SINGLE NEUTRON TRANSFER IN $^{238}U+^{238}U$ COLLISIONS

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Cross sections measured for single neutron transfer reactions in $^{238}U+^{238}U$ collisions at sub-Coulomb energies are qualitatively reproduced using a simple semi-classical formula.

A few years ago Wirth et al. [1] published single neutron transfer cross sections for $^{238}U+^{238}U$ collisions. The radiochemical technique used enabled data to be obtained at energies well below the nominal Coulomb barrier. It was therefore surprising that the semi-classical analysis in ref. [1] did not give a good description of the measurements. Two theoretical papers tried to explain the data in terms of prolonged contact times [2] or by deviations from Rutherford trajectories due to the well-deformed structure of ^{238}U [3]. Another set of experiments was carried out to determine whether sequential fission could explain the discrepancies; but this effect was judged to be small [4]. Additional radiochemical transfer reaction measurements have been made for $^{238}U+^{197}Au$ and $^{197}Au+^{197}Au$ collisions [5]. A preliminary analysis of the $^{238}U+^{197}Au$ single neutron transfer data obtains a consistent semi-classical description [5]; which makes the previous result for $^{238}U+^{238}U$ appear even more unusual. There have also been recent reports of an anomalous behavior of sub-Coulomb single-neutron transfer cross sections for $^{58}Ni+Sm$ collisions when the Sm isotope is deformed, but not when it is spherical [6].

We undertook a new analysis of the $^{238}U+^{238}U$ data with the original aim of looking for similar types of deformation effects as have been discussed recently for the case of two-particle transfer reactions [7]. We have found, however, that a simple semi-classical analysis, without including deformation, does give a good overall description of the low energy $^{238}U+^{238}U$ transfer data. We emphasize this in the present communication by showing the results obtained with an analytic formula. The concepts behind the formula have already been discussed in the literature (see in particular ref. [8]).

We start from the following amplitude for the transfer reaction from the state i to f and leading to the center-of-mass scattering angle θ:

$$T_{\rm fi}(\theta)=a_{\rm fi}^{(1)}(\theta)\exp\left(\frac{1}{\hbar}\int_{-\infty}^{+\infty}{\rm d}t\,W(t)\right)f_{\rm C}(\theta)\,. \quad (1)$$

Here f_C is the Coulomb scattering amplitude and W is the absorptive potential which describes the loss of flux from the elastic channel. The absorptive potential is integrated along the Rutherford trajectory which leads to the angle θ. Similarly, the first-order amplitude for the transfer process is given by an integral along the same trajectory; namely,

$$a_{\rm fi}^{(1)}(\theta)=-\frac{\rm i}{\hbar}\int_{-\infty}^{+\infty}{\rm d}t\,F_{\rm fi}(t)\exp\left(-\frac{\rm i}{\hbar}Q_{\rm fi}t\right), \quad (2)$$

where F_{fi} is the formfactor for the transfer and Q_{fi} is the reaction Q-value.

The integrals along the trajectory can be carried out by exploiting the exponential behavior of F_{fi} and W at large distances and by making a parabolic approximation to the trajectory. Thus we first write

$$F_{fi}(t)=F_0 \exp\left(-\frac{r(t)-R_f}{a_f}\right), \tag{3}$$

$$W(t)=W_0 \exp\left(-\frac{r(t)-R_w}{a_w}\right). \tag{4}$$

Then we expand

$$r(t)=r_0+\tfrac{1}{2}\ddot{r}_0 t^2 , \tag{5}$$

where

$$r_0=\frac{Z_1 Z_2 e^2}{2E_{cm}}\left(1+\frac{1}{\sin(\theta/2)}\right) \tag{6}$$

is the distance of closest approach and

$$\ddot{r}_0=\frac{Z_1 Z_2 e^2}{\mu r_0^2} \tag{7}$$

is the radical acceleration at the turning point. In this way one obtains

$$\frac{1}{\hbar}\int_{-\infty}^{+\infty} \mathrm{d}t\, W(t)=\sqrt{\frac{2\pi a_w}{\hbar^2 \ddot{r}_0}}\, W(r_0) \tag{8}$$

and

$$a_{fi}^{(1)}(\theta)=-\mathrm{i}\sqrt{\frac{2\pi a_f}{\hbar^2\ddot{r}_0}}\, F_{fi}(r_0)\exp\left(-\frac{a_f Q_{fi}^2}{2\hbar^2\ddot{r}_0}\right). \tag{9}$$

Thus, taking the square of the absolute value of eq. (1), we obtain the transfer cross section in terms of an analytic function times the Rutherford scattering cross section,

$$\sigma_{fi}(\theta)=\frac{2\pi a_f}{\hbar^2\ddot{r}_0}F_{fi}(r_0)^2 \times \exp\left(-\frac{a_f Q_{fi}^2}{\hbar^2\ddot{r}_0}+2\sqrt{\frac{2\pi a_w}{\hbar^2\ddot{r}_0}}\,W(r_0)\right)\sigma_{Ruth}(\theta). \tag{10}$$

It may be noted that eq. (9) neglects the angular momentum, mass and charge transferred in the reaction. Corrections for such effects can be made by using an effective Q-value [8]. Notice also that in the expression of $\ddot{r}_0$ we have neglected the contribution of the orbital angular momentum. This is quite small for the back angle we are interested in. In the above derivation we have also neglected the effect of the nuclear interaction on the relative motion of the two ions. In the case under study this approximation should be relevant only at the highest energy where its effect is also masked by the imaginary potential.

In the present case where there are identical even nuclei in the entrance channel one must add the exchange amplitude $T_{fi}(\pi-\theta)$ to eq. (1) and then take the modulus squared. The experiments in ref. [1] actually sum over many final states, in which case the interference terms between the direct and exchange amplitudes should average to zero. Thus we have used the averaged, symmetrized expression

$$\langle\sigma_{sym}(\theta)\rangle=\sigma_{fi}(\theta)+\sigma_{fi}(\pi-\theta) \tag{11}$$

in order to compare to the data of ref. [1].

The slope parameter a_f of the transfer coupling for a given transition can be accurately obtained from the neutron binding energy. The value of a_f= 1.942 fm corresponds to the ground state $^{238}U(^{238}U,\,^{239}U)^{237}U$ reaction. We have used a_f= 1.825 fm in fitting the data of ref. [1], where many states are summed together. Furthermore, because of the many final states, we have used the optimum Q-value for single neutron transfer, which is zero. Since the number of states populated by the reaction also depends on the bombarding energy, we have adjusted the coupling strength parameter F_0 for each case. The radius parameter R_f is arbitrary. We have let $R_f=1.2(A_1^{1/3}+A_2^{1/3})$ fm in order to have a convenient scale for F_0. The values are F_0= 1.65, 1.65, 1.85, 2.0 and 2.0 MeV for the five energies E_{lab}=5.05, 5.36, 5.65, 5.85 and 6.07 MeV/nucleon, respectively. The diffusivity of the absorptive potential was fixed at a_w=0.6 fm, which is typical for heavy-ion collisions, and we let $R_w=R_f$. The value $W_0=-45$ MeV was determined by fitting the backward angle data for E_{lab}=5.85 MeV/n. The results of the calculations are shown by the solid curves in figs. 1a–1e. The dashed curves correspond to $W_0=0$.

We note that the analysis in ref. [1] made comparisons to unsymmetrized calculations. To allow for the symmetry, the four data points closest to $\theta=90°$ were reduced by approximately 50%, 25%, 9% and 3%, respectively [1]. Since here we are comparing to sym-

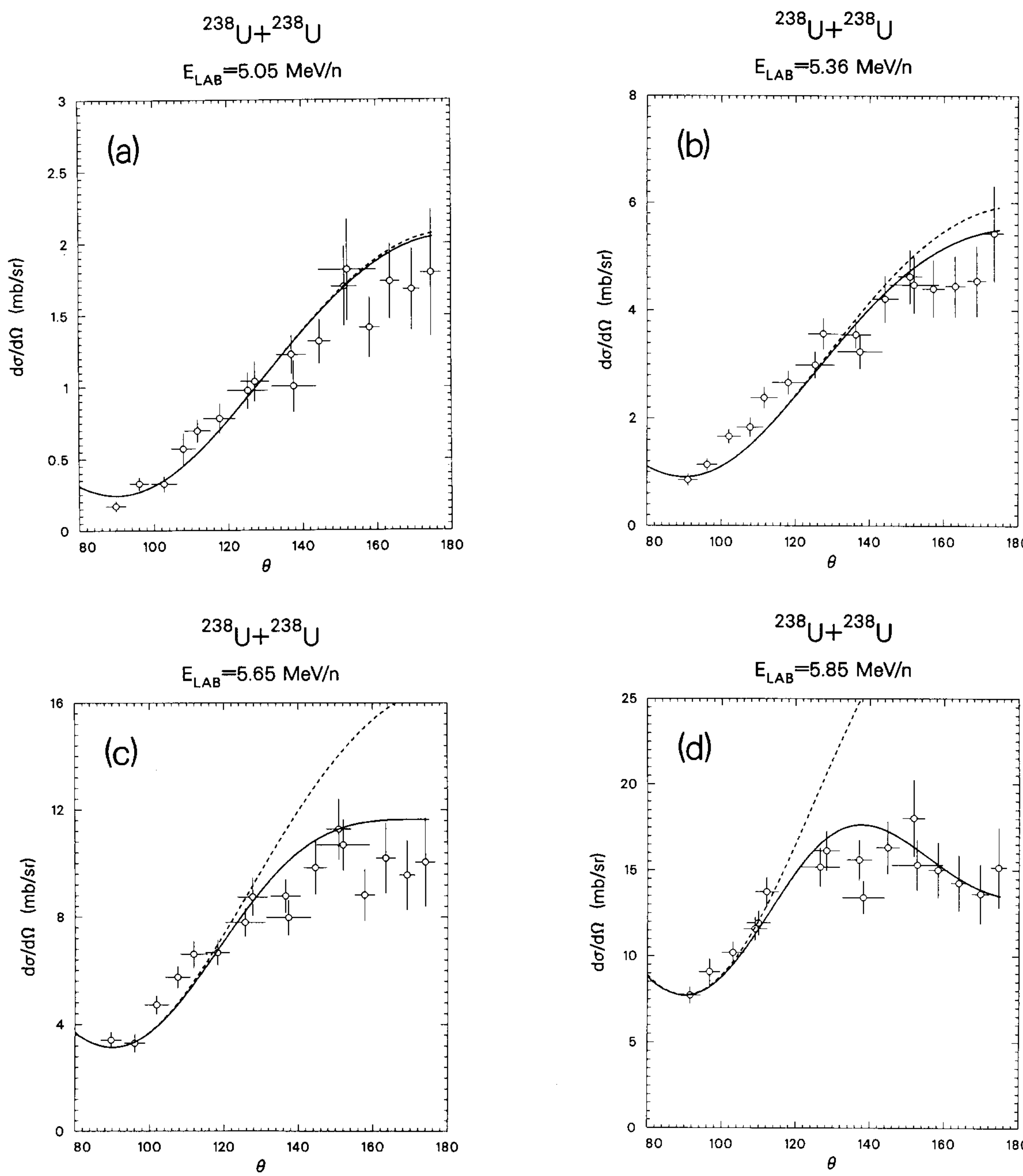

Fig. 1. Angular distributions for single neutron transfer reactions in $^{238}U+^{238}U$ collisions at the five energies indicated in parts (a)–(e). The curves are calculated with the analytic formula and parameters given in the text. The dashed curves correspond to setting the absorptive potential equal to zero. The data points correspond to those given in ref. [1] (see text).

metrized calculations, we divided the first four forward angle data points shown in ref. [1] at each energy by 0.5, 0.75, 0.91 and 0.97, respectively, in order to construct fig. 1.

It is apparent in fig. 1 that a good overall agreement with the data is obtained. It may be noted that the effect of the absorption is negligible at the lowest two energies. At the highest two energies where the

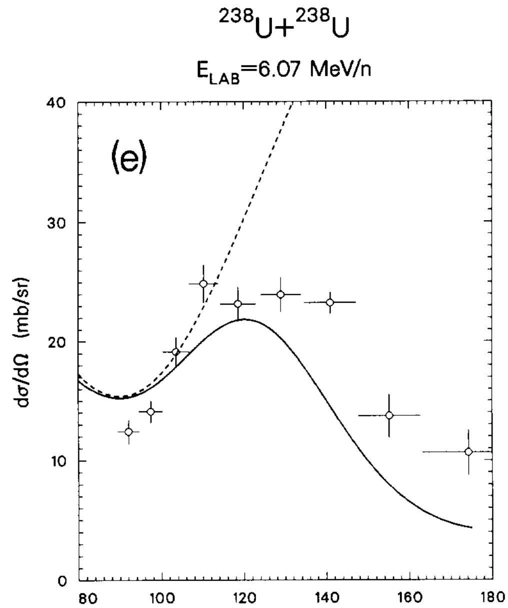

Fig. 1 (continued).

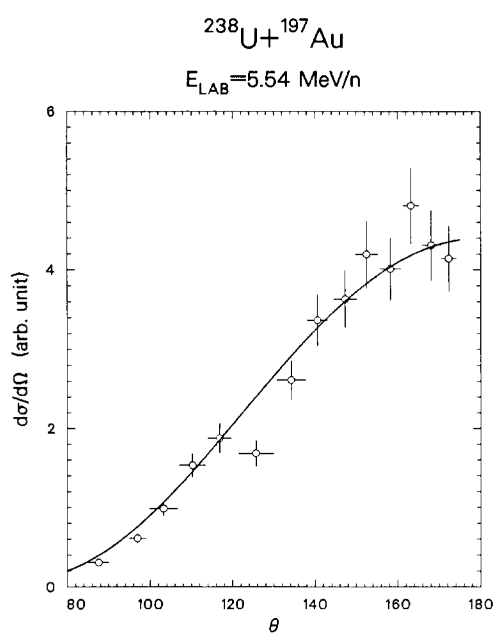

Fig. 2. Angular distribution for single neutron transfer reaction in $^{238}U+^{197}Au$ collision at the indicated energy. The data points are from ref. [5].

absorption is quite pronounced, one should consider the agreement as being qualitative since here the effect of the nuclear attraction should also be taken into account.

In fig. 2 we show the calculated angular distribution for $^{238}U+^{197}Au$ at $E_{lab}=5.54$ MeV/n using directly eq. (10). The parameters used to determine this fit are generally consistent with the ones above, but their detailed significance cannot be ascertained since the cross sections from ref. [5] are quoted in arbitrary units.

We conclude that the semi-classical formalism gives a good description of the low-energy single-neutron transfer reactions for $^{238}U+^{238}U$ collisions measured in ref. [1]. The simple analytic formula which we have used is quite helpful in getting an overall view of such reactions.

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