Energy Deposition in Intermediate-Energy Nucleon-Nucleus Collisions

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A global study of the mass, energy, and angular distributions of all products formed in collisions of 180-MeV protons with ^{27}Al is reported. These data are compared with calculations based on intranuclear-cascade-plus-evaporation, preequilibrium hybrid, and semiempirical models. It is found that there is evidence for enhanced energy deposition in nucleon-nucleus collisions relative to predictions of intranuclear cascade calculations. In contrast, preequilibrium calculations produce stronger energy damping, more consistent with observed data.

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In order to derive a broader understanding of the salient mechanisms which characterize nucleon-nucleus collisions at intermediate energies, a global study of the $p + {}^{27}$Al reaction has been performed. The term global, as applied to this experiment, implies the simultaneous measurement of complete energy spectra, angular distributions, and isobaric cross sections for all fragments produced in the reaction. These measurements represent the first such global study at intermediate energies and thus provide useful new insights into the nature of nuclear reactions in this energy regime.

The data obtained in these experiments are relevant to several problems of current interest. Of primary concern in this Letter is the question of energy deposition in reactions of intermediate-energy protons with complex nuclei.[1-4] On a more macroscopic scale these measurements provide a complementary test of elastic-scattering and beam-attenuation methods for determining the energy dependence of the total reaction cross section.[5] Similarly, the spectrum of products in nucleon-induced reactions serves as an underlying base for the understanding of the more complex intermediate-energy heavy-ion data that will soon be forthcoming from the new generation of heavy-ion accelerators. Finally, these data are of broader interest, relating to studies of cosmic-ray origins and propagation[6] and to the response of microcircuit components in satellites due to cosmic-ray exposure.[7]

For nucleon-induced reactions at intermediate energies the low recoil momenta of the heavy reaction products have severely limited attempts to perform measurements of a global nature. In the measurements reported here we have employed a channel-plate fast-timing detector with a silicon semiconductor detector telescope to identify uniquely all isobaric products from the 180-MeV $p + {}^{27}$Al reaction. These studies were carried out at the Indiana University Cyclotron Facility, where a 200–400-nA beam of 180-MeV protons was used to bombard a 100-μg/cm^2 self-supporting Al target. The detector system consisted of a channel-plate (CP) fast-timing start detector (located 13 cm from the target) and a triple-silicon-semiconductor-detector telescope containing elements of thickness 50 μm, 500 μm, and 5 mm, respectively. The 50-μm detector, placed 67 cm behind the CP device, served as a timing stop detector. With this system a timing resolution of < 140 ps was achieved, yielding a mass resolution of 0.3–0.8 u (full width at half maximum), depending on fragment mass and energy. This system provided complete definition of the energy spectra for all fragments with $A \geq 6$ and $E/A \geq 0.05$ MeV/u. A sample on-line mass spectrum is shown as an inset in Fig. 1.

All differential cross section values, $d^3\sigma/d\Omega\, dE \times dA$, were extrapolated systematically to zero energy to estimate the missing yield below the electronic cutoff energy, using a Maxwellian spectral shape $P(E) \propto E^{1/2}\exp(-E/T)$. Because the recoil energies for a significant fraction of the yield for simple reactions such as (p,p') and (p,pn) fall below our lower detection limit, isobaric cross sections for $A=26$ and 27 used in these discussions were taken from the in-beam gamma ray studies of Ref. 8.

The fragment isobaric yields shown in Fig. 1 are spread broadly over the entire range of possible products, with a large contribution from relatively light ($A<20$) fragments. Peak yields are found to be in the $A=20-22$ region. Under the assumption that nucleon removal is correlated with energy deposition, the results imply that relatively large amounts of energy must be transferred to the struck nucleus in these collisions. It is also noted that nuclei with $A=12$ and 16 have substantially enhanced yields, presumably due to nuclear-binding-energy effects.

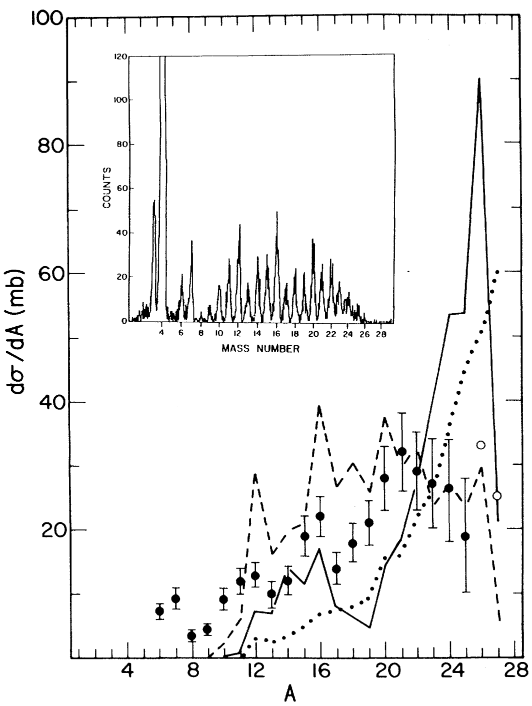

FIG. 1. Isobaric cross sections for fragments from the 180-MeV proton + ^{27}Al reaction. Inset: On-line mass spectrum for fragments with $E>10$ MeV emitted at 20 deg. Symbols are as follows: closed circles, these data; open circles, data from Ref. 8; solid line, intranuclear-cascade-and-evaporation code of Refs. 2 and 3; dashed line preequilibrium exciton model of Ref. 4; and dotted line, semiempirical calculation of Ref. 9.

Also shown in Fig. 1 are yield predictions based on the intranuclear-cascade-plus-evaporation code,[3] preequilibrium-hybrid-model calculations,[4] and the semiempirical estimates of Silberberg and Tsao.[9] The semiempirical estimates clearly underestimate the probability for high-energy-deposition events leading to light-fragment production. This shortcoming may significantly influence current calculations of cosmic-ray-related phenomena,[6,7] which depend upon these calculated cross sections.

The intranuclear cascade calculations also overpredict the yields of products near the target; this is due to the relatively low excitation energies of residual heavy nuclei formed in simple quasifree scattering processes. The cascade calculation also exhibits a peak near $A\sim 14$ which arises from deexcitation of compound-nucleus-like products with high excitation energies. The experimental results suggest a much broader distribution of energy deposition in which the initial collision step is more effective in transferring linear momentum and excitation energy than predicted by the model. Specifically, the cascade code overpredicts the probability for few-nucleon removal processes ($A=23-27$) by about 30%, while failing to account for this same amount of cross section for lighter fragments ($A=6-22$). Thus, it would appear from these comparisons that, in addition to the basic nucleon-nucleon aspects of these collisions, as represented by the cascade code, some additional mechanism for energy deposition must also be present. Similar conclusions have been proposed on theoretical grounds.[1] This conclusion is also consistent with that of Ref. 10, which shows that the quasifree peak in proton-induced reactions at 164 MeV is skewed toward lower energies relative to the spectrum predicted by intranuclear-cascade calculations.[2] In Ref. 10 this observation is interpreted in terms of a shorter mean free path for the outgoing nucleons after collision.

On the other hand, agreement with the preequilibrium-hybrid-plus-evaporation predictions[4] is relatively good, suggesting that the energy sink associated with particle-hole excitations in this model is accounting for energy deposition in the initial stages of the nucleon-nucleon cascade more successfully. In this respect we note that, whereas for heavier targets such as Ni the cascade and preequilibrium exciton models predict rather similar product mass distributions,[11] for ^{27}Al the predictions are distinctly different. This behavior is explained in terms of the diffuse nature of the nucleon distribution in ^{27}Al relative to heavier targets, which leads to a significantly lower probability for multiple collision steps in the cascade in ^{27}Al. Since multiple collisions also serve to enhance energy deposition, signatures of the initial collision step are masked in heavier target nuclei.

Representative angular distributions are shown in Fig. 2. Here one observes a trend from forward-peaked yields for the lightest fragments to two-component distributions for fragments a few nucleons removed from the target. The two components presumably arise from (1) high-linear-momentum-transfer collisions which give rise to a forward component and (2) peripheral processes such as (p,p') and (p,pn) in which the light ions are strongly forward peaked, leading to excited recoiling heavy fragments which are focused in the laboratory system near 50–70 deg. The strong forward-peaking of the angular distribution suggests that the initial nucleon-nucleon collision step in these reactions involves a significant amount of energy deposition in the struck nucleus. On comparison with predictions of the cascade model, qualitative agreement between experiment and theory is found for the backward-angle component ($\theta \geq 50$ deg) of the data, whereas a marked divergence is evident at forward angles. The observation implies that, although the cascade model may describe peripheral, quasifree processes relatively well, it exhibits a deficiency in accounting for the strength of high-linear-momentum-transfer events leading to forward-peaked recoil nuclei. Since the preequilibrium hybrid model presently does not predict differential angular and energy distributions, comparisons with the data are not possible.

In Fig. 3, representative energy spectra for $A = 7$, 16, and 22 fragments at angles of 20, 40, and 70 deg are shown. The spectra are characterized by a broad peak at low energies followed by an exponential decrease with increasing energy, extending up to relatively high energies. These spectra exhibit many similarities with data from 2.1- and 4.9-GeV proton bombardments of ^{27}Al (Ref. 12). The slopes of the exponential tails become systematically steeper as a function of both increasing fragment mass and angle, suggesting that the fragments are emitted from a hot, moving source.[12,13] However, attempts to fit these spectra with a Maxwellian spectral shape

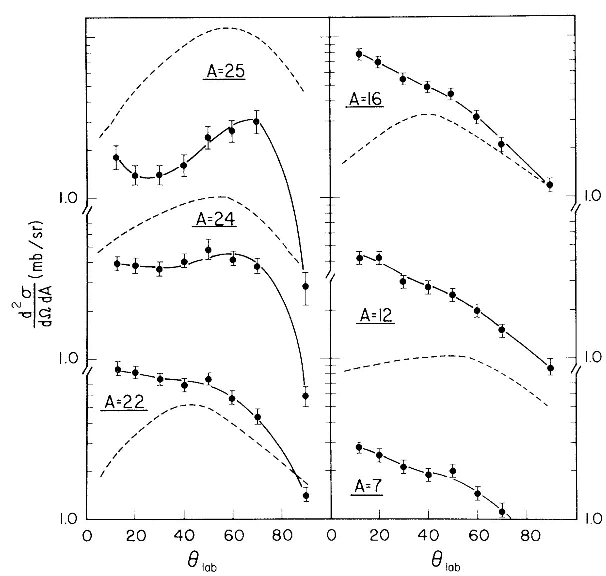

FIG. 2. Fragment angular distributions for the masses indicated, $d^2\sigma/d\Omega\, dA$, from the 180-MeV $p + {}^{27}Al$ reaction. Dashed lines are predictions of the intranuclear-cascade-plus-evaporation code (Refs. 2 and 3); solid lines represent a smooth average of the data (closed circles). The calculations predict no significant yield for $A = 7$.

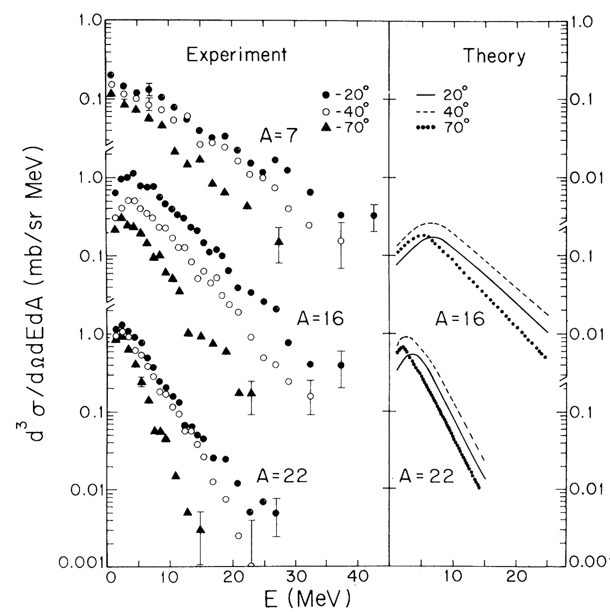

FIG. 3. Laboratory energy distributions, $d^3\sigma/d\Omega\, dE\, dA$, for fragments with $A = 7$, 16, and 22 in the 180-MeV $p + {}^{27}Al$ reaction. Points represent data obtained at laboratory angles of 20 (closed circles), 40 (open circles), and 70 (triangles) deg in the laboratory system. Lines are predictions of the intranuclear-cascade-plus-evaporation code (Refs. 2 and 3).

$P(E) \propto E^{1/2} \exp[-E/T]$, corrected for Coulomb effects, source velocity and temperature, and transformation to the laboratory frame, were neither qualitatively nor quantitatively successful. In order to improve the quality of the fit, mass-dependent temperatures and source velocities are required, as well as very small values for the Coulomb barrier. The cascade calculations yield energy spectra with spectral shapes that describe the data relatively well. However, because of the high yields of light fragments and the forward peaking of the angular distributions, the angle-integrated energy spectra for the data contain a much larger fraction of high-energy fragments than predicted by the cascade model.

Finally, we obtain a total reaction cross section for these data that ranges from $\sigma_R = 370$ mb, assuming that all fragments with $6 \leq A \leq 9$ have heavy partners, to $\sigma_R = 394$ mb, assuming that all fragments with $A \geq 6$ have no heavy partners. Within the uncertainties of the data (~10–15%) these values are consistent with elastic-scattering analyses which give $\sigma_R = 410$ mb.[14] The results are substantially larger than the semiempirical value of 326 mb of Ref. 9.

In summary, we have performed a global measurement of the energy, angular, and mass distributions which characterize intermediate-energy nucleon-induced reactions on light complex nuclei. For such systems, substantial differences exist between the predictions of the two principal models proposed to account for intermediate-energy nucleon-nucleus collisions. The present data are able to distinguish between the two models and point to where improvements are necessary. In particular, the data provide evidence for enhanced energy deposition (or shorter mean free path) in nucleon-nucleus reactions relative to intranuclear cascade calculations, suggesting that within the nucleus, nucleon-nucleon interactions are modified by the presence of other nucleons.[1] Agreement between the data and preequilibrium-hybrid-model calculations provides further support for this conclusion.

Among possible mechanisms which might account for the observed data we suggest the following. First of all, it has been shown[3] that cascade calculations performed with preformed clusters in the target nucleus are quite effective in damping relative projectile energy into internal excitation energy. However, such a scattering model also predicts a much stronger quasifree scattering peak for the projectile, which is absent in the proton spectra of Ref. 10. A second possible energy-deposition mechanism is the influence of many-body effects leading to nuclear correlations which modify the nucleon-nucleon interaction in the nuclear medium.[1] Such forces would serve to shorten the mean free path and dissipate energy in such a way as to account for both our global data and the proton spectra of Ref. 10. Finally, modifications of the free nucleon-nucleon scattering cross sections due to the formation of virtual Δ resonances might also influence these results. Although far off the energy shell, intermediate states of this type may be enhanced in the nuclear interior since formation of the Δ's is not Pauli blocked. Subsequent interactions of the Δ with other nucleons can then lead to three-body scattering, resulting in enhanced energy and momentum loss. Such processes are probably distinguishable only with relatively light targets, since multiple collisions produce the same net effect in heavy targets.

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[1]E. R. Redish and D. M. Schneider, Phys. Lett. 100B, 101 (1981).

[2]V. S. Barashenkov *et al.*, Nucl. Phys. A187, 531 (1972); K. Chen *et al.*, Phys. Rev. 166, 949 (1968).

[3]G. J. Mathews *et al.*, Phys. Rev. C 25, 2181 (1982).

[4]M. Blann, Annu. Rev. Nucl. Sci. 25, 123 (1975).

[5]N. J. DiGiacomo *et al.*, Phys. Rev. Lett. 45, 527 (1980).

[6]R. A. Mewalt *et al.*, Astrophys. J. 235, L95 (1980); M. E. Weidenbeck and D. E. Greiner, Phys. Rev. Lett. 46, 682 (1981); M. E. Weidenbeck and D. E. Greiner, Astrophys. J. 247, L119 (1981).

[7]P. J. McNulty, Phys. Today 36, No. 1, 9 (1983).

[8]O. Artun *et al.*, Phys. Rev. Lett. 35, 773 (1975).

[9]R. Silberberg and C. H. Tsao, Astrophys. J. 25, 315 (1973), and private communication.

[10]R. E. Segel *et al.*, Phys. Rev. C 26, 2424 (1982).

[11]M. E. Sadler *et al.*, Phys. Rev. C 21, 2303 (1980).

[12]G. Westfall *et al.*, Phys. Rev. C 17, 1368 (1978).

[13]A. Goldhaber, Phys. Rev. C 17, 2243 (1978).

[14]C. Olmer, private communication; A. Johansson, Ark. Fys. 19, 527 (1961).