Photonuclear reactions in giant dipole resonance region

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Introduction

In recent years the study of photonuclear reactions has attracted considerable interest. Availability of intense n-rich ion-beams will open new perspectives in the study of nuclei very far away from the valley of stability especially in the vicinity of ^{78}Ni. Photofission of Uranium is a very powerful mechanism to produce such radioactive beams. Although the photofission cross section for ^{238}U at giant dipole resonance (GDR) energy is about an order of magnitude lower than for the 40 MeV neutron induced fission, still it is advantageous because the electrons/γ-photons conversion efficiency is much more significant than that for deuterons/neutrons. The aim of present work is to obtain photonuclear cross sections covering the GDR energy region.

The GDR photoabsorption, the nuclear excitation and fission

In the total photoabsorption cross section σ_a^T at energies covering the GDR region, both the Lorentz type GDR cross section σ_a^{GDR} and the quasideuteron (QD) cross section σ_a^{QD} contribute and therefore $\sigma_a^T = \sigma_a^{GDR} + \sigma_a^{QD}$. QD model [1] is based on the assumption that incident photon is absorbed by a correlated n-p pair inside the nucleus, leaving the remaining nucleons as spectators and is proportional to available number of n-p pairs inside nucleus and to the free deuteron photodisintegration cross section $\sigma_d(E_\gamma)$. Thus

$$\sigma_a^T = \sigma_a^{GDR}(E_\gamma) + \frac{L}{A} NZ\sigma_d(E_\gamma)e^{-D/E_\gamma} \quad (1)$$

where N, Z and A are the neutron, proton and mass numbers respectively, L/A factor represents the fraction of correlated n-p pairs and the function e^{-D/E_γ} accounts for the reduction of the n-p phase space due to the Pauli exclusion principle. A systematic study of total nuclear photoabsorption cross section data in the intermediate energy range shows that $D = 0.72A^{0.81}$ MeV [2]. The free deuteron photodisintegration cross section is given by $\sigma_d(E_\gamma) = \frac{61.2[E_\gamma - B]^{3/2}}{E_\gamma^3}$ mb [3] where B=2.224 MeV is the binding energy of the deuteron. The quasideuteron model [1] of nuclear photoabsorption is used together with modern rms radius data to obtain Levinger's constant $L = 6.8 - 11.2A^{-2/3} + 5.7A^{-4/3}$ of nuclei throughout the Periodic Table and is in good agreement [4] with those obtained from the experimentally measured σ_a^T values. Lorentz type GDR cross section is given by [5]

$$\sigma_a^{GDR}(E_\gamma) = \sigma_1 \frac{(E_\gamma\Gamma_1)^2}{(E_\gamma^2 - E_1^2)^2 + (E_\gamma\Gamma_1)^2} + \sigma_2 \frac{(E_\gamma\Gamma_2)^2}{(E_\gamma^2 - E_2^2)^2 + (E_\gamma\Gamma_2)^2} \quad (2)$$

where σ_1, E_1, Γ_1 and σ_2, E_2, Γ_2, the Lorentz line parameters are taken from Refs.[5, 6].

The recoiling nucleus can be viewed as a compound nucleus having the same composition as the target nucleus but with excitation energy $E^* = m_0c^2[(1+2E_\gamma/m_0c^2)^{1/2} - 1]$ [7] where E_γ is the photon enegy and m_0 is the rest mass of the nucleus before photon absorption. This excited compound nucleus then undergoes successive evaporation of neutrons and light particles or fission. Hence the photonuclear reaction cross section σ_r is a product of the total nuclear photoabsorption cross section σ_a^T and the statistical decay probability $\frac{\Gamma_r}{\Gamma}$ and is, therefore, given by $\sigma_r = \sigma_a^T . \frac{\Gamma_r}{\Gamma}$ where Γ_r and Γ are the partial and the total reaction widths respectively. This model was used [8, 9] previously for photonuclear reactions in the QD region quite successfully whereas in the present work we explore the nuclei excited by photons at the GDR region.

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TABLE I: Comparison of calculated photofission cross sections for GDR and QD contributions.

Target nucleus	Fissility $\frac{Z^2}{A}$	E_γ MeV	σ_a^{GDR} mb	σ_f^{GDR} mb	σ_a^{QD} mb	σ_f^{QD} mb
^{237}Np	36.49	10	244.0	237.0	1.165	1.131
		15	392.6	391.7	5.442	5.427
		20	92.5	91.9	10.306	10.235
^{238}U	35.56	10	269.1	186.4	1.140	0.787
		15	360.0	336.7	5.361	5.011
		20	73.7	64.9	10.189	8.967
^{232}Th	34.91	10	247.5	17.7	1.259	0.092
		15	355.6	66.5	5.680	1.080
		20	75.3	15.7	10.574	2.212

Calculation and results

Each calculation is performed with 40000 events using a Monte-Carlo technique for the evaporation-fission calculation. This provides a reasonably good computational statistics. The photonuclear reaction cross sections are calculated at different energies for various elements. In Table-I, the results of these calculations for GDR and QD contributions are listed and compared.

Upper limits of the cross sections can be calculated using $\sigma_r = \sigma_f = \sigma_a^T/\mathrm{N}$ for cases where not a single fission event occured in N events, where N=40000 is the number of incident photons. The statistical error in the theoretical estimates for the photonuclear reaction cross sections can also be calculated using the equation $\sigma_r \pm \Delta\sigma_r = \sigma_a^T[n_r \pm \sqrt{n_r}]/N$ which implies that $\Delta\sigma_r = \sqrt{\sigma_a^T \sigma_r / N}$.

Summary and conclusion

The present calculations provide excellent estimates of photofission cross section for the actinides. The fission percentage increases with the fissility parameter. The contribution to the photofission cross sections from the QD process is very small compared to that from the GDR. For medium mass nuclei such as ^{64}Zn, there are no fission events from QD or GDR at the energies considered here. This model was used previously for the photonuclear reactions in the QD energy region quite successfully [8, 9] whereas in the present work we explore the nuclei excited by photons at the GDR energy region which is particularly important in relation to the production of neutron rich nuclei.

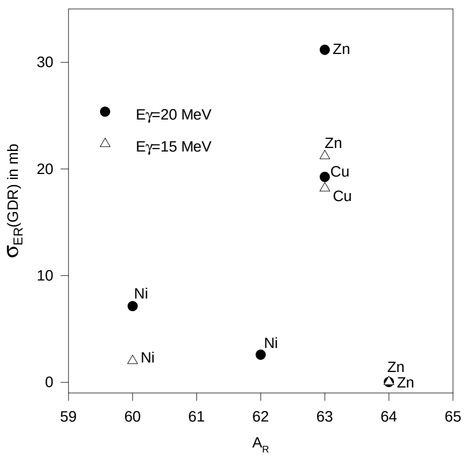

FIG. 1: The plots of cross sections σ_{ER}^{GDR} as a function of mass number A_R of the evaporation residues for ^{64}Zn at E_γ=15 MeV, 20 MeV. There is no fission event at these energies.

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