COULOMB EXCITATION NEAR THE COULOMB BARRIER

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The interference between Coulomb and nuclear excitation processes is discussed in the framework of the DWBA formalism. The conditions at which the nuclear effects start to manifest themselves are investigated and it is shown that the usually accepted estimation of the Coulomb barrier energy gives a rather too high result. It is also shown that the interference between the two processes might serve as a tool to measure the nuclear surface parameters.

The Coulomb excitation process is one of the most important means to investigate the properties of excited nuclear states. The strong dependence of the excitation probability on the energy of the bombarding particle renders it advantageous to perform experiments using the highest possible bombarding energies. However, the energy range is limited by the Coulomb barrier energy, above which nuclear effects start to interfere with the pure electrostatic process. The commonly used estimate of the Coulomb barrier energy is taken from the classical picture of two colliding charged spheres. No penetration will occur as long as the energy in the center-of-mass system is kept below:

$$E_{\mathrm{C.B.}}(\theta) = \frac{z_1 z_2 e^2}{r_0(A_1^{1/3} + A_2^{1/3})}\, \tfrac{1}{2}(1 + \operatorname{cosec} \tfrac{1}{2}\theta) \quad (1)$$

where r_0 is the nuclear radius parameter, and θ is the scattering angle.

In several Coulomb excitation experiments [1] carried out in the past, the bombarding energies were chosen so that they would not exceed (1). In some other reports [2], it was argued that the actual barrier energy is the energy at which the *elastic* cross-section starts to deviate from the Rutherford expression, and, as long as no such deviation occurs, the *inelastic* cross-section is also of pure Coulomb type.

It is the purpose of the work reported here to check the range of applicability of the argument mentioned above, in a more quantitative way. This was done by calculating the elastic and inelastic scattering cross-sections under the following conditions: The target was assumed to be an even-even spherical nucleus with a 0^+ ground state, and a 2^+ excited state corresponding to the excitation of one surface phonon of multipolarity $\lambda = 2$. The projectile was taken to be a spinless particle, and it was further assumed that it cannot be excited.

The elastic scattering wave functions were calculated for an optical potential of the form:

$$V_{\mathrm{opt}}(r) = -(V + \mathrm{i}W)\{1 + \exp[(r-R)/a]\}^{-1} \quad (2)$$

and a Coulomb potential induced by a homogeneous charged sphere of radius R.

The excitation cross-section was calculated using the DWBA, with the interaction:

$$V_{\mathrm{int}} = \{-(V+\mathrm{i}W)\frac{R_0}{a} \times \exp[(r-R_0)/a]\,[1+\exp[(r-R_0)/a]]^{-2} + \tfrac{3}{5} z_1 z_2 e^2 r_<^2\, r_<^{-3}\} \sum_\mu \alpha_\mu^{(2)} Y_{2\mu}(\theta, \phi) \quad (3)$$

where $R_0 = r_0(A_1^{1/3} + A_2^{1/3})$, $r_<$ and $r_>$ are the greater and smaller of r and R_0 respectively. This form of V_{int} follows from eq. (2) by assuming the nuclear radius to be

$$R = R_0[1 + \sum_\mu \alpha_\mu^{(2)} Y_{2\mu}(\theta, \phi)]\,. \quad (4)$$

With potentials of the forms (2) and (3), only the lowest partial waves are affected by the nuclear interaction. Therefore, the DWBA procedure was carried out explicitly only for the lowest l values. Because of the long range of the Coulomb part in eq. (3) it was necessary to include the contribution of higher l values. This was done by assuming that for these partial waves the nuclear interaction can be neglected, and only

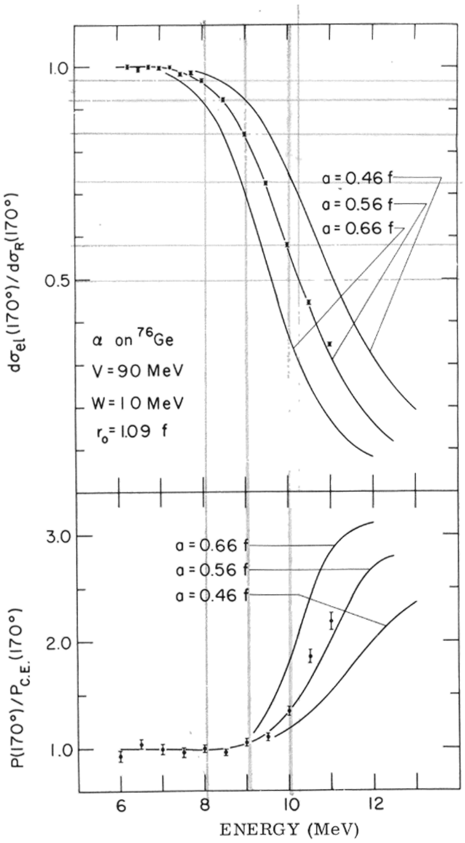

Fig. 1. The experimental results for scattering of α-particles on ^{76}Ge and the theoretical fit which was obtained with the optical parameters indicated in the figures. The ratio $P(170^{o})/p_{c.e.}(170^{o})$ is the ratio of the excitation probabilities $d\sigma_{inel}/d\sigma_{el}$.

the Coulomb interaction gives rise to the excitation. Thus, the methods of ref. 3 could be applied, and 300 partial waves were taken into account. This number of partial waves was found to give the correct behaviour of the Coulomb excitation contribution to the cross-section. The reduced matrix element of the operator $\alpha_{\mu}^{(2)}$ was calculated from the B(E2) value using the simple theory of vibrational nuclei.

The calculations were carried out for two examples, i.e. scattering of α-particles on ^{70}Ge and ^{76}Ge, at the energy range of 6-13 MeV, using experimental B(E2) values. These cases were also investigated experimentally [2], and thus the predictions of the calculations could be compared to the experimental results.

The results are presented in a convenient way by the ratio $d\sigma_{el}(\theta)/d\sigma_R(\theta)$, and the double ratio $(d\sigma_{inel}(\theta)/d\sigma_{el}(\theta))/(d\sigma_{inel}(\theta)/d\sigma_{el}(\theta))_{C.E.}$, where $d\sigma_R$ is the Rutherford scattering cross-section, and the subscript C.E. means pure Coulomb excitation. The dependence upon energy of these ratios is shown in fig. 1 for one scattering angle of α-particles on ^{76}Ge. The optical parameters which were used in the calculations are indicated there. It is worthwhile to mention that the results are almost insensitive to the depths of the real and imaginary wells, but quite sensitive to the radius R_0 and the diffuseness a.

By looking at the elastic and inelastic ratios, for backward angles as functions of energy, one can perceive two important features: (a) The nuclear effects start to manifest themselves at quite low energies (in the case of ^{76}Ge, already at the energy of 8.2 MeV, the elastic ratio deviates by 5% from unity, whereas formula (1) would give 8.8 MeV as the barrier energy for r_0 as large as 1.8 fm. (b) The nuclear effects in the inelastic ratio start to appear at higher energies than in the elastic ratio, for backward angles (greater than 100^{o}). This behaviour is a result of the special representation which we chose, in which the nuclear contributions cancel out, as long as they are small.

An attempt to check the validity of expression (1) was also made. The energies, at which the elastic and inelastic ratios deviate from unity by more than one and five percents respectively, were defined as the barrier energies for the scattering angle under consideration. Formula (1) was derived from the assumption of a nuclear square well. Repeating the calculations with the potential (2) will lead to another formula, which differs from eq. (1) by the first factor. The barrier energy calculated with this formula for backward angles ($120^{o}<\theta<180^{o}$), is higher than both elastic and inelastic barriers by a constant value, independent of the scattering angle (about 2.5 MeV and 1 MeV respectively). This can be explained by the tunnel effect. For more forward scattering angles, the definition of the barrier energy looses its meaning, because of the oscillating dependence of the cross-sections upon the projectile energy.

The total excitation cross-section starts to deviate from the pure Coulomb excitation value at about the same energy at which the backward elastic scattering starts to deviate from the Rutherford expression.

Three main conclusions might be drawn from the results obtained above: (a) The nuclear effects start to appear at energies which are lower than the usually accepted Coulomb barrier energies. (b) The dependence of the energy, at which nuclear effects start to appear, upon the scattering angle behaves according to the classical picture only at a limited range of backward angles. (c) Elastic and inelastic scattering of α-particles in the vicinity of the Coulomb barrier are very sensitive to the nuclear surface parameters.

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