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Viscous fluid dynamical calculation of the reaction ^{12}C(85 MeV/nucleon)+^{197}Au

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Proton spectra have been calculated for the reaction ^{12}C(85 MeV/nucleon)+^{197}Au using a three-dimensional hydrodynamical model with viscosity and thermal conductivity and final thermal breakup. The theoretical results are compared to recent data. It is shown that the predicted flow effects are not observable as a result of the impact parameter averaging inherent in the inclusive proton spectra. In contrast, angular distributions of medium mass nuclei ($A > 3$) in nearly central collisions can provide signatures for flow effects.

[NUCLEAR REACTIONS Theoretical fragment spectra, ^{12}C $E_{\rm lab}=85$ MeV/nucleon + ^{197}Au.]

Heavy ion reactions in the intermediate energy regime (from 50 to 200 MeV/nucleon) have received increasing interest in the last few years. First experiments on light fragment production have been done recently using the 84 MeV/nucleon ^{12}C beam at CERN (Refs. 1 and 2) and the low energy beam line at Berkeley.[3]

One of the motivations for these experiments is the possibility of creating nuclear matter at higher than ground state densities but at moderate temperatures.[4] Another topic of interest is the exploration of the dominant reaction mechanism in this transitional regime from the mean-field-dominated lower energies, where the time-dependent Hartree-Fock (TDHF) methods are applicable, to the many-body-collisions-dominated higher energies.[5,6]

It has been claimed that owing to exchange effects the mean free path of nucleons in nuclei, λ, may be large compared to the nuclear radius, R, for energies 50–150 MeV/nucleon.[7] Other authors report essentially smaller values ($\lambda \sim 1$–2 fm) at the same bombarding energies.[8,9] Since the question of the reaction mechanism and of the nucleonic mean free path seems to be rather open at present, we have taken the following point of view: We will attempt to tackle these questions by a detailed comparison of the results of the hydrodynamic model, which assumes $\lambda \ll R$, with the experimental data.[1–3] Previous three-dimensional fluid dynamical calculations[10] neglected the influence of the nuclear viscosity and thermal conductivity on the reaction dynamics. We have now extended the previous one-dimensional[11,12] and two-dimensional[13,14] viscous calculations to a first fully three-dimensional viscous hydrodynamical treatment of the collision process. The transport properties of nuclear matter are included in the present calculation via the dissipative terms in the Navier-Stokes equations.[11–14] This allows for the systematic study of the viscous effects at all impact parameters.[15] Furthermore, we include a realistic treatment of the nuclear binding via Coulomb and Yukawa potentials.[10] The formation of light fragments is calculated on the basis of a chemical equilibrium model.[16] The final thermal emission of the fragments is calculated using the evaporation model described in Ref. 12.

Figure 1 shows a sequence of density contour plots for the calculated reaction ^{12}C(85 MeV/nucleon) + ^{197}Au. The laboratory velocity is indicated by the arrows. At all impact parameters the matter is compressed by $\sim 30\%$ and, except for peripheral collisions, $b \geq 7$ fm, is squeezed to the side.

At a late stage of the reaction, i.e., when the density is sufficiently low, the system breaks apart in light nuclear fragments which finally reach the detector. To simulate this transition we stop the hydrodynamic calculation when the average density is $\approx 0.5\rho_0$. The baryon number and energy per particle in the interacting nucleon fluid are then used to calculate the distribution of the light fragments produced. We use a simplified classical statistical model[16] assuming that chemical equilibrium between the emitted fragments (p, n, d, t, ^{3}He, and α's in the present calculation) is established towards this late stage of the collisions.

The particle cross sections are then calculated by transforming the internal thermal momentum distribution for each particle density in every fluid element to the laboratory system with the corresponding flow velocity.[12] The inclusive cross sections are obtained by a weighted average over the impact parameter. Since these procedures require a great deal of computer time, we have not yet been able to implement an improved quantum statistical treatment including particle unstable nuclear clusters[16,17] into our calculation.

Figure 2(a) compares the revised CERN inclusive proton spectra obtained from the ^{12}C + ^{197}Au reaction at (85 MeV/nucleon) (full lines)[1] to the present theoretical results (dashed lines). Although the overall shape, as well as the angular dependence of the higher energy part of the spec-

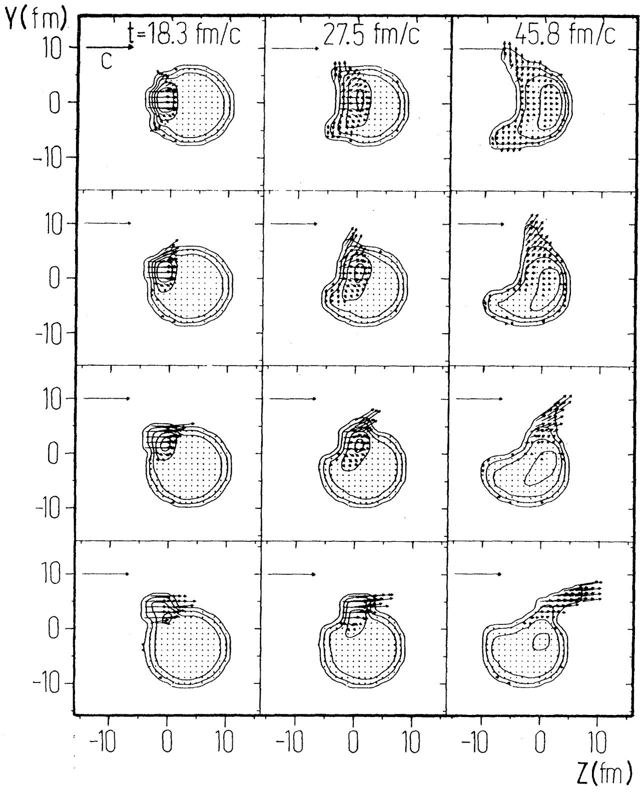

FIG. 1. Time evolution of the ^{12}C(85 MeV/nucleon) + ^{197}Au reaction for impact parameters $b=1$, 3, 5, and 7 fm. The nuclear matter is squeezed to the side for small impact parameters, $b<5$ fm.

tra, agree reasonably well, the calculations underestimate the total proton yield by about a factor of 6. Another discrepancy between the calculation and the data occurs at low energies, $30<E_p<60$ MeV, where the data[1] exhibit a dip-bump structure in the spectra, while the theory shows a monotonic decrease. Hence the data seem to rule out a hydrodynamic description of intermediate energy collisions. Such a negative result is to be expected if the mean free path of nucleons is larger than the nuclear radius, in contrast to the assumption $\lambda<R$ underlying the hydrodynamic model. However, the decay of particle unstable nuclei neglected in the present statistical model calculation can contribute substantially to the total number of protons produced[17]: We find that at entropy values $S/A\approx 1$, as obtained in the present calculation, the decay of the particle unstable clusters contributes about four times as many protons to the total proton yield as the free protons present in the chemical equilibrium alone. Hence the disagreement in the absolute value of the proton cross section can be understood as being due to the present simplified treatment of the cluster production. We expect a reasonable agreement of the proton yields once the decay protons are included. At higher energies, the decay of metastable nuclei (and of hadrons) still contributes with

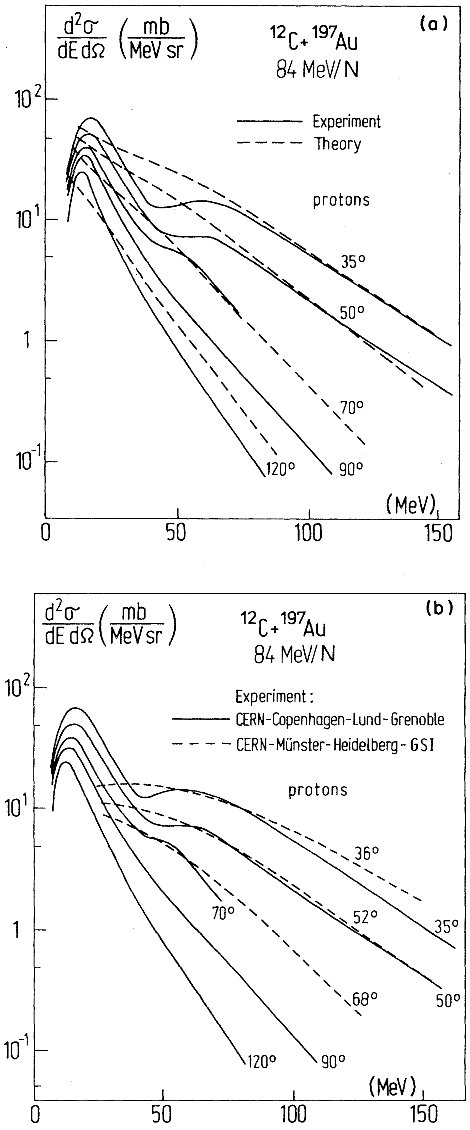

FIG. 2. (a) Comparison of the present theory and the experimental data for ^{12}C(84 MeV/nucleon) + ^{197}Au p + x. Full lines correspond to the experiment; dashed lines represent the calculations. The theoretical curves are multiplied by six to account for protons stemming from the decay of particle unstable fragments (see text). (b) Comparison of experimental inclusive proton cross section for ^{12}C(84 MeV/nucleon) + ^{197}Au. The full lines correspond to the experiment of the Lund-Grenoble-Copenhagen collaboration (Ref. 1); dashed lines show the data of the Munster-Heidelberg-GSI collaboration (Ref. 2).

about 50% to the total proton yield.[17] An improvement of the fragment production model is precluded for the time being because of computational expenditures.

On the other hand, concerning the dip-bump structure in the data, a comparison of the data[1] with the results of a different, more recent, experiment[2] also reporting proton inclusive spectra for the same system and the same bombarding energy shows quite drastic deviations of the two data sets [see Fig. 2(b)]. [Reference 3 reports results for ^{20}Ne(100 MeV/nucleon) + ^{197}Au qualitatively similar to those of Ref. 2; but, because of the different bombarding energy and projectile mass, these cannot be compared directly to Ref. 1.]:

(1) The total cross sections differ in some points by factors > 5, which is especially apparent at $E_p < 40$ MeV.

(2) The data[2,3] do not show the reported dip at proton energies $30 < E_p < 70$ MeV, but indicate a monotonic decrease of $d^2\sigma/d\Omega\, dE$, in agreement with our calculations. Hence, experimental difficulties may to a large extent be responsible for the differences between data[1] and theory at $E_p < 70$ MeV. Before concluding one should await further experiments to resolve these differences.

In view of the uncertainties in the experimental data and because of the neglect of the decay of particle unstable nuclides in the present calculations, it is obvious that it would be premature to rule out the hydrodynamical mode, with its assumption of a short mean free path λ, for producing a reasonable description of nuclear collisions even at energies as low as 84 MeV/nucleon.

We would like to point out that little information about the details of the reaction mechanism can be extracted from the comparison of the inclusive data and impact parameter averaged calculations. For example, in spite of its obvious appearance at $b = 1$ and 3 fm (see Fig. 1), no signatures of the collective sidewards flow seem to be visible in the *calculated* cross sections; only by triggering for nearly central collisions, i.e., high multiplicity events, can we improve the sensitivity of the experiments.

Figure 3(a) shows the calculated proton cross section for an impact parameter at $b \leq 3$ fm: Due to the sidewards emission there is a flattening of the cross sections in comparison to inclusive data.

Since the proton production probability is largest in hot regions,[16] the effect of the collective flow is smeared out by the thermal motion, which makes the proton cross sections almost isotropic. This phenomenon has been observed at higher energies[18] and seems in agreement with previous three-dimensional nonviscous calculations.[19] A better experimental testing ground for the flow effects would be the centrally triggered α (or also Li, Be, C) cross sections: These particles are produced in colder regions of the system.[19] Hence, they tend to exhibit the signatures of the collective flow.[20] Indeed, if central collisions ($b \leq 3$ fm) are selected in the calculation, a strong peak is observed at 50° in the ^{4}He cross section [Fig. 3(b)]. This would give clear evidence of collective sidewards flow of nuclear matter if observed.

We conclude that nuclear fluid dynamics together with a relatively simple statistical model for fragment production reproduces the shape of the measured proton cross sections for the ^{12}C(84 MeV/nucleon) + ^{197}Au reaction. More definite conclusions are precluded by apparent problems in the experimental data as well as the vast necessity for a more realistic cluster production calculation.

The predicted collective sidewards flow cannot be tested with inclusive proton data, but may be observable in high multiplicity selected events for which the α particles should show a strong sidewards maximum in the angular distribution.

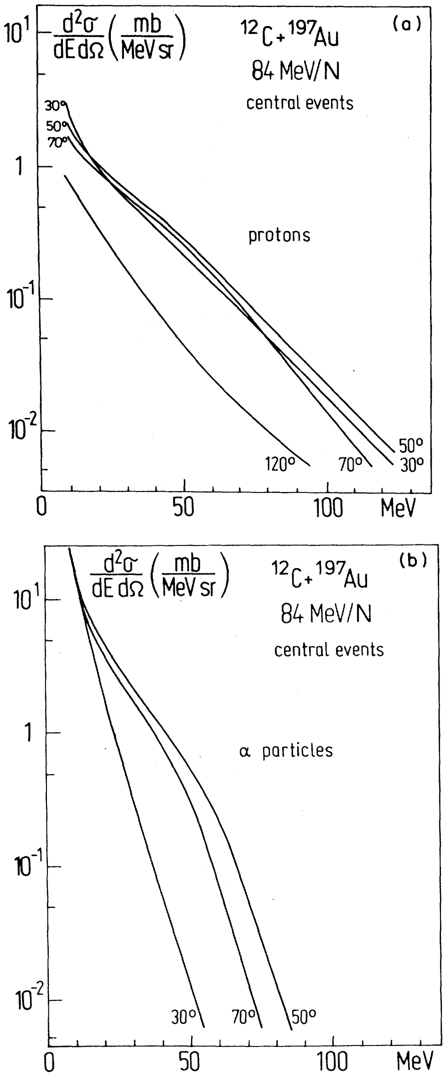

FIG. 3. (a) Calculated proton cross sections for centrally selected reactions. The forward proton emission is suppressed. The 50° and 70° cross sections are similar to those at 30°. (b) As in (a) but for α particles. As α's are produced in cold regions of the reacting system, they depict the collective flow more clearly: The predicted cross section is about one order of magnitude larger at 70° than at 30° at $E_\alpha = 50$ MeV.

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