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FAST PARTICLE EMISSION IN THE DEEP INELASTIC REACTION $^{nat}Cu + ^{20}Ne$ AT 12.6 MeV/NUCLEON

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Abstract

Protons with velocities up to 2.4 times that of the beam have been measured and the largest number of these fast protons are observed to be in coincidence with medium-velocity projectile-like fragments. Despite large proton velocities and angular distributions which peak near 0^o, it appears that evaporation is probably the dominant production mechanism for fast protons although the possibility of some preequilibrium events contributing to the highest energy extreme of the spectrum can not be ruled out.

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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 pre-equilibrium α-particle emission in deep-inelastic reactions, possibly due to the decay of a "hot spot" formed during the collision [7,8]. On the other hand, studies of neutron emission accompanying deep-inelastic reactions [9-10] do not show evidence for any appreciable non-equilibrium component even though theoretical considerations have led to the suggestion that fast nucleons could be ejected as "Fermi" or "PEP" jets [11]. The marked contrast of the above observations and the theoretical possibility of fast-nucleon emission underlines the need for additional data to better define the conditions under which equilibrium or non-equilibrium particle emission dominates. To this end we have studied high-energy proton emission from a deep-inelastic reaction which is likely to offer a recognizable signature of a pre-equilibrium process.

Self-supporting ^{nat}Cu foils (~1 mg/cm^2) were bombarded with 252-MeV $^{20}Ne^{6+}$ ions produced by the Lawrence Berkeley Laboratory 88-inch cyclotron. Projectile-like fragments were detected in a solid state Z-telescope (ZT) consisting of an 11.3μm Si ΔE-counter and a 250μm Si E-counter. Light particles (i.e., p, d, and t) were detected with 2 to 4 proton telescopes (PT) each consisting of a 400 to 600μm ΔE counter and a 3.2cm NaI E-counter. The PT's were collimated by Ta annuli thick enough to stop 60 MeV protons and were shielded in thick aluminum tubes. The latter counters could stop protons with energies as great as 100 MeV and had an energy resolution of 1.5-2.0 percent.

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 ($+14^{o}$) 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 colinearly 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^{o} (on the side opposite the ZT) to $\pm 131^{o}$. By monitoring the proton-coincidence cross section in the PT at $+14^{o}$, 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 percent over the entire proton spectrum.

Singles and coincidence proton energy spectra are shown in Figs. 1 (a) and (b). The low energy cutoff in all the energy spectra is due to the ΔE detectors and the protective window (0.25mm Al) on the NaI E-detectors. Representative proton singles spectra are shown at the top of the figure. In general, the singles energy spectra fall off smoothly with increasing energy. At 20^{o}, protons with energies up to 70 MeV are observed. This corresponds to 2.4 times the beam velocity. Even at 80^{o}, protons up to about 55 MeV or twice the beam velocity are observed.

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 lab energies of 50-220 MeV. Although fast protons are again observed, the coincidence proton spectra fall off more rapidly with increasing energy than do the singles. This difference probably reflects the fact that for coincident protons a projectile-like fragment must be detected at 14^{o}, whereas in singles there are also contributions from all other possible emission angles of the Ne-like fragment, and possibly from fusion processes. One should note that the highest energy coincident protons (E_p > 35 MeV, V_p > 8.3cm/ns) are most abundant at forward angles and that their production cross section is low ($\lesssim$1 mb/sr^2-Mev).

It has been proposed [12] that these high-energy protons could result from the sequential decay of fast moving quasi-elastic (QE) events via a velocity addition effect. If so, then the telescope with the colinear geometry for the ZT and one of the PT's should exhibit energetic protons in coincidence with the QE events. To check this, the ZT energies were converted to velocities on an event-by-event basis and three equal width gates were set on the Ne-like fragment velocities (V_Z = 2.6 to 4.9cm/ns). Colinear proton energy spectra generated for each of these velocity bins are shown in Fig. 1c for $\theta_{PT} = +14^{o}$. The diamonds correspond to the low velocity (DI) events, whereas, the circles correspond to the high velocity (QE) events (all Z's between 6 and 11 are included to obtain better statistics). It is fairly clear that the yield of protons associated with QE processes drops off rather abruptly above 35 MeV, and hence, the QE events are not the source of the fastest protons. In fact, the highest energy protons are associated with the intermediate velocity events (squares). It should be noted that a similar pattern is observed for non-colinear geometries.

This opposing dependence of the proton energy spectra on the fragment's velocity can be interpreted as a trade off 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. In contrast, for fragments with lower kinetic energies the excitation energy is higher, enhancing the emission probability of higher velocity protons. This effect can more than compensate for the fact that the emitting fragment's velocity is lower, so that higher energy protons are observed in the lab.

In Fig. 1(d) proton lab energy spectra are shown for three pairs of atomic numbers ($\theta_{PT} = +14^{0}$). Surprisingly enough the spectral shapes are essentially the same for all cases. Only the yield varies significantly with Z. (To within about 30 percent the proton yield is simply proportional to the yield of the projectile-like fragments). While it is tempting to explain the lack of Z-dependence in the spectral shapes by invoking a preequilibrium process in which the protons are emitted before the exit channel asymmetry has been determined, this is not the only explanation. Indeed, calculations of equilibrium evaporation seem to indicate a similar trend. We have performed these calculations by using the experimental average fragment velocities and assuming that the excitation energy divides according to the mass ratio of the primary fragments [13,14,15]. The calculated spectra do a reasonable job of reproducing the data except at the highest proton energies (see curvesin Fig. 1d). The high energy portions of the calculated spectra are due to emission from the projectile-like fragment. The failure of the calculations to reproduce this portion of the spectra is related to the low excitation energy in the projectile-like fragment. Increasing its share of the excitation energy (perhaps due to statistical fluctuations) would increase the yield of high-energy protons although the possibility of some preequilibirum contribution in this region of the spectrum is not ruled out on the basis of the simple model applied here.

In Fig. 2, in-plane proton-angular distributions are shown for representative atomic numbers and for protons with velocities greater than 1.4 times the beam velocity. The most striking feature of these correlations is the strong peak near 0^{o}. (Similar features were observed for protons of 15-25 MeV (not shown).) 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 target-like 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. One should also note that the width of the 0^{o} peak decreases slightly as the Z-value of the coincident projectile-like fragment increases.

To determine the extent to which these features of the data are consistent with evaporation from the projectile-like and target-like fragments, we have performed a simple calculation. For the measured lab angle, atomic number and mean kinetic energy of the project-like fragment, the total excitation energy of both fragments was calculated from two-body kinematics. Assuming that the excitation energy divides according to the fragment masses [15], the proton yield was then calculated in the moving frame using simple evaporation theory [16]. This yield was then transformed into the lab frame and the contributions from projectile and target emission were summed. Typical results (dashed lines) are shown in Fig. 2 for Z-values of 6, 8 and 10. In this particular example, it was assumed that the initial angle of the pre-evaporative projectile-like fragment was emitted at 10^0 in an effort to crudely mockup evaporation-recoil effects (see below).

It is encouraging that the calculations reproduce the overall shape of the experimental data, however, one should note that the peak position predicted for projectile emission occurs at slightly larger angles than does the data. This position is sensitive to the velocity distribution of the emitting fragment (an average value was used in the calculations) and to evaporation-recoil effects. Because of the recoil imparted to the projectile-like fragment by the emitted proton, the emission angle is usually altered from its original value (except of course in the case of a single colinear emission). Furthermore, because the angular distributions of the projectile-like fragments are strongly forward peaked [17], the initial emission angle should, on the average, be less than 14^o. The situation is further complicated by the fact that the projectile-like fragments could subsequently emit other particles.

Although the simple calculation described above does a fair job of reproducing both the energy spectra and the angular distributions, it does not predict proton energies as large as those observed experimentally. More energetic protons could perhaps be produced by fluctuations in the division of the excitation energy between the fragments [18]. However, on the basis of the simple model applied here, the possibility of some small nonequilibrium contribution to the spectra can not be ruled out.

In conclusion, light particle emission in the 252-MeV $^{20}Ne + ^{nat}Cu$ reaction has been studied. Protons with velocities up to 2.4 times that of the beam velocity have been observed and the largest number of these fast protons are observed to be in coincidence with medium-velocity projectile-like fragments. The in-plane correlations exhibit a strong peak near 0^o for all proton energies. Both the proton energy spectra and angular distributions are crudely reproduced by a simple evaporation model. Thus it appears that the bulk of the fast protons, are due to evaporation from the target and projectile-like fragments. Although it is possible that the highest energy protons may result from a prompt process, it is very difficult to isolate an unambiguous signature of the small pre-equilibrium component from the background of equilibrium evaporation because of possible large perturbations from recoil, multiple-particle emission and fluctuation effects.

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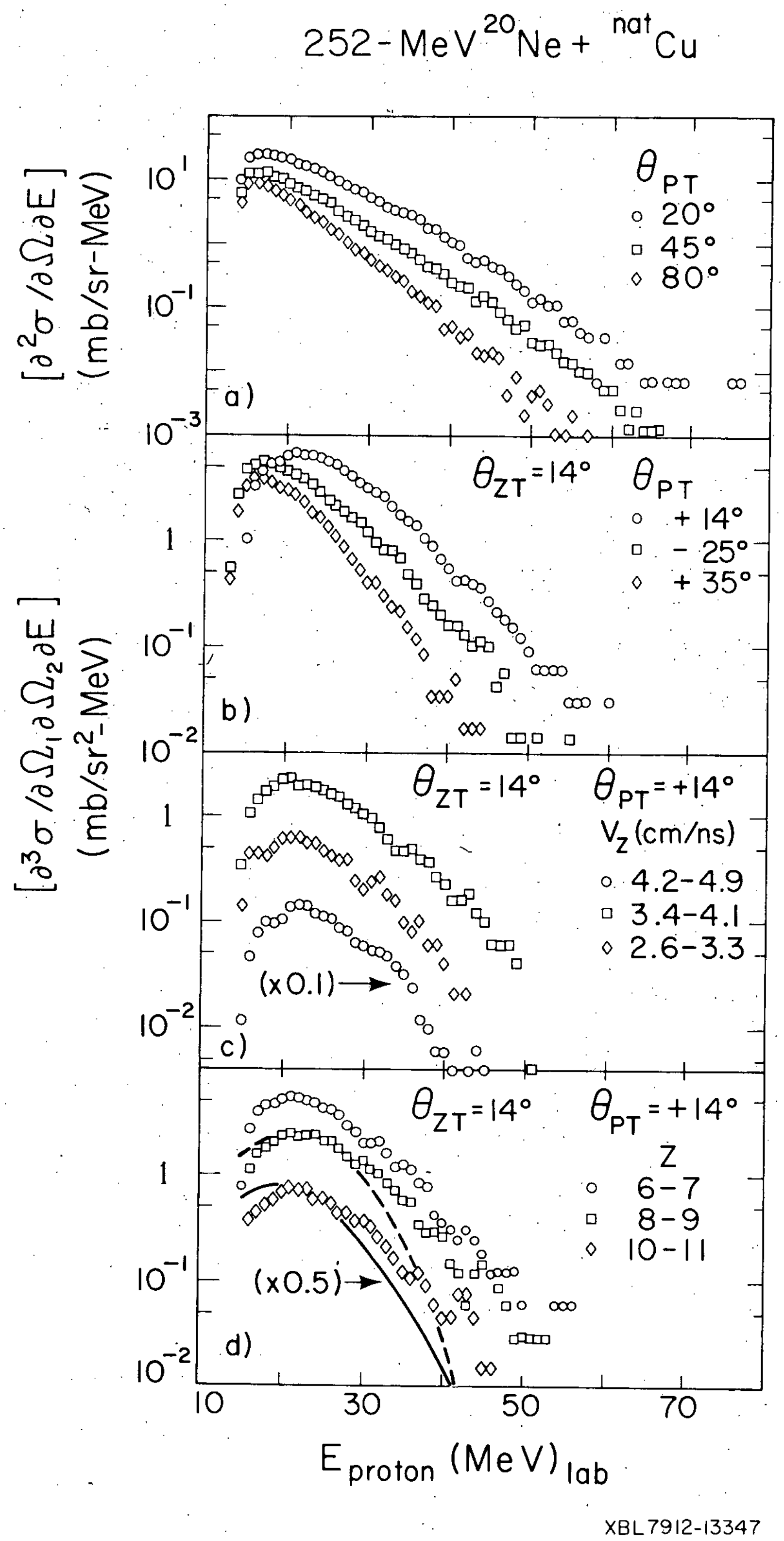
Figure Captions

Fig. 1. (a) Singles proton-energy spectra for representative lab angles. (b) For three angles the energy spectra of protons in coincidence with fragments of Z = 6 to 11 detected at 14^{o}. (c) Proton energy spectra detected in a colinear geometry with Z-fragments of three different velocities, and (d) three Z-value bins. The curves are the predicted spectral shape from a simple evaporation model calculation.

Fig. 2. In-plane angular correlation of high energy protons (>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.



252-MeV ^{20}Ne + ^{nat}Cu
$[\partial^2\sigma/\partial\Omega\partial E]$ (mb/sr-MeV)
$[\partial^3\sigma/\partial\Omega_1\partial\Omega_2\partial E]$ (mb/sr^2-MeV)
a)
θ_{PT}
20°
45°
80°
b)
θ_{ZT}=14°
θ_{PT}
+ 14°
− 25°
+ 35°
c)
θ_{ZT} =14°
θ_{PT} = +14°
V_Z (cm/ns)
4.2-4.9
3.4-4.1
2.6-3.3
(x0.1)
d)
θ_{ZT}=14°
θ_{PT} = +14°
Z
6-7
8-9
10-11
(x0.5)
10
30
50
70
E_{proton} (MeV)$_{lab}$
XBL7912-13347

Fig. 1

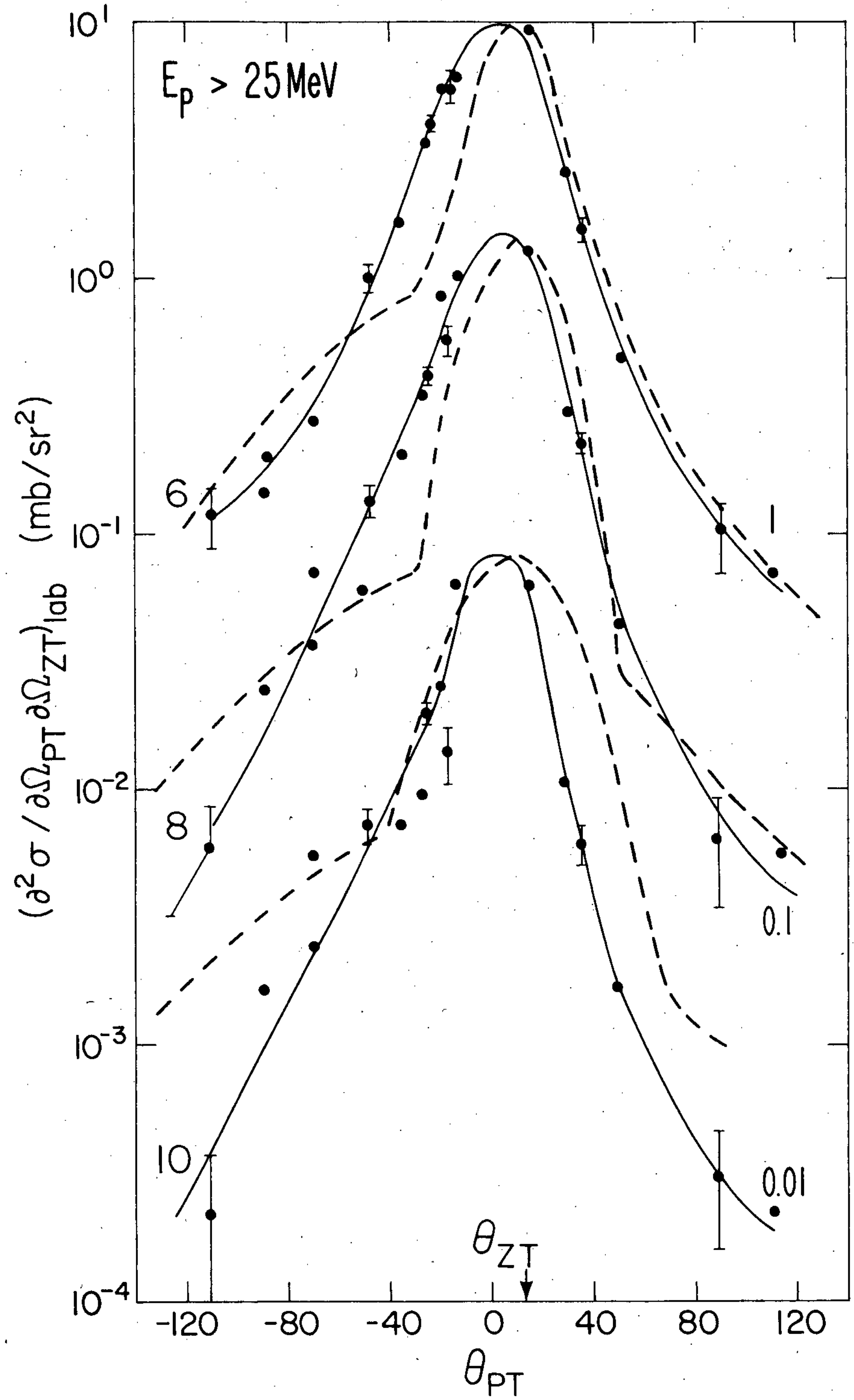


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Fig. 2