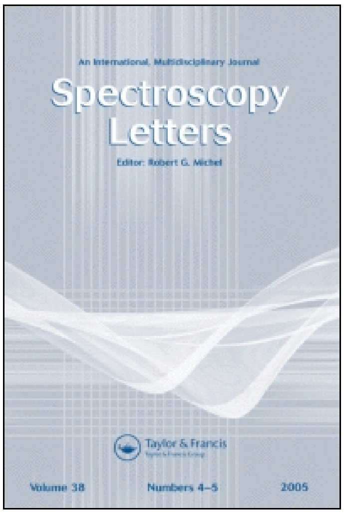

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Rayleigh Scattering of 59.5 keV γ-Rays by Mo and Sn

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Abstract

The differential cross sections for coherent scattering of 59.5 keV γ-rays by Mo and Sn were measured using a high-purity germanium detector. The results were compared with predictions of form factor theories and S-matrix calculations.

I. Introduction

At low energies elastic scattering of photons from neutral atoms is primarily to be understood in terms of scattering from bound electrons, leaving the target atom unchanged after scattering, generally called Rayleigh scattering[1]. At the energy of 59.5 keV the only contribution to elastic scattering is due to Rayleigh scattering by bound electrons. The terms "elastic scattering" and "coherent scattering" have often been used interchangeably in discussing Rayleigh scattering[2]. This leads to some confusion, the two concepts are not equivalent. While the Rayleigh scattering amplitude is both elastic and coherent, we shall understand these words to refer to different properties of the amplitude. By "elastic scattering" we shall understand that in the center-of-mass system of projectile and target, the incident and final projectile energy are the same; this implies in particular that there is no transfer of energy between projectile and internal degrees of freedom of the target.If $\hbar\omega$ is the energy of the incident photon and $\hbar\omega'$ is the energy of the scattered photon as measured in the center-of-mass frame, to say that scattering is "elastic" means that $\hbar\omega = \hbar\omega'$.On the other hand, by "coherence" we shall understand that it is only possible to definite a cross section for a process that corresponds to a transition between observable initial and final states. It may be convenient to definite such states in terms of their constituents, and in some cases the transition between states can be described in term of amplitudes for transitions among consitutents, but all such amplitudes corresponding to the same initial and final states must be summed before squaring to obtain a cross section. Note that coherence here does not refer to coherent states of photons; we will assume there is only one photon in the inital and in the final state. Coherence in the Rayleigh scattering amplitude first refers to the fact that in an independent-electron description of an atom one must add the amplitudes A^i for photon scattering off each of the atomic electrons. Furthermore, the Rayleigh scattering amplitude itself must be combined with other amplitudes to obtain the total atom elastic scattering amplitude A. In a commonly used approximation $A = A^R + A^{NT} + A^D + A^{NR}$, and the total atom cross section is proportional to $|A|^2$,where $A^R = \sum_i A^i$ is the Rayleigh scattering amplitude, A^{NT} is the nuclear Thomson scattering amplitude, A^D is the Delbrück scattering amplitude, and A^{NR} is the nuclear resonance scattering amplitude. In some circumstances (as in a lattice) the amplitude A for scattering from one atom must be added coherently to scattering amplitudes from other atoms, before squaring, to obtain a total scattering amplitude. With these definitions, amplitudes can be inelastic but coherent, or elastic but incoherent. But the Rayleigh amplitudes are elastic, and they are coherent with other elastic amplitudes.

In this study, whole-atom differential cross sections for coherent scattering for the elements Mo and Sn have been experimentally determined at 59.5 keV photon energy in the angular range of 55^o-105^o.

2. Experimental

The experimental setup used in the present investigation was given in our previous study[3]. The experiment is performed using a filtered point source of Am-241 of intensity 3.7×10^9 Bq (100 mCi) which essentially emits monoenergetic (59.5 keV) γ-rays. The source was housed at the center of a cylindrical lead shield of 1 cm diameter and 3.4 cm length. High-purity thin elemental foils of Al, Mo and Sn (all of purity higher than 99.5 %) were used as scatterers. The thickness of these foils ranged from 0.0057 to 0.0182 g/cm^2. A high-purity Ge detector N type was used to detect coherently scattered 59.5 keV γ-rays. The detector was also shielded by a lead collimator. The resolution of the detector of 200 mm^2 active area (FWHM) was found to be 230 eV at the 5.9 keV Mn Kα line. The manufacturer lists the Be window thickness as 130 μm and the gold contact thickness as 40.0 μg/cm^2. The detector was connected to a Nuclear Data series multichannel analyser. The spectra were recorded in a 1024 channel analyser. The target-detector and target-source distances were set to 3.2 cm and each circular target had an area of 25π mm^2. Each pulse height spectrum of scattered γ-rays was collected for 14400 s live time. Partly overlapped coherent and Compton peaks are resolved by a method proposed by Şahin et al.[4]. To obtain the net pulse height spectra of scattered γ-rays, a background spectrum without the scatterer was stripped from the spectrum acquired for the same time and experimental conditions. The self-absorption correction was performed for all samples used in our experiments[5].

As described by Basavaraju et al.[6], the error in the measured coherent scattering cross section $d\sigma_{coh}/d\Omega$ is reduced if the coherent scattering counts n_{coh} due to a target under study are compared with the Compton scattering counts n^{Al} due to an aluminum target. With such a procedure, the source strength and the detector solid angle do not need to be determined. Then we have the relation[7]

$$\frac{n_{coh}}{n^{Al}} = \frac{T}{T^{Al}}\frac{N}{N^{Al}}\frac{\epsilon}{\epsilon_c}[\frac{d\sigma^{Al}}{d\Omega}]^{-1}\frac{d\sigma_{coh}}{d\Omega} \tag{1}$$

where T^{Al} and T are, respectively, the transmission factors for Al at Compton energy and for 59.5 keV energy with the target, N^{Al} and N are the number of scattering atoms in Al and the scatterer, ϵ_c and ϵ are, respectively, the detector photopeak efficiencies for Compton and coherent scattered γ-rays[$(\epsilon/\epsilon_c)\approx$1 at 59.5 keV energy] and $d\sigma^{Al}/d\Omega$ is the Compton scattering cross section of an aluminum atom:

$$\frac{d\sigma^{Al}}{d\Omega} = \frac{d\sigma^{KN}}{d\Omega}S(x, Z = 13) \tag{2}$$

where $d\sigma^{KN}/d\Omega$ is the Klein-Nishina cross section per electron, $S(x, Z = 13)$ is the incoherent scattering function for Al, x is the photon-momentum transfer:

$$x = \frac{\sin(\theta/2)}{\lambda} \tag{3}$$

where θ is the angle of scattering, λ is the wavelength of the incident radiation in Ångström.

The theoretical coherent scattering differential cross sections are calculated by using

$$\frac{d\sigma_{coh}}{d\Omega} = \frac{1}{2} r_e^2 (1 + \cos^2\theta)[F(x, Z)]^2 \tag{4}$$

where, r_e is the classical electron radius, Z is the atomic number of the scattering atom and $F(x, Z)$ is the atomic form factor . Historically, the terms "atomic sacttering factor," "atomic form factor" and "atomic structure factor" have all been used in describing the elastic scattering of photons by atoms. The "atomic scattering factor" was defined by Hartree[8] as the "ratio of the amplitude of the wave scattered by this atom to the amplitude scattered by an electron."

3. Results and discussion

The experimental results for coherent scattering differential cross sections are presented with theoretical values calculated using nonrelativistic form factors(NRFF)[9], relativistic form factors(RFF)[10] and relativistic modified form factors(RMFF)[11] in Tables 1-2, and are also given the S-matrix results taken from the tabulations of Kane et al.[1] except for $\theta = 100^o$. S-matrix values are higher than the experimental scattering cross section for both Mo and Sn. The error associated in the evaluation of the photopeak area is less than 1.06%. The precision in the scattering angle is about ±4%. The estimated maximum overall error in the experimental scattering cross sections is smaller than 4.4%. This error arises due to various parameters involved in eq.(1) to evaluate the scattering cross sections.

The experimental results are also graphically compared with predictions of form factor theories in Fig.1-2. It is clear from Fig.1-2 that the present measured values differ slightly from the predictions of the RFF theory. Al-

Table 1. Comparison of experimental and theoretical differential cross sections for Mo in b/sr at 59.5 keV.

θ	x	Expt. $d\sigma_{coh}/d\Omega$		Theoretical $d\sigma_{coh}/d\Omega$			
		Present	Literature	NRFF	RFF	RMFF	S-matrix
(deg.)	(A^{-1})	work	expt.	Ref.[9]	Ref.[10]	Ref.[11]	Ref.[1]
55	2.219	1.209	-	1.439	1.503	1.418	1.60
60	2.403	1.152	1.28(5)[a]	1.181	1.239	1.164	1.33
			1.406(±0.058)[b]				
			1.306[c]				
65	2.583	0.981	-	0.980	1.030	0.963	1.10
70	2.757	0.801	-	0.816	0.854	0.796	0.922
75	2.926	0.697	0.741(30)[a]	0.682	0.715	0.664	0.777
80	3.090	0.613	-	0.572	0.603	0.558	0.660
85	3.248	0.473	-	0.484	0.516	0.475	0.570
90	3.399	0.424	0.513(20)[a]	0.415	0.449	0.412	0.500
			0.578(±0.027)[b]				
			0.5030[c]				
			0.380(±0.028)[d]				
95	2.544	0.363	-	0.365	0.398	0.364	0.449
100	3.682	0.338	-	0.335	0.360	0.327	-
105	3.814	0.314	0.392(15)[a]	0.318	0.331	0.299	0.383

[a]See Ref.(19)
[b]See Ref.(20)
[c]See Ref.(21)
[d]See Ref.(16)

Table 2. Comparison of experimental and theoretical differential cross sections for Sn in b/sr at 59.5 keV.

θ	x	Expt. $d\sigma_{coh}/d\Omega$		Theoretical $d\sigma_{coh}/d\Omega$			
		Present	Literature	NRFF	RFF	RMFF	S-matrix
(deg.)	(A^{-1})	work	expt.	Ref.[9]	Ref.[10]	Ref.[11]	Ref.[1]
55	2.219	2.052	-	2.061	2.212	2.056	2.34
60	2.403	1.802	1.90(8)[a]	1.629	1.746	1.618	1.86
			1.780(±0.076)[b]				
65	2.583	1.326	-	1.350	1.435	1.324	1.54
70	2.757	1.116	-	1.148	1.207	1.109	1.30
75	2.926	1.012	1.10(4)[a]	0.998	1.041	0.953	1.13
80	3.090	0.853	-	0.877	0.946	0.833	1.00
85	3.248	0.715	-	0.772	0.816	0.741	0.900
90	3.399	0.618	0.844(34)[a]	0.686	0.741	0.670	0.824
			0.826(±0.040)[b]				
			0.8259[c]				
			0.765(±0.045)[d]				
95	2.544	0.556	-	0.620	0.684	0.616	0.767
100	3.682	0.548	-	0.580	0.641	0.576	-
105	3.814	0.526	0.719(27)[a]	0.555	0.610	0.546	0.697

[a]See Ref.(19)
[b]See Ref.(20)
[c]See Ref.(21)
[d]See Ref.(16)

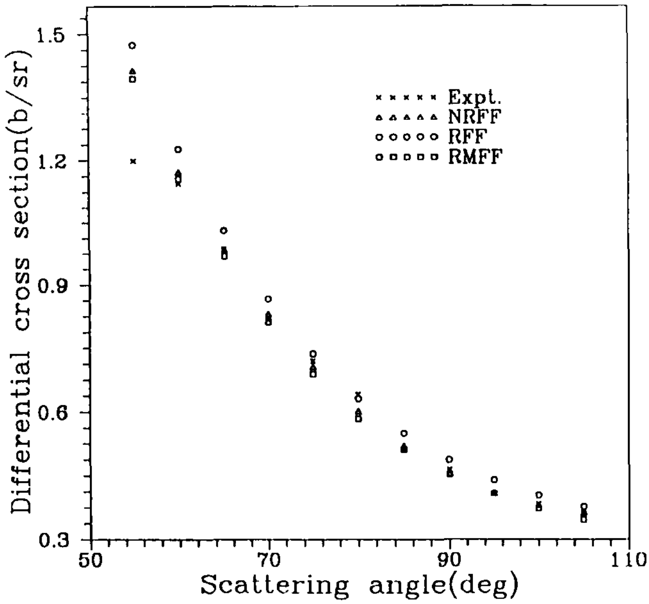

Figure 1. The differential cross sections vs scattering angle for Mo.

though our experimental results agree with the NRFF theory there is over all better agreement with the RMFF theory. So, the present experimental work upholds the superiority of the RMFF theory as reported by earlier investigators[3,5,7,11-18]. The percentage of difference between the experimental scattering cross sections and theoretical estimates calculated using the RMFF varies from 0.2 to 14.7% for Mo, 0.1 to 11.3% for Sn. The average difference is 4.05% for Mo, 4.57% for Sn. As pointed out by Rao et al.[17], the accuracy of the RMFF theory increases with decreasing binding energy of the electrons. This means that the relative difference between the RMFF and the exact calculation is smaller for light atoms than for heavy atoms and smaller for outer shells than for inner shells.

The differential cross section of Mo and Sn measured by Schumacher and Stoffregen[19], Nandi et al.[20], Casnati et al.[21] and Nayak et al.[16] in Table 1-2 support our present results at the 59.5 keV energy. There are no

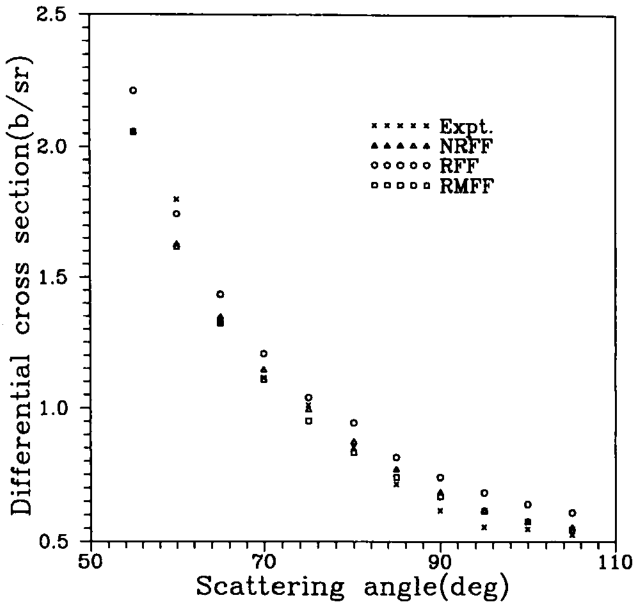

Figure 2. The differential cross sections vs scattering angle for Sn.

experimental data on differential cross sections reported in literature for 59.5 keV by Mo and Sn at these angles except for 60°, 75°, 90° and 105°.

This work show that the form factor theories in the intermediate photon momentum transfer region ($1 < x < 10Å^{-1}$) are successful in explaining γ-ray coherent scattering cross sections.

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