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Low energy particles produced in heavy ion reactions

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A model is presented for the low energy spectrum of nucleons produced in small impact parameter heavy ion reactions. Special attention is paid to the effects of the Coulomb force which not only gives rise to an energy shift but also to a sideward focusing. Calculated angular distributions are compared with high multiplicity selected events in the Ne on U reaction at 393 MeV/nucleon.

[NUCLEAR REACTIONS U(Ne,x) at 400 MeV/nucleon, calculated $\sigma(\theta)$ for emitted neutrons and protons at energies < 50 MeV.]

Considerable attention has recently been focused on the reaction Ne on U at 400 MeV/nucleon[1]; in particular, it has been suggested that the high multiplicity selected data might show some evidence for collective phenomena. These arguments are based primarily on the angular distributions of protons at low energies. However, Coulomb forces and source velocities influence the proton spectra significantly in this energy regime. It is the purpose of this Communication to show that the high multiplicity selected data now available, including side-peak features and neutron-proton ratios, is consistent with a schematic model that involves little more than conservation laws, the long range Coulomb force, and a simple geometry based on two sources. We find that the spectra of the lowest energy protons places strong constraints on the mass, velocity, and excitation energy of the portion of the system from which they come.

Our assumptions concerning the collision geometry are based on the following observations: For high multiplicity selected events the most probable impact parameter is one for which all the nucleons in the projectile can collide with target nucleons, i.e., $b_0 \simeq R_T - R_P$ where R_T and R_P are the target and projectile radii. For the case of Ne on U this amounts to $b_0 \simeq 4$ fm. Smaller impact parameters will contribute less to the total cross section for geometrical reasons, whereas for larger impact parameters the multiplicity of the event will decrease. We shall consider here only collisions of a small projectile with a much larger target nucleus. Collisions of this kind at the impact parameter b_0 will involve on the order of half the target nucleons directly.

Our model is therefore to assume two portions in the excited system, roughly though not literally, associated with the traditional participant-spectator division. Both parts are moving in the laboratory and both parts are excited. It is envisioned that the part directly involved (referred to as hot) is excited to high excitation energy in the early stages of the collision. The remaining part (referred to as cold) acquires both its momentum and excitation from energetic nucleons coming from the hot portion. The final spectra, especially those at low energies, are then obtained as a sum of the particles coming from these two sources, taking the acceleration and deflection by the Coulomb field into account.

The number of particles in the hot part will, in general, be larger than in a purely participant-spectator approach since during the initial stages of the collision process nucleons will scatter away from the beam direction, thereby involving more nucleons of the target than those on the path of the initial projectile. For this reason, this number has been kept as a free parameter in the model. A sharp boundary is assumed between the cold and the hot part. In order to avoid introducing additional parameters the boundary is taken to be a plane. It is assumed that in the initial stage of the collision all the kinetic energy of the projectile is shared by all the nucleons in the hot part and that the cold part is affected in a secondary manner. To describe this the plane boundary between the two parts is taken to be tilted by an angle β with respect to the beam axis (see Fig. 1). For $\beta = 0$ the cold part is not involved. In our approach

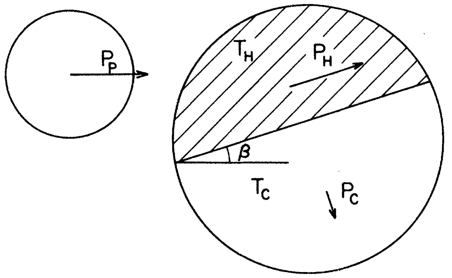

FIG. 1. Sketch of the geometry used, as explained in the text.

we treat β as a free parameter.

The angle β is used to calculate the transverse momentum transfer in the reaction. After the collision we assume for the hot part a collective momentum $P_H = P_0 \cos\beta$ parallel to the cutting surface where P_0 is the momentum of the projectile. Momentum conservation gives $P_c = P_0 \sin\beta$ for the momentum of the cold part.

To determine the temperature of the hot part and excitation energy of the cold part we use the following procedure. We assume that the transfer of momentum and energy to the cold region is provided by the flow of N_t particles from the initial hot to the cold region. These particles provide the momentum P_c and total energy E_c for the final cold region:

$$P_c = N_t \langle P_\perp \rangle = N_t \left(\frac{2mT_H}{\pi} \right)^{1/2} , \tag{1a}$$

$$E_c = N_t (\tfrac{3}{2} T_H) \ . \tag{1b}$$

Here, m is the proton mass, $P_\perp$ is the momentum perpendicular to plane separating the regions, and we assume that the original hot particles have a Maxwell Boltzmann distribution with temperature T_H. Since P_c is also expressed in terms of P_0 and β, N_t can be obtained in terms of these quantities and T_H:

$$N_t = \left(\frac{P_0^2}{2mT_H} \pi \right)^{1/2} \sin\beta \ . \tag{2}$$

The value of T_H is determined from the conservation of energy in the initial collision, i.e.,

$$\frac{P_0^2}{2mN_P} = \frac{P_0^2}{2mN_H} + \tfrac{3}{2} N_H T_H \ , \tag{3}$$

where N_H is the number of particles in the hot part and N_P the number of nucleons in the projectile. The internal excitation energy of the cold part E_c^* is determined by conservation of energy

$$E_c = N_t (\tfrac{3}{2} T_H) = \frac{P_c^2}{2mN_c} + E_c^* \ , \tag{4}$$

where N_c is the final number of particles in the cold part.

The emission spectra at the surface (before Coulomb acceleration) of the hot and the cold part is described as

$$\frac{d^2\sigma}{d\Omega\, dE} \propto \sqrt{E} e^{-E/T} \ , \tag{5}$$

where the temperature of each part was calculated separately. For the hot part we take T_H from Eq. (3), whereas for the cold part we assumed a Fermi gas relation to obtain $T_c = \sqrt{E_c^*/a}$ where we have taken the level density parameter $a = N_c/8$, and E_c^* is obtained from Eq. (4). The respective normalization in Eq. (5) are determined by the number of particles emitted by each part. Due to the high temperatures the hot part totally disintegrates. The number of particles emitted from the cold source is determined as the ratio of the total excitation energy and the average energy carried away by an emitted particle. The ratio of the number of neutrons versus protons is determined by requiring that they are in equilibrium inside the source. The ratio of neutron to proton yields at high energies will be equal to the neutron-proton ratio in the source; for low energy particles, however, the existence of the Coulomb barrier decreases the proton yield, and the neutron-proton ratio will be considerably larger than this. The effects of the Coulomb force outside the emitting source have been taken into account, assuming classical trajectories for the particles. For simplicity, the Coulomb potential at the emission point was taken as $V_C = 8$ MeV, equal for all emitted particles. For the hot part, the force center is taken at the center of the combined system and only those particles are considered which are emitted in the solid angle not shadowed by the cold part. For the emission of the cold part the force center is taken at the center of the cold part. Since the temperature in the cold part is low, its emission takes place in a relatively long time span. For this reason the emission of the cold part is taken to be that of a spherical source emitting over the full solid angle.

To compare the predictions of the above model with the 400 MeV/nucleon Ne on U high multiplicity selected data we chose $\beta = 4°$ and $N_c = 158$ as to give a best fit, leaving 100 particles in the hot part. The parameters were determined from a best fit, however, a variation of 20% does not alter the results in a qualitative way. From the angle β we obtain a velocity of $0.17c$ for the hot and $0.009c$ for the cold part. For the temperature of these sources we obtain, from Eqs. (3) and (4), $T_H = 37$ MeV and $T_c = 5.0$ MeV. From the cold part, 5.9 protons and 34.5 neutrons are evaporated. To obtain cross sections in our model a total reaction cross section σ_M leading to high multiplicity must be specified. The best fit to the data is obtained by taking $\sigma_M = 0.90$ b. Using $\sigma_M = \pi b_M{}^2$, an impact parameter of 5.4 fm can be related to this cross section, which is of the same order as the impact parameter b_0 introduced above.

Figure 2 shows a comparison of the calculated proton cross section with the experimental data. The calculation reproduces the shapes of the angular distributions and the dependence of their relative magnitudes on energy. The proton cross section at energies below 30 MeV is nearly isotropic. In our model this is due to the effect of the Coulomb force and the isotropic evaporation of particles from the cold part. It should be noted that this isotropy at low energies is not reproduced in either cascade[2] or in hydrodynamic models.[3]

The influence of the Coulomb force can be seen by

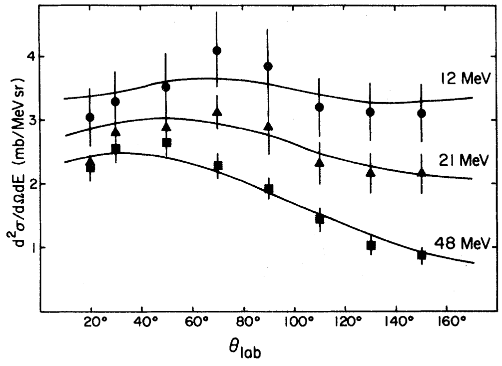

FIG. 2. Comparison of the calculated proton cross section with the high multiplicity data as measured in the reaction Ne on U[1] at 393 MeV/*n*. The curves are labeled by the proton energies.

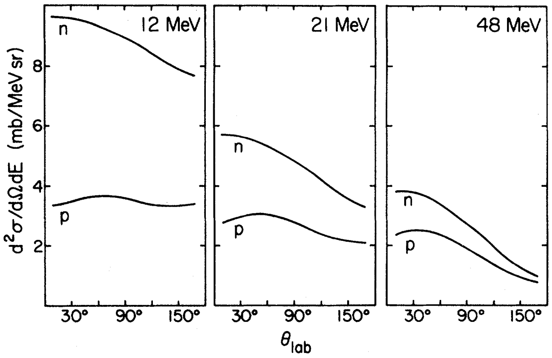

FIG. 3. Calculated cross section for the production of neutrons and protons in high multiplicity events in the Ne on U reaction at 393 MeV/*n*. The curves are labeled by the energy of the emitted particle.

comparing the neutron and proton spectra shown in Fig. 3. Due to the Coulomb barrier there are many more neutrons than protons emitted from the cold source as noted above. Therefore, with increasing energy, the ratio σ_n/σ_p decreases since the relative contribution of particles coming from the cold source becomes less. The proton cross section shows a slight sideward peak not present for the neutrons. The angle at which this peak occurs arises from the focusing of the particles emitted by the hot gas that move in the Coulomb field of the cold part and is not influenced by the specific direction of P_c. This effect is strongest for the lowest proton energies; the change in σ_n/σ_p with angle is therefore less pronounced at higher energies. These features, coming from the Coulomb focusing and the Coulomb barrier are in qualitative agreement with the results of the experiment reported in Ref. 4.

We expect that the emission of composites (not included in our calculation) will not change our general conclusions. Composites are not likely to be formed in large numbers from either source; the high temperature of the hot source favors emission of free nucleons while the excitation energy of the cold source is too low to allow many composites. Composite particle production will increase the ratio of emitted neutrons versus protons. We, however, expect this change to be similar for both sources.

We have used our model to explore the sensitivity to specific elements of the reaction mechanism and report here some of our general observations: (i) to reproduce the 12 MeV angular distribution, it is insufficient to assume a single charged source moving with a velocity on the order of that of the center of mass; (ii) the observed relative magnitudes for the 12 and 48 MeV yields place strong constraints on both the mass and the temperature of the cold part. Thus, somewhat paradoxically, much information about high energy heavy ion collisions can be obtained by examining their lowest energy products.

Our results show that the main features of the data considered here can be explained in a simple model based primarily on conservation laws without specifying any details on the microscopic reaction mechanism. One should therefore be hesitant in attempting to extract information on the latter from these data. In particular, one does not have to invoke a hydrodynamical collective flow pattern[2] to explain the data.

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