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Absorptive breakup of ^{14}N projectiles

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The $^{14}N + ^{27}Al$ reaction of 62 MeV shows a surprisingly strong yield of breakup particles. These fragments, whose spectra peak at approximately the beam velocity, represent a total cross section of about 150 mb. A Serber-type projectile breakup model with no adjustable parameters reproduces the shapes of the experimental spectra and angular distributions reasonably well and indicates that the mechanism producing these fast particles involves the breakup of the projectile combined with the absorption of the remainder of the projectile by the target.

[NUCLEAR REACTIONS ^{27}Al (^{14}N,X), x=Li, Be, B, C; E=62 MeV; measured $d\sigma/d\Omega(E,\theta)$.]

I. INTRODUCTION

The distribution of reaction strength is an important question in the study of the macroscopic properties of heavy-ion reactions. It has long been known[1] that the loosely bound deuteron breaks up readily in the field of target nuclei, but the importance of the process for other projectiles has become apparent more recently. Even the tightly bound α particle has been shown to break up with significant yield.[2] In this light we have looked at reaction products lighter than the beam from the $^{14}N + ^{27}Al$ reaction. While it is now generally assumed that the fragmentation process is strong at high incident energies, the present work was undertaken at a relatively modest beam energy of 62 MeV.

A signature of the fragmentation process is a broad peak centered at an energy corresponding approximately to the beam velocity. Broad structures have often been seen in heavy-ion induced reactions and have been interpreted in various ways. At lower energies the peak centroids have frequently been described in terms of the corresponding or optimum Q value.[3-6] Of the models proposed to account for the optimum Q values, that of Brink[7] is most consistent with a fragmentation interpretation, although it has not always agreed with the data.[3,4] Another approach has been to infer the momentum distribution of the fragments in the projectile frame of reference from the experimental spectra.[6,8]

Recently, more exact calculations using a DWBA formalism have been applied to breakup spectra from light- and heavy-ion induced reactions.[9-12] Such calculations are technically difficult but reproduce the spectral shapes rather well except for the ^{40}Ca (^{20}Ne, ^{16}O) reaction.[9] A further refinement involves adding a seond step to the calculation for a subsequent fusion process.[13]

EXPERIMENTAL PROCEDURE

NH_2^- ions from an inverted sputter source were accelerated and stripped in the FSU super FN tandem to yield 62 MeV beams of ^{14}N. Freshly prepared 100 $\mu g/cm^2$ ^{27}Al targets were used in a carbon-free cryopumped scattering chamber. No evidence was seen in the elastic scattering spectrum for appreciable C or O contaminants. The reaction products were detected and identified using an E-ΔE detector telescope. In different phases of the experiment either a gas ionization counter or a 15 μm Si surface-barrier detector was used for the ΔE measurement.

Examples of the spectra obtained from the $^{14}N + ^{27}Al$ reaction are shown in Fig. 1. They have been compressed by varying amounts to improve the statistical accuracy. The experiment provided mainly Z identification, so the spectra are labeled by chemical symbols. In some cases the mass identification was adequate to resolve ^{6}Li from ^{7}Li and ^{7}Be from ^{9}Be; no other isotopes were observed. By analogy we have assumed that the B and C spectra are comprised only of stable isotopes. Direct evidence for ^{13}C is seen in some of the discrete lines. The absolute cross section scale has an uncertainty of about $\pm 25\%$.

II. RESULTS AND ANALYSIS

Broad continuum peaks are seen in Fig. 1, whose centroids move to lower energies with decreasing

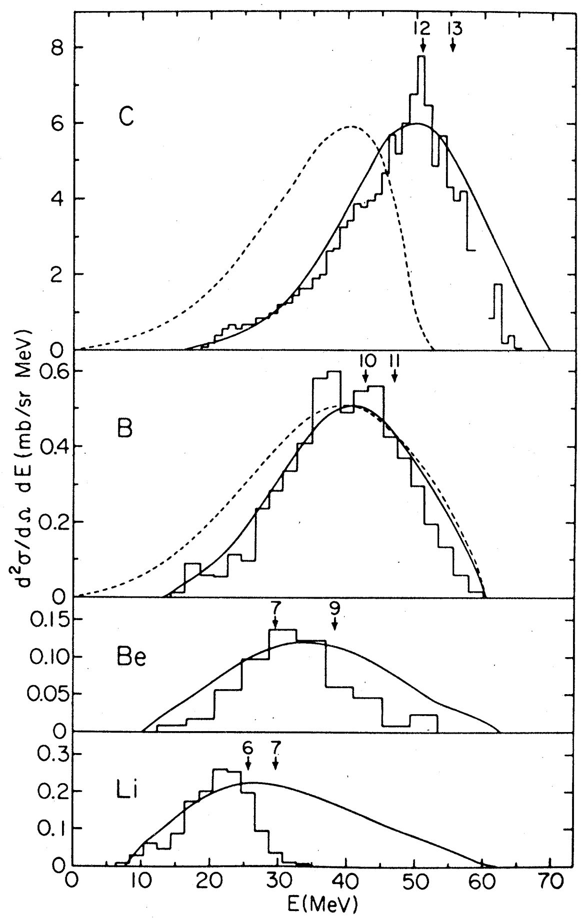

FIG. 1. Spectra of Z groups from the ^{14}N + ^{27}Al reaction at 15°. The missing segment of the C spectrum was obscured by a tail from the elastic peak. The arrows show where beam velocity fragments of the indicated mass are expected. The dashed curve in the C spectrum represents a fragmentation calculation assuming three bodies in the final state. The dashed curve in the B spectrum represents a two-body fragmentation calculation without any Coulomb correction. The smooth solid curves in all four spectra show the results of the fragmentation calculation assuming two bodies in the final state and using a Coulomb correction.

mass. The simplist fragmentation prediction is based on the assumption that the detected particle is literally a spectator whose velocity remains unchanged. A particle of mass m would then have an energy $m/14$ times the energy of the elastically scattered projectiles, as indicated by arrows in Fig. 1. These arrows track the peak centroids rather well, although they are systematically a little high.

The fact that the measured spectra agree roughly with the simplist expectations of a fragmentation picture led us to apply a more realistic model. In this model[1,14] the momentum of the detected fragment is the sum of two components: (1) its fraction of the projectile's momentum; and (2) its intrinsic momentum relative to the other fragment in the projectile. The distribution of momenta in the projectile introduces a width in energy and in angle for the fragments. The transition matrix is proportional to the internal momentum distribution of the fragments in the projectile,

$$|T|^2 \alpha \left| \Psi \left[\vec{P}_1 - \frac{m_1}{m_B} \vec{P}_B \right] \right|^2, \quad (1)$$

where subscripts 1 and B refer to the detected particle and to the beam, respectively, and $\Psi(\vec{P})$ is the projectile wave function in momentum space. A Yukawa shape was used for the fragment's relative wave function in coordinate space,

$$\Psi(\vec{r}) = \alpha^{1/2}(e^{-\alpha r})/r, \quad (2)$$

where α was chosen to give the correct separation energy E_s required to break the projectile into the two fragments, $\alpha = (2\mu E_s)^{1/2}/\hbar$. The cross section is then proportional to the square of the T matrix multiplied by the phase space factor.

Our first calculation was modeled after that of Ref. 14 by assuming three bodies in the final state—the target and the two projectile fragments. The Q value is the separation energy of the projectile into two fragments and the three-body phase space factor is proportional to

$$m_1 P_1 \int d\vec{P}_2 d\vec{P}_T \delta(\vec{P}_1 + \vec{P}_2 + \vec{P}_T - \vec{P}_B) \times \delta(E_1 + E_2 + E_T + E_s - E_B), \quad (3)$$

where the subscript 2 refers to the unobserved fragment and T refers to the target nucleus. The result of this calculation is shown as a dashed curve in Fig. 1 for the case of C fragments. (This curve, like the others to be discussed, represents the sum of the predictions for all the stable isotopes of that element, normalized to the data.) The shape of the three-body calculation is similar to the data, but the position of the peak is about 10 MeV too low.

The dashed-curve peak is too low in energy because energy conservation requires that the phase space factor go to zero at the beam energy minus the separation energy. Much of the C yield is above this point and can only come from the ^{27}Al (^{14}N, ^{13}C)^{28}Si and ^{27}Al(^{14}N, ^{12}C)^{29}Si reactions, which have positive Q values. For example, we must consider a breakup process in which the unobserved fragment is absorbed by the target. In fact, Serber[1] and Dancoff[15] predicted that this would be the dominant process even for deuterons. Coincidence measurements[16] for α-particle fragmentation and several calculations[8,11,12] also show that the other fragment is usually transferred to the target.

The only modification that this requires for our calculation is to replace the three-body phase space factor by the two-body one, which is just

$$m_1 P_1 m_2 P_2 . \qquad (4)$$

The Q value will then be that appropriate for a two-body rather than a three-body final state and will be less negative. The result of the modified calculation is shown as a dashed curve for the B isotopes in Fig. 1. The calculated peak now corresponds well with the data in position, but its width is somewhat larger.

The calculations described above are plane wave ones which ignore distortions of the trajectories or wave functions of the incoming or outgoing particles. The simplist correlation for Coulomb distortion is the local momentum approximation, which is frequently used in electron scattering. To apply it we have replaced the assymptotic momenta in Eq. (1) with their effective local values at the point of interaction,

$$P_{\text{eff}} = [2m(E - E_C)]^{1/2} . \qquad (5)$$

The Coulomb energy E_C was calculated at the touching distance, but the results are not sensitive to the exact distance used.

The results of the two-body fragmentation calculation using the local momentum approximation are shown as solid curves for each of the particle groups in Fig. 1. The agreement is quite good for C and B, not bad for Be, and not so good for Li. The remaining discrepancy may result from a fusion barrier between the other fragment and the target which is not included in this calculation.[13,17,18]

The calculation can also be applied to the angular distributions, as shown in Fig. 2. Again the

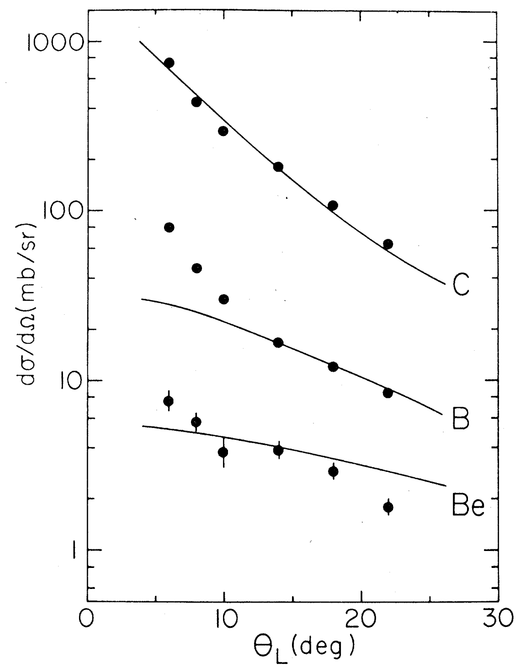

FIG. 2. Angular distributions for Z groups from the ^{14}N + ^{27}Al reaction. Statistical error bars are shown where larger than the dots. They do not include uncertainties in the absolute normalization. The smooth curves represent the same calculations as the solid curves of Fig. 1, a two-body fragmentation model with Coulomb correction.

agreement between theory and experiment is better for the heavier fragments.

An approximate angular integration of the measured yields gives a total cross section of around 150 mb for the production of fast Li, Be, B, and C fragments. The value is only rough because of the 25% uncertainty in absolute normalization and the limited angular range observed. Nevertheless, it shows that projectile breakup represents a significant part of the total reaction strength at this energy.

SUMMARY

In conclusion, the spectra of particles lighter than the ^{14}N projectile exhibit rather strong continuum structures which peak at energies corresponding approximately to the beam velocity. The shapes of the energy spectra and angular distributions are explained rather well by a simple breakup mechanism. The breakup model calculations done here assume an internal momentum distribution for the fragments based on their separation energy, assume that the final state consists of two bodies, and use a local momentum approximation. (These calculations use no free parameters other than the normalization.) A comparison of the calculations using two and three bodies in the final state shows clearly that the unobserved fragment is usually transferred to the target. More accurate reaction models involving continuum DWBA calculations[9,12,13] offer hope for an even better description of this process.

While it is generally assumed that the fragmentation process is strong at high incident energies, the present work shows that the breakup yield in the $^{14}N + ^{27}Al$ reaction is surprisingly large at a rather modest beam energy. The facts that the projectile is not tightly bound and the Coulomb barrier is relatively low undoubtedly contribute to this result.

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