# THE ROLE OF COULOMB POTENTIAL IN ELECTROMAGNETIC TRANSITIONS

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Studies conducted on a range of rare-earth nuclei indicate that the Coulomb potential plays a significant role in electromagnetic transitions, particularly at low energies. In this regime, it acts to inhibit the interaction between the proton and the nucleus. The inclusion of the long-range Coulomb interaction alongside the short-range nuclear potential leads to substantial modifications in the asymptotic behavior of the wave functions, which in turn affects the matrix elements of the electromagnetic operators. Even a slight increase in the spatial extent of the wave functions results in an enhancement of the electric quadrupole *E*2 matrix elements. Furthermore, the Coulomb repulsion between protons increases the difference in charge radii between the ground and excited states, thereby amplifying the matrix element of the monopole *E*0 operator.

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## 1. INTRODUCTION

Among the excited states of even-even deformed nuclei, a large number of $0^+$ states have been identified [1-5]. Studies of these states through two-nucleon transfer reactions, along with measured electromagnetic transition probabilities, indicate that these states possess a complex internal structure. Despite numerous theoretical investigations of $0^+$ states using both phenomenological and microscopic models, including those that consider the quark structure of nucleons [7], significant discrepancies remain between theoretical predictions and experimental observations."

The aim of this work is to clarify the influence of Coulomb forces on the properties of the lowest $0^+$ states. At low energies of incident charged particles, excitation of the target nucleus can occur primarily due to the Coulomb field. At higher energies, the excitation arises from both nuclear interactions and the Coulomb field. When the Coulomb interaction between the incoming particle and the nucleus is strong, corrections associated with Coulomb excitation of nearby levels become increasingly significant.

In this study, we calculate the energies and key characteristics of the $0^+$ states, including the probabilities of electric quadrupole *E*2and monopole *E*0 transitions, as well as the Rasmussen parameter-*X*.

## 2. EXPRESSION FOR THE TRANSITIONMATRIX

Let us consider a system of nucleons in an average deformed field, described by h the Hamiltonian

$$H = H_0 + H_C , \tag{1}$$

where $H_0$ is the mean field with Woods-Saxon potential

$$V_N = \frac{-V_0}{1+\exp\left(r-R_0\right)/\alpha} , \tag{2}$$

$H_C$ - Hamiltonian of Coulomb interaction with potential

$$V(r) = Z_A e^2 / r , \ r \geq R_0 \ . \tag{3}$$

We are interested in the excitation of $0^+$ states in reactions (p,t). The wave function of the initial state is given by:

$$\Psi_i = e^{ik_p r}\Psi_A\left(\xi_A\right), \tag{4}$$

where $e^{ik_p r}$ – wave function of proton .

The final state wave function has the following form

$$\Psi_f = e^{ik_t r_t}\Psi_B(\xi_B) , \tag{5}$$

there $e^{ik_t r_t}$ –is wave function of triton, $\Psi_B(\xi_B)$ - wave function of final nucleus *B*.

The Coulomb interaction of the proton with the nucleus leads to the excitation of nucleus *B*. At proton energies below the Coulomb barrier, the final nuclei are predominantly found in excited states. In this case, an additional term characterizing the excited states of nucleus *B* is introduced into (5):

$$\Psi_f = e^{ik_t r_t}(\Psi_B(\xi_B) + \sum_{\xi'_B} a_{\xi'_B}\Psi_B(\xi'_B)) . \tag{6}$$

Here, $\Psi_B(\xi'_B)$ -the wave functions of the excited states of nucleus *B* are orthogonal to the wave functions of its ground state.

Using the obtained wave functions for the ground and excited states, we derive expressions for the transition probabilities of electric quadrupole *E*2 and monopole *E*0 transitions, as well as for the



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dimensionless Rasmussen parameter. These quantities are fundamental in characterizing the structure of the excited states and the nature of the electromagnetic transitions:

$$B(E\lambda) = \sum < f\left|\int \rho r^{\lambda} Y_{\lambda\mu}(\theta,\varphi) \,|\, i >\right|^2 , \quad (7)$$

$$X = \frac{\rho^2(E0)e^2R_0^4}{B(E2)} . \quad (8)$$

Due to the cumbersome nature of these expressions, we do not provide expressions for these quantities here.

## 3. ANALYSIS OF RESULTS

Calculations were carried out for a number of isotopes Sm и Gd.

In work [6], the properties of $0^+$ excited states generated by pairing, quadrupole, and spin-orbit forces were studied. For comparison of the roles of residual and Coulomb forces, Table 1 presents calculation results that take into account residual pairing and quadrupole-quadrupole interactions (Theory 1) [6], as well as data obtained within the approach developed in the present work (Theory 2).

Table 1.

| | Nucleus | $Sm^{152}$ | | | $Sm^{154}$ | | | $Gd^{154}$ | | | $Gd^{156}$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Theory 1 | $\omega$ (MeV) | 0,68 | 2,30 | 2,44 | 1,10 | 2,10 | 2,25 | 0,68 | 1,94 | 2,14 | 1,05 | 1,80 | 1,98 |
| | $B(E2)_{s.p.u.}$ | 10,78 | 0,04 | 0,15 | 7,80 | 0,13 | 0,02 | 7,63 | 0,04 | 0,01 | 6,51 | 0,37 | 0,04 |
| | $\rho$ $(E0)$ | 0,47 | 0,05 | 0,09 | 0,41 | 0,06 | 0,04 | 0,39 | 0,03 | 0,01 | 0,37 | 0,09 | 0,03 |
| | $X$ | 0,14 | 0,49 | 0,41 | 0,15 | 0,21 | 0,60 | 0,14 | 0,17 | 0,69 | 0,15 | 0,24 | 0,19 |
| Threoy 2 | $\omega$ (MeV) | 0,68 | 2,55 | 3,12 | 1,10 | 2,45 | 2.89 | 0,68 | 2,15 | 2,34 | 1,05 | 2,15 | 2,30 |
| | $B(E2)_{s.p.u.}$ | 10,80 | 0,05 | 0,16 | 7,92 | 0,15 | 0,01 | 7,68 | 0,05 | 0,01 | 6,54 | 0,38 | 0,03 |
| | $\rho$ $(E0)$ | 0,58 | 0,19 | 0,31 | 0,61 | 0,19 | 0,05 | 0,65 | 0,17 | 0,08 | 0,67 | 0,12 | 0,07 |
| | $X$ | 0,17 | 0,64 | 0,76 | 0,22 | 0,42 | 0,79 | 0,25 | 0,23 | 0,77 | 0,21 | 0,14 | 0,25 |
| Experiment | $\omega$ (MeV) | 0,68 | 1,09 | 1,66 | 1,10 | 1,22 | - | 0,68 | 1,29 | | 1,05 | 1,17 | 1,71 |
| | $B(E2)_{s.p.u.}$ | 6,50 | - | - | 1,20 | <0,01 | - | 4,80 | - | | 4,00 | - | - |
| | $\rho$ $(E0)$ | 0,26 | - | - | - | - | - | 0,31 | - | | 0,41 | - | - |
| | $X$ | 0,07 | - | - | - | - | - | 0,11 | - | | 0,10 | 0,02 | - |

The Coulomb potential affects the energies of the excited $0^+$ states through changes in the proton density structure, configuration mixing, and the shape of the nucleus. As can be seen from theory 1, taking into account pair and quadrupole forces leads to overestimated values of the calculated quantities for the first excited state. Within the framework of this model, for the lowest $\beta$ - vibrational states, the probabilities of $E(2)$ transitions significantly exceed single-particle values. For these states, the parameter $X$ is less than unity. In addition, the second excited state appears at energies greater than the energy gap- $2\Delta$ . The values of $B$(E2) and $\rho(E0)$ for them are of the order of $10^{-1}$ – $10^{-2}$. Such values are characteristic of paired vibrations.

The Coulomb potential affects the probabilities of $E2$ transitions by changing the energy levels. A small increase in the spatial extent of the wave functions leads to a moderate increase in the matrix elements of the $E2$ transitions. This effect is small in magnitude, but shows a trend in all isotopes considered (theory 2).

The Coulomb potential, causing the proton density to be pushed outward, leads to a more extended distribution of proton density. The difference between the distributions of protons in the ground and excited $0^+$ states increases, which contributes to an increase in the probability of the $E0$ transition. In addition, the influence of the Coulomb field enhances the mixing between single-particle-single-hole (1p-1h) and collective configurations, and this leads to an increase in the $E0$ of the matrix elements. In some isotopes, such as $^{152}$Sm, $^{154}$Gd, etc., this leads to low-lying states with strong $E0$ transitions - signs of mixing of configurations enhanced by Coulomb interaction effects.

Due to the increase in the transition probability $E0$, a slight increase in the Rasmussen parameter $X$ is observed.

## 4. CONCLUSION

The Coulomb potential influences both the energy and the collectivity of excited $0^+$ states by altering the potential energy surface of the nucleus, leading to the stabilization of deformed configurations. Additionally, the Coulomb interaction modifies the energy spectrum of proton single-particle levels, which in turn affects the mixing of configurations—particularly the interplay between normal (non-collective) and collective states.

It should be noted, however, that significant challenges remain in accurately describing the properties of $0^+$ states. Addressing these discrepancies requires not only a refinement of the mean-field approximation but also the exploration of new mechanisms responsible for the generation of collective excitations in nuclei.

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