Small Momentum Widths in Heavy-Ion Fragmentation at 20 MeV/amu and Below

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The widths of the momentum distributions for quasielastic fragments produced by ^{20}Ne on ^{197}Au at 20 MeV/amu and below are found, in contrast to a previous similar measurement, to be much smaller than at 2 GeV/amu. This contradicts a rapid change of reaction mechanism near 20 MeV/amu, in particular, the sudden onset of fragmentation or the decay from a nonequilibrated high-temperature subsystem.

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Recently, there has been interest in heavy-ion reactions involving projectiles at $\geqslant 10$ MeV/amu. At these energies the projectile velocity is approaching the velocity with which perturbations propagate in nuclear matter, and one might expect the onset of reaction processes different from those observed at lower bombarding energies. Important observations pertaining to this question have been reported by Gelbke *et al.*,[1-3] who studied the system ^{16}O+^{208}Pb at energies $\leqslant 20$ MeV/amu. They found the strength in energy spectra of ejectiles with $Z \leqslant 7$ to be concentrated at an energy corresponding to a velocity near that of the projectile. If the momentum width of this strength distribution is extracted as a function of bombarding energy, it is found[2,3] that the width grows rapidly so that at 20 MeV/amu it is similar[1] to that observed in ^{16}O reactions at 2.1 GeV/amu.[4] This result is presented[2,3] as evidence that there is a rapid change in mechanism as one goes from 10 to 20 MeV/amu. Two possible implications are discussed by Gelbke *et al.*[1] (i) At 20 MeV/amu the same reaction mechanism already begins to dominate, which is established for the relativistic energies, namely the fast fragmentation of the nuclear Fermi gas constituting the projectile. In this picture[5] the momentum width σ of a fragment of mass A_f is given by

$$\sigma^2 = \sigma_0{}^2 A_f (A_p - A_f)(A_p - 1)^{-1}, \qquad (1)$$

where A_p is the projectile mass, and σ_0 is calculated from the Fermi momentum to be $\simeq 90$ MeV/c. (ii) Alternatively, the momentum spreading may be attributed to thermal motion inside the decaying projectile pictured to be excited to a certain temperature. The momentum width extracted at 20 MeV/amu corresponds to a temperature of 7.4 MeV,[1] implying a steep rise for the temperature between 10 and 20 MeV/amu bombarding energy.[2,3]

Both of these implications are unexpected. Concerning the first one we note that the projectile energy per nucleon (on top of the barrier in the center-of-mass system) is a factor of 3 or more *below* the Fermi energy of the nucleons and thus does not fulfill the conditions of the fragmentation model[5] which works in the high-energy limit. The thermal interpretation, on the other hand, implies the extracted temperature to exceed many times the equilibrium temperature. Actually, the fragment mean velocity being only slightly below the projectile velocity, the decaying projectilelike nucleus has lost at most 20–30 MeV of energy, and this excitation energy ought to be entirely concentrated on a subsystem comprising less than six or seven nucleons to attain a temperature of 7 MeV. Thus, the thermal interpretation, too, meets difficulties in supplying a consistent picture of the underlying process, and more detailed investigations are required.

Here we report on a study of a system similar to that of Gelbke *et al.*[1]; however, on the basis of improved experimental data and more detailed analysis, we arrive at results for the momentum widths contradicting those reported previously.[1-3] The data were obtained in course of a systematic study[6,7] of light and projectilelike fragments produced in ^{20}Ne + ^{197}Au reactions. The experiments which comprise both singles and coincidence measurements were carried out at the heavy-ion facility VICKSI of the Hahn-Meitner-Institut in Berlin. Conventional solid-state detector telescopes were used to detect the reaction fragments. The ΔE-E measurements were sufficient to make both Z and A identifications.

The energy spectra of projectilelike fragments are similar to those seen before.[1,3] As an example, the spectra of the most frequent fragment, ^{16}O, near the grazing angle are shown for the four studied bombarding energies in Fig. 1. Following Refs. 1–5, we assumed a theoretical momentum

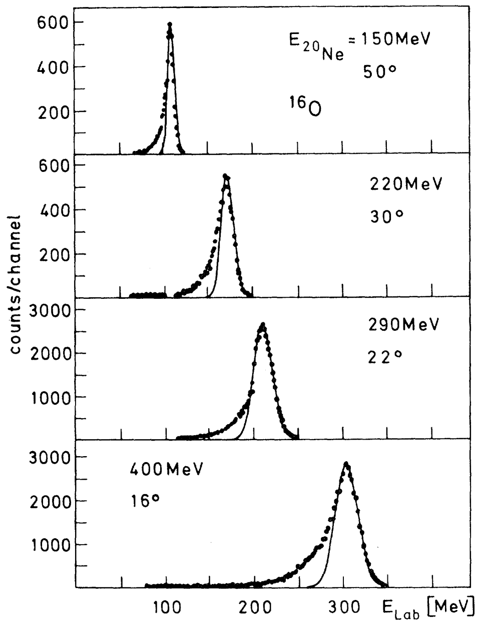

FIG. 1. Laboratory energy spectra of ^{16}O fragments from the interaction of ^{20}Ne with ^{197}Au. Incident energy and laboratory angle are indicated at the spectra. The curves are fits described in the text.

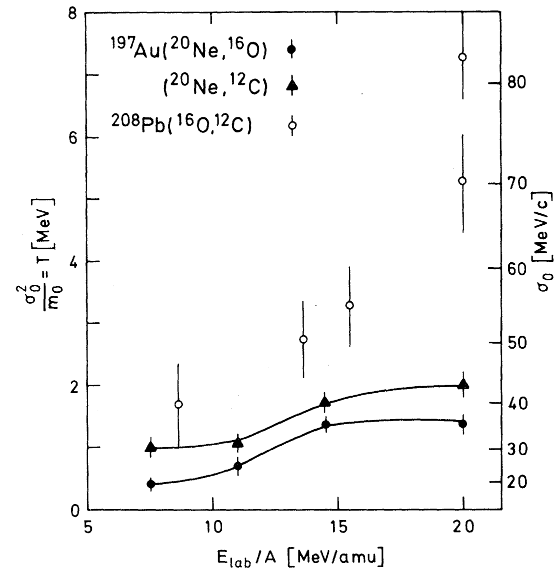

FIG. 2. Dependence of experimental momentum widths σ_0 (right scale) of the quasielastic peak and related temperature (left scale) on incident energy. Full circles and triangles represent the results of the present $^{20}Ne+^{197}Au$ study, open circles those of Refs. 1 and 3 on $^{16}O+^{208}Pb$. (The highest value at 20 MeV/amu is used in Ref. 1 to describe the spectrum of elemental carbon.)

distribution of the form

$$d^3\sigma/dp^3 \propto \exp[-(p-p_0)^2/2\sigma^2], \qquad (2)$$

applicable for both the fragmentation and the thermal model. In the first model, σ^2 is given by Eq. (1). The temperature T of the thermal picture is related to σ^2 by the relation (see Ref. 5)

$$\sigma_0^2 = m_0 T(A_p - 1)A^{-1} \simeq m_0 T, \qquad (3)$$

where m_0 is the nucleon mass. Expression (2) was converted to the energy scale and fitted to the energy spectra as shown in Fig. 1. The obtained best-fit values of σ_0 are significantly smaller than those given in Refs. 1 and 3. We next discuss the details of the derivation.

(i) In contrast to Refs. 1 and 3, we did not compare the total quasielastic peak to expression (2), but constrained the fit to reproduce the maximum and the high-energy slope of it. The measured cross section exceeding the fit on the low-energy side of the peak belongs, as we see it, to a different reaction mechanism with different (larger) Q value, the fit correctly describing the pure and most frequent process of sharp (and very small) Q value.

(ii) It turns out that at angles away from the grazing angle the relative importance of the additional component on the low-energy side of the quasielastic peak increases, indicating a broader angular distribution of this (large-Q-value, large-momentum-transfer) process than that of the pure quasielastic process. At angles 2 or 3 deg away from the grazing angle, this leads already to an additional increase in σ if one makes the fit over the total peak. Thus, the width σ of the pure quasielastic process is most precisely determined at that angle where it has its maximum relative intensity.

(iii) The fits were applied to spectra of definite isotopes. If, instead, one considers the summed energy distribution of all isotopes of an element, one finds an additional spreading, because the most frequent energies per mass unit are approximately constant; thus the energies themselves are proportional to the isotope mass.

Each of the precautions (i)–(iii), if omitted, gives rise to a (20–40)% increase of σ, cumulating to a factor of 2. Thus the deviations between our results and those of Refs. 1 and 3 are mostly due to a different extraction and not to a different physical behavior of the two studied and rather similar nuclear systems. [Applying refinement (i), for instance, to the 20-MeV/amu spectrum of ^{12}C in Ref. 3, which already takes care of refinement (iii), reduces the width by (25 ± 5)% and the temperature from 5.3 ± 0.9 to 3.0 ± 0.9 MeV, a value much closer to our results.]

The widths σ_0 extracted from ^{12}C and ^{16}O fragments are displayed in Fig. 2 as a function of the incident energy. While increasing with energy, they are observed at the highest measured energy (20 MeV/amu) to still be smaller by factors of 2–3 than the values found[4] at 2.1 GeV/amu. If one converts the momentum widths into a temperature T by means of the relation (3) this difference is even more pronounced, since T is quadratic in σ_0. For the most frequent process (^{20}Ne, ^{16}O), comparable to the (^{16}O, ^{12}C) reaction studied by Refs. 1 and 3, the temperature stays below 1.5 MeV at 20 MeV/amu.

Our finding has consequences for both the fast fragmentation mechanism and the thermal emission discussed above as possible origin of the momentum spreading. In the picture of particle emission from an excited projectile, the formally extracted temperatures of less than 1.5 MeV correspond to less than 5 MeV excitation energy in the emitting ^{20}Ne nucleus. Obviously, at such a low excitation in ^{20}Ne, a thermodynamic concept cannot be applied. Still, the momentum width may serve as a measure of the average ^{20}Ne excitation energy, which turns out to be very small. Thus, the underlying process cannot be visualized to be a decay of very hot nuclear matter, but rather a very "cold" process, which converts very little kinetic energy into internal excitation populating only few levels just above the threshold for α-particle emission in ^{20}Ne.

If, on the other hand, we follow Goldhaber[5] and assume that fast fragmentation is responsible for the spectra observed at 20 MeV/amu and below, we have to face a pronounced difference with respect to the type of fragmentation found[4] at 2.1 GeV/amu. As already discussed, the extracted momentum widths σ_0 are much smaller at 20 MeV/amu than at 2.1 GeV/amu, and, moreover, they are not independent of the fragment mass A_f, which is equivalent to saying that the experimental widths σ do not follow the relation in Eq. (1). Now this relation and the magnitude of $\sigma_0 \cong 90$ MeV/c have been derived[5] by assuming that in producing an ^{16}O fragment, for instance, any four nucleons out of the whole ^{20}Ne Fermi gas are ejected, and that the momentum distribution over the whole Fermi gas comes into play. Apparently the picture cannot be applied for the formation of ^{16}O fragments out of ^{20}Ne at 20 MeV/amu and below.

Staying within the fragmentation model, one may speculate that it is the well-known ^{16}O + α cluster structure of ^{20}Ne in its ground state that comes into play. The ejected nucleons then are four nucleons from the Fermi surface, highly correlated to form an α cluster which is only weakly bound (by 4.7 MeV) and thus has a wave function extending far outside the nucleus. From its spatial extension one can estimate the width of the corresponding Fourier transform obtaining a momentum spreading $\sigma_0 \simeq 25$ MeV/c, which is much nearer to the experimental observations than the Fermi-gas fragmentation prediction.[5] Similar considerations are presented in a study[8] of the ^{6}Li → $\alpha + d$ breakup, where also small momentum widths were observed. According to Nemes and McVoy,[9] such a breakup is nothing else than the direct transfer (of an α particle) into a continuum state, and the observed increase of momentum width with energy (cf. Fig. 2) may reflect the transition from stripping into bound to stripping into continuum states. If this is so then much higher energies are needed for the core nucleons to participate in the fragmentation process, and for all nucleons to act independently, as assumed in the Fermi-gas fragmentation model.

In conclusion, the present data show that in heavy-ion reactions the crossing of the 10–20-MeV/amu range is not accompanied by spectacular features. In particular, no rapid onset of the fragmentation[2] process, nor formation of abnormally hot nuclear matter,[1,2] is observed. The expected transition of reaction mechanism must occur at larger projectile energies.

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