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COMPTON BACKSCATTERING OF Hf K X-RAYS IN GERMANIUM

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The differential cross section, $d^2\sigma/d\Omega dE$, for Compton scattering in germanium was measured by observing detector-to-detector scattering using the coincidence method. The experiment was performed at incident energies of 55.791 and 54.612 keV and scattering angle of $\vartheta = 180°$. The method applied is compared with the corresponding measurements in the singles mode, i.e. using the source-scatterer-detector assembly. We found that the coincidence method yields better results, especially in the region below the peak due to scattering on weakly bound electrons. However, it is restricted to the investigation of Compton scattering in detector materials. Experimental results are compared with theoretical calculations based on the "A^2-Born" and the impulse approximations.

1. Introduction

Compton effect was discovered more than seven decades ago, but great interest for its theoretical and experimental investigations still persists [1]. Various types of experiments were made, like the measurements of $d\sigma/d\Omega$ on whole atomic systems and on K-electrons, investigations of electron momentum distributions in metals, and measurements of $d^2\sigma/d\Omega dE$ on whole atoms and on K-electrons. In the last twenty years, strong emphasis has been laid mainly on the last three types of experiments.

In the seventies, many experiments were made with the aim to determine accurately the differential cross section $d^2\sigma/d\Omega dE$ on bound atomic electrons [2 – 4]. The method of measurement applied in those experiments was the well-known measurement in the singles mode. The experimental set up consisted of a radioactive source, target and a detector. The most common detector was either lithium drifted germanium Ge(Li) or high purity germanium (HPGe) detector in a planar geometry. X-ray sources and more often γ-emitters like ^{241}Am (60 keV),^{123}Te (159 keV), ^{203}Hg (279 keV), ^{51}Cr (320 keV), ^{198}Au(412 keV) and ^{137}Cs(662 keV) were used as sources. Typical activities of the sources were from 0.1 Ci up to 10 Ci. In recent experiments, synchrotron radiation was used, too [1]. Various materials, like foils or sheets of Pb, Zn, Cu and Al, were used as targets.

The method of the differential cross section ($d^2\sigma/d\Omega dE$) measurement in the singles mode has several important features: high efficiency, possibility of measurement at almost all scattering angles and using any material as a target. It is also relatively simple. Almost all measurements of $d^2\sigma/d\Omega dE$ on atoms were performed this way. We can name this method the standard method.

In this work we present another approach to the measurement of the differential cross section $d^2\sigma/d\Omega ddE$. It is a coincidence method based on cross-talk between two planar germanium detectors. We also present comparison between the coincidence and the singles mode measurement. We found that the coincidence method gives generally better results. The obtained experimental values are also compared with theoretical values, based on the "A^2-Born" and on the impulse approximation.

To the autor's knowledge, no measurement of Compton scattering on atoms using the coincidence method has been published so far. Similar method for measuring $d^2\sigma/d\Omega dE$ on K-electrons of germanium, using three detectors, was reported [5, 6].

2. *The apparatus and measurements*

Two planar high purity germanium detectors were used in a close head-on geometry (Fig. 1). A shield was placed between the detectors that had a hole in the middle where the source was placed. The apparatus was fully symmetric. The principle of measurement $d^2\sigma/d\Omega dE$ on whole atoms with the coincidence method is the following: A photon emitted from the source is Compton backscattered on an electron in the sensitive volume of one ("the first") detector and a pulse, proportional to the energy transferred to the electron, is produced. The backscattered photon passes through the hole in the shield and is completely absorbed in the other ("the second") detector. The event is recorded as a coincidence of pulses from the two detectors that also satisfies the condition that the sum of energies transferred to the two detectors, $E_1 + E_2$, equals the energy of the incident photon. The first detector is detector of the recoil electron and the target at the same time, and the second detector is the detector of the scattered photon. Because of the symmetry of apparatus, in another event detectors can interchange their roles. The small hole gives a good definition of the scattering angle ($\vartheta = 180°$).

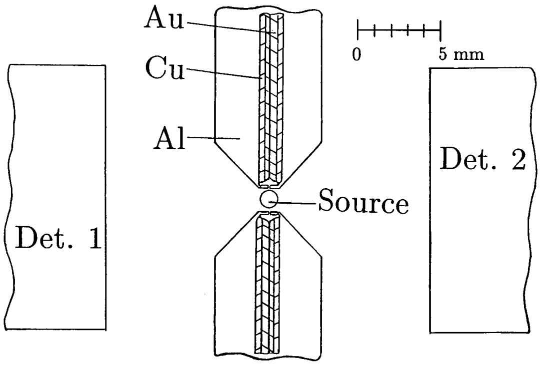

Fig. 1. Experimental arrangement with two detectors, the shield and the source.

The detectors were supplied by ORTEC, Oak Ridge, TN, USA. Nominal size of their sensitive volumes was 200 mm^2 x 13 mm thick. The detectors were placed in a cylindrical lead shield to reduce the background. Pulses from the detectors were fed into a fast-slow coincidence system with a three-parameter 128 x 512 x 512 channel pulse-height analyzer. If a coincidence event occurred in the 200 ns range, the time difference was recorded in the time channel (k_0), and the amplitudes of the pulses from the detectors were recorded in the energy channels (k_1 and k_2). The data were recorded event-by-event. The stability of the system was checked from the data. The records were divided into four groups of consistent data. Each group was analysed separately. The total time of collection of the data was about 115 days.

The shield was a double disc with copper and gold inserts and the hole was a double-taper with an opening 1.23 mm in diameter. The diameters of copper and gold openings were 1.75 mm and 2.07 mm respectively.

The source used in measurement was ^{179}Ta. K-electron capture decay created K-shell vacancies and K X-rays of Hf. We used the Kα_1 and Kα_2 X-rays of Hf of 55.791 keV and 54.612 keV, respectively. The activity of the source was 0.6 kBq.

3. Comparison of the coincidence and the standard method

The standard (singles mode) measurements of $\mathrm{d}^2\sigma/\mathrm{d}\Omega\mathrm{d}E$ for Compton scattering have serious disadvantages that considerably limit the results. In the analysis of the spectra, in order to determine the numbers of counts due to Compton scattering in the target, the following corrections have to be made [2]:

a) Subtraction of background due to exterior radiation.

b) Subtraction of the spectrum due to elastic scattering of incident photons in the target (the peak at high energy and the continuum).

c) Deconvolution of the remaining spectrum to take into account the response of the detector for the continuous energy distribution of the photon. That is the most difficult problem of the standard method in the region below the Compton peak.

d) We can generally say that the standard method does not distinguish recorded photon due to Compton scattering in the target from events due to any other process e.g. scattering of incident photon in the shield, target and the detector, bremsstrahlung by the recoil electron etc.

In the coincidence measurements of Compton scattering, the above difficulties are almost entirely absent.

a) The background is negligible due to the requirement of simultaneity of pulses from the two detectors.

b) Detection of elastic scattering (both of the peak and the continuum) is entirely eliminated due to the coincidence requirement.

c) Partial absorption of energy of either recoil electron (first detector) or of the Compton scattering photon (second detector) does not appear as an event at a "wrong energy" because of the requirement of constant energy sum.

d) In some cases, the coincidence method can distinguish Compton events from other events.

In the detection of Compton scattered photon, two detectors cooperate with each other in a manner that if one detector (the "second" one) detects a photon, then the other detector (the "first" one) confirms that Compton scattering took place by detecting the recoil electron.

Generally, the coincidence measurement is simpler than the standard measurement because there is no need for additional auxiliary measurements and corrections. Therefore, the possibility of systematic errors in the final results is largely reduced.

General drawback of the coincidence method is the restriction to Compton scattering in detector materials. Also, it can not distinguish Compton scattered event from some other processes. In our experiment, only the double Compton scattering on two atoms could be important among these processes. The rough analysis shows that the total of the double Compton events can not exceed 3 percent of the total of single Compton events. This number is many times smaller than the average standard deviations of the data obtained and we neglected that effect. Fully symmetrical experimental set up introduces two other disadvantages: detection of coincident emissions from the source and overlap of the spectra recorded by the detectors.

In the present experiment, strong coincident peaks were recorded due to the simultaneous emission of Hf Kα and L X-rays from the source. Although they are reasonably far in the E1-E2 plane from the Compton events, their continuum spreads parallel to the E1 and E2 axes and crosses the high energy Compton events at 45 degrees. In principle, the two-photon transition could influence to Compton spectra. These events are parallel with Compton events. In the present experiment, fortunately, only Compton events due to energy $E_0 = 54.612$ keV are partially overlapped with the two-photon transition (2s $\rightarrow$ 1s, $E = 54.079$ keV) [7]. They could be easily resolved by a nonlinear fitting procedure.

The overlap of Compton spectra recorded from detector 1 and detector 2 restricts the analysis of the data from the mid-energy to high energy range.

4. Analysis of data, results and theory

The differential cross section, $\mathrm{d}^2\sigma/\mathrm{d}\Omega\mathrm{d}E$, was derived from the numbers of counts using the cross-talk theory [8]. The basic relation in Ref. 7 was modified a little in order to adapt it for Compton scattering. The following relation was obtained:

$$\left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}E\mathrm{d}\omega}\right)_{exptl} = \frac{n_c[\sigma_0 + \sigma(E_c)]}{2\pi^2 J_{0i}\ 10^{28}\epsilon_i \Delta t \epsilon_c \frac{r^2}{D^2} a_i \int\limits_0^{\vartheta_{max}} F_2(\vartheta, E_c) cos^3\vartheta \sin\vartheta \mathrm{d}\vartheta} \tag{1}$$

where n_c is the number of Compton events per channel, σ_0 and $\sigma(E_c)$ are total cross-sections (barn/atom) for interaction of incident photon and Compton scattered photon with an atom of germanium [9], J_{0i} is the number of events per second and per steradian recorded in detector i at incident energy, $\epsilon_i = 0.93$ is the estimated efficiency (not including the escape of characteristic Ge X-rays) of detector i, $\epsilon_c = 0.98$ is the efficiency of the coincidence, $D = 9.91$ mm is the distance between source and detector surface plus the mean free path of incident photon in germanium, $\tan(\vartheta_{max}) = R/D$ where $R_1 = 7.98$ mm is the radius of detectors. Δt is the time of measurement and for the groups 1 to 4 it was 366, 893, 682, 819 hours, respectively. a is the channel width (keV per channel) equal to 0.1415 for detector 1 and 0.1402 for detector 2. r describes the effective radius in the shield and is given by the following relation:

$$r^2 = r_0'^2 + (r_0^2 - r_0'^2)\exp(-\mu_{Al}d_{1Al}) + \frac{1}{4\mu_{Al}^2}[1 + 2r_0\mu_{Al} - (1 + 2r_1\mu_{Al})] \times$$
$$\exp(-2(r_1 - r_0)\mu_{Al}) + \exp(-2\mu_{Al}d_{2Al})[1 + ar_1 - (1 + ar_2)\exp(-a(r_2 - r_1)]/a \tag{2}$$

where $a = (2d_{Cu}\mu_{Cu})/(r_2 - r_1)$, $r_0 = 0.613$ mm and $r_0' = 0.749$ mm are the radii of the holes in the two aluminium plates of the shield and $r_1 = 0.875$ mm, $r_2 = 1.035$ mm are radii in copper and gold openings in the shield, respectively, μ_{Al} and μ_{Cu} are linear attenuation coefficients for aluminium and copper [9]. The numerical value of thicknesses of Al and Cu are $d_{1Al} = 0.4$ mm, $d_{2Al} = 0.3$ mm and $d_{Cu} = 0.25$ mm.

The experimental results for $d^2\sigma/d\Omega dE$ for all four groups (the two incident energies and the two energy axes), together with the results of calculations, are presented on the absolute scale in Figs. 2 and 3. The indicated standard deviations are statistical only. An uncertainty of the absolute values of the double-differential Compton cross sections due to the geometrical factors, is about ±9 % (not included in Figs. 2 and 3).

Energy range is limited by overlap of spectra in the low-energy region and by the threshold of the discriminator (≈ 8 keV) in the high-energy region. The calculation of the overlap of spectra recorded by detectors shows that it is about 15 % for the lowest energy point (31.4 keV) for incident energy of E_0 = 55.791 keV and decreases rapidly to a negligible amount for higher energy Compton photons. For the incident energy of E_0 = 54.612 keV, the overlap of spectra is a few percent for the lowest point (33.3 keV).

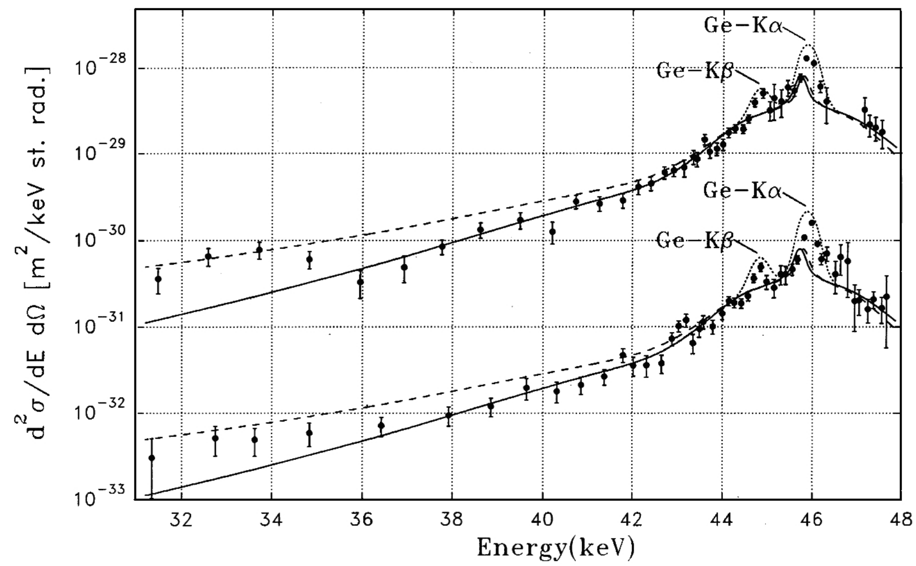

Fig. 2. Compton profile for incident photons of 55.791 keV. *Experimental data are shown by full circles. Full line and dashed lines show the results of calculations using the impulse and the "A^2- Born" approximation, respectively, and the dotted lines shows the sum of the results of calculations for the cross-talk between the detectors via Ge K X-rays and of the impulse approximation. Upper data are due to the detector 1 and lower data (multiplied by the factor 0.01) are due to the detector 2.*

In analysis of the data, the continuum of the coincidence peaks due to the K and L transitions in Hf atoms was taken into consideration. The continuum was represented by a linear or quadratic polynomial as a function of the channel number. Its influence on Compton spectra is from ≈ 45 keV to the high energy end in case of E_0 = 55.791 keV and from ≈ 43 keV to the high energy end in case of E_0 = 55.612

keV. The continuum varies from a small contribution to a very large one, where it exceeds Compton data by a factor of up to 10.

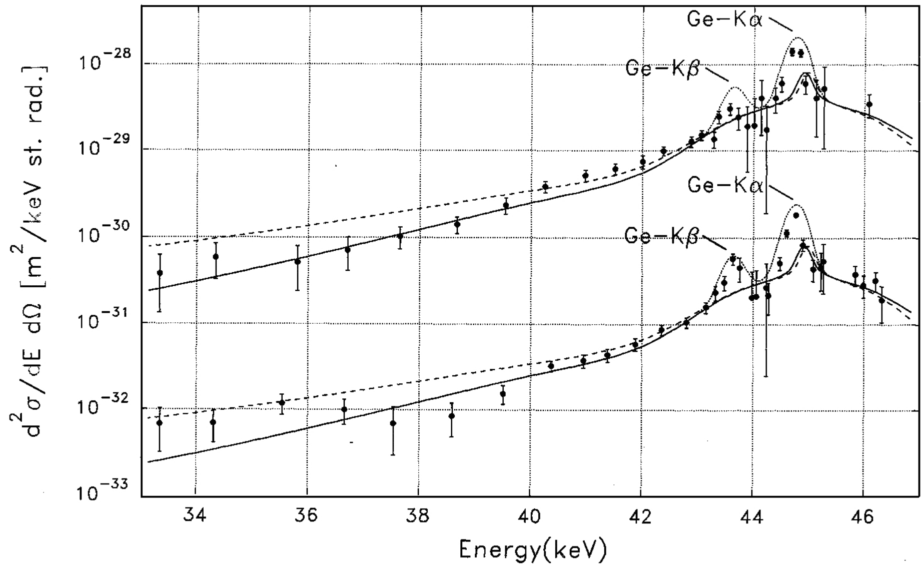

Fig. 3. Compton profile for incident photons of 54.612 keV. *Experimental data are shown by full circles. Full line and dashed lines show the results of calculations using the impulse and the "A^2- Born" approximation, respectively, and the dotted lines shows the sum of the results of calculations for the cross-talk between the detectors via Ge K X-rays and of the impulse approximation. Upper data are due to the detector 1 and lower data (multiplied by the factor 0.01) are due to the detector 2.*

The experimentally obtained Compton spectra contain two additional peaks. They are due to the cross-talk via characteristic germanium Kα ($E = 9.876$ keV) and Kβ ($E = 10.98$ keV) X-rays. The cross-sections for the cross-talk peaks due to Ge K X-rays, shown in Figs. 2 and 3, have been corrected for absorption. Namely, Compton scattering of Kα_1 and Kα_2 X-rays of Hf in the region of the peaks is due to the transfer of photons of energy between 43.5 and 46.5 keV, while cross-talk via characteristic K X-rays of Ge is due to the transfer of photons of 9.876 and 10.98 keV. Their absorption on the way from the position of the scattering event in "the first" Ge detector to "the second" Ge detector is very different. In order to bring the data to the same experimental scale, the calculated cross sections for the cross-talk via Ge K X-rays were multiplied by the factor:

$$\frac{J_{0i} \times [\mu(E_0) + \mu(E_0 - E_\xi)] \times r^2(E_\xi) \times \epsilon(E_\xi) \times T}{J_{0j} \times [\mu(E_0) + \mu(E_\xi)] \times r^2(E_0 - E_\xi) \times \epsilon(E_0 - E_\xi)} \tag{3}$$

where $i, j = 1, 2$ or $2, 1$, $\mu(E)$ is the attenuation coefficient of germanium, E_ξ is

9.876 or 10.98 keV, $\epsilon(E)$ is efficiency of detection for photons of energy E at full energy peak and $T = 0.94$ describes attenuation of germanium X-rays in air, source and beryllium windows. The corrected theoretical values for cross-talk via Ge K X-rays exceed the experimental values by about 40 % on the average. Probable reason is an inadequate calculation of absorption of Ge X-rays in the neoprene glue that was used as the source carrier as we did not know the exact composition of the glue.

For the incident energy of $E_0 = 55.791$ keV, the data from ≈ 44.7 keV to the low energy end and for the incident energy of $E_0 = 54.612$ keV, the data from ≈ 43.5 keV to the low energy end, are as recorded in the measurement, i.e. no corrections to the numbers of counts were needed. No background subtractions was necessary, too. That is the most prominent experimental proof of the advantage of the coincidence method.

Theoretical calculations were based on the "A^2" approximation using the Born approximation [10] and the impulse approximation [10, 11]. If we take into account the incident energy and the binding energy of targets electrons, conditions for application of these approximations are justified [11, 12]. Good agreement between the impulse approximation and experiment was obtained.

5. *Conclusions*

The coincidence method for measuring the differential cross section, $\mathrm{d}^2\sigma/\mathrm{d}\Omega\mathrm{d}E$, in germanium (or in silicon) gives generally better results than the standard method, especially in the energy region below the Compton peak where the standard method gives increasingly unreliable results. The analysis of coincidence data showed that practically no background was observed despite the unusually time of measurement. Also, no corrections were needed in processing of the data. This makes the coincidence method simple and the results are more reliable.

The coincidence measurement of Compton scattering can be applied only in detector materials, and this is it's main disadvantage. Further, with the symmetrical set up (present experiment) two disadvantages were encountered: detection of coincident emissions from the source and overlap of the spectra recorded by the two detectors. We are convinced that with an asymmetrical experimental arrangement much better results for $\mathrm{d}^2\sigma/\mathrm{d}\Omega\mathrm{d}E$ would be obtained.

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COMPTONOVO RASPRŠENJE UNATRAG Hf RENDGENSKOG ZRAČENJA U GERMANIJU

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Diferencijalni udarni presjek, $\mathrm{d}^2\sigma/\mathrm{d}\Omega\mathrm{d}E$, za Comptonovo raspršenje unatrag mjerio se opažanjem raspršenja iz detektora u detektor i primjenom sudesne metode. Energije fotona bile su 55,791 keV i 54,612 keV i kut raspršenj $\vartheta = 180°$. Nova metoda daje bolje rezultate od ranije u kojoj se rabio sustav izvor–raspršivač–detektor. Rezultati mjerenja se uspoređuju s teorijskima, proračunatim na osnovi "A^2-Bornove" i na osnovi impulsne aproksimacije.