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BRIEF REPORTS

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Isobaric ratios of fragments emitted in incomplete fusion reactions

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The emission of light fragments with energies $\geq 1A$ MeV from asymmetric ^{14}N induced reactions at 14A MeV and 32A MeV has been studied. The overall energy and angular dependence of the isobaric ^{3}H/^{3}He and ^{6}He/^{6}Li ratios is understood in terms of standard statistical emission processes from an incomplete fusion source and an intermediate source only if the effective Coulomb barriers are reduced much more than the normal quantum penetration accounts for.

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Asymmetric heavy ion reactions at the energies discussed in this paper, 14A MeV and 32A MeV, are expected to exhibit incomplete fusion [1–3] where nucleons and light fragments are emitted predominantly in sequential evaporative processes [4] from the incomplete fusion source (IFS) and possibly from the projectile (or target) residue. Emission source studies by Westfall *et al.* [5] suggest a common origin for all high energy backward fragments but Chen *et al.* [6] stress the necessity to introduce three sources—also an intermediate one (IMS) – to explain all fragment emission. A very complete three-source analysis of reactions in this energy domain can be found in [7,8]. The production of light fragments has also been discussed in terms of prompt multifragmentation [9, 10] and some experiments indicate that this happens [11], although with small probability at the energies discussed here [12, 13].

In this paper we investigate the strength of the Coulomb barriers through the ratios of the spectra of the equal mass but different charge fragments (^{3}H/^{3}He and ^{6}He/^{6}Li, called isobaric ratios) after mapping the apparent emission sources of light fragments by means of invariant cross section contour plots.

The experiment was performed at the Gustaf Werner Cyclotron in Uppsala, where 1 – 20 nA of ^{14}N beam extracted in the 6+ state bombarded ~1 mg/cm^2 targets of ^{112}Sn, ^{124}Sn, and ^{197}Au. The fragments were registered at several angles between 17° and 160° by four- or five-element Si range telescopes and Si + CsI telescopes in order to include also high energy light particles. The use of very thin first elements in the range telescopes (14 – 23 μm surface barrier detectors) allowed us to identify ^{1,2,3}H, ^{3,4,6}He, ^{6,7,8,9}Li, ^{7,9,10,11}Be, and ^{10,11,12}B isotopes from about 1A MeV. Absolute cross sections were obtained with a systematic error of $\sim$ 20% by integrating the current in a Faraday cup. Further details about the experiment are given in [14].

Invariant cross section ($1/p\ d^2\sigma/d\Omega dE$) contours of protons and ^{6}Li fragments in the $p_\perp$ - $p_\parallel$ plane are shown in Figs. 1 and 2. The appearance of the IFS and the IMS sources is obvious at 32A MeV and even at 14A MeV. The projectilelike emission source (from peripheral events) can be observed but only to a minor extent due to the angular cutoff of 17°. The IFS dominates the backward emission while the IMS contributes significantly to the forward emission and dominates its large momentum part. The velocity of the IMS in ^{14}N + ^{197}Au at 32A MeV reactions is nearly half the projectile velocity (v_p) for protons, 0.43v_p for tritons, and 0.37v_p for ^{6}Li [Fig. 2(c)] following the same tendency as in [15].

The proton emission contours, in 32A MeV ^{14}N +^{197}Au collisions, are compared to predictions from a Boltzmann-Uehling-Uhlenbeck (BUU) code [16] combined with sequential evaporation from the prescription by Friedman and Lynch [17]. The BUU calculation results in size, momentum, and excitation energy of the residual nuclei taken as input parameters for the evaporation process. Naturally, it also provides the early emis-

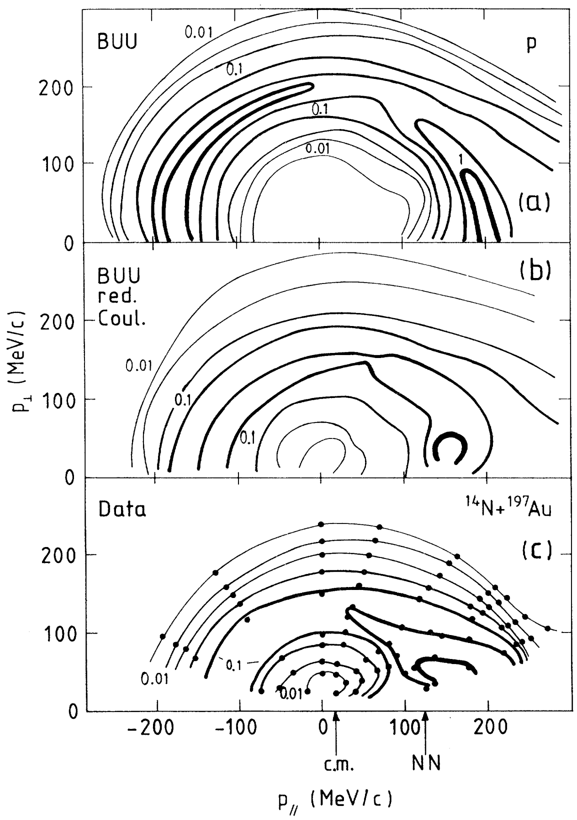

FIG. 1. Invariant cross section contours for protons emitted in $^{14}N+^{197}Au$ collisions at 32A MeV; (a) the standard BUU calculation, (b) BUU with the reduced Coulomb interaction (see text), and (c) the data. The labels on the contours are in units of mb/sr MeV^2.

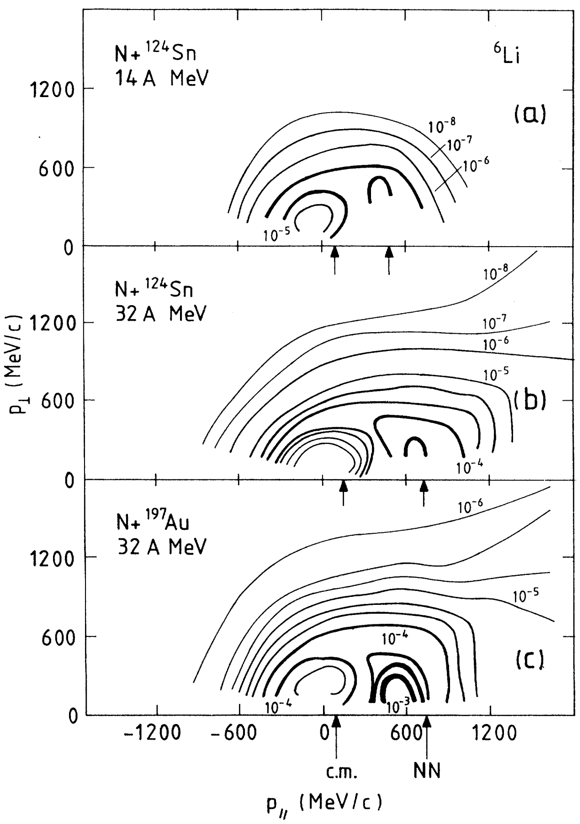

FIG. 2. Invariant cross section contours for ^6Li emitted in the reaction (a) $^{14}N+^{124}Sn$ at 14A MeV, (b) $^{14}N+^{124}Sn$ at 32A MeV, and (c) $^{14}N+^{197}Au$ at 32A MeV. Contour labels as in Fig. 1.

sion of (preequilibrium) protons — here taken as those ones which at the nucleon density smaller than $0.1\rho_0$ have positive energy and are moving away from the residual nucleus at a freeze-out time of 100 fm/c. A mean-field potential, $V(\rho) = -356\rho/\rho_0 + 303(\rho/\rho_0)^{7/6}$ (MeV), corresponding to a soft equation of state was introduced. In this (standard) calculation the Coulomb interaction of protons with the remaining nucleus or nuclei is furthermore included in a pure classical way.

These calculations lead to fusionlike reactions for small impact parameters and deep-inelastic-like reactions for larger impact parameters and therefore the two main sources (IFS and IMS) are easy to observe in the proton cross section contours [Fig. 1(a)]. Although the same overall pattern is observed as in the data [Fig. 1(c)] there are obvious differences. These could be due to an overestimate of the Coulomb interaction. In order to investigate this point qualitatively we recalculated the proton contours [Fig. 1(b)] introducing only half the Coulomb interaction strength (as if the effective charge of the mean-field source is half the normal one) as compared to the normal BUU calculation. This gives better agreement with data, with respect to both source velocities and spectral shapes.

The formation of complex fragments is not easily incorporated into BUU calculations. The similarity between the cross section contours of fragments and protons (cf. Figs. 1 and 2) suggests that they partly originate from the same sources. It should be stressed that the fragments hardly come from strongly damped projectilelike, deep-inelastic residues in the phase-space region considered here.

Early experiments with proton-nucleus [18] and heavy ion collisions at higher energies [19] as well as lower energies [20, 21] reported that charged particles are emitted with energies well below the Coulomb barrier of a target residue. In this work we investigate barrier effects through measurements of the isobaric ratios $^3H/^3He$ and $^6He/^6Li$. Since the binding energies of the isobaric fragments are close to each other, the energy distributions should differ mainly due to the Coulomb effects. Thus the isobaric ratios are very sensitive to these effects.

Figure 3(a) shows the $^3H/^3He$ ratio in $^{14}N+^{197}Au$ collisions at 32A MeV as a function of the laboratory energy for backward (160°), sideways (90°), and forward (35°) emission while Fig. 3(b) presents the $^6He/^6Li$ ratio for 135°. The ratios strongly depend on energy at smaller energies, as expected if the fragments originate from the large IFS which should exhibit strong Coulomb effects. The energy dependence gets weaker with increasing energy [Figs. 3(a) and 4] in agreement with the moving source hypothesis (see below) but the sudden disappearance of this dependence above $\sim$ 50 MeV in 32A MeV

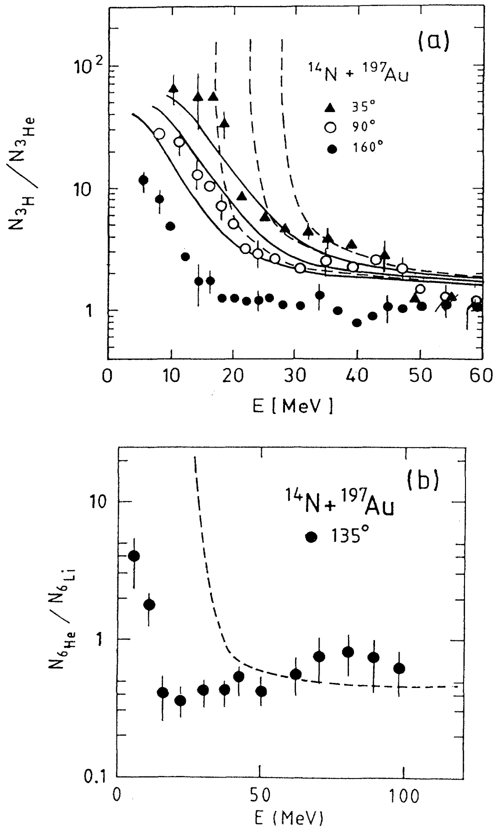

FIG. 3. Isobaric ratios from ^{14}N $+^{197}$Au collisions at 32A MeV as a function of the fragment energy; (a) ^{3}H/^{3}He at 35°, 90° and 160° and (b) ^{6}He/^{6}Li at 135°. The dashed and solid lines correspond to the evaporation and prompt multifragmentation models, respectively (see text).

reactions and above $\sim$ 35 MeV in 14A MeV reactions indicates that another source—the IMS—takes over and dominates the emission even at large angles.

The fact that there is also a strong angular dependence of the isobaric ratios at small energies can be interpreted as a signature of a moving source [22]. An assumption that all nucleons from the projectile are captured in the target gives the largest possible (average) IFS velocity, which is $v_s = 0.017c$ for N + Au collisions at 32A MeV. If the source velocity and the energy dependence of the isobaric ratio at any angle are known, standard transformations predict the ratios for all other angles. The experimental angular dependence is, however stronger than one single IFS source of this kind accounts for [see the solid curves in Fig. 3(a)] but on the other hand much weaker than one single IMS with velocity $\sim 0.1c$ exhibits.

In Figs. 4(a)–4(d) we show the ^{3}H/^{3}He ratio measured in N+^{112}Sn and N+^{124}Sn reactions at 14A and 32A MeV. As expected, the angular dependence appears to be somewhat weaker in 14A MeV reactions than in the 32A MeV case (confirmed by measurements at other angles than those shown in the figure). The neutron excess in the ^{124}Sn target is expected to favor ^{3}H emission and the ^{3}H/^{3}He ratio is also significantly larger in reactions with ^{124}Sn than with ^{112}Sn.

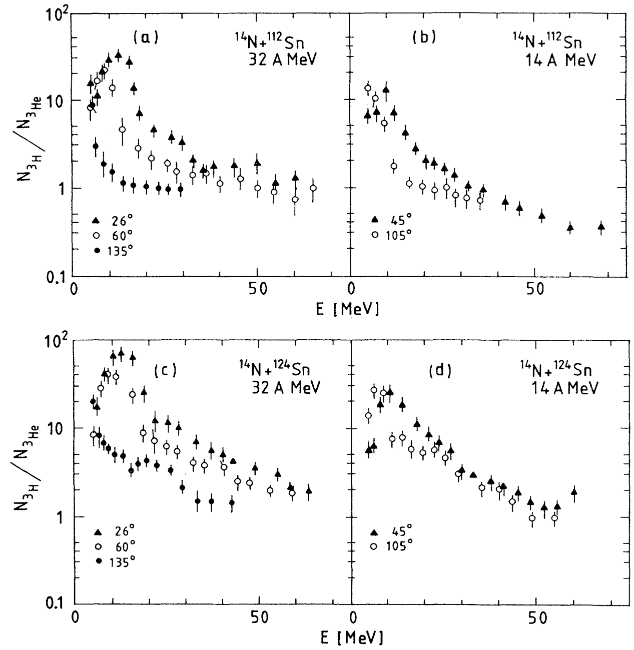

FIG. 4. Isobaric ratio ^{3}H/^{3}He at various angles from ^{14}N+^{112}Sn reactions at (a) 32A MeV and (b) 14A MeV and for ^{14}N+^{124}Sn at (c) 32A MeV and (d) 14A MeV.

The isobaric ratio from binary decays of a compound nucleus in general is governed by the barrier penetration factors

$$R(E') \sim \frac{g_a(E')}{g_b(E')} ,$$

where $g_a(E')$ is the penetration factor of the fragment a with the energy E' in the compound nucleus rest frame. We consider first this factor in classical form,

$$g(E') = \Theta(E - V_c)\left(1 - \frac{V_c}{E'}\right) ,$$

where V_c is the Coulomb barrier, and then in the form which takes into account quantum tunneling [23],

$$g(E') = \frac{\omega_0}{2\pi E'} \ln\left(1 + \exp\left[\frac{2\pi(E' - V_c)}{\omega_0}\right]\right) ,$$

with ω_0 being the potential curvature.

The two forms give nearly the same result. The latter is shown in Fig. 3(a) as the dashed curves. Here we assumed a source velocity of 0.017c. The IFS nucleus has been taken as ^{197}Au and the density at the moment of decay has been taken as half of the normal one. The computed ratio is normalized in such a way that at high energies it becomes $R = (A - Z - 1)/(Z - 1)$, where A and Z are the mass and charge number of the compound nucleus.

This simple estimate of $R(E')$, which basically agrees with the predictions of the sequential evaporation model by Friedman and Lynch [17], gives far too strong a rise of the ratio at small energies. We interpret this mismatch as a significant reduction of the Coulomb energy (cf. the mismatch in the proton contour plots discussed earlier). Of course our qualitative calculations neglect possible deviations from a spherical shape of the IFS, its rotation [24], and also secondary fragment decay. These effects should reduce the efficiency of the electrostatic repulsion to some extent. However, we observe a very strong reduction of the Coulomb effects and therefore we now discuss a scenario where the electrostatic shifts should be minimal.

In order to keep a fairly simple statistical description for the barrier estimations we use the prompt multifragmentation model [9, 10], although this model, as stated earlier, is hardly realistic where the excitation energy per nucleon does not exceed 2.3 MeV. In this prescription, fragments are emitted from the whole source volume, which makes the Coulomb energy on average significantly smaller than in evaporative models. Detailed calculations of the isobaric ratios, within this prescription, are presented in [25]. In these calculations, the fragment energy spectrum is averaged over the Coulomb shifts which depend on the radial position of the fragment in the source. The results are shown in Fig. 3(a) by the solid lines for the ^{197}Au source with a velocity of $0.017c$, with a breakup density of half the normal one and a temperature of 5 MeV. The results are not very sensitive to reasonable changes in density or temperature. Now we observe that, while the angular dependence is still not correctly reproduced, the shape of the energy dependence of the isobaric ratio agrees reasonably well with data. It is at this point worth mentioning that enhanced energy fluctuations, e.g., through nonamplifying degrees of freedom [26, 27], could introduce the same kind of apparent barrier reduction.

In conclusion, we have found that the energy dependence of the isobaric ratios ^{3}H/^{3}He and ^{6}He/^{6}Li manifests a strong reduction of the Coulomb effects which are not easily explained by simple statistical decay models with standard barrier penetration.

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