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Publication Date
1978-10-01
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October 1978

Prepared for the U. S. Department of Energy
under Contract W-7405-ENG-48

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ROLE OF DEFORMATION IN DEEP INELASTIC HEAVY ION COLLISIONS*

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ABSTRACT

The transport theory previously developed for heavy ion deep inelastic collisions is generalized to include phenomenologically nuclear deformations. Calculated cross sections for the reaction $^{136}$Xe + $^{209}$Bi show substantial improvements over previous results obtained without deformations. In particular, the new calculated cross sections exhibit a peak at low relative kinetic energy of the two outgoing nuclei.

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*Work supported by the National Science Foundation and the U.S. Department of Energy.

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A unique feature of deep inelastic heavy ion collisions is the existence of a peak in the cross section at low relative kinetic energy of the two outgoing nuclei, usually at energy below the Coulomb energy of two touching spherical nuclei. Deubler and Dietrich [11, among others, have suggested that such phenomena are due to deformations of the ions in the exit channel.

In order to describe deep inelastic heavy ion collisions, Agassi, Ko and Weidenmüller [2] have derived a transport equation for the phase space probability density function $F(R,\dot{R},P,\dot{P})$ of the relative motion. If $F(R,\dot{R},P,\dot{P})$ is approximated by a Gaussian distribution, then one obtains a set of linear differential equations for the mean values and variances. The equations for mean values are identical to the Newtonian equations of motion for the relative motion with frictional forces as in the model of Gross et al [3]. The tangential friction has the same magnitude as the radial friction. The equations for variances describe the spreading of classical trajectories as a result of the dissipation of the relative kinetic energy. Both friction and diffusion coefficients are determined by the statistical input quantities which are further estimated microscopically [4]. The theory has also been generalized to include nucleon transfers. Many features of the experimental data are reproduced in the transport theory. However, the theory of Ref. [2], which neglected deformations, did not lead to a peak in the cross section at low relative kinetic energy of the two outgoing nuclei.

The generalization of the transport theory to include large scale collective motion other than the relative motion is still not accomplished. However, it has been shown [5,6] that at least for small amplitude
collective excitations, such as shape oscillations and giant resonances, one can consistently include them in the statistical description of deep inelastic collisions. In this letter, the calculations of Ref. [2] are generalized to include phenomenologically shape deformations of both target and projectile. We shall show that much improved results are obtained from this approach. In particular, the above mentioned low energy peak in the cross section is reproduced.

According to Refs. [5,6], deformations can be described by a forced damped harmonic motion similar to the approach of Broglia et al [7],

\[
\frac{d^2 \alpha_i}{dt^2} + \frac{2 \Gamma_i}{\hbar} \frac{d \alpha_i}{dt} + \left[ \omega_i^2 + \left( \frac{\Gamma_i}{\hbar} \right)^2 \right] \alpha_i = - \frac{1}{D_i} \frac{\partial U_0(r,\alpha_i)}{\partial \alpha_i} \quad (1)
\]

where \( \alpha_i \) describes the surface deformation of the ions, with \( i = 1 \) (projectile) and \( 2 \) (target). The frequency \( \omega_i \) is defined to be \( (C_i/D_i)^{1/2} \) with \( C_i \) and \( D_i \) the stiffness and inertia parameters respectively. The damping factor is denoted by \( \Gamma_i \), while the ion-ion potential is given by \( U_0(r,\alpha_i) \) and depends on both the relative distance \( r \) and the deformation \( \alpha_i \).

As in [2], we use the proximity nuclear potential of Blocki et al [8] and the point charge Coulomb potential, both generalized to include deformations as in [9]. We consider quadrupole deformations only. The parameters \( C_i \) and \( D_i \) are taken from the liquid-drop model. Very little is known about the damping factor \( \Gamma_i \); we therefore use \( \Gamma_i = 0.5 \hbar \omega_i \) as a rough estimate so that the quadrupole vibration in the liquid-drop model is damped.
In view of the approach of Broglia et al [7], who include all collective excitations obtained from RPA calculations which contribute most to the sum rules, one might wonder how realistic is our model of taking into account only the quadrupole vibration with the liquid-drop model. This model oversimplifies in two respects: First, the high frequency vibrations are neglected, and second, the liquid-drop stiffness is too low. The neglect of the high frequency vibrations is probably justified for the deep inelastic scattering, because these states act mainly as doorway states for the dissipation of relative kinetic energy. They contribute very little to the deformation of the nucleus due to the large stiffness of the nuclear matter in response to giant vibrations. Concerning the model on liquid-drop dynamics, which leads to too small stiffness parameters, we note that this is mitigated by the fact that we only consider quadrupole deformations. This effectively simulates the total deformation one would obtain by taking into account all multipoles, and the higher states within each multipole.

We have applied the model to study the reaction $^{136}$Xe on $^{209}$Bi at $E_{\text{lab}} = 1130$ MeV [10]. The same statistical input quantities as in [2] are used. The energy dissipation is drastically increased to 250 MeV, compared with the calculation of [2] where it was only 180 MeV. However, the rainbow angles in the deflection function are larger than those of [2], and the calculated cross sections therefore peak at an angle which is larger than that of the experimental data. In an effort to improve the result, we varied the thickness parameter $b$ in the proximity potential from its conventional value of 1 fm to 1.2 fm. Our readjustment of the parameter $b$ increases the strength of the potential and the range of
its tail. These have the effects of reducing the rainbow angles in the deflection function obtained with deformation and $b = 1\,\text{fm}$, and leading to an even larger kinetic energy dissipation of 280 MeV. This increase of the thickness parameter in the potential is consistent with the picture of Iwamoto and Harada [11] who introduced explicitly the dependence of the range of the nuclear interaction on the intrinsic excitation energies.

In Figs. 1-5, we present results of our calculations using the model described above. The dashed curves are from our calculation while the solid curves are the experimental ones [10]. Figure 1 shows the angular distribution integrated over all the final kinetic energies and charges. The results are very similar to previous calculations without deformation [2]. Again, we observe that the calculated results show too little cross section in the small angle region. In Fig. 2, we show the differential cross section as a function of energy loss, integrated over all charges and angles between $25^\circ$ and $75^\circ$. The present result is given by the long-dashed curve which shows clearly the broad deep inelastic peak at about $E_{\text{loss}} = 225\,\text{MeV}$, although the cross section is slightly lower than the experimental value. As a result, we obtain a quasi-elastic peak at small energy loss which is much wider than the experimental one. Note that the low energy peak is missing completely in the model without the deformation degree of freedom as shown by the short-dashed curve in Fig. 2. In Figs. 3 and 4 we show, respectively, the differential cross section for different final kinetic energies but summing over charges, and for different charge states but summing over the final kinetic energies. The low energy cross section agree much better with experiments than before where deformations are not included [2]. The lack of cross section in the
small angle region for low kinetic energies is responsible for the behavior of the calculated cross section in Fig. 1. Therefore, the differential cross sections in Fig. 4 for charge states away from $Z = 54$ are too low in the forward angles, as the charge diffusion is correlated with the energy dissipation. This latter assertion is obviously displayed in Fig. 5 where we show the angle-integrated charge distribution for given final kinetic energies. The agreements with experiment are very good for high energy cases, but not so good for low final kinetic energies.

In conclusion, the transport theory developed in [2] gives calculated multi-dimensional cross sections in much better agreement with experimental data if the deformation degree of freedom is included. However, some outstanding difficulties still remain. A major problem with the model is that cross sections for low final kinetic energies tend to concentrate in large angles rather than small angles as experiments indicate. The answer to this difficulty may be that the ion-ion potential has an attractive interior rather than a repulsive core as in the proximity potential used in our calculations. As shown in [12], such an attractive potential indeed leads to substantially larger cross sections in the small angle region. However, an attractive ion-ion potential will probably yield fusion cross sections that are too high. Another possible explanation of the difficulty with small-angle cross sections at large energy losses is the following. The two ions may stick and spin towards the forward angles, therefore shifting angular distributions to smaller angles. This sticking together may involve neck degree of freedom which we have not considered. We view the second possibility as more likely
than the first one. Another problem of our model is that the calculated quasi-elastic peak is too wide in comparison with the experiment (see Fig. 2). This could indicate that a more microscopic treatment of the initial stages of the reaction is needed.

The author is grateful to G. F. Bertsch for a critical reading of the manuscript.

References

Figure Captions

Fig. 1. Angular distribution integrated over all final energies and charges. Solid curve is from the experiment of Schröder et al [10], dashed curve is from our calculation.

Fig. 2. Energy-loss spectrum integrated over final angles $\theta_{\text{lab}}$ from 25° to 75°. Solid curve is from the experiment, long-dashed curve is from present calculation, and short-dashed curve is the calculation of [2] without deformation degree of freedom.

Fig. 3. Charge-integrated angular distributions for different final kinetic energy bins (50 MeV wide). Solid curve is from the experiment, dashed curve is from our calculation. The cross sections shown are multiplied by the factors indicated on the right-hand side.

Fig. 4. Same as Fig. 3 for energy-integrated angular distributions of different final charge state bins (three Z units wide).

Fig. 5. Same as Fig. 3 for angle-integrated charge distributions of different final kinetic energy bins (50 MeV wide).
Fig. 1

$^{136}\text{Xe} + ^{209}\text{Bi}$

$E_{\text{lab}} = 1130 \text{ MeV}$

$\frac{d^2 \sigma}{d\Omega \, dp}$ vs $\theta_{\text{lab}}$
$^{137}\text{Xe} + ^{209}\text{Bi}$

$E_{\text{lab}} = 1130 \text{ MeV}$

$\frac{d\sigma}{dE_{\text{loss}}}$ (mb/MeV)

E_{\text{loss}} (MeV)

Fig. 2
Fig. 3
Fig. 4
Fig. 5

$^{209}\text{Bi} + ^{136}\text{Xe}$

$E_{\text{lab}} = 1130$ MeV

$25^\circ \leq \theta_{\text{c.m.}} \leq 75^\circ$
This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.
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