Intermediate Energy Coulomb Excitation of Neutron-rich Nuclei

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The Coulomb excitation of nuclei in a peripheral nucleus-nucleus collision represents a prolific experimental tool to unravel various nuclear structural properties. There exist well established semiclassical theories based on the time dependent perturbation method to describe the low as well very high energy Coulomb excitation [1, 2]. In the formulation of the relativistic Coulomb excitation (RCE) theory the Rutherford bending is neglected while in the low energy theory the relativistic retardation effects are completely ignored. However in the energy range 30-200 MeV/A, available to most of the radioactive ion beams, both of these effects are relevant. Thus C A Bertulani et al [3] have proposed a theoretical formulation in which both of these effects are incorporated properly. According to this theory the expression of differential Coulomb excitation cross section is given by

$$\frac{d\sigma}{d\Omega} = \frac{4\pi^2 Z_P^2 e^2}{\hbar^2} a^2 \varepsilon^4 \sum_{\pi\lambda\mu} \frac{B(\pi\lambda, I_i \to I_f)}{(2\lambda+1)^3} \left|S(\pi\lambda\mu)\right|^2 \quad (1)$$

with

$$S(E\lambda,\mu) = -i\sqrt{\frac{2\lambda+1}{4\pi}}\sqrt{\frac{(\lambda-\mu)!(\lambda+\mu)!}{(\lambda-\mu)!!(\lambda+\mu)!!}}(-1)^{\frac{\lambda+\mu}{2}}\frac{1}{v a^{\lambda}}\left(\frac{v}{c}\xi\right)^{\lambda+1}\frac{1}{\lambda(2\lambda-1)!!}e^{-\frac{\pi\xi}{2}}$$
$$\int_{-\infty}^{\infty} dw\, e^{-\xi\varepsilon\cosh w} e^{i\xi w}\frac{\left(\varepsilon + i\sinh w - \sqrt{\varepsilon^2-1}\cosh w\right)^{\mu}}{(i\varepsilon\sinh w + 1)^{\mu-1}}$$
$$\times\left[(\lambda+1)\, h_{\lambda} - z\, h_{\lambda+1} - \frac{v}{c}\varepsilon\xi\cosh w\, h_{\lambda}\right]$$

where h_λ are the Hankel functions of first kind with argument $z = \frac{v}{c}\xi\,(i\varepsilon\,\sinh w + 1)$ and $\xi\left(=\frac{\omega_{fi}\,a}{\gamma\,v}\right)$ and γ represent the adiabaticity parameter and Lorentz factor respectively.

Recently, this theory was applied to analyze the Coulomb excitation data at intermediate energies involving beams of neutron-rich unstable nuclei and the results so obtained were compared with those obtained by using the following approximate expression particularly for E2 excitations [4]

$$\sigma_{app}^{E2} = \frac{8\pi^2}{75}\frac{Z_T^2 e^2}{(\hbar c)^4} E_\gamma^2\, B(E2)\left(\frac{c}{v}\right)^4$$
$$\left[\frac{2}{\gamma^2}K_1^2 + \xi\left(1+\frac{1}{\gamma^2}\right)K_0 K_1 - \frac{v^4\xi^2}{2c^4}\left(K_1^2 - K_0^2\right)\right] \quad (2)$$

where K_n are the n[th] order modified Bessel functions of second kind. From this analysis Bertulani et al [4] concluded that the Coulomb excitation cross sections were found to be reduced by as much as 30% in comparison to those of corresponding values obtained by using RCE theory. But very recently, these conclusions were contradicted by H Scheit et al [5] by pointing out that the large decrements in the cross section estimates observed by Bertulani et al [4] was due to their wrong choice of experimental parameters. It was pointed out in Ref. [5] that the authors of Ref. [4] have used the average beam energy and maximum scattering angle in the laboratory frame of reference instead of mid-target beam energy and center of mass maximum scattering angle. However the authors of Ref. [5] have used only the approximate expression given by Eq.(2) instead of the exact expression (Eq.(1)). Since Eq.(2) represents the high energy limit of Eq.(1) as shown in Ref. [3] and is analytically equivalent to the corresponding expression in the RCE theory of Winther and Alder [2], therefore in this expression only the retardation effects are taken into account fully while the bending effects are partially accounted for.

Although the correct energy and angle parameters have been used in the analysis of H Scheit et al [5] but the retardation and the bending effects are not fully considered. Thus the quantitative study regarding the role of both of these effects needs reinvestigation. So, in the present work with a motive to ascertain the role of both of the above mentioned effects in the analysis of Coulomb excitation data we have calculated the Coulomb excitation cross section for neutron-rich Sulfur isotopes on gold target at intermediate beam energies.

Table 1. Coulomb excitation cross section of some neutron-rich *S*- isotopes at intermediate energies. E_{beam}, $\theta_{\max}$, E_{γ}, $B(E2)_{RCE}$ and $\sigma_{\exp}$ represent the beam energy, maximum value of scattering angle, excitation energy, experimental reduced transition probability and experimental Coulomb excitation cross section respectively. Entries with superscript ñ#ò represent the mid-target beam energies and the center of mass scattering angles while those with ñ*ò represent the average-beam energies and the scattering angles in the laboratory frame of reference. σ_{IECE}^{CAB} represents the cross section calculated by Bertulani et al [4] using the exact expression i.e. Eq.(1). σ_{app}^{CAB} and σ_{app}^{HS} denote the approximate cross section calculated by Bertulani et al [4] and H Scheit et al [5] respectively using Eq.(2) while the entries with superscript õõ present work õõ are the results of present work.

Iso.[Ref.]	E_{beam}	$\theta_{\max}$	E_{γ}	$B(E2)_{RCE_{rc}}$	$\sigma_{\exp}$	σ_{app}^{CAB}	σ_{app}^{HS}	$\sigma_{app}^{present\ work}$	σ_{IECE}^{CAB}	$\sigma_{IECE}^{present\ work}$
	MeV/A	Degrees	MeV	$e^2\ fm^4$	mb	mb	mb	Mb	mb	Mb
^{38}S [6]	34.6 # 39.2 *	4.92 # 4.10 *	1.292	235	59	---- 45.0	59.3 48.0	58.0 46.4	---- 48.0	**62.0** 48.3
^{40}S [6]	35.3 # 39.5 *	4.96 # 4.10 *	0.891	334	94	---- 70.0	95.0 74.8	93.0 72.4	---- 75.5	**99.0** 75.0
^{42}S [6]	36.6 # 40.6 *	5.00 # 4.10 *	0.890	397	128	---- 94.3	128.9 98.9	125.0 96.0	---- 101.0	**134.0** 101.0

Target is ^{197}Au in all cases.

In Table1, the values of Coulomb excitation cross sections as calculated by Eq.(1) ($\sigma_{IECE}^{present\ work}$) and by Eq.(2) ($\sigma_{app}^{present\ work}$) are compared with the corresponding values of cross sections obtained in Ref. [4] (σ_{IECE}^{CAB}, σ_{app}^{CAB}) and Ref. [5] (σ_{app}^{HS}). It is worth to note that the entries for the mid-target beam energy and the center of mass maximum scattering angle are missing in Ref. [4] while the entries corresponding to exact IECE theory (Eq. (1)) are missing in Ref. [5]. Thus here we have calculated the cross section for mid-target beam energy and center of mass maximum scattering angle using Eq. (1) and the values so obtained are shown as bold in Table 1. These values of the cross sections are found to be approximately six percent larger than those obtained in Ref. [5] using the approximate expression. The enhancement of approximately six percent in the values of the cross sections for neutron rich S-isotopes, may be attributed to the full incorporation of both the retardation as well as bending effects simultaneously.

In conclusion, we have found that when the appropriate beam energy and maximum scattering angle parameters are used in the theoretical formulation proposed by C A Bertulani et al [3] to analyze the intermediate energy Coulomb excitation data, the Coulomb excitation cross sections of neutron-rich Sulfur isotopes get enhanced by six percent due to the full fledged inclusion of the retardation as well as bending effects simultaneously.

References

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