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EVIDENCE FOR ENERGY THERMALIZATION IN DEEP-INELASTIC PROCESSES: $^{63}_{\text{Cu}} + ^{20}_{\text{Ne}}$ at 7.9, 12.6 and 17.2 MeV/nucleon *

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ABSTRACT

Light charged particle emission in the reaction $^{63}_{\text{Cu}} + ^{20}_{\text{Ne}}$ has been studied by simultaneously measuring the atomic numbers of both deep-inelastic fragments. The results seem consistent with an evaporative process and indicate that the entrance channel kinetic energy is essentially thermalized over a broad range of bombarding energies.

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On the basis of single particle inclusive measurements, it is evident that a large fraction of the entrance kinetic energy is dissipated in deep-inelastic collisions (DIC). However, the mechanism responsible for the damping process is not obvious, and a variety of mechanisms have been proposed (see for example 3-5). Correlation measurements between deep-inelastic fragments and either light particles or heavy fragments are powerful techniques for exploring the details of the dissipation process. Furthermore, such studies can also yield information on the relaxation of other modes like the degree of thermalization of the dissipated energy and the sharing of excitation energy between the primary fragments. There are, however, limitations associated with both techniques. Light particle coincidence experiments are complicated by the fact that the spatial correlations can be broad and the interpretation tends to be difficult at high excitation energies when both fragments can emit one or more particles. In addition, the presence of small amounts of light target impurities can seriously contaminate the light particle spectra. On the other hand, coincidence measurements of the heavy fragments necessitate very accurate energy and angular calibrations if meaningful results are to be extracted on the basis of deviations from two-body kinematics.

In this letter we present results obtained with a technique which avoids the above difficulties, and, at the same time, provides a global view of light charged particle emission. The atomic numbers of both deep-inelastic fragments produced in the reaction $^{63}$Cu + $^{20}$Ne have been measured simultaneously, thus allowing the total charge loss ($\Delta Z$) to be determined directly. This system was chosen because the singles
measurements have been performed, and because this technique is optimized for light systems. More importantly, \(^{20}\text{Ne}\) beams were available at high energies where one might possibly expect non-statistical particle emission to play a dominant role in the energy dissipation process.

A self-supporting 560 \(\mu g/cm^2\) thick \(^{63}\text{Cu}\) foil (99% enrichment) was bombarded with \(^{20}\text{Ne}\) ions accelerated by the Lawrence Berkeley Laboratory 88\(^{\circ}\) cyclotron. The energies, atomic numbers and lab angles of the two heavy fragments were measured with two large-solid-angle (5\(^{\circ}\) angular acceptance) particle telescopes, each consisting of a gas ionization \(\Delta E\) detector and a solid-state \(E\) detector. The initial measurements were made at 252 MeV and were designed to study the de-excitation products of the symmetric exit channel (i.e. \(Z_1 = 19\) and \(Z_2 = 20\), before evaporation) at nearly symmetric angles (\(\theta_1 = 42^{\circ}\), \(\theta_2 = 44^{\circ}\)). In this configuration atomic numbers were resolved up to and somewhat above \(Z = 22\). Data were taken over the range of the angular correlation with the first telescope fixed at 42\(^{\circ}\). The in-plane distribution is broad (\(\approx 15^{\circ}\) FWHM) while the out-of-plane distribution is somewhat narrower (\(< 10^{\circ}\) FWHM). Neither of these quantities exhibit much dependence on the exit channel asymmetry. For the 158 and 343 MeV bombarding energies, measurements were taken only at symmetric angles, optimized for the symmetric decay channel. One should note that in all cases, the measurements were made at angles well behind the grazing angle where the energy spectra are relaxed (i.e. no quasi-elastic component).

For a fixed value of the atomic number detected in the first telescope \((Z_1)\), a distribution of atomic numbers \((Z_2)\) are observed in
the second telescope in coincidence. Examples of the $Z_2$ distributions for $Z_1 = 16$ are shown in Fig. 1 for various cuts in the total laboratory kinetic energy of the fragments ($E_T = E_1 + E_2$). The total kinetic energy has been chosen insofar as it may be more indicative of the excitation energy than the energy of a single fragment. Although the sigma of the $Z_2$ distributions is large ($\approx 2.0$), it is approximately independent of the total kinetic energy and asymmetry. The mean value of $Z_2$ does, however, depend on $E_T$: as $E_T$ increases, the mean value of $Z_2$ increases.

This feature is more visible when the mean missing charge ($\Delta Z \equiv 39 - Z_1 - Z_2$) is plotted vs $E_T$ for various $Z_1$ and $\theta_2$ (see Figs. 2a & 2b). Several features are immediately obvious: 1) the number of evaporated charges is large, $\Delta Z$ ranging from 4-8; 2) $\Delta Z$ decreases with increasing $E_T$; 3) the magnitude and shape of the $\Delta Z$ curve is essentially independent of the asymmetry of the fragments (note the clustering for different $Z_1$ values); 4) the above trends do not change significantly over the in-plane correlation. Point 1 is understandable since we are dealing with a light system (low Coulomb barrier) at high excitation energies. The gross dependence of $\Delta Z$ on $E_T$ can be attributed to an excitation energy effect: as the lab energy increases, the available excitation energy decreases so that fewer particles are emitted. The insensitivity of $\Delta Z$ to $Z_1$ can be explained by the fact that for this system the $Q$-values leading to different exit channels are essentially independent of asymmetry (assuming constant $Z/A$ for the fragments). We have confirmed this behavior at even larger exit channel asymmetries (i.e. $Z_1 = 10$) in other measurements. The fourth point (i.e. the weak dependence on $\theta_2$) seems consistent with an evaporation process. In
cases of copious particle emission (as observed for this system), the random variations in the direction of emission for sequential decays smear the correlation over a substantial angular range, so that any angular effects would be washed out.

The out-of-plane data (see Fig. 2c) shows a definite angular dependence. The symmetric angle setting ($\theta_1 = 42^\circ$, $\theta_2 = 44^\circ$, $\phi_2 = 0$) is again shown for comparison. For $\theta_2 = 44^\circ$, $\phi_2 = 10^\circ$ the mean evaporated charge $\Delta Z$ at $E_T = 105$ MeV is slightly higher by about one Z-unit. For $\phi_2 = 20^\circ$ $\Delta Z$ has increased by almost 2.5 Z-units. It is probable that by looking out of the reaction plane one preferentially selects events for which more extensive particle emission has occurred, perhaps via a emission which tends to impart large recoil momentum.

The reason that this effect is not visible in-plane may be because there is an inherent width due to the range of Q-values for the deep-inelastic process which leads to the broader in-plane width.

The in-plane correlation data can be used to estimate the total mass loss due to particle emission. Simple calculations, based on the average energies and angles of the fragments, yield an average mass loss of 15 ± 3 (the appreciable uncertainty is due to the large angular acceptance of the detectors), which seems consistent with the measured average $\Delta Z$ value.

In Fig. 3a the average $\Delta Z$ is plotted vs $E_T$ for the three bombarding energies. Again the angles have been chosen at the peak of the correlation for symmetric decay. As expected $\Delta Z$ increases with increasing bombarding energy. An interesting feature of the data is the dip in the 158 MeV data and the change in slope at intermediate values of $E_T$ for the 252 MeV data. While it is tempting to associate these features with some kind
of non-equilibrium process, this behavior is not inconsistent with
equilibrium particle evaporation. In general, the effective barriers for
n, p and α-particle emission are expected to be different. Since the
ratio \( \Delta Z/\Delta E \) strongly depends on the decay mode (e.g. \( \Delta Z = 0 \) for n emission),
the competition between n, p and α decay can produce variations in
\( \Delta Z/\Delta E \). This effect is expected to be strongest at low excitation
energies where the differences in the barriers is felt most strongly
due to low temperatures. The fact that a minimum is present in the low
energy data (i.e. 158 MeV) but not in the higher energy data lends support
to such a picture.

In Fig. 3b \( \Delta Z \) has been plotted as a function of the total
excitation energy deposited in the fragments. The excitation energy
scale has been calculated assuming that the fragment velocities are
not altered as a result of particle emission. For purposes of emphasis,
only the points that are associated with relatively large cross sections
have been plotted (the plotted data correspond to roughly 80% of the
yield for the asymmetries considered). A smooth, almost linear increase
in \( \Delta Z \) with excitation energy is readily apparent implying that the
excess kinetic energy is effectively thermalized over a very broad
range of excitation energies. The slope of the line corresponds to
about 25 MeV/charge. Since the total mass loss is about twice the
evaporated charge (within experimental errors), one obtains an average
energy loss per particle of \( \sim 12.5 \) MeV, which is consistent with simple
estimates assuming evaporation. Of course, we have only considered
symmetric products at angles behind the grazing angle. The situation
may be more complicated for Z's below the projectile, where there are indications that high energy particles are emitted.\textsuperscript{16}

In conclusion, the technique of simultaneous Z identification of the major fragments is a powerful tool for studying deep-inelastic processes since it directly provides the multiplicity of the evaporated charge. The data support the view that the dissipated kinetic energy is thermalized in both fragments and that they dispose of their excitation energy by evaporating light particles. This picture seems to be valid over a broad range of bombarding energies as evidenced by the fact that the energy loss per nucleon does not vary strongly as it might if non-equilibrium particle emission became a dominant mechanism at high energies. Thus it appears that most of the available phase space for the intrinsic degrees of freedom of the fragments appears to be explored in deep-inelastic processes.
References

15. L. G. Moretto, in Proc. IPCR Symp. on Macroscopic Features of Heavy-ion Collisions and Pre-equilibrium Processes (Hakone, Japan, 1977), eds. H. Kamitsubo and M. Ishihara.
Figure Captions

Fig. 1  Distributions in $Z_2$ for constant $Z_1$ for various cuts in the total laboratory kinetic energy of the fragments.

Fig. 2  

a) Mean missing charge ($\Delta Z$) as a function of the total laboratory kinetic energy ($E_T$) for several exit channels. Note the false zero in the energy scale.

b) Mean $\Delta Z$ vs $E_T$ averaged over the exit channel asymmetry for several values of $\theta_2$. The error bars represent the $\text{rms}$ deviation corresponding to different asymmetries.

c) Same as b) except for various out-of-plane angles $\phi_2$ ($\theta_2 = 44^\circ$).

Fig. 3  

a) Mean missing charge vs $E_T$ for three different bombarding energies.

b) Mean missing charge plotted as a function of the excitation energy. The line through the data points serves only to guide the eye.
252 MeV $^{20}$Ne + $^{63}$Cu

$Z_i=16, \theta_1=42^\circ, \theta_2=44^\circ$

$E_T=60-70$ MeV

70-80

80-90

90-100

100-110

110-120

120-130

130-160

Fig. 1

XBL 777-1517
$^{63}\text{Cu} + 252 \text{ MeV} \rightarrow ^{20}\text{Ne}$

$\theta_1 = 42^\circ, \theta_2 = 44^\circ$

$\Delta Z$ (missing charge)

$\theta_2$

$\phi_2$

$\theta_1 = 42^\circ, \theta_2 = 44^\circ$

$E_T$ (MeV)

Fig. 2

XBL 787-2601
$^{20}\text{Ne} + ^{63}\text{Cu}$

(a) B.E.

$\theta_1 = \theta_2$ (MeV)

- $50^\circ$ 158
- $42^\circ$ 252
- $38^\circ$ 343

(b) $\Delta Z$ (missing charge) vs. $E_T$ (MeV)

$\left(E_1^* + E_2^*\right)$ (MeV)

Fig. 3

XBL 783-436
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