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Simulations of collisions between nuclei at intermediate energy using the Boltzmann-Uehling-Uhlenbeck equation with neutron skin producing potentials

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Asymmetry dependent potentials, which produce neutron skins, are utilized in the Boltzmann-Uehling-Uhlenbeck equation in order to simulate intermediate energy heavy-ion collisions. Compared to calculations done with the commonly used equation of states, the calculations which use the asymmetry dependent potentials produce neutron rich neck regions which reduces the orbiting of the major fragments and can produce primary, neutron rich, intermediate velocity ("neck") fragments.

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One of the main goals of heavy-ion nuclear physics is to study the nuclear matter equation of state (EOS). Aside from finite particle effects, one is forced to address the question of what can be extracted about the equilibrium properties of the matter from the collision dynamics. This has lead to the development of reaction models which incorporate nuclear matter properties with an assumption of local equilibrium as well as assumptions about the in-medium nucleon-nucleon cross section. It is the hope that by comparison of such models to experimental data that insight can be gained into the nuclear matter EOS. Some of the important models in this endeavor (and cental to the present work) are those which solve the Boltzmann-Uehling-Uhlenbeck (BUU) equation [1]. Since the paramount question is the nuclear incompressibility, the nuclear potentials which are most frequently used in these calculations are abbreviated in the sense that only the density dependence is considered. Important extensions of these models have been the inclusion of momentum dependent potentials [2] and simple asymmetry terms [3]. This work focuses on the importance of asymmetry dependent potentials, and in particular the importance of going beyond the consideration of a simple (Weizsäcker) asymmetry term in the potential to terms which conspire to create reasonable neutron "skins" for heavy nuclei.

The enhancement of the neutron density, relative to the proton density, with decreasing overall density (increasing radius) is found to have a pronounced effect on fragment deflection and neck formation (and decay) in intermediate energy heavy-ion reactions. The predicted magnitudes of these effects are as large as those from the overall density dependence, taken over a reasonable range. Therefore any hope of extracting information on the density dependence of the EOS from the dynamics of collisions of heavy nuclei at moderate energy, must be coupled to the realization that the surface properties must be carefully considered.

The density potentials usually considered are often called "Skyrme-like" in that the density dependence is that of the Skyrme interaction. The success of the modified Skyrme II interaction in the time dependent Hartree-Fock treatment of heavy-ion collisions at low energy [4] suggests that the asymmetry or isospin dependence of the Skyrme interaction as well as the density dependence should be investigated. This motivates the present work which also takes its inspiration from the Skyrme interaction; however, I do not reduce the potential to the case for symmetric matter. In the zero range limit, this yields a Hamiltonian of the following form:

$$\mathcal{H} = \tau + \frac{4a}{\rho_o}(\rho_n^2 + b\rho_n\rho_p + \rho_p^2) + \frac{4c}{\rho_o^2}(\rho_n^2\rho_p + \rho_n\rho_p^2). \quad (1)$$

In the above expression, τ represents the kinetic energy terms and ρ_n and ρ_p are the individual neutron and proton densities. The coefficients are not trivially related to those of the full Skyrme interaction (due to the dropped terms) and are chosen to reproduce the saturation properties of nuclear matter, see below.

The form of the single particle potentials are deduced by taking the derivatives with respect to the individual densities. The neutron potential is then

$$U_n = \frac{\partial \mathcal{H}}{\partial \rho_n} = 8a\frac{\rho_n}{\rho_o} + 4ab\frac{\rho_p}{\rho_o} + 8c\frac{\rho_n\rho_p}{\rho_o^2} + 4c\frac{\rho_p^2}{\rho_o^2}. \quad (2)$$

For the case of symmetric matter, the potentials reduce to the standard "STIFF" EOS (nuclear compressibility $K=380$ MeV), $U(\rho) = \alpha_h(\rho/\rho_o) + \beta_h(\rho/\rho_o)^2$, if $2a(2+b) = \alpha_h$ and $3c = \beta_h$. The subscripted coefficients are those which give the standard "STIFF" EOS [5]. The parameter b is chosen to reproduce the asymmetry stiffness from the droplet model [7]. The resulting values are $a = -3.66$ MeV, $b = 15.0$, and $c = 23.4$ MeV.

Figure 1 displays the binding energy per nucleon (top) and the neutron potential (bottom) as functions of the asymmetry for three different values of the total density. This potential is labeled "ISO-STIFF." It is important to note that the asymmetry stiffness decreases with decreasing overall density. This is the feature which is required to produce reasonable neutron skins.

The unmodified Skyrme interaction does not directly provide insight into a form for a "SOFT" asymmetry dependent potential (K=200 MeV). The *ad hoc* solution used in the present work is to paste the asymmetry dependence of the "ISO-STIFF" EOS onto the density dependence of the standard "SOFT" EOS, $U(\rho) = \alpha_s(\rho/\rho_o) + \beta_s(\rho/\rho_o)^{7/6}$. The effect of the "ISO-SOFT" potential can then be thought of as producing an asymmetry force of magnitude equal to the difference between the slope of the potential (see Fig. 1) at a particular asymmetry and density to that at symmetry and the

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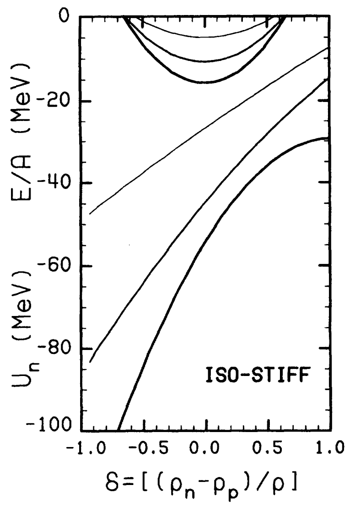

FIG. 1. The binding energy per nucleon (top) and the neutron potential (bottom) as functions of the asymmetry for three different values of the total density. The heaviest line shows the results when $\rho=\rho_o$, while the lines of medium thickness and the thinest lines, show the results when $\rho=\rho_o/2$ and when $\rho=\rho_o/4$, respectively.

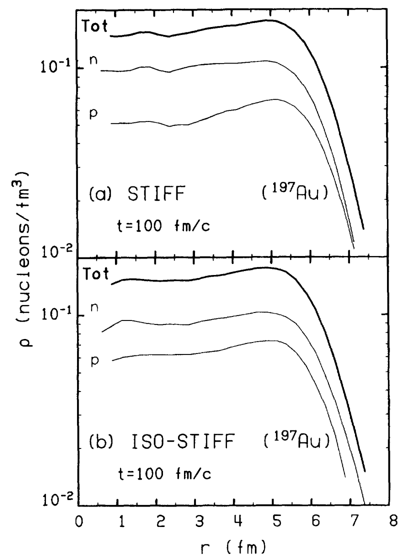

FIG. 2. The surface profiles for Au nuclei from (a) the standard "STIFF" EOS and (b) the "ISO-STIFF" EOS described in the text.

same density, added to a force which results from the standard "SOFT" density dependence.

The two potentials described above were used in a BUU code [6]. Two different simulations will be described. The first is simply to investigate the density profiles of light and heavy nuclei. The nuclei investigated were ^{20}Ne and ^{197}Au. In each case 450 test particles/nucleon were used and the nuclei followed for times up to 150 fm/c. For the light symmetric nucleus, the neutron and proton density profiles are similar to each other and the time development similar to that found for the standard EOS's. On the other hand, for the heavy nucleus, the "ISO" EOS's quickly ($\approx$ 10 fm/c) produce density profiles which are progressively more enriched in neutrons as the radius increases. This quality, the neutron skin, is robust and remains unchanged to the end of the simulation.

Figure 2 shows snap shots of these distributions, after 100 fm/c, generated by using the standard "STIFF" EOS [2(a)] and the "ISO-STIFF" EOS [2(b)]. The "ISO" potential effectively counteracts the false enrichment of protons at the surface (due to the Coulomb potential) and produces a neutron skin. For this heavy nucleus, the skin amounts to approximately a 1/3 fm radial expansion of the neutron profile relative to the proton profile. This skin thickness is what is predicted by the droplet model [7]. (As a side issue, it would not be surprising if an uncounteracted Coulomb potential played a role in the formation of the interesting pancake, ring, and bubble shaped configurations, which have been predicted by these codes [8,9].)

The next set of simulations presented are for 28.2 MeV/nucleon ^{136}Xe+^{209}Bi. This energy is not well suited to the BUU logic because of the extreme importance of Fermi blocking. Despite this, it is a good choice of a system to simulate, because of the recent exclusive experiment studying this system [10,12]. However, due to the severe demands put on the logic which does the Fermi blocking, these calculations should be considered as illustrative of the effects of the inclusion of asymmetry potentials rather than being sufficiently precise to allow quantitative conclusions to be drawn.

Heavy systems, such as the one studied here, do not completely decompose even for central collisions at intermediate energies. The survival of projectilelike and targetlike fragments raises the question of whether the deflection function can be used as a probe of the EOS. Figure 3 shows the calculated deflection functions for 28.2 MeV/nucleon ^{136}Xe+^{209}Bi with four different potentials, "STIFF," "SOFT," "ISO-STIFF," and "ISO-SOFT." The solid symbols show the results for the standard EOS's while the open symbols are the results from the asymmetry dependent potentials. The calculated deflection functions are not completely smooth. One of the reasons for this is the occurrence

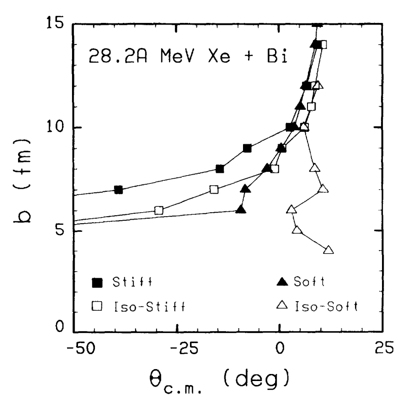

FIG. 3. Deflection functions for 28.2 MeV/nucleon ^{136}Xe + ^{209}Bi calculated with various EOS's. The solid symbols are the results when the EOS's do not have a density dependent asymmetry dependence while the open symbols have such a dependence. The squares are the results when a "STIFF" dependence on the overall density is used, while the triangles are the results when a "SOFT" EOS is used.

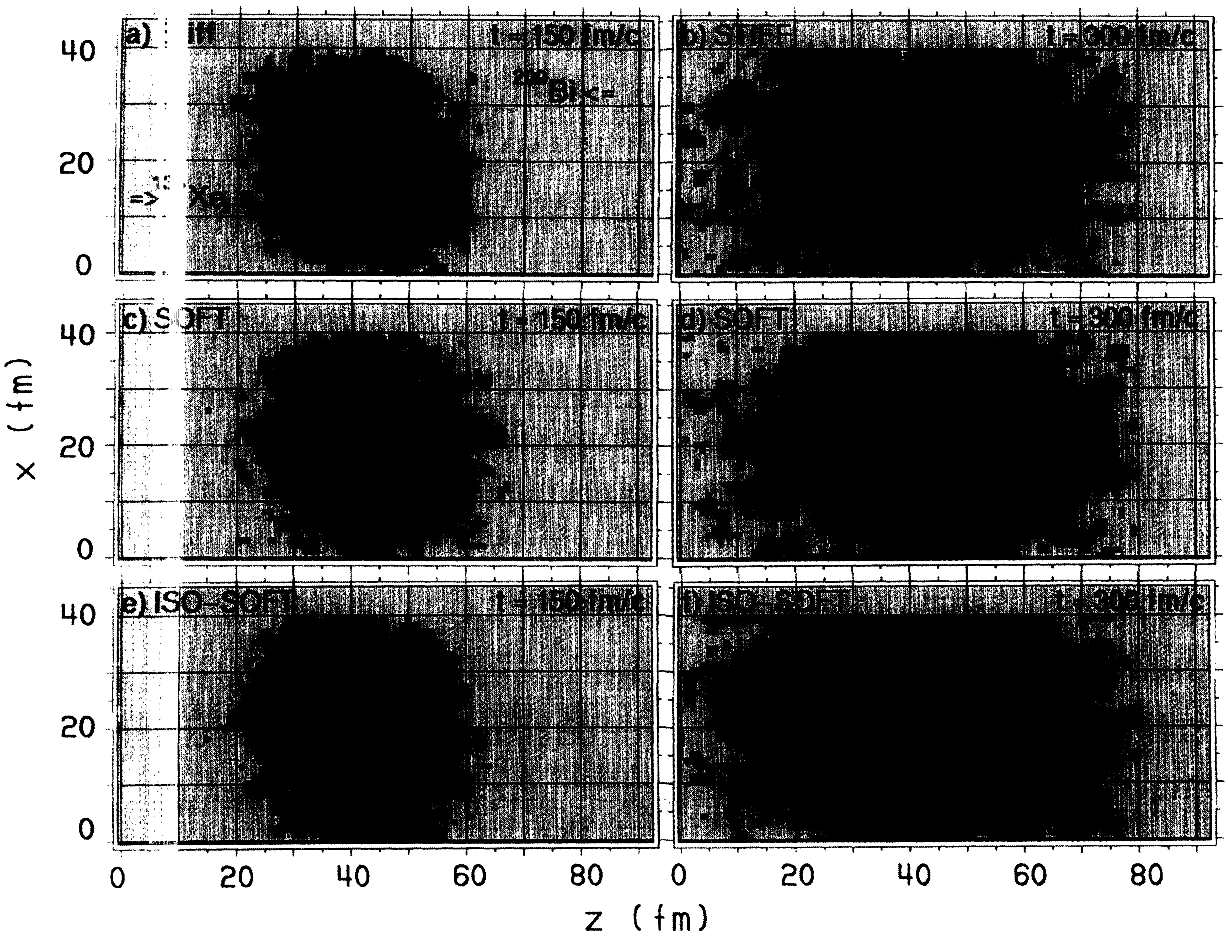

FIG. 4. Density distributions which result from calculations with (a,b) "STIFF," (c,d) "SOFT," and (e,f) "ISO-SOFT" EOS's, at two different times for 28.2 MeV/nucleon ^{136}Xe + ^{209}Bi. The Xe is initially traveling to the right and starts out at the bottom [see part (a)]. The density in the suppressed direction is integrated in this display. The color scale is logarithmic.

of neck fragments in some of the simulations, see below. (These simulations were done with 100 test particles/nucleon.)

The deflection functions exhibit the following trends. The use of "STIFF" EOS's result in more deflection, and thus orbit more than do the calculations using the "SOFT" EOS's and the use of the "ISO" EOS's result in less deflection than do the calculations which use the corresponding standard EOS's. The explanations for both of these trends are readily understood. The "STIFF" EOS's produce a more robust neck region (rather than building up the density in the space regions of the primary fragments). The necks last longer which results in more orbiting. However, if the "ISO" versions of the EOS's are used the neck regions end up to be very neutron rich. Therefore, it is energetically costly to create a robust (high density) neck. Thus the necks are not as long lived as they are in the corresponding calculation with the standard EOS.

The difference in the density of the neck regions can be seen in Fig. 4, where snap shots of the density distributions for three calculations ("STIFF," "SOFT," and "ISO-SOFT") are shown. The impact parameter for these calculations is $b = 7$ fm. The greater rotation of the "STIFF" EOS is already apparent at 300 fm/c, where the simulation with this potential has rotated the dinuclear complex nearly through 0° while the other simulations have not orbited nearly as much.

The second effect mentioned above can also be seen in Fig. 4. The neck produced using the "ISO-SOFT" potential is breaking-up already at 300 fm/c while the neck is still present in the other simulations. The neck fragment seen in the "ISO-SOFT" calculation survives as a cluster out to long times ($t \approx$ 1000 fm/c) and has a neutron to proton ratio of $\approx$ 2.5.

Neck fragments have been observed in a few intermediate heavy-ion experiments [10,11,13]. The work by Charity *et al.* [13] is particularly relevant in that it identifies a component of neutron rich fragments (d's and t's), produced in peripheral reactions of 40.0 MeV/nucleon ^{20}Ne with targets of ^{197}Au and ^{120}Sn, which are slow in the projectile frame. The present work suggests that these fragments are produced in the neck region and are composed to a large extent of neutrons from the target nucleus. Detailed calculations of such processes would require BUU calculations with final-state clustering and a statistical decay afterburner, which are beyond the scope of the present work.

In summary, the importance of using asymmetry dependent potentials in BUU calculations has been shown. This issue must be considered as central to studies of heavy-ion deflection functions and neck fragment production.

The foundation of this work is Professor W. Bauer's BUU code. I am grateful to him not only for supplying his well documented code, but also for several discussions concerning this project. I also wish to acknowledge several informative discussions with Professor R. J. Charity. This work was supported by the Office of High Energy and Nuclear Physics, Nuclear Physics Division of the U.S. Department of Energy under Contract No. DE-FG02-87ER40316.

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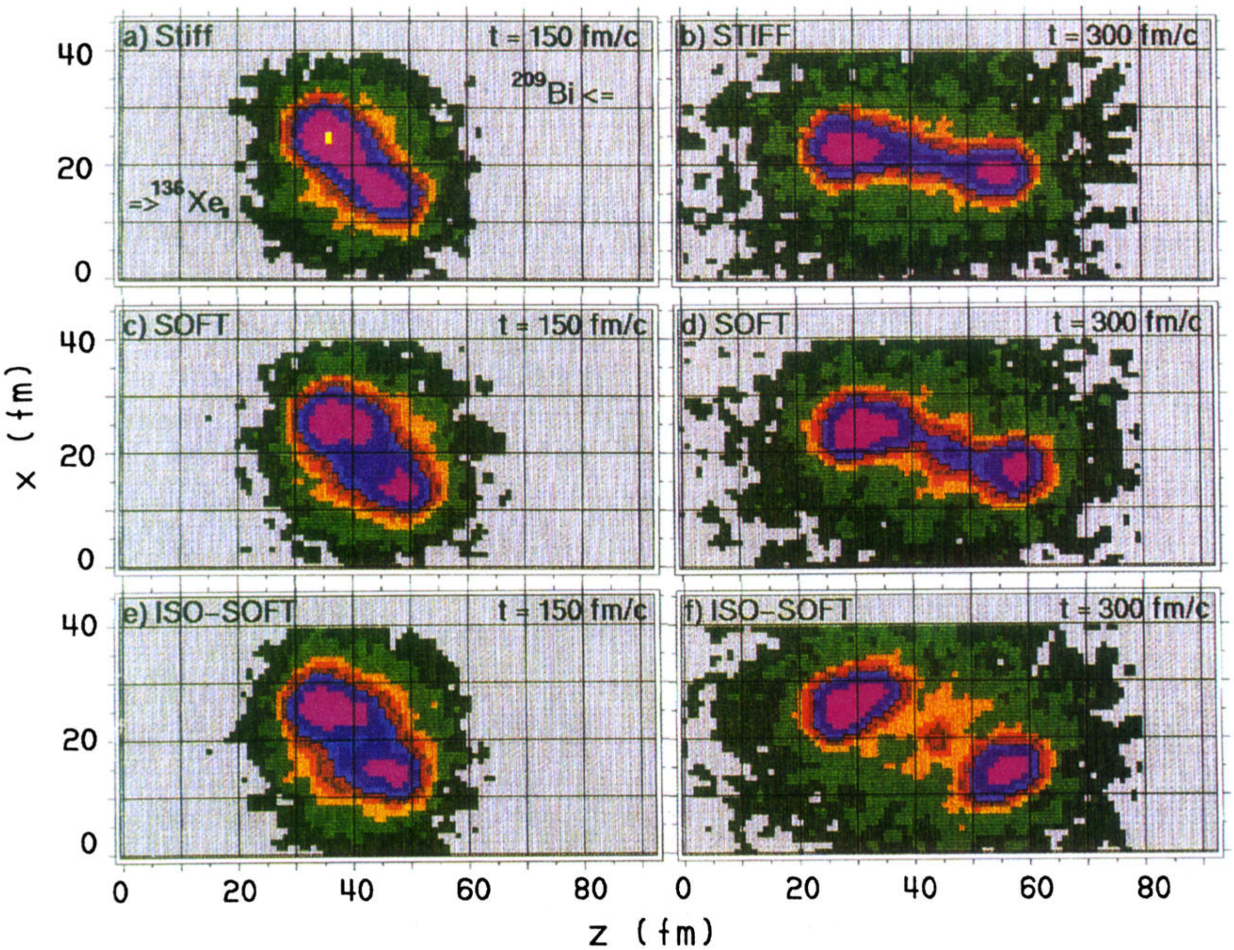

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