Fast-Particle Emission in the Deep-Inelastic Reaction Cu+ ^{20}Ne at 12.6 MeV/nucleon

R. P. Schmitt,[(a)] G. J. Wozniak, G. U. Rattazzi, G. J. Mathews,[(b)]
R. Regimbart,[(c)] and L. G. Moretto
Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 25 July 1980)

Fast protons (1–2.4 times the beam velocity) have been studied. The spectral shapes in both singles and coincidence are similar. The most energetic protons are associated with intermediate-velocity products rather than beam-velocity ones. The observed high energies and the forward-peaked angular distributions could be explained by evaporation calculations which included thermal fluctuations in the division of the excitation energy between the two fragments of the intermediate complex.

PACS numbers: 25.70.Bc

Alpha-particle–heavy-ion coincidence measurements[1-6] at bombarding energies ranging from 4 to 20 MeV/A have been interpreted in terms of a large probability for prompt α-particle emission, possibly due to the decay of a "hot spot" formed during the collision.[7,8] In contrast, studies of neutron emission accompanying deep-inelastic reactions[9,10] have not shown evidence for any appreciable nonequilibrium component even though theoretical considerations suggest that fast nucleons could be ejected as "Fermi" or "PEP" jets.[11] In an effort to clarify the situation, we have studied fast-proton emission in a deeply inelastic reaction, with the idea that energetic protons might offer a recognizable signature of nonequilibrium processes.

Self-supporting natural Cu foils (~1 mg/cm^2) were bombarded with 252-MeV $^{20}Ne^{6+}$ ions produced by the Lawrence Berkeley Laboratory 88-in. cyclotron. Projectilelike fragments were detected in a solid-state Z telescope (ZT) consisting of an 11.3-μm Si ΔE counter and a 250-μm Si E counter. Light particles (i.e., p, d, and t) were detected with two to four proton telescopes (PT), each consisting of a 400–600-μm ΔE counter and a 3.2-cm NaI E counter. The latter counters could stop protons with energies as great as 100 MeV and had an energy resolution of (1.5–2.0)%. The PT's were calibrated with protons and deuterons produced in (p,p), (d,d), (d,p), and (α,p) reactions on ^{12}C in the energy range from 25 to 55 MeV. The uncertainties in the measured proton energies are approximately ±1 MeV.

The ZT was fixed at a forward angle (+14°) to maximize the cross section for Ne-like fragments. One of the PT's was located directly behind the ZT in order to detect particles emitted collinearly with the Ne-like fragment. The other PT's, which were mounted on a separate movable arm, were used to measure the in-plane correlations from −8° (on the side opposite the ZT) to ±131°. By monitoring the proton-coincidence cross section in the PT at +14°, and from a comparison with the measured coincidence yield for the 252-MeV ^{20}Ne + ^{12}C reaction, we estimate that the yield of protons from carbon contamination could not have been larger than 15% over the entire proton spectrum.

Representative proton singles spectra are shown in Fig. 1(a). In general, the singles energy spectra fall off smoothly with increasing energy. At 20°, one observes protons with energies up to 70 MeV, corresponding to 2.4 times the beam velocity. Even at 80°, protons up to about 55 MeV or twice the beam velocity are observed. The low-energy cutoff in all the energy spectra is due to the ΔE detectors and the protective window (0.25-mm Al) on the NaI E detectors. Three representative coincident-proton energy spectra are shown in Fig. 1(b). These spectra were generated by gating on ZT events with Z values of 6 to 11 and laboratory energies of 50–220 MeV. Fast protons are observed and these coincidence-proton spectra fall off with essentially the same slope as the forward-angle singles data. Although in singles there are also contributions from all other possible emission angles of Ne-like fragments, and possibly from fusionlike processes,[12,13] the similar slopes of the singles and coincidence data would indicate that selecting on the deep-inelastic channel should not introduce any special bias.

It has been suggested[14] that these high-energy protons could result from the sequential decay of a projectilelike fragment via a velocity-addition effect. To check this, the Ne-like fragment energies were converted to velocities on an event-by-event basis and three equal width gates were set. Collinear proton-energy spectra generated for each of these velocity bins are shown in Fig. 1(c) for $\theta_{PT} = +14°$. Almost all of the highest-energy

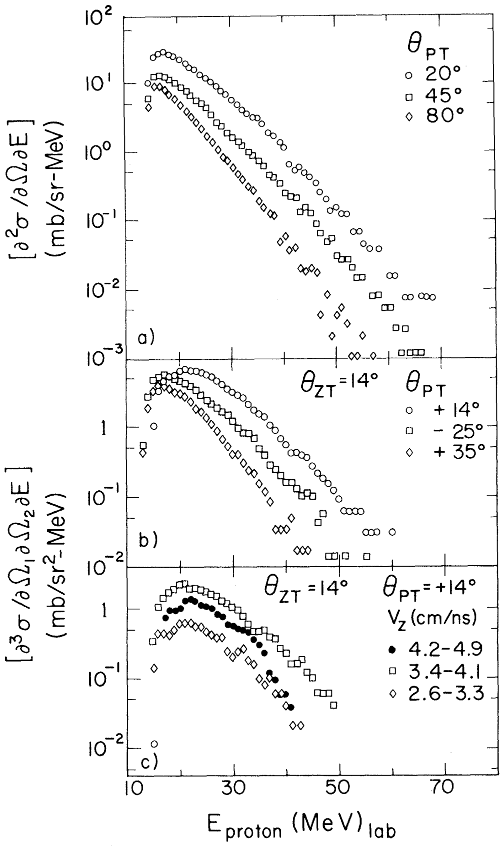

FIG. 1. (a) Singles proton-energy spectra for representative laboratory angles. (b) For three angles the energy spectra of protons in coincidence with fragments of $Z=6-11$ detected at 14°. (c) Proton-energy spectra detected in a collinear geometry with fragments ($Z=6-11$) of three different velocities.

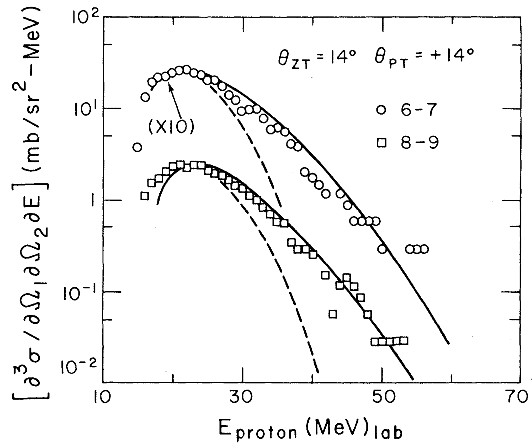

FIG. 2. Proton-energy spectra detected in a collinear geometry with $Z=6-7$ (circles) and $Z=8-9$ (squares). The curves are the predicted spectral shapes from a simple evaporation model with $\sigma=10$ MeV (solid lines) and with $\sigma=0$ (dashed lines).

protons are associated with the intermediate velocity events (squares). In contrast, the yield of protons associated with the fastest quasielastic events (circles) drops off rather abruptly above 35 MeV. A similar pattern was observed for the noncollinear geometries.

This dependence of the proton energy spectra on the fragment's velocity is consistent with the proposed velocity-addition effect[14] and can be interpreted as a tradeoff between the kinetic energy and the available excitation energy. For high kinetic energies the fragment's excitation energy is low, favoring the emission of low-velocity particles in the frame of the fragment. For fragments with lower kinetic energies, the excitation energy is higher, enhancing the emission probability of higher-velocity protons. This effect more than compensates for the lower velocity of the emitting fragment in terms of the final laboratory energy.

In Fig. 2, proton laboratory energy spectra are shown for two Z bins ($\theta_{PT}=+14°$). We have attempted to understand these spectral shapes in terms of equilibrium evaporation[15,16] and have assumed that after the deep-inelastic collision the excited fragments undergo sequential decay. For the measured laboratory angle, atomic number, and mean kinetic energy of the projectilelike fragment, the total excitation energy of both fragments was calculated from two-body kinematics. Assuming that the average excitation energy divides according to the fragment masses (see, i.e., Ref. 17), the proton yield was then calculated in the moving frame with use of simple evaporation theory.[15] This yield was then transformed into the laboratory frame and the contributions from projectile and target emission were summed. The calculated spectra fail to predict the data above 30 MeV (see dashed curves in Fig. 2). Since the high-energy portions of the calculated spectra are due to emission from the projectilelike fragment, the failure of the calculations in this region may be attributed to a deficiency in the excitation energy of the projectilelike fragment. Trivially, increasing its share of the excitation energy would increase the yield of high-energy protons but would also similtaneously destroy the agreement with the angular distributions (see below).

This difficulty can be overcome by considering the thermal fluctuations[18] in the division of the excitation energy, E^*, between the fragments which have been neglected so far. To evaluate this effect, we have calculated energy spectra for various divisions of E^* and have folded them with a Gaussian probability distribution

$$P(E_1^*) \propto \exp - (E_1^* E_{1,\mathrm{eq}}^*)^2/2\sigma^2.$$

On purely statistical grounds a value for σ of 10 MeV is predicted from the expression $\sigma^2 = 2T^3 a_1 a_2/(a_1 + a_2)$, where T is the temperature of the intermediate complex and a_1 and a_2 are the level density parameters of the two fragments (see Moretto[18] for a derivation). While the calculations with (solid lines) and without (dashed lines) thermal fluctuations are essentially identical at low energies (see Fig. 2), the incorporation of fluctuations produces a dramatic increase in the number of high-energy protons. Including thermal fluctuations in the calculations clearly reproduces the experimental data at 14°. A calculation for the noncollinear angle of − 25° yields similar agreement.

For protons with velocities greater than 1.4 times the beam velocity, the in-plane angular distributions associated with representative Z values are shown in Fig. 3. The most striking feature of these correlations is the strong peak near 0°. (Similar features are observed for protons in other energy bins.) At larger angles, on both sides of the beam axis, the yield falls off rapidly at first and then more gradually. The more gradual falloff could be due to emission from targetlike fragments, which generally have low velocities and hence very broad in-plane distributions. This interpretation is consistent with the fact that the observed yield at large negative angles (target-recoil side) is somewhat greater than the yield at large positive angles.

To determine whether equilibrium evaporation could account[16] for the observed angular correlations, we have utilized the model described earlier to calculate the in-plane proton angular correlation neglecting fluctuations (for this broad energy bin fluctuations in E^* do not change the yield appreciably). Typical results (dashed lines) are shown in Fig. 3 for Z values of 6, 8, and 10. In this particular example, it was assumed that the initial angle of the preevaporative projectilelike fragment was emitted at 10° in an effort to crudely simulate evaporation-recoil effects[19] (see below).

While the calculations do a reasonable job of reproducing the overall shape of the data, the predicted peak of the correlation occurs at slightly larger angles. The position of the peak is sensitive to the velocity distribution of the emitting fragment (an average value was used in the calculations) and is *especially sensitive* to evaporation-recoil effects. Because of the large recoil imparted to the projectilelike fragment by the emitted proton, the emission angle is usually altered from its original value (except, of course, in the case of a single collinear emission). Furthermore, because the angular distributions of the projectilelike fragments are strongly forward peaked,[19,20] the initial emission angle should, on the average, be less than 14°. Unfortunately, it is very difficult to account for these effects in any transparent way since one does not know the charge and angular distributions of the primary fragments.

While many of the above experimental features

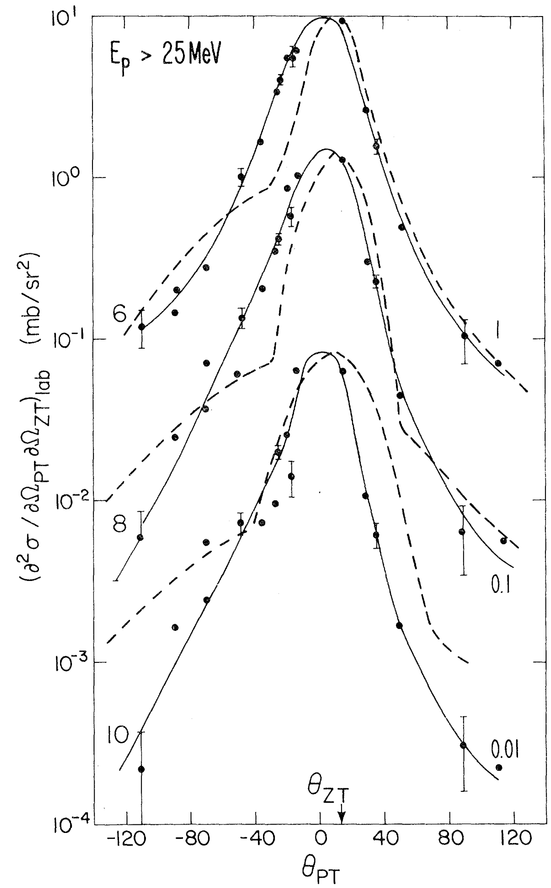

FIG. 3. In-plane angular correlation of protons with energies greater than 25 MeV (solid symbols) for three representative Z values ($Z = 6$, 8, and 10). The solid lines drawn through the data points are to guide the eye and the dashed lines are the result of simple evaporation-model calculations.

possibly could be explained by invoking a prompt mechanism, we feel that one should not ignore the well-known evaporation process, which is certain to be present. In fact, we have shown that evaporation in the presence of thermal fluctuations in the division of the excitation energy could reproduce the high-energy protons associated with the deep-inelastic channel.

[(a)]Present address: Cyclotron Institute and Department of Chemistry, Texas A & M University, College Station, Tex. 77843.
[(b)]Present address: W. K. Kellogg Radiation Laboratory, 106-38, California Institute of Technology, Pasadena, Cal. 91125.
[(c)]Present address: Laboratoires de Physique Corpusculaire, Université de Caën, F-1400 Caën, France.

[1]J. W. Harris *et al.*, Phys. Rev. Lett. 38, 1460 (1977).
[2]C. K. Gelbke *et al.*, Phys. Lett. 71B, 83 (1977).
[3]A. Gamp *et al.*, Phys. Lett. 74B, 215 (1978).
[4]R. K. Bhowmik *et al.*, Phys. Lett. 80B, 41 (1978).
[5]H. Ho *et al.*, Phys. Lett. 96B, 51 (1980).
[6]J. M. Miller *et al.*, Phys. Rev. Lett. 40, 100 (1978).
[7]P.-A. Gottschalk and M. Weström, Phys. Rev. Lett. 39, 1250 (1977).
[8]T. Nomura *et al.*, Phys. Rev. Lett. 40, 694 (1978).
[9]Y. Eyal *et al.*, Phys. Rev. Lett. 41, 625 (1978).
[10]B. Tamain *et al.*, Nucl. Phys. A330, 253 (1979).
[11]M. Robel, Ph.D. thesis, University of California, Berkeley, 1979 (unpublished), Lawrence Berkeley Laboratory Report No. LBL-8181; J. P. Bondorf *et al.*, Phys. Lett. 84B, 162 (1979).
[12]D. G. Sarantites *et al.*, Phys. Rev. C 18, 744 (1978).
[13]H. Yamada *et al.*, Phys. Rev. Lett. 43, 605 (1979).
[14]J. B. Ball *et al.*, Phys. Rev. Lett. 40, 1698 (1978).
[15]V. Weisskopf, Phys. Rev. 52, 295 (1937).
[16]J. Gomez del Campo, in Proceedings of the Symposium on Heavy Ion Physics from 10 to 200 MeV/A, Brookhaven National Laboratory, Upton, N.Y., 1979, Brookhaven National Laboratory Report No. BNL-51115, 1979 (unpublished), Vol. 1, p. 93.
[17]B. Cauvin *et al.*, Nucl. Phys. A301, 511 (1978).
[18]L. G. Moretto, in Proceedings of Workshop of Physics of Plasmas Close to Thermonuclear Conditions, Varenna, Italy, October, 1979 (to be published), Lawrence Berkeley Laboratory Report No. LBL-9130.
[19]C. K. Gelbke, in *Proceedings of the International Conference on Continuum Spectra, San Antonio, Texas, 1979*, edited by T. Tamura, J. B. Natowitz, and D. H. Youngblood (Harwood Academic Publishers, New York, 1979); G. R. Young *et al.*, Phys. Rev. Lett. 45, 1389 (1980).
[20]G. J. Mathews *et al.*, Lawrence Berkeley Laboratory Report No. LBL-5075, 1976 (unpublished), p. 123.

Properties of the (α, α^*) Reaction at Very Forward Angles: Coupled-Channels Effects in Single and Mutual Excitation

J. van Driel, M. N. Harakeh, R. Kamermans,[(a)] and R. J. de Meijer
Kernfysisch Versneller Instituut der Rijksuniversiteit, 9747-AA Groningen, The Netherlands
(Received 1 May 1980)

Use was made of a special feature in the detection of unbound ejectiles, to extend previous measurements of the (α, α^*) reaction on ^{24}Mg and ^{28}Si to very forward angles. The characteristic differential cross sections obtained for mutual as well as for single excitation are well reproduced in a full coupled-channels calculation in which the strong couplings to the first excited 2^+ states of the target nuclei are taken into account.

PACS numbers: 25.60.Cy, 24.10.Dp, 27.30.+t

Nuclear reactions in which the projectile is excited via inelastic scattering from the target nucleus into a bound state have already been studied[1,2] for a number of heavy-ion systems. More recently, there has been much interest[3] in studies of nuclear reactions resulting in unbound ejectiles. This type of studies, including projectile excitation into an unbound state, opens[4] many new possibilities in nuclear reaction investigations. It also necessitates extending our theoretical understanding of direct nuclear reactions into a new domain in which very little work has been done. Recently for instance, Kunz, Saha, and Fortune[5] developed a new method of finite-range distorted-wave Born approximation (DWBA) to treat pickup reactions to unbound ejectiles.

In order to understand the reaction mechanism involved in the (α, α^*) reaction, exciting the α particle to its first excited state ($J^\pi = 0^+$, $E_x = 20.1$ MeV), Kamermans *et al.*[6] studied this reaction at $E_\alpha = 65$ MeV on a wide range of nuclei. Surprisingly, strong mutual excitation of both target and