Evidence for a Limitation of the Linear Momentum Transfer in ^{12}C-Induced Reactions between 30 and 84 MeV/u

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Linear momentum transfers have been determined for ^{12}C-induced reactions at energies from 30 to 84 MeV/u on U, Au, and Ni. The folding-angle distribution of the fission fragments for the first two targets, and the angular distribution of low-energy protons emitted by the nickel-like nucleus, provide evidence for a limitation of the transferred momentum at 2 GeV/c. This limitation effect is reached above a bombarding energy around 15 MeV/u.

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Heavy-ion reactions induced at bombarding energies below 10 MeV/u have been extensively studied during the last decade and the reaction mechanism is rather well understood. The dominant part of the cross section is found in fusion (complete and incomplete) and deep-inelastic processes. In both channels the interacting nuclei exhibit a large degree of coherency in that very few direct light particles are ejected during the collision itself. Most of the observed particles can be accounted for by evaporation from either the thermally equilibrated fusion nuclei or the thermally equilibrated and fully accelerated deep-inelastic fragments.[1]

Marked changes in the reaction mechanism are supposed to occur at bombarding energies of several tens of megaelectronvolts per nucleon. When the collective relative momentum becomes larger than the intrinsic Fermi momentum of the nucleons in the colliding nuclei, the Pauli principle becomes less effective and individual nucleon-nucleon collisions become more probable.[2] Direct emission of knocked out nucleons is thus expected to take place in the early stages of the reaction.

Before investigating these questions in some detail,[3] we looked at gross quantities such as energy deposit or linear momentum transferred from projectile to target. In this Letter we report on two different experimental approaches to evaluation of linear momentum transfer: first, the fission of heavy targets (Au, U); then, for a natural Ni target, the emission of light charged particles was studied.

From the two sets of experimental data, we extracted the maximum amount of linear momentum transferred from projectile to target. This quantity was found to reach its maximum at a constant value close to 2 GeV/c, independent of the bombarding energy between 30 and 84 MeV/u and of the interacting target nucleus.

The ^{12}C beams at 84 MeV/u provided by the synchrocyclotron at CERN were slowed down to 60 and 30 MeV/u by using appropriate graphite degraders located upstream of a switching magnet.

A method commonly used to determine the amount of linear momentum transferred from a projectile to a target nucleus is based on the fission properties of the targetlike nucleus. In particular, the distribution of the folding angle for correlated fragments expresses, to first order, the distribution of the amount of linear momentum remaining in the fissioning nucleus.[3-7]

The natural UF_4 and Au targets were bombarded by a C beam at 30 and 60 MeV/u. U was chosen because of its low fission threshold; as a consequence fission is expected to be the dominant decay mode of the targetlike nucleus. On the contrary, for Au, a large selectivity arises from its high fission barrier.

The fission fragments were detected by four standard 500-μm thick, 5-cm^2 active area, silicon surface-barrier detectors. One detector was held at a fixed angle of 75°, 170 mm from the target ($\Delta\theta \simeq 8.5°$). The three other counters were placed on a rotating table on the opposite side of the beam, 17° from each other, at about 280 mm from the target ($\Delta\theta \simeq 5°$). In addition to energy signals, time signals were generated through standard voltage-sensitive preamplifiers associated with constant-fraction discriminators. A time-of-flight difference was thus determined for any coincidence event, allowing rejection of random events.

With use of the correlated kinetic energies and the time-of-flight difference it is easy to distinguish the associated fission fragments from coincidence events between either a fission fragment with a light particle or two light particles.

In Fig. 1, the differential cross sections are given versus an angular scale and relative and absolute linear momentum scales. The relative scales show the fraction of the projectile linear momentum transferred to the fissioning nucleus. The connection between momentum and folding angle, θ_{corr}, was simply derived neglecting the transverse momentum and using the systematics of Viola[8] to estimate the most probable fission kinetic energy for the targetlike fissioning nucleus. Events are observed beyond $\theta_{corr}=180°$ (i.e., $P_{\parallel}>P_{proj}$) due to the detector apertures and particle emission which tend to broaden the correlation. Moreover, the present scale is strictly valid for symmetric mass division and would extend towards slightly smaller θ_{corr} values when considering the mass distribution around symmetry.

In Fig. 1, we have added results for 10.4 MeV/u ^{12}C-induced reactions on the same targets,[5] using an arbitrary scaling factor. The evolution with bombarding energy is striking: whereas at 10 MeV/u about 75% of the reaction proceeds through compound-nucleus formation, this process is essentially missing at 60 MeV/u. The rare events which are located at θ_{corr} corresponding to full momentum transfer for a symmetric mass splitting are most likely due to asymmetric divisions and evaporation which tend to smear out the angular distribution. These effects as well as the lack of off-plane measurements do not allow us to give accurate figures for full transfer probability.

The second noticeable change in the reaction behavior with increasing energy is the broadening in the transferred-momentum distribution. This property is clearly shown on the U nucleus, whose high fissility does not preclude the observation of low momentum transfers. At 60 MeV/u, for example, the momentum transfer ranges with similar probabilities from essentially zero to about one-half or two-thirds of the maximum possible transfer. At 30 MeV/u the measured distribution is intermediate in shape between what is observed at 10 and 60 MeV/u. Thus as long as momentum transfer is considered, there is a steady evolution with bombarding energy. This is confirmed by the Au data. As expected, the high fission barrier strongly hinders the occurrence of small transfers in the fission channel. Nevertheless, a displacement of the centroid of the distribution is clearly exhibited in Fig. 1. The most probable relative momentum transfer is shifted from nearly 100% at 10 MeV/u to about 50% at 60 MeV/u.

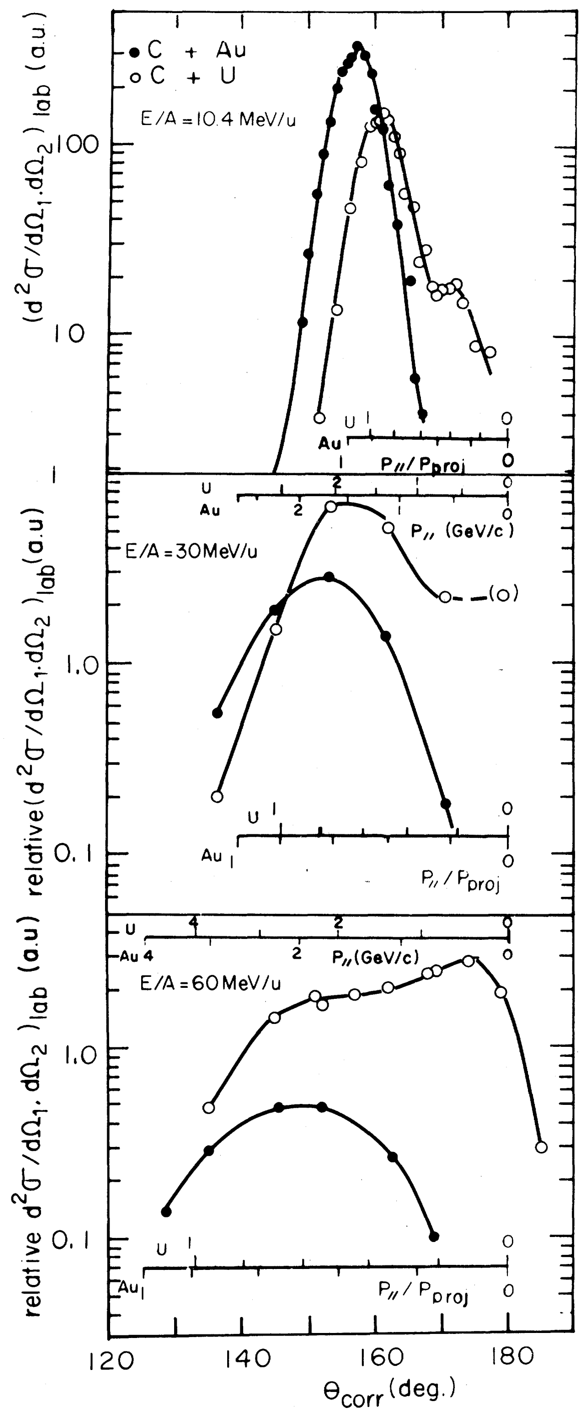

FIG. 1. Plots of the folding-angle distribution of the fission fragments. Top figure is from Ref. 5. A linear momentum scale relative to the projectile momentum is given for each system as well as an absolute scale (see text).

When considering the correlation functions in an absolute linear momentum scale, it is striking to observe a similar falloff above 2 GeV/c in all cases. The value 2 GeV/c appears to be the highest transfer that can be obtained with a large probability. The descent at higher momenta can essentially be accounted for by the broadening effects already mentioned. A similar falloff was also observed on the data at 84 MeV/u.[9]

In the second part of the experiment, we investigated C-induced reactions on a Ni target at energies of 30, 60, and 84 MeV/u. Light particle emission, which is in this case the main decay channel, was measured using six standard telescopes made of 100-, 500-, 5000-μm thick Si detectors.

Protons could be unambiguously distinguished from deuterons and tritons from 4 up to 25 MeV. Measurements were performed in the forward hemisphere only, from 9° or 18° up to 90°. The data are presented in Fig. 2 in terms of invariant cross sections as a function of parallel and transverse velocities relative to light velocity. The maximum of the energy spectra stands at about 6 MeV and depends weakly on both the detection angle and the bombarding energy, strongly suggesting, in this region at least, the dominance of a slow-moving proton source connected with the targetlike nucleus. From measurements of high-energy protons by Jakobsson *et al.*[10] on the similar C+Cu system, more rapid sources show up in releasing protons essentially forward with velocities strongly connected with the beam velocity.

At 60 and 84 MeV/u, between 20° and 90°, the pattern of the highest isoinvariant cross sections clearly identifies the emitter. Its average velocity relative to light $\langle v_t/c\rangle$ (dashed vector in Fig. 2) can be deduced by fitting the contour lines by concentric circles centered on the $v_\parallel$ axis. As expected, below 20°, additional contributions show up with larger and larger intensities as the proton energy increases. These contributions also appear in the tails of the energy spectra at larger angles. At 30 MeV/u the contributions from the high-velocity sources appear at lower energies causing a mixing of the different sources.

The deduced velocity of the slow-moving source is a weighted value. Indeed, due to the higher multiplicity of particles associated with a large energy deposit this velocity is dominated by high momentum transfers. Under the assumption that the emitter is on the average the target nucleus the transferred momentum can be deduced.

The values of the transferred momentum deduced from the Ni experiment, being essentially

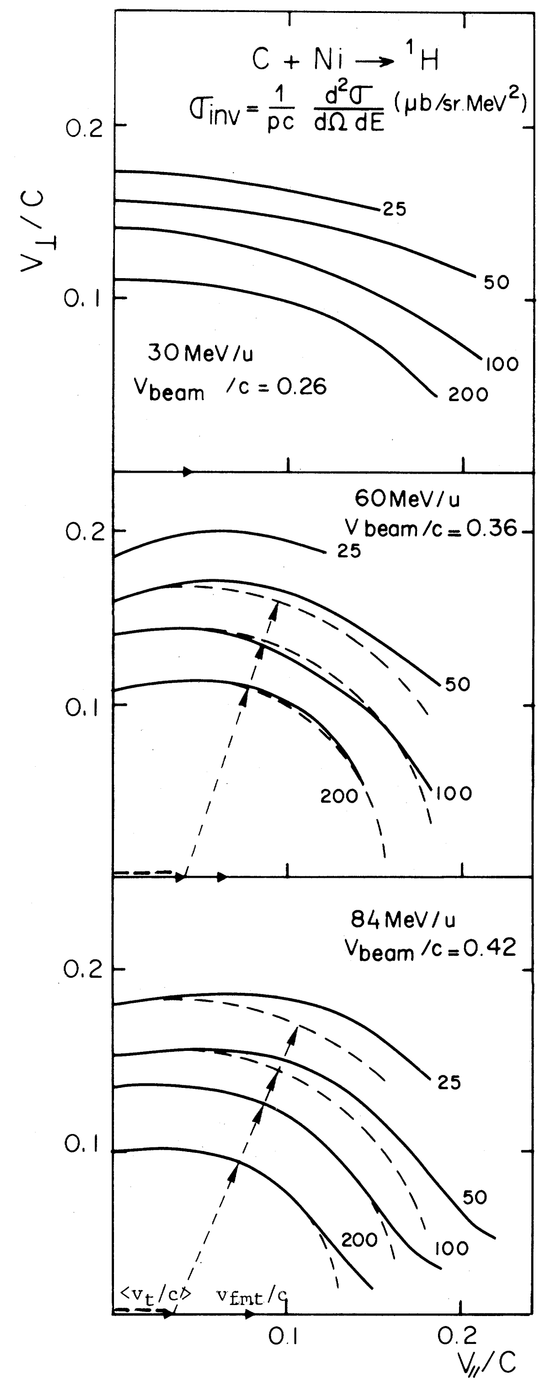

FIG. 2. Contour plots of the isoinvariant proton cross sections (solid lines) vs parallel and transverse proton velocities relative to light velocity. $v_{\mathrm{f.m.t.}}/c$ expresses the relative velocity of the targetlike nucleus if full momentum transfer (or compound-nucleus formation) were reached. $\langle v_t/c\rangle$ stands for the average relative recoil velocity of the proton emitter as deduced from fitting the high-intensity contours. The dashed-line circles are centered on tip of $\langle v_t/c\rangle$.

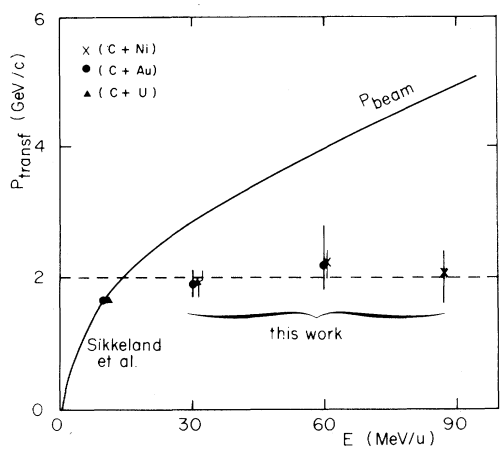

FIG. 3. The maximum linear momentum transfers (see text) for C-induced reactions between 10 and 84 MeV/u.

upper limits, are compared with the ones carried out from the fission experiment. As shown in Fig. 3 a limitation effect at about 2 GeV/c shows up for bombarding energies larger than about 15 MeV/u. Below 15 MeV/u complete fusion is the dominant channel. Above this energy one can not be sure whether, as in the incomplete-fusion picture, only part of the projectile communicates the full momentum of its nucleons to the target nucleus or if the nucleon-nucleon cascades are the origin of the observed effect. To investigate this question further it would be useful to study the influence of the projectile mass on the amount of transferred momentum with heavier projectiles.

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