Detection of Possible Density Isomers by Means of High Energy Reaction Products*

G. Buchwald, L.P. Csernai**, G. Graebner, J.A. Maruhn, and W. Greiner
Institut für Theoretische Physik der Johann Wolfgang Goethe-Universität, Frankfurt am Main, Federal Republic of Germany

H. Stöcker
Lawrence Berkeley Laboratory, University of California, Berkeley, California, USA, and Gesellschaft für Schwerionenforschung, Darmstadt, Federal Republic of Germany

Received June 4, 1981; revised version August 6, 1981

We present a drastic effect in the cross section of high energy target fragments caused by a possible density isomer in the nuclear equation of state. The fluid dynamical model used here contains dissipative processes such as shear viscosity and heat conduction as well as a thermodynamic evaporation model at a late stage of the nuclear collision. In our calculations we consider as an example the reaction Ne+U at an impact parameter $b = 4$ fm.

The nuclear equation of state (EOS) is an important input for various theoretical models of heavy ion collisions. Recent speculations consider the influence of abnormal states in the EOS on the quantities observable in the reaction $[2, 3, 5, 7]$, but up to now only barely measurable influences such as jumps in temperature and compression as well as changing pion production rates have been predicted for the reaction center. If we consider zones where nuclear matter has already been squeezed out, these jumps will become considerably smaller thus diminishing the probability of their being measured. But for isomers in the EOS we now found a dramatic influence on the cross section. In the excitation function for the cross section of fast particles the isomer causes a sudden jump of about a factor of two from an expected exponential decay. Recent experimental data $[1]$ show evidence for $180^\circ$ azimuthal correlations between slow heavy fragments and light fast particles in noncentral nuclear collisions. This correlation is interpreted as being due to the highly inelastic bounce - off effect $[2]$ where the experimentally observed large collective momentum transfer is explained. As the main features of the reaction may be described in one plane, we expect that a two dimensional fluid dynamical model including nuclear viscosity and heat conduction will be reasonably valid.

In our fluid dynamical model we integrate the continuity equation,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,$$

the Navier-Stokes equation including shear viscosity $\eta$, bulk viscosity $\xi$ and heat conductivity $\kappa$ as well as a long-range nucleon-nucleon interaction in the form of a Yukawa potential $U$:

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\frac{1}{m} \frac{\partial}{\partial t} \rho + \frac{1}{m} \nabla [\eta \frac{\partial}{\partial t} \rho \mathbf{v} + \xi \frac{\partial}{\partial t} \rho \mathbf{v} | -\frac{\partial}{\partial t} \frac{1}{m} \frac{\partial}{\partial \mathbf{r}} U. \quad (2)$$
and the equation for the thermal energy density
\[ \partial_t (\rho E_T) + \partial_j (\rho E_T v_j) = \kappa \partial^2_i T + \partial_i v_i \left[ -p \delta_{ij} + \eta (\delta_{ij} v_j + \delta_{ij} v_i - \frac{2}{3} \delta_{ij} v_k v_k) + \zeta \delta_{ij} \delta_{ik} v_k \right] \]
\[ (3) \]
The indices \( i, j, k \) run over the spatial coordinates and indices occurring twice are summed over.

The pressure \( p \) is calculated from the internal energy as
\[ p = \rho^2 \frac{\partial E}{\partial \rho} \Big|_{\sigma = \text{const}}. \]
\[ (4) \]

The internal energy is separated into two parts
\[ E(\rho, T) = E_T(\rho, T) + E_c(\rho, 0) \]
\[ (5) \]
where \( E_T \) is the thermal energy associated with a low-\( T \) Fermi gas expansion.

\( E_c \) resembles the short range nuclear interaction, i.e. the binding and compression energy. The binding effects of a possible density isomer would occur here.

For normal nuclear matter one stable ground state exists at \( \rho_0 = 0.17 \text{fm}^{-3} \) with a binding energy of \( W_0 = -16 \text{MeV/n} \) and a compressibility of about 200 MeV. In our model calculation we assumed a flat second minimum in \( E_c(\rho) \) at \( \rho_1 = 0.425 \text{fm}^{-3} \) with \( W_1 = -14 \text{MeV/n} \). This did not influence the dynamics of the reaction too much but affected mainly the temperature and through this the spectra changed their behaviour systematically (see below).

In our calculation the barrier between the two minima in \( E_c(\rho) \) was set at \( \rho = 2 \rho_0 \). Thus density isomers will only appear when the compression is higher than \( 2 \rho_0 \). From the idealized shock relations [3] the minimum \( E_{lab} \) for this can be estimated to be around 60 MeV/n, most of this energy being transformed into heat. The more realistic fluid dynamical model requires a somewhat higher energy; in the two-dimensional situation the matter can be squeezed to the side thus damping the compression.

Considering a light projectile reacting noncentrally with a heavy nucleus leads to a further decrease of the compression. As we will see below these effects are responsible for a minimum \( E_{lab} > 200 \text{MeV/n} \) to reach density isomers.

At a late stage of the reaction the density becomes so small that the nucleons rarely collide. Here the process cannot be described hydrodynamically owing to the mean free path becoming too large. This condition is approximately reached when every cell has a significantly lower density than \( \rho_0 \) (break-up condition). Here an evaporation model is attached where in principle a thermal momentum distribution is added to the collective flow [9, 8] and only particles above the binding energy of nuclear matter are taken into account.

The bounce-off process typically proceeds as follows: (Fig. 1). After the nuclei contact, a hot and dense shocked zone develops. After half the reaction time (\( t \) depending on \( E_{lab} \), here \( \sim 17 \text{fm/c} \)) roughly half of the target nucleons are in the hot zone, while the other target nucleons are still undisturbed. The shocked nuclear matter behind the front remains compressed and heated for a while. Due to high thermal and compressional pressure in the shock zone the residual projectile and target fragments are pushed to the side. In the beginning of the reaction the heat produced was concentrated in the compressed matter. Later on, owing to the propagation of the shock and dissipative processes the expanding remnants of the target and projectile are heated up also. The light projectile fragment is fast and hot, while the heavy target fragment is slower and colder [2, 3, 7].

This can clearly be seen in the triple differential cross section [8] (Fig. 2).

The main contribution on the target side comes from the evaporated low energy particles, whereas on the projectile side, the collective flow in the bounce-off peak still gives comparable contributions at high energies (\( E \sim 1 \text{E}_{lab} \)). It was shown in [8] that the bounce-off peak is an order of magnitude larger for impact parameter \( b = 4 \text{fm} \) than for \( b = 2 \text{fm} \). Thus a bounce-off peak occurring in high multiplicity selected data will be due mostly to \( b = 4 \text{fm} \) contributions.

The \( \frac{1}{2} E_{lab} \) cross section (high energy yield, HEY) is suitable for the investigation of isomeric influences.

Especially the tails in the HEY will be strongly influenced by temperature changes due to condensation effects.

Fig. 1. Density contour-plots of the Ne+U reaction at \( E_{lab} = 400 \text{ MeV/n} \) and \( b = 4 \text{fm} \) calculated in the equal speed system from \( t = 0 \) to 34.26 fm/c with the small viscosity being temperature-dependent with \( \eta = \eta_0 \sqrt{T + T_0} \), \( \eta_0 = 3 \pi \text{m/8} \sigma_{tot} \), \( \sigma_{tot} = 40 \text{mb} \), \( T_0 = 0.25 \text{MeV} \).