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ON THE COULOMB-EXCITATION ANALYSIS FOR MEDIUM AND HEAVY NUCLEI

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Abstract. The cross sections for nuclear reactions are generally consider to be well known in spite of many reactions for which the data are conflicting or incomplete to make the validation of different model calculations possible. The Coulomb-excitation process has been used for decades to obtain information related to the low-lying nuclear states. Besides the several hundreds of new observed states, the most important contribution of the Coulomb-excitation process has been the information obtained on electromagnetic transition rates between nuclear states. An analysis of the Coulomb-excitation cross sections for a series of medium and heavy nuclei is given in the present paper in order to eventually improve an alpha-particle optical potential.

Key words: Coulomb-excitation, nuclear reactions, cross-section.

1. INTRODUCTION

Coulomb excitation (CE) is the excitation of the target nucleus in the electromagnetic field of the projectile, or vice versa. In the past, this process has been extensively used to study the first excited 2^+ states of even-even nuclei. For pure CE, where the nuclei stay outside the range of the strong force, the excitation cross section can be expressed in terms of the same multipole matrix elements that characterize the γ decay of excited nuclear states. Therefore, a determination of the CE cross section leads directly to the determination of basic nuclear structure information.

The CE process, as outlined below, is well understood, and results are largely model independent. Keeping the bombarding energy below the Coulomb barrier ensures that no nuclear excitation can take place.

2. EXCITATION CROSS SECTION

As stated in the early years of CE experiments, a good approximation consist in assuming that the relative motion of the projectile follows a Rutherford trajectory, and the cross section for exciting a definite state $|f>$ from a state $|i>$ is given by [1, 2]:

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_f = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{Ruth} \cdot P_{i\to f}\,, \tag{1}$$

where $P_{i\to f}$ is the probability of excitation from the initial state $|i>$ to the final state $|f>$. If the interaction between projectile and target is weak, $P_{i\to f}$ is obtained in the perturbation theory as:

$$P_{i\to f} = \left|a_{i\to f}\right|^2, \tag{2}$$

with

$$a_{i\to f} = \frac{1}{i\hbar}\int_{-\infty}^{\infty} \mathrm{e}^{i\omega_{fi}t} \left\langle f\left|V\left(r(t)\right)\right|i\right\rangle\, \mathrm{d}t, \tag{3}$$

where $\omega_{fi}=(E_f-E_i)/\hbar$ and E_i and E_f being the energies of the initial and final states, respectively.

The amplitudes $a_{i\to f}$ can be further expressed as a product of two factors:

$$a_{i\to f} = i\sum_{\lambda} \chi_{i\to f}^{(\lambda)} f_{\lambda}(\xi), \tag{4}$$

where the excitation strength χ is a measure of the strength of the interaction and the function $f_\lambda(\zeta)$ measures the degree of adiabaticity of the process in terms of the adiabaticity parameter ζ. Details can be found in [2].

The excitation cross section can be obtained by integrating the excitation probability from a minimum impact parameter $b_{\min}$, to infinity. An approximate result is obtained by introducing the adiabatic cutoff and integrating the absolute square of the excitation strength from $b_{\min}$ to $b_{\max}$:

$$\sigma = 2\pi\int_{b_{\min}}^{\infty} P_{i\to f} b\mathrm{d}b = \int_{b_{\min}}^{b_{\max}} |\chi|^2\, b\mathrm{d}b\,. \tag{5}$$

This leads to an approximate expression for the excitation cross section of parity π and multipolarity λ:

$$\sigma_{\pi\lambda} \approx \left(\frac{Z_t e^2}{\hbar c}\right)\frac{B(\pi\lambda, 0\to\lambda)}{e^2}\pi b_{\min}^{2(1-\lambda)} \cdot \begin{cases} (\lambda-1)^{-1} & \text{for } \lambda\ge 2 \\ 2\ln\left(b_{\max}/b_{\min}\right) & \text{for } \lambda = 1, \end{cases} \tag{6}$$

where $b_{\max} >> b_{\min}$ was assumed.

In the above expression $B(\pi\lambda,0\to\lambda)$ is the reduced transition probability, defined as:

$$B(\pi\lambda, I_i \to I_f) = \sum_{\mu M_f}\left|\left\langle J_f M_f\left|\mathrm{M}(\pi\lambda\mu)\right|J_i M_i\right\rangle\right|^2 = \frac{1}{2J_i+1}\left|\left\langle J_f\left\|\mathrm{M}(\pi\lambda)\right\|J_i\right\rangle\right|^2 \tag{7}$$

where $\mathrm{M}(\pi\lambda\mu)$ stands for the multipole operator for electromagnetic transitions.

3. RESULTS AND DISCUSSIONS

CE cross section data for the alpha-induced reaction in the low energy region, below the Coulomb barrier, are scarce in the literature. Therefore comparisons with some previous results are difficult to obtain.

The CE calculations for this work were performed using the semiclassical coupled-channel CE least-squares search code GOSIA, which was developed at Rochester University by Czosnyka *et al.* [3–5], as a data analysis software package. GOSIA performs a least squares fit of calculated transition yields to the experimentally observed transition yields. In its original form, the code fits a number of calculated transition yields to a set of experimental yields, by adjusting the transition matrix elements.

3.1. α-INDUCED COULOMB-EXCITATION FOR NUCLEI WITH MASS A~100

In the work of Stelson and McGowan [6], beside the (α, n) and the total reaction cross-sections, the CE cross sections are also given for the first excited 2^+ state for alpha-induced reaction on several even-even nuclei, namely ^{92}Zr, ^{96,100}Mo and ^{106}Pd.

For the analysis performed for the nuclei given in Table 1, the CE was limited only to the excitation of the first 2^+ state, all of E2 character. Other transition multipolarities were not considered. Hence the matrix elements to be minimized by GOSIA are: $<0_1^+||E2||2_1^+>$. The internal conversion coefficients were taken from [7] and known spectroscopic information was input.

Table 1

Excitation energies of the first 2^+ states, reduced transition probabilities for the studied nuclei

Nucleus	$E(2_1^+)$ (keV)	B(E2) (e^2b^2)	Current evaluated B(E2) (e^2b^2)
^{92}Zr	934.51(4)	0.090(15)	0.080(6)
^{96}Mo	778.237(10)	0.310(47)	0.270(4)
^{100}Mo	535.561(22)	0.66(10)	0.513(9)
^{106}Pd	511.850(23)	0.59(9)	0.670(19)

Figure 1 shows the CE cross sections of the first 2^+ states obtained with the code GOSIA for the four studied nuclei using the reduced transition probabilities B(E2) values available at that time [8, 9] and the current ones [10] (third and respectively, forth column of Table 1). The calculations are given in comparison with the CE and the (α, n) cross sections from [6] and also with the total reaction cross section prediction of Igo [11]. Given are also the deformation parameters taken from [12].

As can be seen, good agreement between the GOSIA and the Stelson *et al.* [6], results was obtained for zirconium and molybdenum isotopes and a bit underestimation for the palladium isotope. From this comparison, as already proved, one can conclude that the CE cross sections vary much more slowly with the α-particle energy.

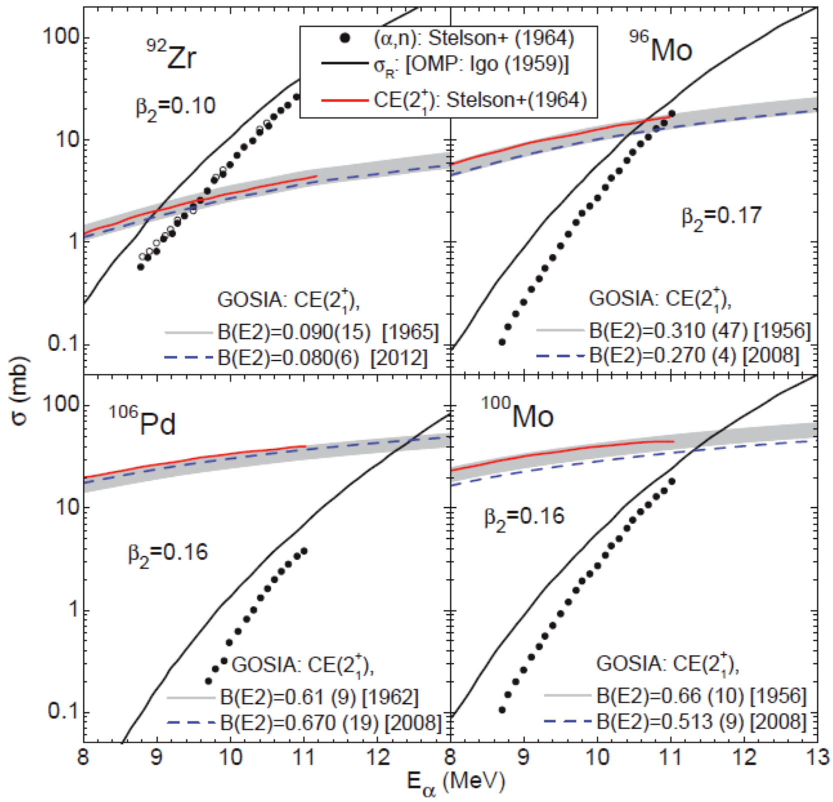

Fig. 1 – Comparison of former [6] (red curves) and present calculation (shaded regions) of CE cross section of the first 2^+ state for α-induced reaction on ^{92}Zr (upper left), ^{96}Mo (upper right), ^{106}Pd (bottom left) and ^{100}Mo (bottom right). Given are also the GOSIA results obtained using the up-to-date B(E2) values from [10] (dashed curves) and the (α, n) [6] and the total reaction cross section of [11].

As expected, the obtained CE cross sections at lower α-particle energies are several orders of magnitude larger than the predicted reaction cross section. Opposite, at high energies the CE cross sections are quite small compared to the total reaction cross sections.

3.2. α-INDUCED COULOMB-EXCITATION FOR HEAVIER NUCLEI

On the basis of the good agreement obtained between the results shown above and the results reported in [6] further investigations were made for the calculation of the CE cross sections for several other α-induced reactions on even-even or odd nuclei (^{113}In, ^{127}I, ^{130,132}Ba, ^{141}Pr, ^{144}Sm, ^{165}Ho, ^{166}Er, ^{168}Yb and ^{169}Tm). Similar to the previous calculations, in the case of even-even nuclei only the first excited states were an E2 transition occurs were taken into consideration, while for the odd nuclei we considered the states with the highest excitation strength as was done in [13].

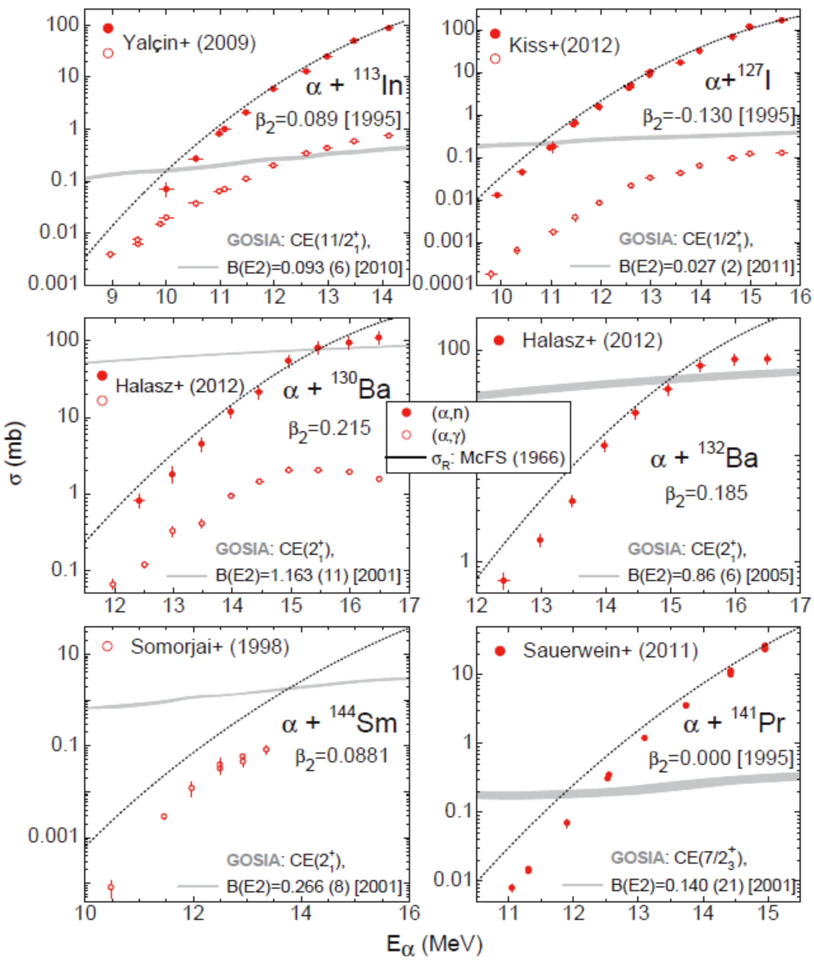

Fig. 2 – CE cross section in comparison with the statistical model calculations using the α-particle OMP of [16] for total reaction cross sections and also with the measured (α, n) or (α, γ) reaction cross sections (full and open symbols).

In Figs. 2 and 3 are given the present results of the CE cross sections obtained with the code GOSIA for α-induced reaction on the above mentioned nuclei. The deformation parameters shown in the figures are taken from [12] in the case of the even-even nuclei and from [14] in the case of the odd nuclei, respectively. Part of the results were also presented in [15].

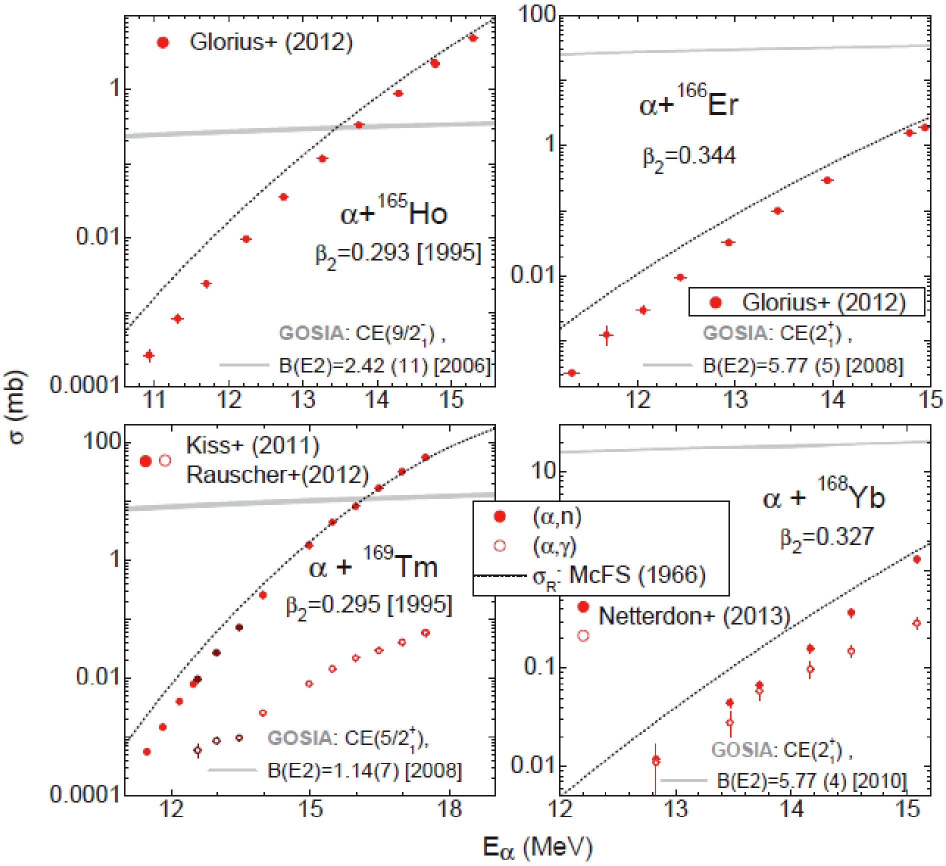

Fig. 3 – As Fig. 2 but for target nuclei ^{165}Ho, ^{166}Er, ^{169}Tm and ^{168}Yb.

Table 2 contains the energies, the spins of the excited states and the corresponding reduced transition probabilities for the levels considered in the calculations taken from [10] together with the deformation parameters [12, 14].

As expected, for all the reactions shown in Figs. 2 and 3, the CE cross sections present similar behavior as the ones shown in Fig. 1: a small variation with the α-particle energy compared to the optical model reaction cross sections.

Different slopes are also obtained which contradict the supposition of Rauscher [17, 18] who considered the CE as an additional reaction channel which is competing with the compound nucleus formation at α-particle energies well below the Coulomb barrier. Furthermore, the author of [17, 18] has considered necessary to introduce a renormalization factor in order to describe the (α, n) reaction on ^{141}Pr and ^{169}Tm and the (α, γ) reaction on ^{144}Sm, but not for the (α, n) reaction on ^{130,132}Ba or for the two reactions on ^{168}Yb.

Table 2

Excitation energies of the considered states in the calculations, reduced transition probabilities and deformation parameters for the studied nuclei

Nucleus	Eγ (keV)	$J_i^\pi \rightarrow J_f^\pi$	B(E2) (e^2b^2)	β_2
^{113}In	1173.06(9)	$11/2^+ \rightarrow$ g.s.	0.093(6)	0.089
^{127}I	374.992(9)	$1/2^+ \rightarrow$ g.s.	0.027(2)	-0.130
^{130}Ba	357.38(8)	$2^+ \rightarrow$ g.s.	1.163(11)	0.215
^{132}Ba	464.508(12)	$2^+ \rightarrow$ g.s.	0.86(6)	0.185
^{141}Pr	1786.48(13)	$7/2^+ \rightarrow$g.s.	0.140(21)	0.000
^{144}Sm	1660.027(10)	$2^+ \rightarrow$ g.s.	0.266(8)	0.0881
^{165}Ho	94.700(3)	$9/2^- \rightarrow$ g.s.	2.42	0.293
^{166}Er	80.5776(20)	$2^+ \rightarrow$ g.s.	5.77(5)	0.344
^{168}Yb	87.73(1)	$2^+ \rightarrow$ g.s.	5.77(4)	0.327
^{169}Tm	118.1894(11)	$5/2^+ \rightarrow$ g.s.	1.14(7)	0.295

4. CONCLUSIONS

In keeping with the E2 character of the Coulomb excitation only one excited state was considered in this work. The CE cross section results obtained with the code GOSIA for the first 2+ state in α-induced reaction on ^{92}Zr, ^{96,100}Mo and ^{106}Pd were in good agreement with the previously reported results. Based on these results further calculations were performed for a series of heavier nuclei, and a similar trend for the CE cross sections compared to the total reaction cross sections has been obtained. In the case of the odd nuclei further investigations are needed.

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