ANALYSIS OF ELASTIC SCATTERING OF VERY HEAVY IONS WITH POOR ENERGY AND MASS RESOLUTION

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Recent data on the elastic scattering of ^{86}Kr on ^{144}Sm with poor resolution is analysed in terms of the coherent surface excitation model with the ion–ion potential of Christensen and Winther.

The usual way of extracting reaction cross sections for heavy-ion collisions is through analysis of the elastic scattering angular distributions by means of the optical model. For very heavy systems, limitations in energy and mass resolutions may lead to situations in which the recorded data include sizable contributions from inelastic and transfer channels. An optical model fit to such data could still be used to estimate the reaction cross section to channels not included in the "elastic" scattering, but the interpretation of the real part of the optical potential as the interaction potential between the two colliding ions is hardly warranted.

We shall address this question by calculating the reaction cross sections using the ion–ion potential of ref. [1] in a scheme of coupled semi-classical equations of motion where the channels that couple to the elastic channel are explicitly taken into account. Thus, we can calculate reaction cross sections without resorting to the introduction of an imaginary potential. Furthermore, since we can calculate the cross section as a function of the Q-value, we may incorporate the energy resolution limitations of the experiment into the analysis thus allowing for a more detailed comparison with the data.

To illustrate these points we consider the reaction ^{86}Kr + ^{144}Sm at laboratory energies of 493 and 614 MeV [2]. The calculations are carried out within the framework of the coherent surface excitation model of ref. [3]. The spectrum of low-lying surface modes and damped giant resonances used in the present calculation is shown in table 1. The mass transfer degrees of freedom are taken into account in the one-body dissipation approximation [4] as explained in ref. [5].

We assume that for the reactions in question the wavelength of relative motion is small enough so that leading quantal effects in the relative motion are due to the quantal nature of the inelastic excitation of collective surface modes [‡1]. To take these effects into account we have performed for each impact parameter, ρ, ensemble calculations with initial conditions for the coordinates and momenta of the low-lying surface modes which are compatible with the ground-state uncertainties as described in ref. [3]. Fluctuations in the energy loss due to mass transfer resulting from different shapes of the two ions as they come in contact are included in the calculation, while the fluctuations in the transfer itself are not.

The ion–ion potential V_{dA} used in this calculation should be constructed such that when averaged over the zero point fluctuations of the surface it agrees with the ion–ion potential U_{aA} of ref. [1]. In the exponential tail where $U_{aA} \sim \exp[-(r-R)/a]$ this means that we should use

[‡1] This is not necessarily the case for lighter ions, cf. for example ref. [6].

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$$V_{aA} = \exp(-\sigma^2/2a^2)\, U_{aA}, \tag{1}$$

where $a = 0.63$ fm is the diffuseness of the potential. The total zero point fluctuation σ in the surface–surface distance is defined by

$$\sigma^2 = \sum_{n\lambda i} \frac{2\lambda+1}{4\pi} \frac{\hbar\omega_\lambda^{(i)}(n)}{2C_\lambda^{(i)}(n)} (R_0^{(i)})^2, \tag{2}$$

where $R_0^{(i)}$ is the radius parameter of nucleus i. Using the values from table 1, one finds $\sigma^2 = 0.4\ \mathrm{fm}^2$.

Table 1
Spectra of surface modes used in the calculation to represent the excitation of nuclei close to ^{86}Kr and ^{144}Sm. They have been constructed utilizing the distributions of isoscalar strength resulting from RPA calculations with separable multipole–multipole residual interactions. The coupling strengths were determined adjusting the energy of the lowest states to coincide with the levels of a nucleus in the vicinity of the projectile and target. In particular, the table for ^{86}Kr results from energy levels of ^{88}Sr. This choice is not expected to affect the results and is, in any case, consistent with the assumed poor mass resolution. The multipolarity λ and the excitation energy $\hbar\omega_\lambda(n)$ in MeV are given together with the width $\Gamma_\lambda(n)$ in MeV and the isoscalar oscillator strength $f_n(\lambda)$. The latter represents the fraction of the isoscalar energy weighted sum rule ascribed to the mode (cf. ref. [3], eq. (II. 16)). Random initial conditions in coordinate and momenta were given to the modes indicated with an asterisk.

	λ	n	$\hbar\omega_\lambda(n)$	$f_n(\lambda)$	$\Gamma_\lambda(n)$
^{86}Kr	2	1	1.8	3	0*
	2	2	5.0	6	0*
	2	3	13.0	74	4
	3	1	2.7	3	0*
	3	2	4.0	14	0*
	3	3	21.5	83	4
	4	1	9.0	27	4
	4	2	16.0	25	4
	5	1	7.0	13	0*
	5	2	20.0	69	4
^{144}Sm	2	1	4.0	12	0*
	2	2	10.7	59	4
	3	1	1.8	4	0*
	3	2	5.0	7	0*
	3	3	19.0	57	4
	4	1	10.0	37	0*
	4	2	23.0	46	4
	5	1	6.0	13	0*
	5	2	16.0	26	4
	5	3	28.0	45	4

A distribution of events as a function of energy loss in the relative motion is constructed for each value of ρ. A quantal energy distribution on the surface modes can be obtained by a projection on the intrinsic quantal states of the reacting nuclei. Illustrations of this procedure have been given in refs. [7,8].

Below we study the dependence of the reaction cross section on the Q-value in energy bins of about 10 MeV. We work directly with the unprojected energy distributions. As a consequence, a small fraction of events where the final energy of the relative motion exceeds the bombarding center-of-mass energy are included in the analysis. These events are necessary to obtain the quantal result after projection. They extend, in the present case, over an energy range of the order of a couple of MeV. This value gives a measure of the expected redistribution of probability due to projection. It is not expected to affect a histogram in which events are accumulated in energy bins of ~ 10 MeV.

In fig. 1 we have plotted, for the two bombarding

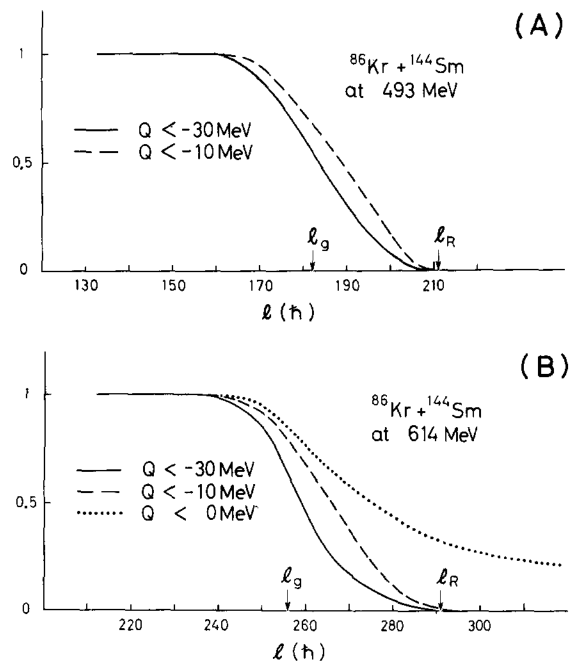

Fig. 1. Generalized transmission coefficients for the reaction ^{86}Kr + ^{144}Sm at bombarding energies (A) 493 and (B) 614 MeV. The arrows labelled by l_g and l_R indicate the orbiting and the rainbow angular momenta, respectively, associated with potential scattering.

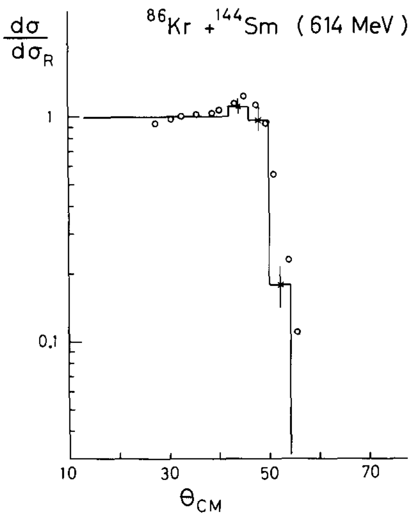

Fig. 2. Ratio of "elastic" to Rutherford cross section for the reaction $^{86}Kr + {}^{144}Sm$ at 614 MeV. The experimental data of ref. [2] are shown by open circles while the model calculation associated with a Q-value resolution of 30 MeV is shown as a histogram with indication of the statistical uncertainty.

energies, the probability that a collision with given incoming angular momentum l leads to reaction channels with energy loss larger than 30 and 10 MeV by full-drawn and dashed lines, respectively. For illustrational purposes we have also included by a dotted curve the result for $Q = 0$. This curve was constructed from the ground-state probabilities obtained by the projection technique. The long tail is due to Coulomb excitations.

In the figure we have also indicated the orbiting angular momentum l_g and the rainbow angular momentum l_R associated with simple potential scattering in the field $Z_a Z_A e^2/r + U_{aA}(r)$. It is interesting to observe that while for light ions l_g indicates the point where the $Q = 0$ transmission function reaches the value 1/2 it indicates for these very heavy ions an l-value where more than 50% of the collision have a large energy loss ($>$ 30 MeV).

In fig. 2 we show the elastic angular distribution for the bombarding energy of 614 MeV. This has been constructed by adding incoherently the contribution of all reaction channels with energy loss less than 30 MeV. Also shown in the figure are the experimental points from ref. [2].

The slight theoretical underestimate of the cross section may arise from a small overestimate of the effective experimental resolution. It could also indicate that the surface–surface interaction should be reduced by about 10%.

The conclusion is that one may use the standard ion–ion potential, which was determined empirically from rather light ion scattering, also for very heavy ions. This conclusion is supported by folding calculations (cf. ref. [9]). It is an interesting observation that the potential of ref. [10] agrees rather well with the potential V_{aA} (cf. eq. (1)) describing the surface–surface interaction between the ions without zero point fluctuations. Thus, the tail of the former may have to be enhanced by a factor of $\sim \exp(\sigma^2/2a^2)$ in the analysis of very heavy ion elastic scattering data.

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