting procedure with incoherent Breit-Wigner shapes for the resonance levels and a constant term due

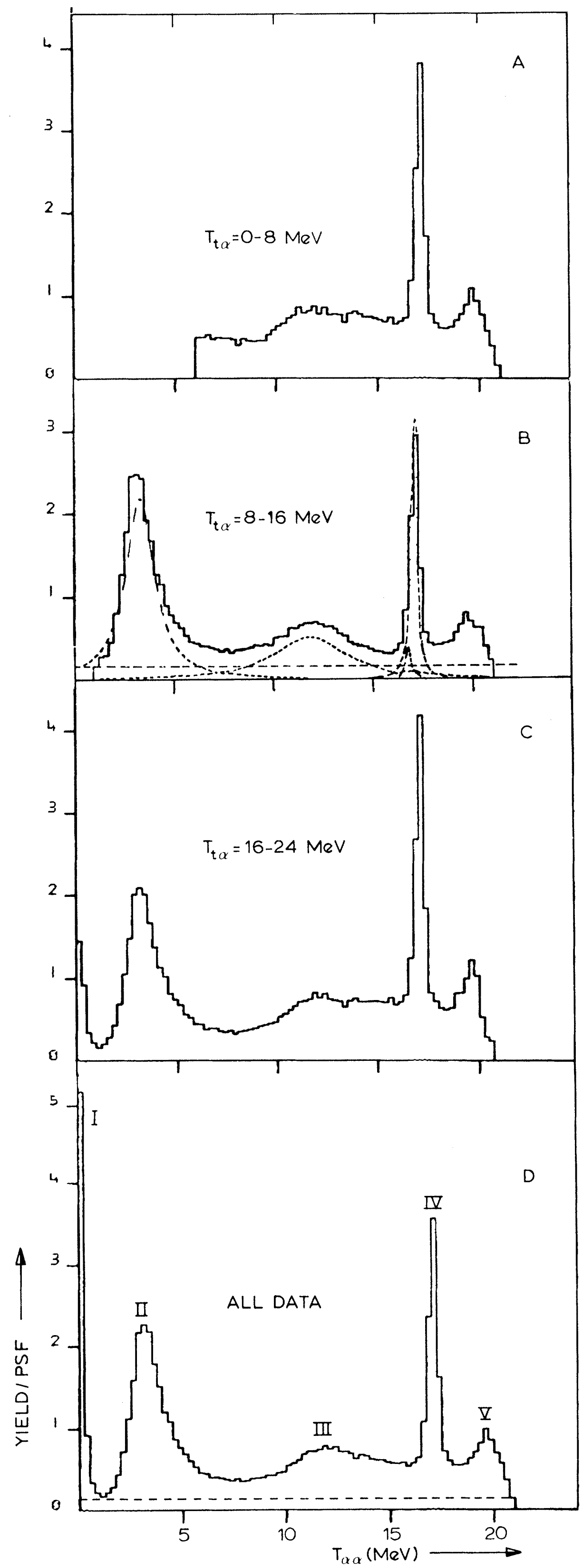

FIG. 2. Relative energy ($T_{\alpha\alpha}$) spectra for 8-MeV-broad slices in relative energy $T_{t\alpha}$ of the Dalitz plot (curves A, B, and C; see inset in Fig. 1). Curve D has been integrated over the entire Dalitz plot. The curves are normalized with respect to the three-body phase-space prediction. Roman numerals correspond to the ^{8}Be resonances in Fig. 1. The dashed curves are an adjustment with Breit-Wigner curves and a constant for the three-body breakup contribution (see text).

to three-body breakup (phase-space dependence). The widths have been corrected for the effective instrumental broadening, as determined from the narrow 16.9-MeV ($\Gamma = 90$ keV) peak, which has a full width at half-maximum of 0.33 MeV. The following results are obtained (in MeV): 2^+ state; $E_x = 3.20 \pm 0.03$, $\Gamma = 1.72 \pm 0.09$; 4^+ state, $E_x = 11.70 \pm 0.07$, $\Gamma = 4.41 \pm 0.5$.

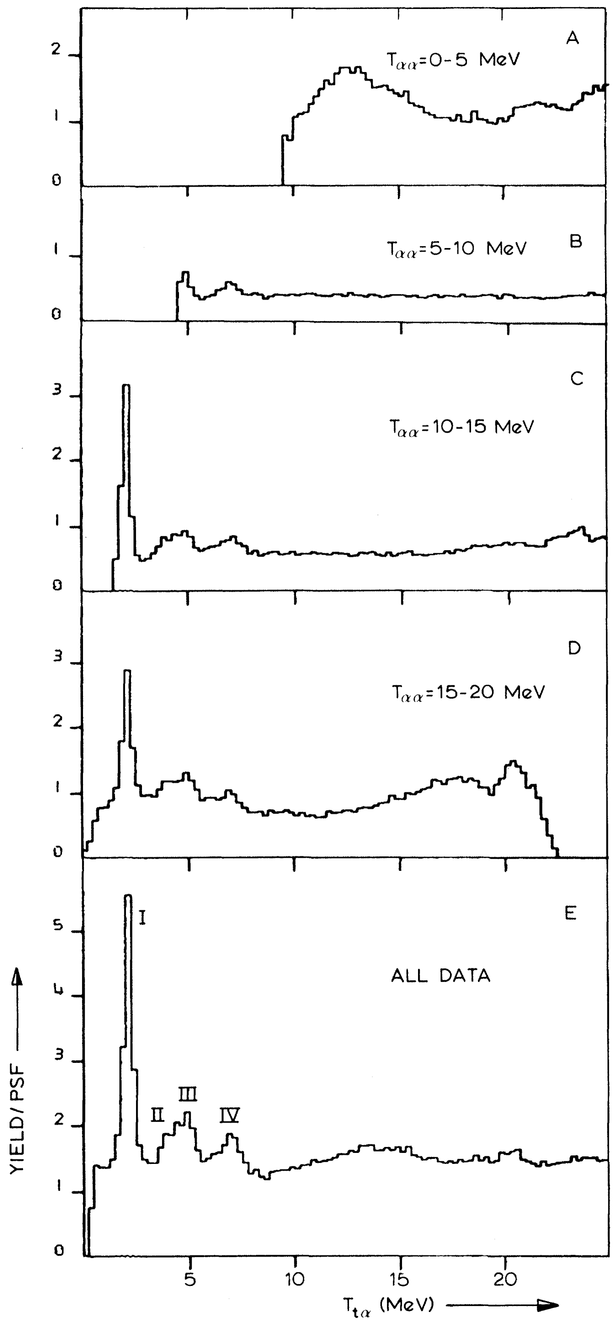

FIG. 3. Relative energy ($T_{t\alpha}$) spectra for 5-MeV-broad slices in relative energy $T_{t\alpha}$ of the Dalitz plot (curves A, B, C, and D). Curve E has been integrated over the entire Dalitz plot. See also caption to Fig. 2. The Roman numerals correspond to the ^{7}Li resonances in Fig. 1. The background due to ^{8}Be peaks is particularly strong. Curve B is used to extract peak parameters for the alleged level in ^{7}Li at about 9 MeV.

(c) The "background" in ^{8}Be spectra due to formation of ^{7}Li states is quite significant. It is clearly visible from the difference in curves A and B of Fig. 2.

(d) The yield due to three-body breakup, as estimated by extrapolation of the constant term in curve B (negligible effect from ^{7}Li "background") over the whole Dalitz plot, is $(19 \pm 4)\%$ of the total yield. This value has been obtained by simultaneously fitting the spectrum B with Breit-Wigner–shaped resonances with position and width taken as free parameters and a constant three-body breakup term. This result is somewhat high compared to values reported for related reactions at lower energies (e.g., Ref. 2), but is consistent with the general idea that three-particle breakup becomes more important at higher bombarding energies.

The 5-MeV-broad slices in the $T_{\alpha\alpha}$ direction of the Dalitz plot, projected onto the $T_{t\alpha}$ axis (Fig. 3), reveal resonance structure in ^{7}Li. The various curves correspond to regions of phase space where different ^{8}Be resonances contribute. Curve A corresponds to the ground state and first excited state of ^{8}Be. In curve B the contribution of ^{8}Be levels is relatively small (region between the two rotational states); in curve C the 11.4-MeV (4^+) state contributes and, at the upper part of the spectrum, ^{7}Li resonance structure corresponding to the alternative t-α pair; in curve D the 16.9-MeV (2^+) state predominates (all curves relative to phase-space dependence).

The ^{7}Li excitation spectra have the following characteristics: (a) α-particle–decaying states in ^{7}Li at 4.6, 6.5, 7.5, and 9.4 MeV are strongly excited. The $\frac{5}{2}^-$ doublet at 6.5 and 7.5 MeV is not fully resolved. (b) The excitation spectrum of ^{7}Li between 10 and 25 MeV does not show any structure, indicating that no sharp α-particle–decaying levels are present (curve B, Fig. 3). Notice that enhancements near 20 MeV in the integrated ^{7}Li spectrum (curve E) arise from the sharp ^{8}Be(g.s.) resonance and from resonances in the other t-α system (see Fig. 1 and curve D of Fig. 3). The ^{7}Li excitation curve in the region of minimum contribution from ^{8}Be resonances (curve B) is constant above 10 MeV, which implies essentially a phase-space-like behavior in this region of the Dalitz plot. (d) The existence of a level in ^{7}Li at 9.7 MeV[4] and its decay into $\alpha + t$ is well established in the present measurements. Its level parameters, estimated from the resonance peak in curve B, Fig. 3, are $E_x = 9.36 \pm 0.05$ MeV, $\Gamma = 0.8 \pm 0.2$ MeV.

The resonance parameters found for the rotational states in ^{8}Be are in fair agreement with the results of free α-α scattering.[4,7] This strongly supports a sequential nature of the reaction process. The peak position of the 2^+ state seems to be somewhat high. The spectra in Fig. 2 indicate, though, that the shape of this peak is asymmetric, which makes a Breit-Wigner fit questionable. The asymmetry is similar along the whole band in the Dalitz plot, and has also been observed in singles data. It therefore seems to be an inherent feature of the ^{8}Be continuum structure. Our value for the level width of the 4^+ state is in agreement with the result obtained in a 50-MeV proton experiment,[8] but is much higher than results for low incident energies.[9] A narrowing effect of a two-particle resonance in a three-particle reaction,[10] as observed at lower energies, does not show up in this measurement. The apparent decay width even for the very broad resonances is hardly influenced by the third particle, unless one is close to one of the ^{7}Li resonances.

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Possibility of Neutrino Emission from Matter Accreting into a Neutron Star

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We analyze the possibility of neutrino emission from matter accreting into a neutron-star member of a binary x-ray source. Estimates of the expected fluxes and neutrino energy are given for selected values of the accretion rate under the assumption that the neutrino production is mainly due to the reaction $\gamma \rightleftarrows e^- + e^+ \rightarrow \nu_e + \bar{\nu}_e$.

It has recently been shown that purely on the grounds of the rate of change of the periods of pulsating binary x-ray sources, it is possible to infer some limits on the rate of mass accretion into a neutron star and on the rate of matter leaving the system.[1] Limits on the rate of matter accreting on the system can also be placed on pure energetic grounds from the observed energy flux