CLASSICAL DYNAMICS OF DAMPING EFFECTS AND OF SUB-COULOMB TRANSFER IN COLLISIONS OF DEFORMED HEAVY IONS: 238U + 238U REACTION

Rajiv Gupta, M. Münchow, R. Maass, W. Scheid

To cite this version:

HAL Id: jpa-00226505
https://hal.archives-ouvertes.fr/jpa-00226505
Submitted on 1 Jan 1987

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
CLASSICAL DYNAMICS OF DAMPING EFFECTS AND OF SUB-COULOMB TRANSFER IN COLLISIONS OF DEFORMED HEAVY IONS: $^{238}\text{U} + ^{238}\text{U}$ REACTION(1)

R.K. GUPTA(2), M. MÜNCHOW, R. MAASS and W. SCHEID

Institut für Theoretische Physik der Justus-Liebig-Universität, Giessen, D-6300 Giessen, F.R.G.

Résumé - Un modèle classique avec degrés de liberté dynamiques pour déformations et orientations aux collisions entre noyaux déformés sera présenté. Ce modèle sera appliqué aux effets de l'amortissement dans la réaction $^{238}\text{U} + ^{238}\text{U}$ à $E_{lab} = 7.42$ MeV/u et au sub-Coulomb-transfert à 5.05-6.07 MeV/u.

Abstract - A classical model with dynamical deformations and orientations degrees of freedom is presented for collisions of deformed nuclei. Applications of this model are made to the damping effects and to sub-Coulomb transfer in $^{238}\text{U} + ^{238}\text{U}$ reactions at $E_{lab} = 7.42$ and 5.05-6.07 MeV/u, respectively.

I - INTRODUCTION

The $^{238}\text{U} + ^{238}\text{U}$ reaction is well studied at beam energies of both above and below the Coulomb barrier. For the incident energy above the Coulomb barrier, namely $E_{lab} = 7.42$ MeV/u, the characteristic damping effects were observed /1/ and at $E_{lab} = 5.7$-6.1 MeV/u a new effect of peaked structure in positron energy spectra was found /2/. More recently, there have been the measurements /3/ of excitation function and angular distributions for the one-neutron-transfer product $^{239}\text{U}$ at $E_{lab} = 5.05$-6.07 MeV/u.

The deformation and orientation degrees of freedom affect strongly the dissipation of energy and angular momentum in deep inelastic collisions /4/. Inclusion of deformation and orientation effects of the colliding nuclei also indicated /5/ the possibility of a minimum or "pocket" in the interaction potential of $^{238}\text{U} + ^{238}\text{U}$. Such a pocket in the heavy-ion potential is shown to have significant bearing on the cross sections for sub-Coulomb transfer of neutrons /6/. For the sub-Coulomb transfer in $^{238}\text{U} + ^{238}\text{U}$ the interpretation of the data on the semi-classical theory for spherical nuclei show large deviations, particularly for central collisions /3/. The deformation and orientation effects, not yet included, might also be important for these data.

In this paper, we describe a classical dynamical model for collisions of two deformed nuclei and consider its application to the data on damping effects and sub-Coulomb transfer in $^{238}\text{U} + ^{238}\text{U}$ reactions.

II - THE MODEL

We use the classical Hamilton equations of motion for the collective coordinates $q_v$ and their canonically conjugate momenta $p_v$, with frictional forces $Q_v$ included:

$$\dot{q}_v = \frac{\partial H}{\partial p_v}, \quad \dot{p}_v = -\frac{\partial H}{\partial q_v} + Q_v$$  \hspace{1cm} (1)

with $H = T(p,q) + V(q)$, \hspace{0.5cm} $v = 1,2,\ldots,13$.  \hspace{1cm} (2)

(1) Work supported by BMFT and GSI (Darmstadt)
(2) Permanent address: Physics Department, Panjab University, Chandigarh-160014, India

Article published online by EDP Sciences and available at http://dx.doi.org/10.1051/jphyscol:1987238
The coordinates are: the relative vector \( \mathbf{R} = (R, \theta, \phi) \) between the nuclear centres of mass, the Euler angles \( \mathbf{\alpha} = (\phi_1, \delta_1, \psi_1) \) defining the orientation of the intrinsic principal axes of the two nuclei \((i=1,2)\) with respect to the laboratory system and the intrinsic quadrupole deformations \( \beta_i \) and \( \gamma_i \). We assume \( \gamma=0 \) here.

The potential \( V \) in (2) consists of Coulomb, nuclear, and deformation energies that are calculated in Ref./7/. The mass parameters, defining the kinetic energy \( T \) of the rotation and vibration of the nuclei in (2), are determined by the rotation-vibration model. For the calculation of frictional forces \( Q_{ij} \), the Tsang model /8/ is extended to the case of two arbitrarily oriented deformed nuclei by allowing a finite range \( \mu_0 \) of the frictional force between the matter elements of two nuclei moving with certain velocity fields. For details, we refer to Ref./4/.

The time evolution of the process is studied for \( ^{238}\text{U}+^{238}\text{U} \) by solving the coupled equations (1) for various incident energies and orbital angular momenta. For incident energies below the barrier, the nuclear interaction potential and the frictional forces are zero, such that only the Coulomb potential acts. Since the deformed nuclei initially can have various orientations, we have solved the equations of motion for arbitrary initial orientations of \( ^{238}\text{U} \) nuclei.

III - DISSIPATIVE EFFECTS IN 7.42 MEV/U COLLISION OF \(^{238}\text{U}+^{238}\text{U}\)

The trajectory calculations are first used to calculate the dissipation of energy \( \Delta E \) and angular momentum that depend on the choice of the frictional force parameters \( \mu_0 \) and \( k \). Then, the total kinetic energy (TKE) after the collision, defined as

\[
TKE = E_{cm} - \Delta E - \sum_{i=1}^{2} E_{rot,i}
\]  

is calculated as a function of the scattering angle \( \theta_{cm} \). Fig.1 shows the results of this calculation for various orientations (solid lines) as well as that obtained by averaging over all possible initial orientations (dashed line). We notice in Fig.1, a spreading of TKE about the mean value, which is largest for central collisions \( (\theta_{cm}=180^\circ) \) and arises mainly due to the nose-to-nose configuration.

We have then calculated the double differential cross section \( d^2\sigma/(dTKE \ d\theta_{cm}) \), the differential cross section \( d\sigma/d\Omega \) and the total cross section. Fig. 2 illustrates our
calculated $d\sigma/d\Omega$ (integrated over TKE>25 MeV) in comparison with transport model calculations of Schmidt et al. /9/ and of Wolschin /10/ and the experimental data /9/. The comparison is satisfactory. Integrating over $\Omega$ for $50^\circ<\theta_{cm}<130^\circ$, and multiplying by 0.5 because of the identity of the projectile and target nuclei, the total calculated cross section is 972 mb compared with the experimental (800±50) mb. The qualitative agreement is once again obtained.

IV - SUB-COULOMB TRANSFER IN $^{238}$U+$^{238}$U AT 5.05-6.07 MEV/U

For deformed nuclei, apparently the trajectory is no more the true Rutherford trajectory. However, the variation of angular momentum $L$ as a function of $\theta_{cm}$ does not change much in going from spherical to deformed nuclei, with a very weak dependence on the orientations of nuclei. Also, for larger impact parameters the distance of closest approach for deformed nuclei $R_{min}$ coincides with that for spherical nuclei, and at zero and smaller impact parameters the variation of $R_{min}$ with $\theta_{cm}$ is such that for, say, the nose-to-nose configurations the deformed nuclei behave as spherical nuclei of larger radii and for the belly-to-belly configurations as spherical nuclei with smaller radii.

According to the semi-classical theory of neutron tunneling, first developed by Breit and his collaborators /11/, and later deduced from DWBA expressions by Buttle and Goldfarb /12/ the integrand of the transfer amplitude is well localized near the distance of closest approach $D(\theta_{cm})$ for spherical nuclei. The differential cross section can be written in terms of the dimensionless factor $C_{AB}$ containing spectroscopic factors and the wave number $\alpha=(2\mu E_B/n^2)^{1/2}$ associated with the appropriate neutron binding energy $E_B$, as

$$
\frac{d\sigma}{d\Omega} = \left[ \frac{d\sigma}{d\Omega} \right]_{cm} \sin(\theta_{cm}/2) \exp(-2\alpha D(\theta_{cm})),
$$

(4)
given in terms of classical Rutherford scattering cross section and the Sommerfeld parameter $\eta$.

Allowing for the deformation of colliding nuclei in this formalism would mean that the corresponding distance of closest approach $R_{min}$ now depends on the orientations of the nuclei. The averaging over the various possible initial orientations $\theta_i$ (i=1,2) is carried out analytically by using the following parametrized form:

$$
R_{min}(\theta_1,\theta_2,\phi_1,\phi_2,\theta_{cm}) = R_{min}(\theta=90^\circ, \theta_{cm}) + \frac{1}{2} \Delta R(\cos \phi_1, \cos \phi_2)
$$

(5)

where $\theta=\theta_1,\theta_2$, or $0^\circ$ refer, respectively, to belly-to-belly and nose-to-nose configurations. Eq. (5) is found to fit the actual trajectory calculations made for $^{238}$U+$^{238}$U at 5.65 MeV/u. The averaged differential cross section is then given by

$$
\frac{d\sigma}{d\Omega} = \left[ \frac{d\sigma}{d\Omega} \right]_{cm} \sin(\theta_{cm}/2) \cdot \frac{C_{AB}}{(\alpha \Delta R)^2}
$$

(6)

However, for transfer between deformed nuclei one may argue that the corresponding distance between the surfaces, $d_{min}$, may be more relevant rather than the centre-to-centre distance $R_{min}$. This argument follows from the fact that $d_{min}(\theta=90^\circ)$ $>d_{min}(\theta=0^\circ)$ whereas $R_{min}(\theta=90^\circ)<R_{min}(\theta=0^\circ)$. On the other hand the belly-to-belly configuration offers larger surfaces as compared to the nose-to-nose configuration. We test this hypothesis by replacing $R_{min}(\theta,\theta_{cm})$ in (6) by $R_{01}+R_{02}+d_{min}(\theta,\theta_{cm})$, with $R_{01}$ as the radii of equivalent two spherical nuclei. Since the determination of $d_{min}$ for a finite impact parameter is rather complex, we use this formula only for $\theta_{cm}=180^\circ$.

Fig. 3 shows the calculated differential cross sections (dashed lines) for centre-to-centre distance $R_{min}$ in (6) compared with the spherical case (solid lines) for $C_{AB}$ and $\alpha$ fitted by Wirth et al. /13/ to 24 experimental data points at five energies
in the angular range $\theta_{cm}=90^0-110^0$. For the $d_{\min}$-hypothesis the corresponding calculated points at $\theta_{cm}=180^0$ lie much higher (by at least 50%). In any case, our calculations show that the deformations of nuclei in the semiclassical theory make significant modifications of the differential cross section at the backward angles. For the $R_{\min}$-hypothesis, the belly-to-belly configuration contributes most whereas for $d_{\min}$-hypothesis, the configurations with $\theta>45^0$ are found to contribute equally.

Fig. 3 The differential cross sections vs. scattering angle for one-neutron-transfer in $^{238}\text{U}+^{238}\text{U}$ at 5.05-6.07 MeV/u.

V - SUMMARY AND CONCLUSIONS

A classical dynamical model for collisions between deformed nuclei is studied where the deformations and orientations of nuclei are also treated as the dynamical variables. The model is shown to give the results of deep inelastic collision in $^{238}\text{U}+^{238}\text{U}$ at 7.42 MeV/u and modify the sub-Coulomb transfer amplitudes for central collisions.

REFERENCES