Energy Dissipation Process for 100-MeV Protons and the Nucleon-Nucleon Interactions in Nuclei

A. A. Cowley,[a] C. C. Chang, H. D. Holmgren, J. D. Silk, D. L. Hendrie,[b] R. W. Koontz, P. G. Roos, and C. Samanta
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

and

J. R. Wu[c]
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830
(Received 15 September 1980)

Coincidence studies of two protons emitted from $p+{}^{58}$Ni at 100 MeV have been carried out. The proton spectra in coincidence with scattered protons suffering an average energy loss of 60 MeV are similar to those resulting from 60-MeV incident protons. This suggests that the initial interaction of the incident proton is with a bound nucleon and that one or both of these nucleons is emitted or initiates a cascade leading to more complex states.

PACS numbers: 25.40.-h, 21.30.+y

Interactions of nuclear projectiles with energy ≥ 10 MeV/nucleon are dominated by processes involving large dissipation of the incident kinetic energy. A number of experimental and theoretical studies have recently been carried out for light[1,2] and heavy[3,4] ions. It is not clear whether the basic mechanisms are similar for different projectiles and/or whether they change as functions of their incident and emitted particle energies. In this Letter we report the preliminary findings of a rather detailed coincidence study of the energy dissipation processes for 100-MeV protons. We conclude that the nucleon-nucleon interaction between a target nucleon and the incident proton plays the major role and that possibly nucleon-nucleon interactions continue to be the dominant mechanism as the system proceeds to more complicated states via multiple scattering.

In 1965 Roos and Wall[5] observed broad peaks in the forward-angle (p,p') spectra for 160-MeV protons incident upon a variety of target nuclei. These peaks exhibited the kinematic behavior expected for the scattering of the incident proton by a bound target nucleon, the quasifree scattering (QFS) peak.[5] Such peaks have also been seen in the forward-angle (p,p') spectra for protons with energies up to 1 GeV,[6] and even with a bombarding energy as low as 90 MeV.[1,7]

Studies of quasifree $(p,2p)$ scattering have been carried out over the energy range from about 50 to 460 MeV.[8,9] Calculated distorted-wave impulse-approximation (DWIA) cross sections which provide reasonable absolute fits to the experimental values are almost a factor 10 smaller than those calculated with the plane-wave impulse approximation (PWIA), even at the highest energies.[9] This suggests that both of the nucleons rarely escape without undergoing further interactions and/or that they are emitted in regions of phase space not generally studied in such $(p,2p)$ experiments.

In our coincidence study, four counter telescopes were used, each of which allowed particle identification and energy measurements for all light ions from below the evaporation peak to the maximum available energy. Measurements were made over a wide range of the available phase space in the reaction plane.

The major component of the charged-particle coincidence yield is associated with the emission of two protons. The two-dimensional energy spectrum of Fig. 1 shows four distinct regions; i.e., the QF region lies between the kinematic limits set by the three-body and four-body thresholds ($Q=-8.178$ and -14.205 MeV, respectively) and is characterized by kinematic loci corresponding to well-defined levels in ^{57}Co; the "preequilibrium" (PEQ) region is defined to include the phase space between the evaporation peaks and the four-body kinematic limit; the EVAP region corresponds to the emission of a fast proton in coincidence with an evaporation proton; and the EVAP-EVAP region is characterized by the observation of two coincident evaporation protons.

The angular correlations for both the EVAP (with the fast particles detected at $-15°$ and the low-energy particles at various angles) and the EVAP-EVAP yields were isotropic (in the center-of-mass system). The angular correlations for the QF and PEQ regions are shown in Fig. 2 for one of the fast protons detected at $-15°$ and at

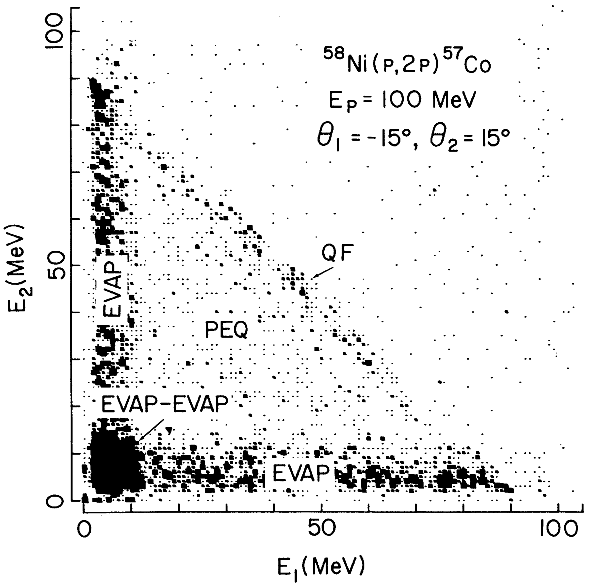

FIG. 1. Typical two-dimensional energy spectrum for the ^{58}Ni(p, p_1p_2) reaction at E_p = 100 MeV. Four regions of interest are indicated.

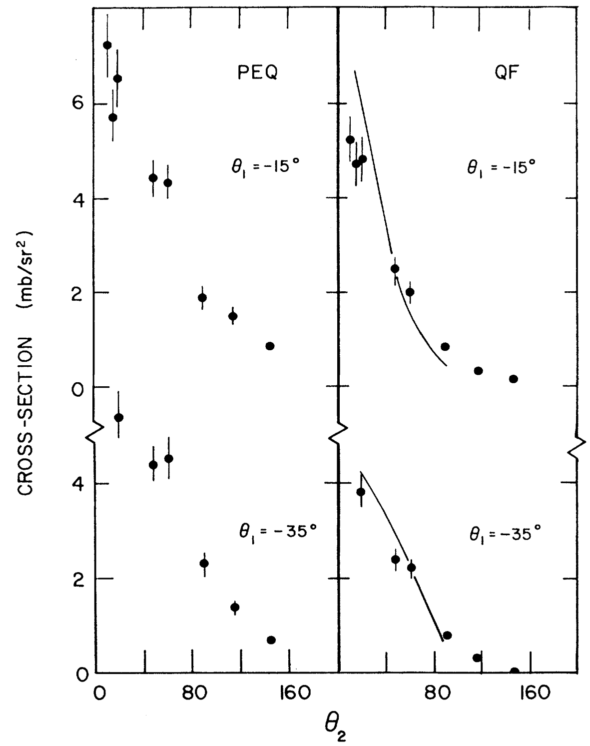

FIG. 2. Angular correlations for the total yield in the quasifree and "preequilibrium" regions as a function of θ_2 for θ_1 fixed at $-15°$ and $-35°$. The solid curves are the result of a DWIA calculation for QFS leading to the low-lying states of ^{57}Co.

$-35°$ as a function of the angle of the second proton. We have integrated the spectra over the energy of both protons in the appropriate regions to obtain these correlation functions. The striking feature of these angular correlation functions is the strong peaking near the direction of the incident beam, which appears to be stronger if both protons are emitted at small angles. This forward-peaking behavior of the QF region is well reproduced by DWIA calculations.[10] The line shown in Fig. 2 is the result of a DWIA calculation in which the contributions from filled $1f_{7/2}$ and $2s_{1/2}$ orbitals have been summed with spectroscopic factors of 60% of the sum-rule limit. The forward peaking in the calculation results mainly from the fact that when two protons are both emitted in the forward direction their relative energy becomes small, leading to a strong enhancement in the p-p cross section which enters the DWIA calculation. In addition, the momentum wave function for a $1f_{7/2}$ orbital has a maximum at ~ 100 MeV/c, which is close to the internal momentum needed for the emission of two protons in the forward direction. Thus, the shape of the angular correlation function for the QF region is consistent with the assumption that the yield results primarily from the interaction of the incident proton with a bound target nucleon (proton).

By similar arguments, the PEQ region would be expected to exhibit forward peaking if the yield is due primarily to QFS of the incident proton on more tightly bound nucleons. The PEQ contribution may also result from small-angle multiple scattering following an initial QFS, which should preserve the forward peaking of the initial QFS.

To see whether the forward-angle peaking for QF and PEQ remains for noncoplanar geometry, we have carried out DWIA calculations for emission of one of the protons out of the reaction plane. These calculations suggest that it is a reasonable approximation to assume the beam direction as an axis of symmetry for the angular correlation function. If we make this assumption, it is then possible to estimate the total yield associated with the QF and PEQ regions. The total yield in the EVAP region can also be obtained by assuming that the observed isotropy extends out of the reaction plane. The total yields, obtained by integrating the coincident spectra over the energies and solid angles for both detectors, are in the ratio QF:PEQ:EVAP ≈ 1:2:6.

Figure 3 shows the spectra of protons at differ-

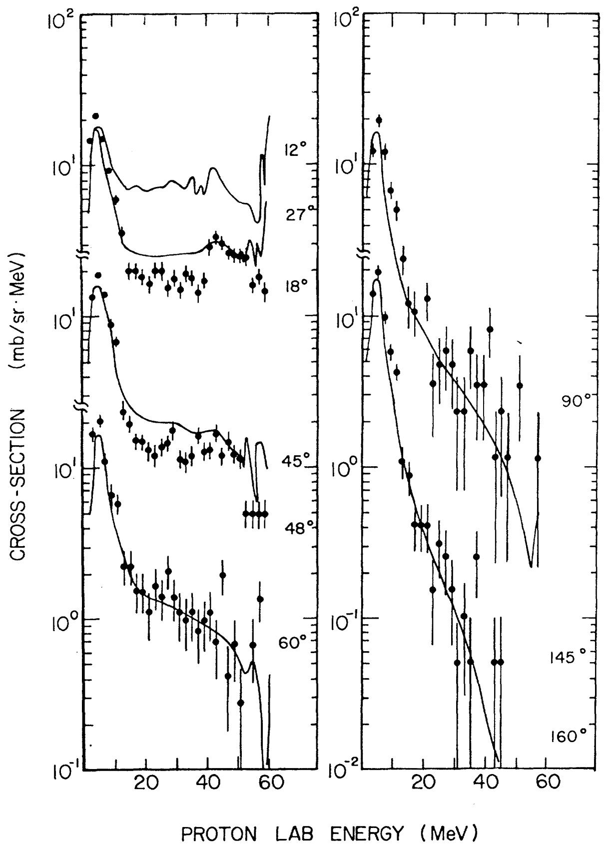

FIG. 3. Proton spectra detected at $\theta_2 = 18°$, 48°, 60°, 90°, and 145° in coincidence with inelastically scattered protons at $\theta_1 = -15°$ with an average energy loss of ~60 MeV. The solid lines are the experimental (p,p') spectra at $\theta_{1ab} = 12°$, 27°, 45°, 60°, 90°, and 160° of Ref. 11.

ent angles observed in coincidence with protons emitted at $-15°$ with energies between 30 and 50 MeV. These coincident proton spectra can be thought of as resulting from an inelastic scattering in which the incident 100-MeV proton transfers, on the average, 60 MeV to the target nucleus and is emitted at $-15°$. The solid curves, shown in Fig. 3, are the (p,p') spectra of Bertrand and Peelle for 62-MeV protons on ^{54}Fe.[11] The coincident spectra have been arbitrarily normalized to the singles data at one angle; viz., 60°. The similarity of the coincidence spectra to the (p,p') spectra indicates that the resultant spectra of particles (protons) are independent of whether an incident nucleon transfers 60 MeV to the target nucleus or whether a 60-MeV nucleon is incident on the target nucleus. One simple way of explaining the similarity is to assume that the incident 100-MeV proton transfers 60 MeV to a target nucleon, which then proceeds to interact with the remainder of the nucleus in the same manner as a 60-MeV incident proton. The angular correlations and DWIA calculations shown in Fig. 2 suggest that the transfer of energy from an incident proton to a target nucleon would strongly favor interactions which result in the scattered and struck nucleons both moving in the forward direction. As the nucleon velocities would in general be large compared to that of the recoil nucleus, the angular dependence of the coincident spectra should then be approximately determined by the beam direction, as seen in Fig. 3.

Although reactions induced by 100-MeV protons appear to be dominated by an initial nucleon-nucleon interaction, our coincidence results indicate that both participants have only about a 30% chance of escaping from the nuclear volume without suffering further large-energy-dissipation interactions. Approximately 55% of the time one of the initial nucleons escapes with the remaining energy being totally dissipated, resulting in an equilibrated system. The remaining 15% of the interactions lead to the emission of composite particles.

Comparisons of recently observed (p,n) spectra[12] with (p,p') spectra at various angles for nuclei ranging from ^{27}Al to ^{209}Bi are also consistent with the assumption that the interaction of the incident protons is dominated by nucleon-nucleon interactions. Furthermore, the calculations of Wu, which include both QFS and preequilibrium contributions, provide an excellent fit to both the energy and the angular dependence of (p,p') spectra.[13] We believe that the results of the (p,n) experiments and Wu's calculations combined with the observations presented herein provide strong evidence that the primary mechanism, by which the incident kinetic energy of a nucleon in the 100-MeV region is dissipated, is via the nucleon-nucleon interaction with bound nucleons. Furthermore, the results suggest that further energy loss subsequent to the initial interaction is also via secondary interactions with target nucleons. It will be particularly interesting to look for the effects of similar nucleon-nucleon interactions in reactions induced by composite particles with energies in the range of 100 MeV/nucleon.

The authors wish to express their gratitude to N. S. Chant and E. F. Redish for many stimulating discussions. A grant from the University of Maryland Computer Science Center for carrying out the calculations is acknowledged. This work was supported in part by the National Science Foundation.

[a]Permanent address: National Accelerator Centre, Council for Scientific and Industrial Research, Pretoria, South Africa.

[b]Present address: Lawrence Berkeley Laboratory, Berkeley, Cal. 94720.

[c]Present address: Bell Laboratories, Naperville, Ill. 60540.

[1]J. R. Wu, C. C. Chang, and H. D. Holmgren, Phys. Rev. C 19, 370, 659, 698 (1979).

[2]H. Feshbach, A. Kerman, and S. Koonin, to be published; P. Benoist-Gueutal, M. L'Huillier, Edward F. Redish, and P. C. Tandy, Phys. Rev. C 17, 1924 (1978), and references therein.

[3]D. K. Scott, in Proceedings of the NATO–National Science Foundation Advanced Studies Institute on Theoretical Methods in Medium Energy and Heavy Ion Physics, Madison, Wisconsin, June 12–23, 1978 (to be published), and references therein.

[4]F. Beck, J. Blocki, M. Dworzecka, and G. Wolschin, Phys. Lett. 76B, 35 (1978), and references therein.

[5]P. G. Roos and N. S. Wall, Phys. Rev. 140, B1237 (1965); N. S. Wall and P. G. Roos, Phys. Rev. 150, 811 (1966).

[6]D. M. Corley *et al.*, Nucl. Phys. A184, 437 (1972); R. Chrien *et al.*, to be published; B. E. Bonner *et al.*, Phys. Rev. C 18, 1418 (1978).

[7]A. A. Cowley, C. C. Chang, and H. D. Holmgren, Phys. Rev. C 22, 263 (1980).

[8]G. Jacob and T. A. J. Maris, Rev. Mod. Phys. 38, 121 (1966), and 45, 6 (1973).

[9]P. G. Roos, in Proceedings of the Workshop on the Determination of Momentum Wave Functions, Bloomington, Indiana, May 31–June 4, 1976 (unpublished).

[10]N. S. Chant and P. G. Roos, Phys. Rev. C 15, 57 (1977).

[11]F. E. Bertrand and R. W. Peelle, Phys. Rev. C 8, 1045 (1973).

[12]B. D. Anderson *et al.*, Phys. Rev. Lett. 45, 699 (1980).

[13]J. R. Wu, Phys. Lett. 91B, 169 (1980).