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Asymmetric neutron emission in $^{14}N + ^{165}Ho$ reactions at 35 MeV/nucleon

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We report results from neutron coincidences with projectile-like fragments in collisions of 35 MeV/nucleon ^{14}N with ^{165}Ho. Quasi-elastic events show a clear left-right asymmetry, decreasing with fragment Z, which gives more high energy neutrons on the side of the beam opposite the detected fragment, while strongly damped events are left-right symmetric. A moving-source fit to the spectra in quasi-elastic events requires a source with a velocity near half the beam velocity and moving on the side of the beam opposite the projectile-like fragment. The fitted temperature and kinetic energy of this source are consistent with previous analyses of charged particle emission data which involved an intermediate-velocity moving source, except that in our case the source is not moving along the beam axis. Recoil effects in the framework of two moving sources cannot account for both the asymmetry and angular distribution observed.

This Rapid Communication presents results from our study of neutron coincidences with projectile-like fragments in 35 MeV/nucleon ^{14}N induced reactions on ^{165}Ho. The bombarding energy corresponds to collision speeds just above the average speed of nucleons inside the nucleus and yet well below the regime of independent nucleon-nucleon collisions. Our motivation for detecting the neutrons was that they are not distorted by the strong Coulomb fields present at the time of emission and, therefore, they give a cleaner signature of their origin than do charged particles.

In experiments below 20 MeV/nucleon the dominant mode of neutron emission was reported by several groups to be evaporation from fully accelerated primary fragments produced in damped[1-7] and quasi-elastic[4,8] binary reactions. Such a conclusion follows from their ability to fit nearly all the spectra with two moving sources, one a target-like source and the other projectile-like, and both having the same temperature. Neutrons from such a source are kinematically focused along the directions of the fragments. Each source was assumed to emit neutrons isotropically in its rest frame. In our experiment at 35 MeV/nucleon, where both strongly damped and quasi-elastic events were detected, the neutron spectra for the latter case show an asymmetry about the beam axis. More high energy neutrons are emitted toward the side of the beam *opposite* the projectile-like fragment. In the strongly damped collisions the neutron spectra are symmetric about the beam axis. The asymmetry in quasi-elastic events which we see is in the opposite sense to that reported[4] in preequilibrium neutron emission from quasi-elastic collisions of ^{86}Kr with ^{166}Er at 8.9 MeV/nucleon, and has not been pointed out in other studies. Also, in contrast to the earlier work,[1-8] our symmetry in strongly damped events is about the beam axis instead of the primary fragment directions.

In our experiment, a ^{165}Ho target of 7.6 mg/cm^2 areal density was bombarded by a 490 MeV $^{14}N^{5+}$ beam from the National Superconducting Cyclotron Laboratory K500 Cyclotron at Michigan State University. Projectile-like fragments (PLF's) were detected inside a vacuum chamber using three ΔE-E silicon telescopes at angles $\theta_{PLF} = +10°$ and $-30°$ in the horizontal plane and at 30° below the beam in the vertical plane. Fragment singles and coincidences with neutrons were recorded event by event and analyzed off line. Ten NE213 liquid scintillation counters outside the chamber were employed to detect the coincident neutrons at $\theta_n = \pm 10°$, $\pm 30°$, $-45°$, $\pm 60°$, $\pm 90°$, and $-110°$ in the horizontal plane. NE102A plastic scintillator paddles were placed in front of the neutron counters at forward angles to reject any charged particles that had enough energy to pass through the chamber and enter a neutron counter. Time of flight determined the neutron energies, and a pulse shape discrimination signal was recorded and used off line to separate neutrons from gamma rays. A 3 MeV neutron energy threshold was set for the neutron counters. Corrections were made for accidental coincidences and for neutron scattering in the apparatus. Differential multiplicities were computed by dividing the coincidence cross sections by the fragment singles cross sections. Target contamination measured by α backscattering was estimated at 3 μg/cm^2 for carbon and 20 μg/cm^2 for oxygen. However, the target oxidized noticeably between the experiment reported here and the α-backscattering measurements. Hence, the oxygen contamination was surely much less than 20 $\mu g/cm^2$ during our experiment. No correction was made for this small level of contamination.

Instrumental asymmetries were checked by using the neutron spectra in coincidence with fragments at $\theta_{PLF}=30°$ below the beam. That these spectra are left-right symmetric, as they should be, is confirmed by our measured average left-right ratio (see below) of 0.94 ± 0.12 at $\theta_n=60°$ and is consistent with no instrumental asymmetry.

Figure 1 shows neutron spectra at all ten angles including the four left-right-symmetric angle pairs. The curves are discussed below. The neutrons are in coincidence with quasi-elastic boron ($210 \leq E \leq 400$ MeV, $Z=5$) fragments detected at $+10°$. (We also have similar data for neutrons in coincidence with lithium, beryllium, and carbon fragments.) The $\theta_n=10°$ data show more neutrons detected behind the fragment detector than on the opposite side of the beam. We have analyzed this effect and understand it as kinematic focusing of neutrons from sequential decay of the fragment parent via known resonances just above the neutron separation energy.[5,8] Adding the small fragment-neutron relative velocity to the larger fragment velocity gives a resultant which lies within a small cone around the fragment direction. So most of these neutrons are focused into the counter behind the fragment detector. In Fig. 1 this effect appears only at $\theta_n=+10°$ and does not appreciably affect spectra at other angles.

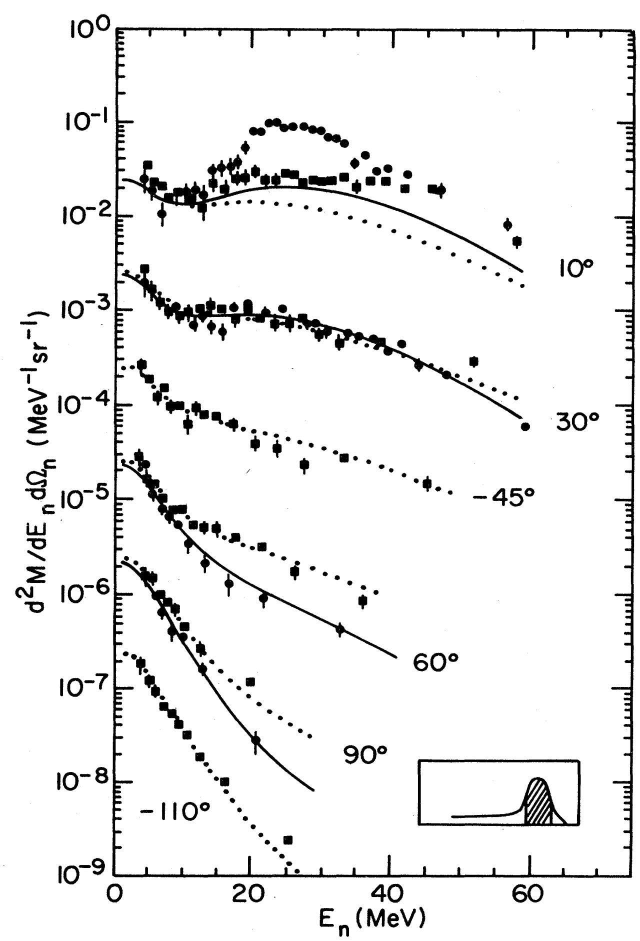

FIG. 1. Neutron multiplicity spectra in coincidence with quasi-elastic boron ($Z=5$) fragments at $\theta_{PLF}=+10°$. Circles represent neutrons detected on the same side of the beam as the fragment and the squares are for neutrons on the opposite side. Where the density of points is high, some points are not plotted for improved clarity. Data at equal angles but on opposite sides of the beam are plotted on the same scale while data at successive angles are offset by factors of 10. The scale for neutrons at 10° is correct. An inset shows a schematic fragment energy spectrum with the region of accepted fragment energies shaded. The curves are results of a three source fit for neutrons on the projectile-fragment side of the beam (solid lines) and the opposite side (dotted lines). The data at $\theta_n=10°$ were not used in the fit.

Aside from the left-right asymmetry due to sequential decay there is another asymmetry which becomes obvious at larger angles and is in the sense opposite to that of the sequential decay. Starting at the most forward angles, at the lowest and highest neutron energies the $\theta_n=10°$ data in Fig. 1 are left-right symmetric, though it is difficult to assess the degree of symmetry for the high energy portion. The $\theta_n=30°$ spectra are almost completely symmetric. However, at $\theta_n=60°$ and 90° more neutrons are emitted to the opposite side of the beam from where the fragment is detected. Furthermore, this asymmetry persists out to the largest neutron energies measured at these two angles. This asymmetry has not been pointed out before in neutron emission, although a similar but not so pronounced asymmetry was reported at lower bombarding energies per nucleon in α-PLF coincidence studies.[9,10]

Instead of gating on quasi-elastic fragments one may gate on strongly damped events, also detected at $\theta_{PLF}=+10°$. The result, again for boron fragments but with energies between 74 and 168 MeV, is shown in Fig. 2. The sequential decay "peak" is lower in energy than in Fig. 1 owing to the smaller fragment velocities. Also, except for the sequential decay component there is no perceptible left-right asymmetry in neutron emission at *any* angle. This symmetry about the beam axis is the observation which differs from others,[1-3,5-8] where the fragment directions were the symmetry axes for neutrons accompanying strongly damped collisions. Although not obvious in Fig. 2 the angular distribution of neutrons with $E_n > 10$ MeV is peaked in the forward direction, while the low energy neutrons have an isotropic angular correlation. The differential multiplicities in Fig. 2 are larger than in Fig. 1, as expected, since there is more kinetic energy loss in the former. Finally, if Fig. 2 is compared with Fig. 1 at $\theta_n=60°$ and 90°, the spectra for strongly damped events agree in shape and relative magnitude with the $+\theta_n$ spectra (circles) for quasi-elastic events. This could be coincidental or perhaps it suggests a similarity in one component of the reaction mechanism for both types of events.

A numerical measure of asymmetry was obtained by forming average left/right ratios $\langle R \rangle$. The quantity $\langle R \rangle$ was computed by energy averaging the *ratio* of cross sections from two neutron spectra, one on the fragment side of the beam and the other on the opposite side, from 10 to 30 MeV. The lower energy corresponds approximately to the onset of the asymmetry and 30 MeV is the largest energy for which there are data at $\theta_n=60°$ for every fragment Z. The rms deviation from $\langle R \rangle$ serves as an estimated uncertainty.

The asymmetry illustrated in Fig. 1 differs in magnitude depending on which fragment is detected. To show this sys-

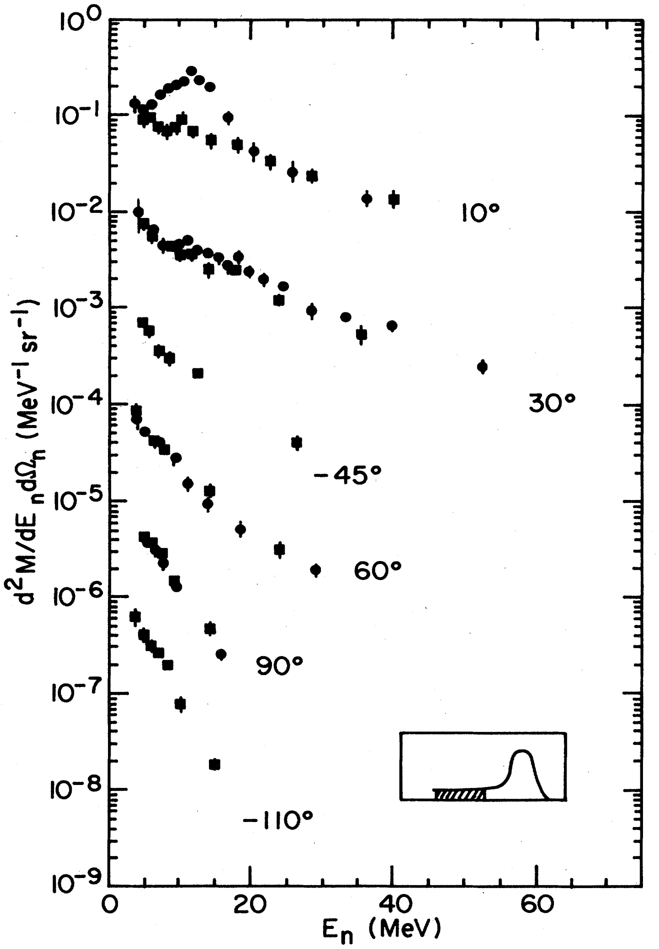

FIG. 2. Similar to Fig. 1 but gated on strongly damped fragments. No fit is shown for these data.

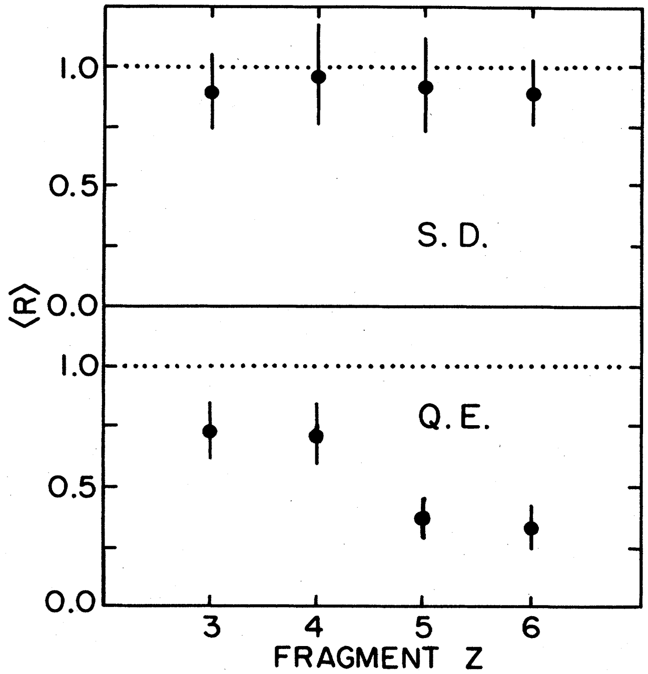

FIG. 3. Left-right average neutron ratios at $\theta_n = 60°$ vs fragment Z for strongly damped (top) quasi-elastic (bottom) fragments at $\theta_{PLF} = +10°$.

tematic effect, Fig. 3 shows a plot of $\langle R \rangle$ for $\theta_n = 60°$ versus fragment Z for both strongly damped (SD) and quasi-elastic (QE) fragments. The asymmetry is clearly largest for quasi-elastic carbon fragments and decreases with fragment Z. This systematic dependence on fragment mass (or Z) was not reported in the α-emission studies.[9,10] For strongly damped fragments of any Z in Fig. 3, $\langle R \rangle < 1$, but only by a small amount which is within the uncertainties.

Typically, analysis of neutron-fragment coincidence data proceeds by using a moving-source model where the projectile-like and target-like fragments have equal temperatures and have velocities determined approximately by two body kinematics. After the fragments separate, they evaporate light particles isotropically until the excitation energies are below particle threshold, and gamma emission completes the cooling process. The lowest energy neutrons in Fig. 1 show the characteristic, nearly isotropic emission pattern from a slow-moving, target-like fragment. The asymmetry of high energy neutron emission is not likely to originate from such a fragment. On the other hand, the projectile-like fragment focuses neutrons to angles near $+10°$ and is not expected to contribute substantially to high energy neutrons at, say, $-60°$. So a standard two-moving-source model simulating the evaporation from the fully accelerated primary reaction products cannot explain our data.

We note that it is possible for projectile-like fragment evaporation to create the sign of asymmetry observed if account is taken of the angular distribution of primary fragments and of the bias introduced by requiring a detected fragment at 10° after it recoils from neutron emission. Those fragments at angles forward of 10° are more numerous than those beyond 10°, and it is the former which would recoil toward 10° upon emission of a neutron toward the opposite side of the beam. A computer simulation of this process was performed using fragmentation formulas for the quasi-elastic energy and angular distributions and an isotropic evaporation spectrum for neutron emission. We assumed the source temperature to be 3 MeV and the centroid of the kinetic energy distribution to be 28 MeV/nucleon. The simulation produced an asymmetry in the same direction as observed at 60° but with a much steeper angular dependence than the data. For example, the calculations give factors of 100–1000 difference between the 60° and 90° spectra whereas the data show less than a factor of 10. Increasing the temperature does not improve agreement with the data. Hence, we find that a two-moving-source model including recoil effects is still incapable of describing the data (Fig. 1).

Reasonable moving-source fits can be obtained, however, if a third source is allowed and if it has characteristics similar to those of the intermediate-velocity sources required to fit light charged particle spectra from intermediate-energy heavy-ion collisions.[11] Such a fit, obtained using all but the 10° data, where sequential decay dominates, is shown in Fig. 1. This fit employs a slow-moving target-like source with $E/A = 0.003$ MeV/nucleon (the fit was rather insensitive to the emission angle of this fragment because of its low speed), a fast-moving projectile-like source with $E/A = 24$ MeV/nucleon and a fixed emission angle of

$+10°$, and an intermediate-velocity hot source. The temperature of the projectile-like source was set equal to the $T = 2.9$ MeV determined for the target-like source from a fit of data at angles greater than 30°. Only the target-like and the intermediate-velocity sources were used in that fit. The third source, which is responsible for nearly all the high energy neutron emission, has a fitted temperature of 8.3 MeV, a kinetic energy of 9.3 MeV/nucleon, and a direction of $-10°$. It is this third, intermediate-velocity source which reproduces our asymmetry in quasi-elastic events, but it is not moving at 0° as was assumed in the analysis of the inclusive charged particle measurements.[11] However, the charged particle data were intentionally biased toward more central collisions than we would expect in our quasi-elastic events. Integrated multiplicities for the fit in Fig. 1 are 1.7, 0.7, and 0.1 for the target-like, intermediate-velocity, and projectile-like sources, respectively.

With a three-source analysis we can obtain a reasonable fit to our neutron spectra, except at 10° where there is a substantial contribution from sequential decay from individual levels very near the neutron separation energy. However, a literal interpretation of at least the intermediate-velocity source is questionable. Nevertheless, analysis in terms of moving sources allows comparison of our exclusive data with analyses of inclusive data at other bombarding energies, and is directly related to analysis of data at lower bombarding energies, where the moving sources can be interpreted literally.

In summary, neutron spectra in coincidence with projectile-like fragments were measured in collisions of 35 MeV/nucleon ^{14}N with ^{165}Ho. We observe an asymmetry in the neutron emission in quasi-elastic events. This asymmetry has more neutrons emitted to the side of the beam opposite the projectile-like fragment. Events in which a strongly damped fragment was detected show no such asymmetry. Analysis of the quasi-elastic events in the framework of the moving-source model required not only the usual projectile-like and target-like sources, but also a third source having a temperature of about 8 MeV and a velocity of near half that of the beam. The parametrization of this third source is responsible for nearly all of the high energy neutrons beyond $\theta_n = 30°$, and the left-right asymmetry results because the direction of the third source is 10° off the beam axis. The new feature arising from our moving-source fits is that the constraint of requiring neutrons to be in coincidence with a fragment at an angle of 10° requires that the intermediate-velocity moving source be traveling in a direction toward the opposite side of the beam from the projectile-like fragment. This differs from analyses of inclusive data where the intermediate-velocity source was simply assumed to be travel along the beam axis.

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