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Wide angle deuteron emission in the ^{9}Be(p,pd) reaction at 300 MeV mimics (p,2p) systematics

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A ^{9}Be(p,pd) coincidence experiment performed to further elucidate the reaction mechanism for the production of energetic wide angle ejectiles in intermediate energy proton induced reactions is reported. Plastic-NaI detector telescopes in a coplanar geometry were used to measure coincidences between deuterons at 90° to the beam and forward angle protons on the opposite side of the beam. The incident proton energy was 300 MeV. Differential mean multiplicities for the coincidence events are presented, with the deuteron energies grouped into 10 MeV bins covering the kinetic energy range from 55 to 115 MeV. Forward protons were measured over a kinetic energy range of 65–280 MeV and an angular range of 14°–60° with respect to the beam. Consequences for the interpretation of wide angle emission of composite ejectiles in proton induced reactions are discussed.

[NUCLEAR REACTIONS ^{9}Be(p,pd), $E=300$ MeV, $\theta_d=90°$; measured p,d angular correlations, deduced differential mean multiplicities.]

The interaction of intermediate and high energy projectiles with complex nuclei often leads to extensive disintegration of the bombarded nucleus. One of the more striking aspects of these interactions, revealed by inclusive reaction studies of the emitted fragments, is that above the Coulomb barrier for each fragment, the energy spectra fall off roughly exponentially.[1,2] Initially, these high energy tails, which are evident even for fragments emitted at very wide angles, were attributed to evaporation from an excited nucleus, but more detailed comparisons[3–5] with the data showed that conventional explanations along these lines were inadequate. Therefore, nonevaporative processes have been incorporated into the description of these reactions, and a number of models have been advanced which describe such mechanisms.[6–15] The inclusive data alone have proven insufficient to distinguish among many of the proposed models, in part because the latter often cannot predict absolute cross sections. Thus it has become necessary to test the applicability of the various models by measurements which are able to place more constraints on them.

A coincidence experiment is one type of measurement which is able to do this, and several studies have been reported recently in which a forward going proton has been detected in coincidence with a proton emitted at a wide angle.[11,16–20] In this Rapid Communication, we present the results of a measurement in which this type of experiment is extended to include a composite particle, a deuteron, emitted at a wide angle. The data were collected simultaneously with the (p,2p) data of Ref. 20, and the reader is referred to that work for many of the experimental details.

To summarize the experiment briefly, a ^{9}Be target was bombarded by 300 MeV protons, and the wide angle deuterons were detected in a plastic-NaI ΔE-E telescope at 90° on one side of the incident beam, while the forward going protons were detected in three telescopes, identical to the deuteron telescope, located in a coplanar geometry on the opposite side of the beam. The energies and times of flight for the particles detected in coincidence between the wide angle telescope and any one of the forward telescopes were recorded on magnetic tape for off-line analysis. This analysis was done in a manner similar to that reported in Ref. 20. The NaI response function corrections for the forward protons were done using the linearly increasing reaction tail form discussed there. Since part of the (p,2p) data were being rebinned to match p and d momenta, the (p,2p) data were also reanalyzed using this form for the reaction tail; the resulting differences from data analyzed with the older form were small and are most noticeable in the magnitudes of energy-integrated multiplicities. Comparisons of (p,pd) and (p,2p) made here use the newer (p,2p) analysis.

Displayed in Fig. 1 are the angular distributions of the energy integrated double differential mean multiplicities. (See Ref. 20 for an explanation of this term, but basically it is a measure of the number of forward going protons whose energy is above 70 MeV, per deuteron emitted at 90° with an energy as indicated.) Two prominent features of these distributions are that they all peak near the angle where the residual system recoil momentum k is a minimum [the "quasi-two-body scaling" (QTBS), angle of Ref. 13], and they have shapes which are very similar to the shapes of the (p,2p) angular distributions. In fact, if the two data sets are compared at the same wide angle ejectile momenta, it is found that, apart from overall magnitudes, the two angular distributions are essentially identical.

The latter result can be seen from Fig. 2 and Table I. Shown in Fig. 2 are the angles corresponding to the maxima of the angular distributions for the two data sets. It can be seen that the peaks occur at the same angles (within the uncertainties) where the two data sets overlap. The widths of the angular distributions are displayed in columns 2 and 3 of Table I. The uncertainties in the widths are approximately ±1°, and so where the two data sets overlap, the widths are also essentially identical.

This similarity of the angular distributions is noteworthy for two reasons. First, according to some models[14,21,22] the deuteron which is ejected is formed by the coalescence of two nucleons inside the nucleus following an initial nucleon-nucleon interaction. It might have been expected that the angular distributions would have been smeared in the deuteron case relative to the proton case because of scattering effects during the deuteron formation. That this is not the case is an encouraging result for the extension of

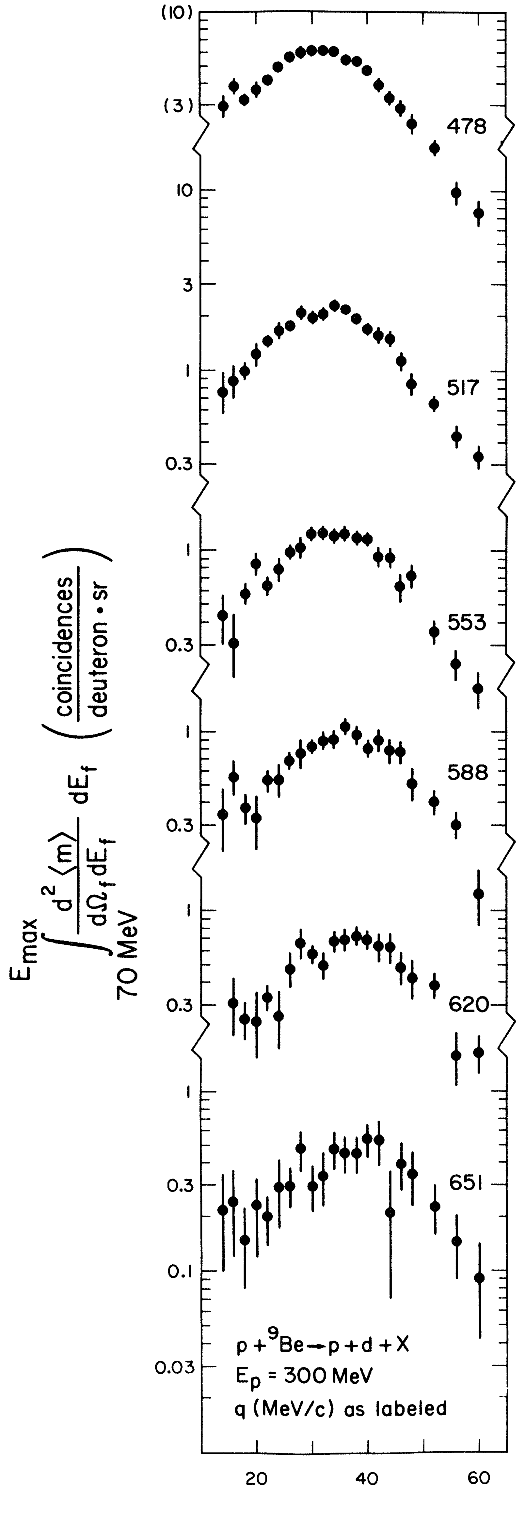

FIG. 1. The integral over forward proton energies E_f above 70 MeV of the measured differential mean multiplicities $d^2\langle m\rangle/d\Omega_f dE_f$ as a function of forward proton angle θ_f for various wide angle deuteron momenta q. Only statistical errors are shown. The overall normalization for 478 MeV/c deuterons is not well determined.

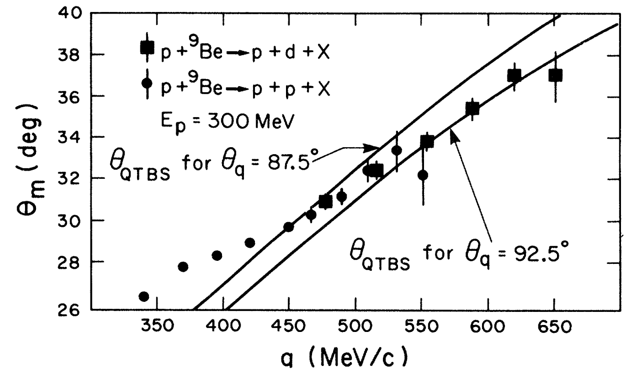

FIG. 2. Forward proton angles θ_m corresponding to maximal differential multiplicities plotted as a function of the wide angle ejectile momentum q. Angles for minimum residual system recoil momenta (QTBS angles) are shown for the two extreme angles θ_q subtended by the telescope centered at 90°. The points and uncertainties were extracted using a five parameter fit which assumes the angular distributions are symmetric (see Ref. 20).

these studies to include those in which wide angle heavier fragments are detected and those in which more complex targets are used.

The second aspect concerning the similarity of the angular distributions is the fact that they have essentially identical shapes at equal ejectile momenta rather than at equal energies. This result has an interesting implication for coalescence models of the type proposed by Boal and Soroushian.[14] There it was assumed that the initially struck nucleon, which subsequently picks up other nucleons to form the observed fragment, starts off with the energy of the observed fragment, but the results presented here suggest instead that if coalescence is involved, the initially struck nucleon starts off with the momentum of the observed fragment.

The differences in the overall magnitudes of the two data sets are illustrated in columns 4–7 of Table I, where the measured and integrated multiplicities are compared. As in Ref. 20, the entries for the measured values are taken from the solid angle actually subtended by our detectors during the experiment while the integrated values are calculated from these by assuming a symmetric distribution about an axis passing through the observed in-plane angle of maximal multiplicity (the integration is terminated at an angle determined by the outermost data point measured). It can be seen that where the two sets overlap, the multiplicities are several times larger when a deuteron is observed at a wide angle than when a proton is observed; i.e., there is an energetic companion proton going forward more often when a deuteron is emitted at a wide angle than when a proton is so emitted. Part of the difference can be attributed to the lower values of k allowed for the deuteron case relative to the proton case, but this cannot account for the whole difference because, even if a comparison is made where the two reactions have the same minimum recoil momentum, the deuteron multiplicities are larger. In any event, it is clear that a very substantial fraction of the deuterons ejected at 90° are accompanied by a forward going proton. This argues strongly against any model which cannot predict such a correlation. For example, it would be quite difficult for a statistical model to make such a connection among the various ejectiles.[20]

TABLE I. Comparison of the angular widths and magnitudes of the associated proton multiplicity distributions for emission of wide angle deuterons and protons.

Wide angle ejectile momentum (MeV/c)	Angular distribution widths (degrees)		Forward proton multiplicities associated with			
			Wide angle protons		Wide angle deuterons	
	Proton	Deuteron	Measured	Integrated	Measured	Integrated
341	24	...	0.025	0.49	...	...
369	24	...	0.017	0.31	...	...
396	26	...	0.014	0.26	...	...
421	27	...	0.012	0.21	...	...
445	28	...	0.011	0.20	...	...
478	28	28	0.009	0.15	a	a
517	29	29	0.006	0.09	0.038	0.64
553	26	27	0.003	0.05	0.022	0.31
588	...	29	...	...	0.017	0.23
620	...	29	...	...	0.012	0.19
651	...	29	...	...	0.009	0.15

[a]The overall normalization for this deuteron momentum is uncertain.

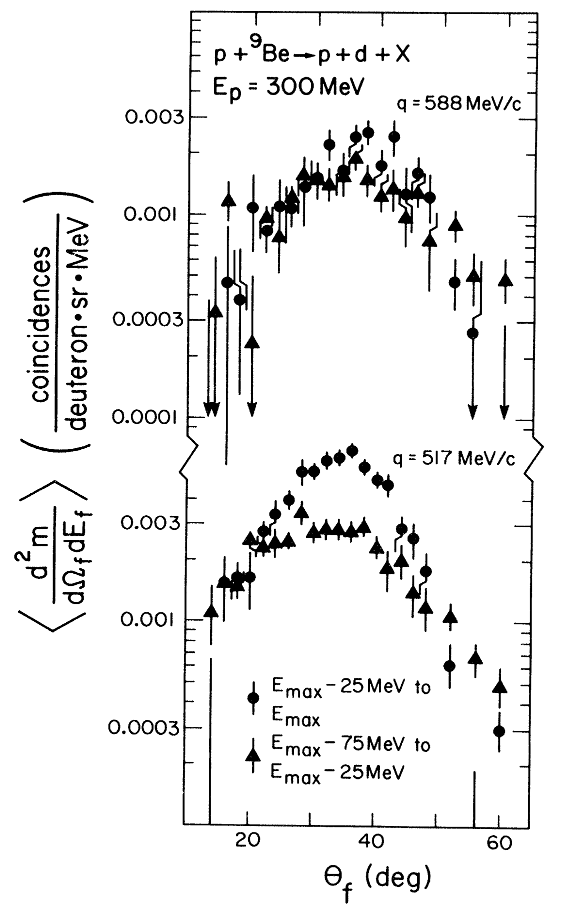

FIG. 3. Comparison of the average values of the differential mean multiplicities $\langle d^2m/d\Omega_f dE_f\rangle$ over two selected summed energy intervals as a function of the forward proton angle θ_f for two deuteron momenta q. Only statistical errors are shown. The two energy intervals selected are the uppermost 25 MeV kinematically allowed (circles) and the 50 MeV region immediately below (triangles).

The deuteron data show another feature qualitatively similar to the (p,2p) data, namely, that when $k < 300$ MeV/c, there is an enhancement of the differential mean multiplicity in the vicinity of the kinematic limit of the summed deuteron plus proton energies. Displayed in Fig. 3 is a comparison, at two deuteron momenta, of the average differential mean multiplicity angular distributions obtained by breaking up the energy spectra into two parts, one including the enhanced region that lies within approximately 25 MeV of the kinematic limit ("coherent recoil"), and one which includes a 50 MeV wide bin below the first region ("continuum"). It can be seen that, in a manner similar to the (p,2p) data, at the lower wide angle ejectile momentum, the coherent recoil data is more sharply peaked than the continuum data, but at the higher ejectile momentum, the two are more nearly the same.

The data presented here, when compared with (p,2p) results, show a number of effects which would be interesting to explore with more complex systems. It would be interesting to see whether the correlation observed between the wide angle ejectile and the forward going proton continues to be a strong effect as heavier wide angle fragments are observed, or whether this correlation is washed out by multiple scattering or some other influence. Similarly, will the correlation remain strong as heavier nuclei are used as targets? The large multiplicities observed in both the proton and deuteron cases is rather strong support in favor of some sort of direct interaction being a major contributor to the reaction process. Again, whether or not the multiplicities remain large as heavier ejectiles are observed will help to determine the limits of applicability of describing the reaction in this way. Finally, it would be of interest to determine whether or not the enhancement seen in the multiplicities near the coherent recoil limit is a general feature of these reactions.

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