

IMPLICATIONS OF NUCLEAR DEFORMATIONS AND ORIENTATIONS FOR  
SUB-COULOMB TRANSFER OF NEUTRONS IN HEAVY-ION COLLISIONS\*

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Wirth et al.<sup>1</sup> have recently measured the excitation function and angular distributions for the one-neutron transfer in the  $^{238}\text{U} + ^{238}\text{U}$  collision at energies near and below the Coulomb barrier (5.05-6.07 MeV/u) and interpreted their data within the semi-classical theory of neutron tunneling (SCTT), derived for spherical nuclei. However,  $^{238}\text{U}$  is a deformed nucleus and thus can arrive with all possible initial orientations. The orientation probability at the classical turning point is shown to depend on the initial configuration<sup>2,3</sup>. In this paper we extend the SCTT to collisions between deformed nuclei and give implications of averaging over the initial orientations on the one-neutron transfer cross section in collisions between two unpolarized  $^{238}\text{U}$  ions.

The differential cross section for spherical nuclei in SCTT is written in terms of a dimensionless quantity  $C_{AB}$ , containing the spectroscopic factors, and the wave number  $\alpha = (2\mu E_B/\hbar^2)^{1/2}$ , associated with the neutron binding energy  $E_B$ , as

$$\frac{d\sigma}{d\Omega} = \frac{\pi\eta\alpha}{8k^3} C_{AB} \frac{1}{\sin^3(\theta_{cm}/2)} \exp(-2\alpha D(\theta_{cm})) \quad (1)$$

Here,  $\eta$  is the Sommerfeld parameter and  $D$ , the distance at closest approach between the centers of mass of the two spherical nuclei on their Rutherford trajectory.

For deformed nuclei the trajectory is no more a Rutherford trajectory<sup>3</sup>. Therefore we determine the corresponding distance of closest approach,  $D=R_{min}$ , by solving the classical Hamilton equations of motion, where both the deformation and orientation degrees of freedom are treated as dynamical collective variables. The averaging over all possible initial orientations of the intrinsic symmetry axes of the  $^{238}\text{U}$  nuclei is carried out analytically by using the following ansatz for  $R_{min}$ :

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

with  $\Delta R = R_{min}(\theta=0^\circ, \theta_{cm}) - R_{min}(\theta=90^\circ, \theta_{cm})$ ,

where  $\theta=\theta_1=\theta_2=90^\circ$  or  $0^\circ$  refer, respectively, to belly-to-belly and nose-to-nose configurations with the symmetry axes in the scattering plane. This ansatz is found to fit well the actual classical trajectory calculations made for  $^{238}\text{U} + ^{238}\text{U}$  at 5.65 MeV/u. The averaged differential cross section is obtained as

$$\langle \frac{d\sigma}{d\Omega} \rangle_{\theta_i} = \frac{\pi\eta\alpha}{8k^3} C_{AB} \frac{1}{\sin^3(\theta_{cm}/2)} \cdot \left[ (\exp(-\alpha R_{min}(\theta=90^\circ, \theta_{cm})) - \exp(-\alpha R_{min}(\theta=0^\circ, \theta_{cm}))) / (\alpha \Delta R) \right]^2 \quad (3)$$

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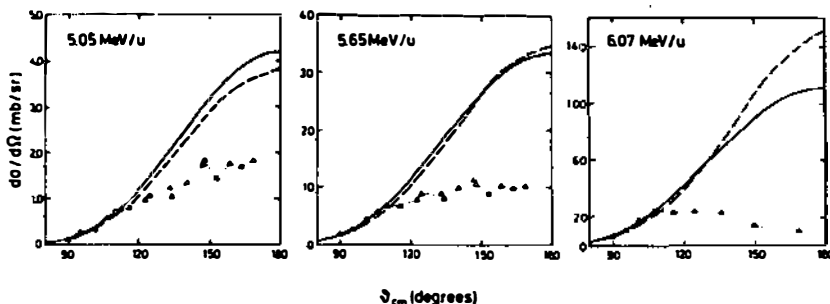


Fig.1 The differential cross sections vs. scattering angle for one-neutron-transfer in  $^{238}\text{U}+^{238}\text{U}$  at 5.05-6.07 MeV/u.

Fig.1 shows the calculated  $\langle d\sigma/d\Omega \rangle_{\theta_j}$  (dashed lines) compared with the spherical case (solid lines) for  $C_{AB}$  and  $\alpha$  fitted by Wirth et al.<sup>1</sup> to 24 experimental data points of  $^{238}\text{U}+^{238}\text{U}$  collisions at five energies in the angular range  $\theta_{cm}=90^\circ-110^\circ$ . The experimental data are also plotted. We notice that the deformation effects are significant for the backward scattering angles. The belly-to-belly configuration is found to contribute most in this averaging of the differential cross section.

For neutron transfer between deformed nuclei it may be that the shortest distance between the nuclear surfaces,  $d_{min}$ , is the more relevant quantity than the centre-to-centre distance  $R_{min}$ . In order to make a first estimate, we have calculated  $\langle d\sigma/d\Omega \rangle_{\theta_j}$  for  $\theta_{cm}=180^\circ$  by replacing the distance  $D(\theta_{cm})$  by  $R_{01}+R_{02}+d_{min}(\theta_j, \theta_{cm})$ , where  $R_{0j}$  are the radii of equivalent spherical nuclei. The calculated values of  $\langle d\sigma/d\Omega \rangle_{\theta_j}$  at  $\theta_{cm}=180^\circ$  are found to have larger values (by a factor of at least 50%) as compared to that for the  $R_{min}$ -hypothesis. Also, for the  $d_{min}$ -hypothesis the configurations with  $\theta_j > 45^\circ$  are found to contribute equally to the averaging of  $d\sigma/d\Omega$  over the initial orientations.

In conclusion, the deformations and orientations of nuclei are shown to be important for the sub-Coulomb transfer of one-neutron in central and nearly central collisions.

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