# Photoeffect cross sections of several rare-earth elements for 323-keV photons

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Total-attenuation cross sections of the oxides of rare-earth elements such as La, Ce, Pr, Nd, Sm, Gd, Dy, Ho, and Er, and also $NaNO_3$ and $NaNO_2$ have been measured in a narrow-beam geometry setup at 323 keV. The total-attenuation cross section for oxygen was obtained as the difference in $NaNO_3$ and $NaNO_2$ cross sections. Using this, the total-attenuation cross sections of the individual lanthanides have been obtained with the aid of the mixture rule. From these, the photoeffect cross sections were derived by subtracting the scattering contribution. These values are found to agree well with Scofield's theoretical data [University of California Report No. UCRL 51326, 1973 (unpublished)].

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## INTRODUCTION

The atomic photoeffect is one of the major ways by which the $\gamma$ rays interact with matter at low photon energies and in high-$Z$ elements. Owing to the importance in radiation physics, nuclear physics, and transport calculations, the photoeffect process has been a subject of considerable interest over the years. On the theoretical side, the data of Scofield [1] on the total and subshell photoeffect cross sections are considered to be the most accurate theoretical data. These data cover elements of $Z=1-101$ in the energy region 1–1500 keV. On the experimental side, the survey reveals that while a large number of data are available for elements such as C, Al, Cu, Zr, Ag, Sn, Ta, Pb, Th, and U, data are relatively scarce or practically nonexistent for rare-earth elements of the lanthanide group [2]. This may be due to the fact that such elements are not abundantly available in their foil form in nature. It is therefore felt desirable to experimentally determine photoeffect cross sections which would fill the gap in the existing data. For this purpose, simple transmission experiments in a good-geometry setup have been performed. Total attenuation cross sections of the simple oxides of the lanthanum group elements such as La, Ce, Pr, Nd, Sm, Gd, Dy, Ho, and Er at 323 keV energy have been measured. From these, the total attenuation cross sections for elements were derived with the aid of mixture rule [3]. Photoeffect cross sections for the elements were derived by subtracting the scattering cross sections from the derived total attenuation cross sections of elements. The subtraction technique is fully justified at the energy of interest since the subtracted cross sections are only a small portion of the total cross sections of elements. These cross sections are found to agree well with the theoretical cross sections of Scofield [1].

## EXPERIMENTAL DETAILS

The transmission experiment was performed in a good-geometry setup similar to the one used in the earlier study [4]. $^{51}Cr$ radioisotope of strength 5 mCi was obtained from the Bhabha Atomic Research Centre, Bombay, in the form of a radiographic capsule. The 323-keV $\gamma$ rays from the radioisotope were detected in a hyperpure germanium detector of ORTEC model "Gamma-X" 23210. The signal from the detector was suitably amplified and recorded in a multichannel analyzer. Each compound in fine powder form was filled in cylindrical plastic containers. The mass of the compound was determined in an electrical balance correct to the third decimal place. From this the mass per unit area was calculated. A list of compounds used in the present study is given in Table I along with their purities and molecular weights.

## RESULTS AND DISCUSSION

In the transmission experiment, spectra were recorded by placing the empty plastic container and the container with the compound alternately in the path of the beam. The counting time was chosen so as to record not less than $10^5-10^6$ counts within the photopeak area. Thus, the error due to counting statistics was less than 0.3% in all cases.

TABLE I. Total attenuation cross sections of compounds along with their purities and molecular weights.

| Compound | Molecular weight | Purity (%) | Total cross sections (barn/mol) |
|---|---|---|---|
| $NaNO_2$ | 69.00 | 99.9 | 11.85±0.09 |
| $NaNO_3$ | 85.00 | 99.9 | 14.65±0.10 |
| $CeO_2$ | 172.91 | 99.9 | 48.10±0.27 |
| $PrO_2$ | 172.91 | 99.5 | 50.10±0.28 |
| $La_2O_3$ | 325.82 | 99.0 | 89.40±0.44 |
| $Nd_2O_3$ | 336.48 | 99.9 | 101.60±0.52 |
| $Sm_2O_3$ | 348.70 | 99.9 | 110.80±0.52 |
| $Gd_2O_3$ | 362.50 | 99.9 | 120.40±0.58 |
| $Dy_2O_3$ | 373.00 | 99.9 | 130.80±0.57 |
| $Ho_2O_3$ | 377.86 | 99.5 | 136.20±0.63 |
| $Er_2O_3$ | 382.56 | 99.9 | 141.00±0.66 |

 

The source-to-detector distance was maintained at 50 cm in the present experiment. The maximum angle of scattering from sample to detector turns out to be 31 min. This greatly minimizes the small-angle-scattering contribution to the measured data.

Nonuniformity of the sample was checked by exposing different portions of the sample material to the incident beam. It was found that any discrepancy in the attenuated intensity in each case was within counting statistics.

The error due to sample impurity could be significant only when large percentages of high-$Z$ impurities are present in the compound. In the present case, the content of high-$Z$ impurities in all compounds was less than 0.005%. Hence the sample impurity corrections were not applied to the measured data.

Any thick target (such as the ones used in the present study) kept in the path of the photon beam would offer an effective mean free path for its interaction. In a good-geometry narrow-beam experiment (such as the present one) most of the photons are absorbed and a few are scattered. The absorbed photons can release $K$-, $L$-, or $M$-shell electrons due to photoeffect which can in turn produce secondary photons due to bremsstrahlung. On the other hand, the scattered photons can undergo multiple scattering and result in energy-degraded photons. On the whole, there is a net photon dose buildup inside the sample. This effect is dependent on the atomic number and thickness of the sample as well as on the incident energy. In the present study, the effect of dose buildup is kept to a minimum by choosing a detector of high resolution and selecting the sample thickness such that the transmission ratio is in the range 0.1–0.4, to reduce the effect of multiple scattering.

There was a built-in provision for dead-time correction in the multichannel analyzer used in the present study. Thus the overall error on the measured value (root mean square of all error calculations) of the total attenuation cross sections of the compounds is less than 2%. The total attenuation cross sections of the compounds are calculated by using the relation

$$\sigma_{\text{comp}} = A \ln(I_0/I)/0.602\,25t$$

in units of barn/mol where $t$ is the mass per unit area, $A$ is the molecular weight, and $I_0/I$ is the transmission ratio.

These values are listed in Table I along with estimated errors, purities, and molecular weights. From the cross sections in Table I, the cross sections for the individual elements were derived with the aid of a mixture rule [3]. All the compounds used were in the form of oxides. Hence, the cross sections for the elements La, Ce, Pr, Nd, Sm, Gd, Dy, Ho, and Er were obtained by subtracting the cross sections of oxygen suitably from their oxides, respectively. The cross section for oxygen was determined as the difference between the experimental cross sections of $NaNO_3$ and $NaNO_2$. The derived values of the total attenuation cross sections are listed in Table II along with the errors. The error $e_{\text{element}}$ on the elemental cross section was calculated according to

$$e^2_{\text{element}} = e^2_{\text{comp}} + e^2_{\text{oxygen}} ,$$

TABLE II. Total attenuation cross sections and photoeffect cross sections in elements (barn/atom) at 323 keV. Photoeffect cross sections in the first row are values derived using semiempirical formula and coherent scattering cross sections of Hubbell *et al.* Photoeffect cross sections in the second row are values derived using the coherent and incoherent scattering cross sections of Hubbell *et al.*

| | | $\sigma_{\text{photo}}$ | |
|---|---|---|---|
| Element | $\sigma_{\text{total}}$ | Present | Theory |
| O | 2.80±0.13 | | |
| La | 40.50±0.46 | 18.05 | 18.20 |
| | | 18.52 | |
| Ce | 42.50±0.30 | 19.56 | 19.85 |
| | | 19.52 | |
| Pr | 44.50±0.31 | 21.07 | 21.37 |
| | | 21.02 | |
| Nd | 46.60±0.54 | 22.67 | 22.90 |
| | | 23.02 | |
| Sm | 51.20±0.54 | 26.26 | 26.30 |
| | | 26.23 | |
| Gd | 56.00±0.59 | 30.03 | 30.20 |
| | | 30.03 | |
| Dy | 61.20±0.58 | 34.18 | 34.40 |
| | | 34.20 | |
| Ho | 63.90±0.64 | 36.35 | 36.65 |
| | | 36.41 | |
| Er | 66.30±0.67 | 38.21 | 38.90 |
| | | 37.81 | |

where $e^2_{\text{oxygen}} = e^2_{NaNO_3} + e^2_{NaNO_2}$. $e_{\text{comp}}$, $e_{\text{oxygen}}$, $e_{NaNO_3}$, and $e_{NaNO_2}$ are the errors on the compound, oxygen, $NaNO_3$ and $NaNO_2$ cross sections, respectively (Table I).

## PHOTOEFFECT CROSS SECTIONS

From the total attenuation cross sections in Table II, the photoeffect cross sections of elements La, Ce, Pr, Nd, Sm, Gd, Dy, Ho, and Er were obtained by subtracting the sum of the theoretical values of coherent scattering cross sections of Hubbell *et al.* [5] and the incoherent scattering cross sections based on the semiempirical formula obtained by Umesh, Ranganathaiah, and Sanjeevaiah [6], interpolated to 323 keV. Photoeffect cross sections were also obtained by subtracting the sum of the coherent and incoherent scattering cross sections of Hubbell *et al.* [5] from the total cross sections in Table II. It is assumed that the error on the total cross sections is carried over to the photoeffect cross sections of the elements. The photoeffect cross sections are listed in Table II along with the interpolated values of Scofield [1]. Good agreement can be observed between the present values and Scofield's values within the stated errors.

It is expected that the present values contribute towards a new pool of experimental values filling the gaps in the available data.

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