NUCLEAR EXCITATION EFFECTS ON HEAVY-ION SCATTERING

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The detailed coupled-channel analysis, including a ground state rotational coupling up to the 4^+ state, for ^{16}O scattering from ^{152}Sm at the incident-ion energy of 72 MeV is performed. It is found that nuclear excitation plays an important role in the reproduction of details of the observed experimental data, and that the extracted nuclear deformation lengths from this analysis agree with those from light-ion experiments.

Very recently a considerable interest [1–8] for heavy-ion scattering has been focused on the coupled-channel (CC) effects on inelastic as well as elastic scattering. It has been accelerated with the help of very accurate measurements [1–4], with a high energy resolution, of scattering of carbon, oxygen and neon from various deformed nuclei. The experiments have shown that (1) in the elastic cross sections there is a remarkable deviation from Rutherford scattering starting from an angle far forward of the grazing angle, and (2) the inelastic cross sections at forward angles are very large compared with those in the usual heavy-ion scattering from lighter targets, and at the most backward angles, the inelastic yield is greater than the elastic yield. It is well understood [5–8] that these phenomena are mostly due to the effects of multi-step processes via the Coulomb interaction. However the effects from nuclear excitation should not be overlooked for details of the experimental angular distribution, and the CC calculations including both nuclear and Coulomb excitation are inevitable.

In order to study the influence of nuclear excitation on heavy ion scattering from deformed nuclei we choose ^{16}O scattering from ^{152}Sm at incident ion energy of $E_{\mathrm{lab}} = 72$ MeV [2]. Since the beam energy is very close to the top of the Coulomb barrier, one could expect that nuclear excitation and, of course, Coulomb excitation play an important role in the scattering processes and so CC analysis allows us to describe the nuclear matter as well as charge deformation. The projectile ^{16}O nucleus is a well-known doubly closed shell nucleus and thus the CC effects could be originated only from the nuclear property of the target ^{152}Sm. Furthermore ^{152}Sm, a highly deformed nucleus, has already been investigated extensively through experiments with various different techniques; light-ion scattering [9,10], electron scattering [11,12], Coulomb excitation [13,14], and muonic X-ray experiments [15]. Therefore we could compare our results with those obtained from other experiments. In this letter we present a very detailed CC analysis, including a coupling among the 0^+ ground (0^+), 2^+ first excited (2^+) and 4^+ second excited (4^+) states, for ^{16}O scattering from ^{152}Sm, and discuss the importance of the nuclear excitation effects. It turns out that the CC analysis for heavy-ion scattering may give a reasonable description of nuclear and charge deformations.

The data were taken recently by the Minnesota group [2]. The experimental data, which are displayed in fig. 1, obviously revealed the same characteristics as mentioned earlier. The dramatic deviation from Rutherford scattering at forward angles in the elastic cross sections and the strong population of the inelastic yield suggest that the coupling is very strong, and thus that a simple optical model and DWBA are not able to reproduce the observed trend of the cross sections.

We carry out CC calculations, using a computer program JPWKB [16], which takes into account the Coulomb excitation effects without too much time consuming in the CC calculations, following the WKB

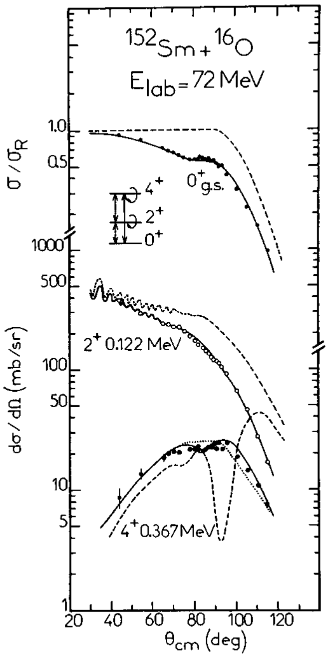

Fig. 1. Angular distributions of $^{16}O + {}^{152}Sm$ scattering. The solid curves are CC fits and the dashed curves are optical model and DWBA fit for elastic and inelastic scattering respectively. The dotted curve for the 4^+ state represents the CC results with $\beta_4^N = 0$. The coupling scheme is inset.

approximation of Alder and Pauli [17] and the Padé approximation. The results are drawn in fig. 1. It is found that the CC calculation reproduces the experimental data very well. In doing this calculation, a deformed Woods–Saxon potential [18] is used and the optical model parameters are $V = 13.0$ MeV, $r_0 = 1.37$ fm, $a_0 = 0.50$ fm, $W = 2.8$ MeV, $r_I = 1.40$ fm, $a_I = 0.55$ fm and $r_C = 1.25$ fm. The rotational coupling $0^+–2^+–4^+$ in ^{152}Sm is considered. The calculation includes 200 partial waves and integrations are carried out up to 300 fm.

In this analysis we choose $B(E2; \uparrow) = 3.45\ e^2b^2$ and $B(E4; \uparrow) = 0.21\ e^2b^4$ from the most recently reported electron scattering experiment [11]. These values agreed very well with the recent Coulomb excitation experiment [13]. The Coulomb form factors in our CC calculations were calculated assuming a deformed uniform spherical charge distribution. The λ-pole excitation probability $B(E\lambda; \uparrow)$ is then related to charge deformation by

$$[B(E\lambda; \uparrow)]^{1/2} = \frac{3Ze}{4\pi} \beta_\lambda^C R_C^\lambda ,$$

where R_C is the radius of the charge distribution and Z the charge of the target. The CC analysis does not provide β_λ^C but $\beta_\lambda^C R_C^\lambda$. It is worth noting that the $B(E\lambda; \uparrow)$ values chosen here account extremely well for the experimental cross sections of the 0^+, 2^+ and 4^+ levels, particularly at forward angles smaller than the grazing angle where the Coulomb interaction is dominating, as can be seen in fig. 1.

The nuclear form factors were constructed by deforming a Woods–Saxon potential [18] with

$$R = R_N \left(1 + \sum_\lambda \beta_\lambda^N Y_{\lambda 0}(\theta')\right),$$

where θ' refers to the body-fixed system. This means that the deformation length, $\beta_\lambda^N R_N$, rather than the deformation parameter β_λ^N itself, has to be determined. In the analysis the λ-pole nuclear matter deformation lengths $\beta_\lambda^N R_N$ were adjusted to obtain the best fit to both the elastic and inelastic scattering data. The values obtained are listed in table 1. We discuss comparisons with other experiments in detail later.

Let us first discuss the CC effects on the elastic scattering for this system. For this purpose we also perform an optical model calculation for the elastic scattering data, and the dashed curve in fig. 1 is the result of such a calculation. It obviously fails to reproduce the data. We have also tried to vary the optical model parameters in order to obtain a better fit, but such an effort was not successful. In the CC calculation, however, use of optical model parameters which provides the fit of the data of neighbouring spherical nuclei [1]

Table 1
nuclear matter deformations in ^{152}Sm

Methods	$\beta_2^N R_N$ (fm)	$\beta_4^N R_N$ (fm)	Refs.	Remarks
Heavy-ion scattering	1.65	0.29	present	72 MeV ^{16}O
Light-ion scattering	1.58	0.31	9	50 MeV α
	1.63	0.30	10	12 MeV d
Electron scattering	1.65 [a)]	0.53 [a)]	11	250 MeV e
Coulomb excitation	1.62 [b)]	0.52 [b)]	13	12 MeV α

a) $\beta_\lambda^C R_C$ deduced from $B(E\lambda; \uparrow)$ assuming a deformed Fermi charge distribution, with $R = 1.08\, A^{1/3}$ fm and $a_0 = 0.545$ fm.
b) Same as a) but with $R = 1.10\, A^{1/3}$ fm and $a_0 = 0.600$ fm.

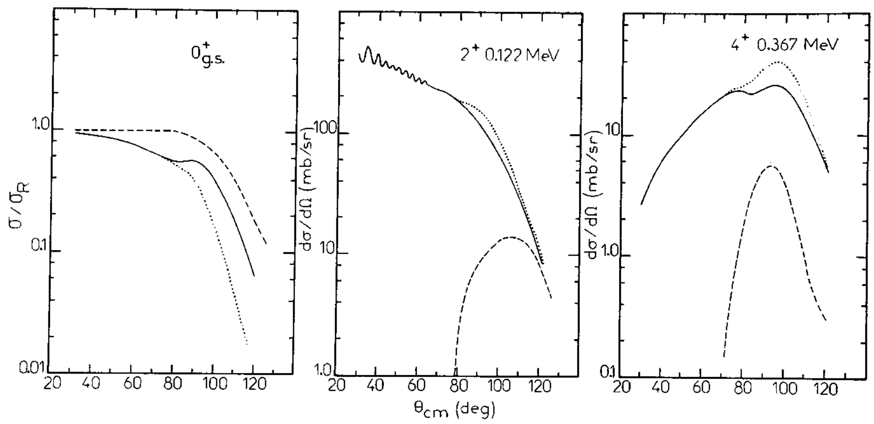

Fig. 2. Individual contributions from Coulomb and nuclear excitation. The dotted and dashed curves represent the contribution respectively from the Coulomb ($\beta_\lambda^N = 0$) and nuclear excitation ($\beta_\lambda^C = 0$). The solid curves are the resultant cross sections including both excitation effects.

can reproduce this experiment. The CC calculation is thus essential to describe the present experimental situation.

The significance of the nuclear excitation effects can be seen from fig. 2 in which we plot individual contributions from Coulomb and nuclear excitation to the elastic cross sections. The deviation at forward angles dominantly comes from the effects of Coulomb excitation. At backward angles the Coulomb excitation effects become relatively small and start to interfere destructively with the nuclear excitation effects. It is very clear that the data can not be reproduced without considering nuclear excitation. The resultant cross sections including both effects fit the elastic scattering data.

Our CC calculations for inelastic scattering leading to the 2^+ and 4^+ states also explain the experimental data well, while DWBA obviously fails to reproduce the data as is seen in fig. 1. This again indicates the importance of carrying out the CC calculations. Fig. 2 also shows that the Coulomb excitation processes are dominating in these inelastic scatterings, but the destructive interference phenomena between nuclear and Coulomb excitations are distinct at backward angles. Neither the cross section including only the nuclear nor that including the Coulomb interaction fits the experiment.

In order to study the effects of inclusion of coupling to the 4^+ state, we also performed CC calculations considering only a rotational coupling between the 0^+ and 2^+ states. We could obtain the same quality fits to the elastic and 2^+ inelastic scattering cross sections if we slightly adjust imaginary potential parameters ($W = 4.5$ MeV and $a_I = 0.58$ fm) so that the incoming flux is more absorbed, and choose deformation lengths smaller by about 3%. This effect on the 0^+ and 2^+ states thus seems weak. However the CC calculation including a $0^+–2^+–4^+$ coupling is necessary to reproduce the data of the 4^+ state. For example the CC calculation only with the $0^+–4^+$ coupling gives almost the same angular distribution for the 4^+ state as obtained from DWBA in fig. 1. In other words, two-step contributions via the 2^+ state are very important.

Now we turn to discuss about the nuclear matter deformation of the target nucleus ^{152}Sm obtained from our analysis. In the situation of the present scattering, the nuclear matter deformations are extracted mostly by fitting the experimental data at backward angles, where nuclear and Coulomb interference occurs strongly, the imaginary potential plays an important role in the cross sections, and the CC effects from the higher excited states could compete. By performing the CC calculations with the known $B(E\lambda;\uparrow)$ values [11], the optical model parameters and nuclear deformation parameters are adjusted to obtain the best fit to data. The extracted nuclear deformation lengths are summarized in table 1. The agreement with those obtained from light-ion scattering experiments [9,10] is seen to be very good.

The sensitivity of β_4^N to the 4^+ state is drawn in fig. 1. One might say that the 4^+ state is mostly populated in a double excitation process. As can be seen in fig. 1, however, the inclusion of β_4^N is significant to fit the details of the 4^+ angular distribution, especially at the nuclear and Coulomb interference region.

The $\beta_\lambda^N R_N$ extracted are also compared with the charge deformation lengths $\beta_\lambda^N R_C$ deduced from electron scattering [11] and Coulomb excitation experiments [13], in table 1. The $\beta_\lambda^C R_C$ were calculated from $B(E\lambda\,;\uparrow)$ values assuming a deformed fermi charge distribution. The quadrupole deformations are similar to each other, but the nuclear hexadecapole deformation length is quite smaller than the Coulomb one by about 40%. One might speculate that the difference between the nuclear and Coulomb hexadecapole deformation is due to neglect of the scaling factor, which is needed in the comparison of deformations determined by the nuclear potential with those of charge distributions. We have scaled $\beta_\lambda^N R_N$ to a charge radius of $R_C = 1.1\,A^{1/3}$ by using the Hendrie's formula [19]. We obtain $\beta_2^C R_C = 1.54$ fm and $\beta_4^C R_C = 0.34$ fm in good agreement with those from the inelastic α scattering [19]. The quadrupole deformation scaled agrees reasonably well with the Coulomb one. However we can still find the apparent discrepancy between those two hexadecapole deformations. We do not have a definite explanation for this difference, but it was suggested [11] that this may be partly due to neglect of the dispersion effects in exciting the 4^+ state.

We conclude by emphasizing the CC method including both nuclear and Coulomb excitation, as opposed to the optical model and DWBA, must be used in order to describe a reasonable heavy-ion scattering process and to extract the deformation property of the colliding nuclei. In the present case of highly deformed rotational nucleus, nuclear excitation plays a significant role to account not only for the inelastic scattering, but also for the elastic scattering. Furthermore it is possible that the CC method gives another method of determining both nuclear matter and Coulomb deformations of the nucleus.

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