Photon scattering from ^{90}Zr below neutron emission threshold

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Cross sections for elastic and inelastic scattering of monochromatic photons from ^{90}Zr have been measured for excitations between 8.1 and 10.5 MeV. The observed inelastic cross sections $\sigma_{\gamma\gamma i}$ correspond to transitions to the 0_2^+, 2_1^+, 2_2^+, and 2_3^+ states. A simple theoretical description using the Brink-Axel hypothesis and estimates of the level density and of the total photon interaction cross section $\sigma_{\gamma T}$ gives predictions for the individual cross sections that are in very good agreement with data. The $E1$ strength corresponding to the inferred $\sigma_{\gamma T}$ amounts to about $B(E1\uparrow)\sim 0.5\ e^2\,\mathrm{fm}^2$ for the energy range under consideration.

I. INTRODUCTION

Photon interactions below nucleon emission threshold reveal the way in which a simple nuclear dipole excitation is shared by many neighboring complicated nuclear states. The energy dependence of these interactions can be effectively measured using tagged photons. When the incident photon resolution ΔE is much larger than the mean nuclear level spacing D, one actually measures cross sections averaged over $n=\Delta E/D$ levels. Nuclear structure information can be readily obtained from the average total photon interaction cross section $\sigma_{\gamma T}$, because it is directly related to the ground state partial decay widths $\Gamma_{\gamma 0k}$; these widths, in turn, are proportional to the squares of the dipole matrix elements between the excited nuclear states and the ground state.

It has been shown[1] that a reliable estimate of $\sigma_{\gamma T}$ below nucleon emission threshold can be obtained from a measurement of the average elastic photon cross section $\sigma_{\gamma\gamma}$. The analysis requires that the level density be sufficiently large for the average ground state widths $\Gamma_{\gamma 0}$ to reasonably follow a Porter-Thomas distribution,[2] and also that the levels be nonoverlapping, which implies that the ratio of the average total radiative width to the average level spacing, Γ_T/D, is much smaller than 1. Previously, the $\sigma_{\gamma T}$ inferred from elastic scattering experiments using tagged photons had been compared with an extrapolation of the giant dipole resonance (GDR) in a number of medium[1,3–5,6] and heavy nuclei.[7] In general the agreement between the extrapolation and the inferred strength is quite good. Deviations which manifest themselves as irregularities or fine structure are observed, but it appears that, except near the doubly magic Pb nucleus, such deviations only modulate the Lorentz-type dependence of the strength function for $E1$ photoexcitation. The underlying nuclear structure is not well established, but may reflect 1p-1h excitations for which the unperturbed $E1$ strength has not been totally subsumed into the GDR.

An additional assumption is required to describe γ decay to states other than the ground state. This assumption, usually referred to as the Brink-Axel hypothesis,[8] states that each excited state has built upon it a giant resonance similar to that for the ground state but shifted upward in energy by the energy of the excited state. This is equivalent to assuming that the energy dependence of photon interactions is independent of the detailed structure of the initial state. It is assumed that if it were possible to prepare a nuclear target in an excited state, the photoabsorption cross section would have the same energy dependence as is found in the case of the ground state.

In this paper we present measurements of elastic and inelastic photon scattering cross sections for ^{90}Zr at excitations between 8.1 and 10.5 MeV. Due to the excellent resolution of the γ-ray detector it has been possible to separate the scattering contributions to the first four excited states to which photodeexcitation can occur. This allows us to perform a significant test of the Brink-Axel hypothesis in that the present elastic and inelastic data can be compared with corresponding low-energy extrapolations derived from a Lorentz-type GDR built on each respective state. An additional motivation for the present work is the need for an accurate determination of the elastic scattering cross section to be used in the extraction of quantitative $M1$ strength distributions from asymmetries measured with tagged polarized photons.[9,10]

The experimental technique is briefly described in Sec. II. In Sec. III the method used to interpret the data is developed, and then is applied to the present measurements in Sec. IV. Final conclusions are summarized in Sec. V.

II. EXPERIMENTAL TECHNIQUE

Photon elastic and inelastic scattering cross sections were measured using monochromatic tagged photons. An electron beam of energy $E_e=15.4$ MeV obtained from the University of Illinois MUSL-2 accelerator[11] was passed through a 25 μm Al foil producing bremsstrahlung γ rays. These photons of energy E_γ are "tagged" by the arrival of a residual electron of energy $E_r=E_e-E_\gamma$ in a scintillation counter on the focal plane of a magnetic spectrometer. Thirty-two adjacent energy intervals between 8.1 and 10.5 MeV were tagged simultaneously using contiguous detectors, each subtending a momentum bite of approximately

1.25%. The absolute energy was determined to about 30 keV.

A high efficiency, good resolution NaI spectrometer was used to detect elastically and inelastically scattered photons at 90°. This detector consists of a NaI(Tl) crystal, 25 cm in diameter and 30 cm long, surrounded by an effective absorber of slow neutrons ($^6Li_2CO_3$) and by a 6 cm thick plastic anticoincidence shield. In addition, the entire NaI spectrometer is shielded from background radiation by 11.4 cm of lead. A coincidence resolving time of 10 nsec was used to compare the arrival time of the scattered photon and the tagging electron.

An enriched (99.3%) ^{90}Zr target in the form of ZrO_2 powder was located 183 cm downstream of the Al foil. The target was packed in a thin-walled (3 mm) Lucite container with an areal density of 4.4 g/cm^2. At these energies, the contribution of the Lucite and the oxygen to the scattering is negligible.

The NaI detector is also used at 0° to measure the detector response and the flux of photons incident on the target per tagging electron. The procedures used to obtain the differential cross sections have been described in detail by Wright *et al.*,[12] and will not be presented in this paper.

Figure 1 shows a typical spectrum corresponding to 9.68 MeV incident photons indicating the final nuclear states populated by the deexcitation γ rays. The first two inelastic states, 0_2^+ at 1.76 MeV and 2_1^+ at 2.19 MeV, were clearly resolved for each of the 32 tagging counters. The next two higher excited states accessible by γ decay are the 2_2^+ at 3.31 MeV and the 2_3^+ at 3.84 MeV. Their cross sections have been extracted after combining spectra from groups of four adjacent counters to improve statistics. Also shown in Fig. 1 are the peak shapes and background curve used in the fitting procedure. The single Gaussian shapes that were fit to the inelastic peaks were corrected for the presence of the one-escape peak, which is clearly seen for the case of the elastic scattering in Fig. 1. The exponential background was parametrized for each energy by fitting the number of counts at two positions where nuclear excitation is not expected.

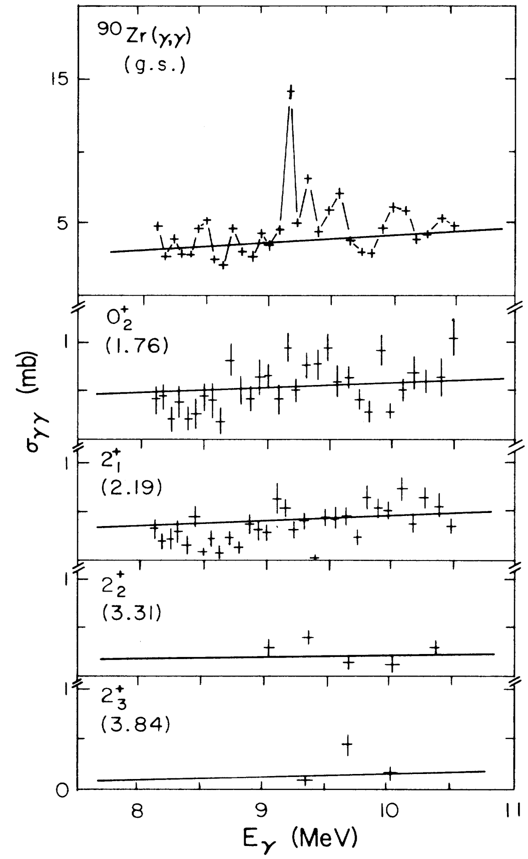

FIG. 2. Photon elastic and inelastic scattering cross sections from ^{90}Zr. The excitation energy of each final state is indicated in parentheses. The data are shown with their statistical uncertainties. For the elastic scattering a line to guide the eye is shown. The solid lines are the result of a theoretical calculation (see the text).

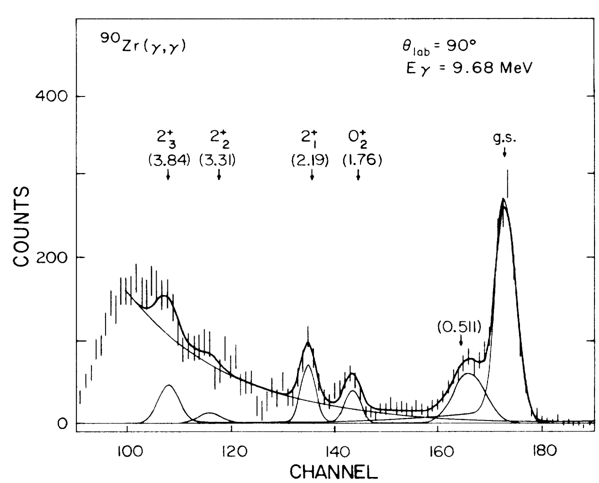

FIG. 1. Measured spectrum of scattered photons from ^{90}Zr. The excitation energies of the final nuclear states are indicated in parentheses. Also shown are the peak shapes and background curve used in the fitting procedure.

The measured differential cross sections at 90° were integrated over angle to give $\sigma_{\gamma\gamma}(E_\gamma)$ for the elastic and $\sigma_{\gamma\gamma i}(E_\gamma)$ for the inelastic scattering. A dipole angular distribution was assumed, with the dependence $(1+\cos^2\theta)$ for $0^+\rightarrow 1^-\rightarrow 0^+$ transitions, and $(13+\cos^2\theta)$ for $0^+\rightarrow 1^-\rightarrow 2^+$ transitions. The final $\sigma_{\gamma\gamma}$ and $\sigma_{\gamma\gamma i}$ cross sections are plotted in Fig. 2 with their corresponding statistical uncertainties.

III. ANALYSIS

Because of the finite width of each tagging counter, incident tagged photons are spread over an energy interval ΔE, which includes n individual excitations. The average nuclear level spacing, D, is equal to $\Delta E/n$. For a zero-spin ground state and dipole excitations, the average of the total γ-ray interaction cross section $\sigma_{\gamma T}$ is

$$\sigma_{\gamma T}=K\langle\Gamma_{\gamma 0}\rangle \ , \tag{1}$$

where

$$K=\left[\frac{10\ \mathrm{MeV}}{E_\gamma}\right]^2\frac{1.15\times10^5\ \mathrm{mb}}{D} \ .$$

$\langle\Gamma_{\gamma 0}\rangle$ is the average over n levels of the partial widths $\Gamma_{\gamma 0k}$ and E_γ is the excitation energy. Corresponding expressions for elastic and inelastic scattering are given by

$$\sigma_{\gamma\gamma}=K\left\langle\frac{\Gamma_{\gamma 0}^2}{\Gamma_T}\right\rangle \tag{2}$$

and

$$\sigma_{\gamma\gamma i}=K\left\langle\frac{\Gamma_{\gamma 0}\Gamma_{\gamma i}}{\Gamma_T}\right\rangle \ , \tag{3}$$

where $\langle\Gamma_T\rangle$ is the average total width of the excited dipole states, and $\langle\Gamma_{\gamma i}\rangle$ is analogous to $\langle\Gamma_{\gamma 0}\rangle$ but corresponds to photon decay to excited states of the nucleus (labeled by the index i).

Below nucleon emission thresholds the total width of the kth level Γ_{Tk}, can be expressed as[1]

$$\Gamma_{Tk}=\Gamma_{\gamma 0k}+\Gamma_c \ , \tag{4}$$

where Γ_c is the sum of many partial widths for γ-ray decays to excited states and is assumed to be roughly constant over some range of excitations. Using Eqs. (1), (2), and (4) it has been shown that[1]

$$\sigma_{\gamma\gamma}(E_\gamma)=\sigma_{\gamma T}(E_\gamma)\frac{E}{1+c} \ , \tag{5}$$

where $c=\Gamma_c/\langle\Gamma_{\gamma 0}\rangle$, and E is an enhancement factor for elastic scattering

$$E=\left\langle\frac{\Gamma_{\gamma 0}^2}{\Gamma_T}\right\rangle\Big/\frac{\langle\Gamma_{\gamma 0}\rangle^2}{\langle\Gamma_T\rangle} \ . \tag{6}$$

Equation (6) reflects the fact that for fluctuating quantities, the average of the square is greater than the square of the average. For any particular distribution, E depends only on the quantity c. In the case of amplitudes which follow a Porter-Thomas distribution[1]

$$E=(1+c)\int_0^\infty\frac{3e^{-\alpha c}d\alpha}{(1+2\alpha)^{5/2}} \ , \tag{7}$$

which can be evaluated numerically. A corresponding reduction factor R for inelastic scattering appears as a consequence of the enhancement factor E for elastic scattering. In fact, assuming that the widths $\Gamma_{\gamma 0}$ and $\Gamma_{\gamma i}$ are uncorrelated, the identity

$$\left\langle\frac{\Gamma_{\gamma 0}^2}{\Gamma_T}\right\rangle+\sum_i\left\langle\frac{\Gamma_{\gamma 0}\Gamma_{\gamma i}}{\Gamma_T}\right\rangle=\langle\Gamma_{\gamma 0}\rangle \tag{8a}$$

can written as

$$E\frac{\langle\Gamma_{\gamma 0}\rangle}{\langle\Gamma_T\rangle}+R\frac{\Gamma_c}{\langle\Gamma_T\rangle}=1 \ , \tag{8b}$$

which yields

$$R=\frac{1+c-E}{c} \ . \tag{9}$$

From this result in conjunction with Eqs. (1) and (3) the inelastic cross section can be written as

$$\sigma_{\gamma\gamma i}(E_\gamma)=\sigma_{\gamma T}(E_\gamma)\frac{R}{1+c}\frac{\langle\Gamma_{\gamma i}\rangle}{\langle\Gamma_{\gamma 0}\rangle} \ . \tag{10}$$

The Brink-Axel hypothesis can be used to estimate $\langle\Gamma_{\gamma i}\rangle/\langle\Gamma_{\gamma 0}\rangle$ and hence provide a prediction for the experimental cross sections $\sigma_{\gamma\gamma i}$. Using Eq. (1) as an expression for giant resonances built on excited states ($E_\gamma-E_i$ in place of E_γ and $\Gamma_{\gamma i}$ in place of $\Gamma_{\gamma 0}$) we have

$$\sigma_{\gamma\gamma i}(E_\gamma)=\sigma_{\gamma T}(E_\gamma)\frac{R}{1+c}f_i^2 \ , \tag{11}$$

where $f_i=(E_\gamma-E_i)/E_\gamma$. The quantity $(1+c)\equiv\langle\Gamma_T\rangle/\langle\Gamma_{\gamma 0}\rangle$ can be obtained from

$$1+c=\frac{\sum_i\sigma_{\gamma T}(E_\gamma-E_i)f_i^2}{\sigma_{\gamma T}(E_\gamma)} \ , \tag{12}$$

where E_i ranges from 0 to E_γ and the sum includes all levels that can be populated by $E1$ deexcitation from a 1^- level. For large enough E_i, the sum over discrete levels can be replaced by an integral using an appropriate formula for the level density $\rho(E_i)$.

In the present analysis, we use the Brink-Axel hypothesis along with an assumed $\sigma_{\gamma T}(E_\gamma)$ and $\rho(E_i)$ to predict the measured quantities $\sigma_{\gamma\gamma}$ and $\sigma_{\gamma\gamma i}$. The enhancement factor E and the reduction factor R are deduced from Eqs. (7) and (9) once the factor c is obtained from Eq. (12). In previous work the approach has been to infer the total photon interaction cross section $\sigma_{\gamma T}$ from the measured elastic scattering $\sigma_{\gamma\gamma}$ using Eq. (5) and an estimate of D/Γ_c.[1] We next compare the predictions of the formalism developed in this section with the present measurements of $\sigma_{\gamma\gamma}$ and $\sigma_{\gamma\gamma i}$.

IV. DISCUSSION

According to the formalism just derived, estimates of $\sigma_{\gamma T}(E_\gamma)$ and the level density are the only factors that are needed to explore the consistency of the experimental $\sigma_{\gamma\gamma}$ and $\sigma_{\gamma\gamma i}$ with cross sections deduced from GDR's built on the ground state and corresponding excited states. In this paper we take $\sigma_{\gamma T}(E_\gamma)$ from a Lorentz line parametrization of the total photoneutron cross section[13] with the parameters $\sigma_0=211$ mb for the peak cross section, $E_{\mathrm{GDR}}=16.74$ MeV for the centroid energy, and $\Gamma_{\mathrm{GDR}}=4.16$ MeV for the width. The inclusion of the photoproton cross section[14] would contribute an increase of only about 8% in the total integrated cross section in the region of the GDR, and therefore it is not expected to significantly affect the low-energy GDR extrapolation deduced from the total photoneutron cross section. For the level density estimate we have used both a standard backshifted Fermi-gas formula[15] with the parameters $a=10.0$ MeV^{-1} and $\Delta=1.40$ MeV, and also the formula suggested by Gilbert and Cameron[16] with the parameters $a=9.76$ MeV^{-1} and $\Delta=2.13$ MeV. In the present case, these formulae give almost identical results. In ^{90}Zr it is possible to count unambiguously, up to an excitation energy of 4.43 MeV, the number of 0^+, 1^+, and 2^+ levels available for photodeexcitation (there are ten such levels). Both level density formulae, which use parameters that were obtained from fits to data in the neutron emission threshold region and above, overpredict this number by about 25%. To avoid a small discontinuity between the known discrete levels below 4.5 MeV and the level density formulae, we have used the expression $\rho_0 e^{-E_\gamma/T}$ to bridge the exctitations between 4.5 and 6.0 MeV; the parameters ρ_0 and T were found by fitting simultaneously the sum of the discrete levels below 4.43 MeV and the number obtained from the density formulae at 6.0 MeV. It should be emphasized that this procedure has only a very small effect on the inelastic cross sections predicted between 4.5 and 6.0 MeV.

The results of the calculation are shown by the solid lines in Fig. 2. The agreement of the simple theoretical predictions with the measured cross sections $\sigma_{\gamma\gamma}$ and $\sigma_{\gamma\gamma i}$ is remarkably good and presents a strong argument for the validity of the Brink-Axel hypothesis. In order to investigate the overall consistency of the theory we plot in Fig. 3 a prediction of the complete scattering spectrum in ^{90}Zr for 10 MeV incident photons. The predicted elastic and inelastic cross sections are averaged in 1 MeV bins. The area under this histogram is found to be equal to 10.7 mb which is just the value of the cross section given by Lorentz line fit to GDR at 10 MeV, and it is an indication that the calculation is indeed valid for all the available levels. The rise in the inelastic cross section above 4 MeV is simply a reflection of the increase in level density.

Another estimate of the total cross section $\sigma_{\gamma T}$ can be obtained from Eq. (5) if D/Γ_c can be determined. This approach is described in detail in Ref. 1. We obtain D from the backshifted Fermi-gas level density formula with the same parameters as before. Values of Γ_c can be estimated from neutron radiative capture[17] from which we take $\Gamma_c=0.20$ eV. The inferred total interaction cross section $\sigma_{\gamma T}$ is plotted in Fig. 4 together with the measured $\sigma_{\gamma\gamma}$. The dashed line is the low-energy extrapolation of

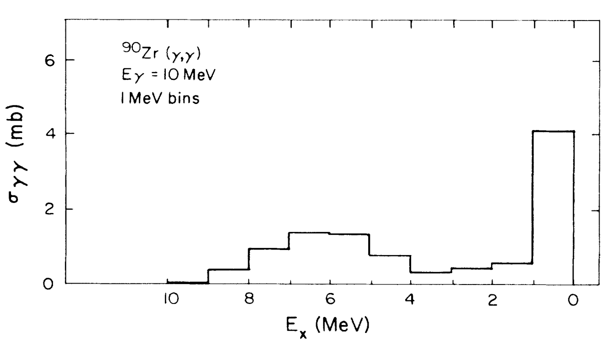

FIG. 3. Calculated elastic and inelastic photon cross sections for ^{90}Zr averaged in 1 MeV bins for an incident energy of 10 MeV.

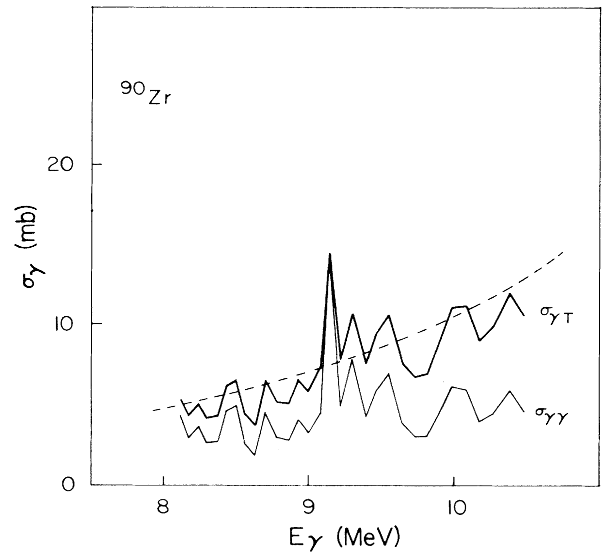

FIG. 4. Inferred $\sigma_{\gamma T}$ (thick solid line) together with the measured $\sigma_{\gamma\gamma}$ (thin solid line). The dashed line is the low-energy extrapolation of the Lorentz line which fits the photoneutron cross section of ^{90}Zr in the GDR region.

the Lorentz line which fits the photoneutron cross section of ^{90}Zr in the giant resonance region.[13] The present agreement between the extrapolated tail and the inferred $\sigma_{\gamma T}$ is considerably better than that found in Ref. 1. This agreement can be attributed both to much better photon detector resolution which allows the complete separation of the first inelastic state from the elastic scattering, and also to the monoisotopic ^{90}Zr target. The integrated total cross section is directly related to the reduced transition probability $B(E1)$, which for the energy range between 8.1 and 10.5 MeV amounts to about 0.5 e^2fm^2.

V. SUMMARY AND CONCLUSIONS

We have measured differential cross sections at 90° for the elastic and inelastic scattering of tagged, monochromatic photons from ^{90}Zr at excitations between 8.1 and 10.5 MeV. The inelastic cross sections include the levels up to 4 MeV. A formalism for calculating the elastic and inelastic cross section, which depends only on the Brink-Axel hypothesis and estimates of the total cross section $\sigma_{\gamma T}$ and the level density ρ, was developed. The predictions for the individual cross sections are in very good agreement with the experimental data. The inferred total cross section agrees very well with the value of the Lorentz-line fit to the GDR. These results are not sensitive to the form of the assumed level density.

All predictions and observations are quite consistent and strongly imply that the low energy photon interactions in ^{90}Zr are dominated by the GDR and that the observed structure is only a modulation of the tail of the GDR.

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