Atomic K-shell photoionization cross sections for ^{46}Sc and ^{60}Co γ rays

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Photoelectron spectra resulting from the interaction of ^{46}Sc (energy 889.2 and 1120.4 keV) and ^{60}Co (energy 1173.2 and 1332.5 keV) gamma rays with tin, tantalum, gold, lead, and thorium targets have been measured by the coincidence method developed by Ranganath *et al.*, for the direct estimation of K-shell cross sections in the case of radioisotopes emitting monoenergetic gamma rays. Since the two coincidence peaks (in both the cases) are not well resolved, K-shell photoionization cross sections are estimated by fitting a Gaussian to each peak. Good agreement is observed between the present cross sections and the theoretical cross sections.

I. INTRODUCTION

Photoionization is one of the major ways by which gamma radiation interacts with matter at low energies. Photoionization cross sections of atoms are of great utility in radiation physics in order to plan radiation shielding and in the study of the transport of radiation in planetary and stellar atmospheres. Also, increasing use of radioisotopes in the field of science and technology warrants an accurate knowledge of each process that gamma rays undergo during interaction. Investigations of the atomic photoionization have been primarily concerned with the K shell because about 80% of the total cross section is due solely from the K shell. In recent years, development of high-speed computers stimulated more and more refined exact numerical calculations of the photoionization. The current understanding of the theory of the photoeffect is reviewed by Pratt *et al.*[1] for incident photon energies above 10 keV. Scofield's[2] numerical calculations of 1973, using the Hartree-Fock-Slater potential have been considered fairly accurate in the photon energy region 1 to 1500 keV.

The experimental situation is rather different as direct measurements of the K shell photoionization cross sections are very scarce, particularly for photon energy above a few hundred keV. In this energy region, the usual subtraction method ceases to be useful.[1,3] Hultberg and Stockendal[4] were the first to measure K shell cross sections at photon energies 1.17 and 1.33 MeV in uranium by the beta-ray spectrometer method. These cross sections are lower than Scofield's theoretical values. Bleeker *et al.*[5] measured K-shell cross sections in lead for 1.33- and 2.75-MeV gamma rays by the same method. These values are high compared to that of Scofield. Prompted by these meager experimental data in this energy region and the discrepancies therein, the present investigation was taken up with a view to provide accurate cross sections.

Experiments using the coincidence technique have been finding ever increasing applications in atomic physics and notably in the studies of the ionization of inner atomic shells. As such a coincidence method developed by the authors[6] for the direct estimation of K-shell photoionization cross sections in the case of monenergetic photons has been successfully employed in the present case of ^{46}Sc and ^{60}Co radioisotopes which emit photons of energies 889.2 and 1120.4 keV and 1173.2 and 1332.5 keV, respectively.

Basically this method involes the detection of K-shell photoelectrons in coincidence with the corresponding K x-rays which follow the ejection of photoelectrons. A fast-slow coincidence assembly in conjunction with a multichannel analyzer was used in the present work. K-shell cross sections in tin, tantalum, gold, lead, and thorium were measured at photon energies 889.2, 1120.4, 1173.2, and 1332.5 keV and compared with the corresponding theoretical values.

II. EXPERIMENTAL

A schematic diagram of the experimental set-up is shown in Fig. 1. Photoelectrons released in the interaction of gamma rays with the target were detected by a flat 25.6-mm diameter, 3.26-mm thick NE-102 plastic scintillator optically coupled to an RCA 6199 photomultiplier. The plastic scintillator was covered with a thin aluminum foil and this was further covered with black adhesive tape except on the face of the crystal to the size of the target foil. K x rays were detected using an NaI (Tl) crystal 36 mm in diameter and 6 mm thick with a 0.12-mm beryllium window mounted on an RCA 6292 photomultiplier. Radiographic capsules of ^{46}Sc and ^{60}Co of 10-mCi strength each were obtained from the Bhabha Atomic Research Centre, Bombay, India. The isotope under investigation was housed in a lead cylinder with a collimating hole of 10-mm dia-

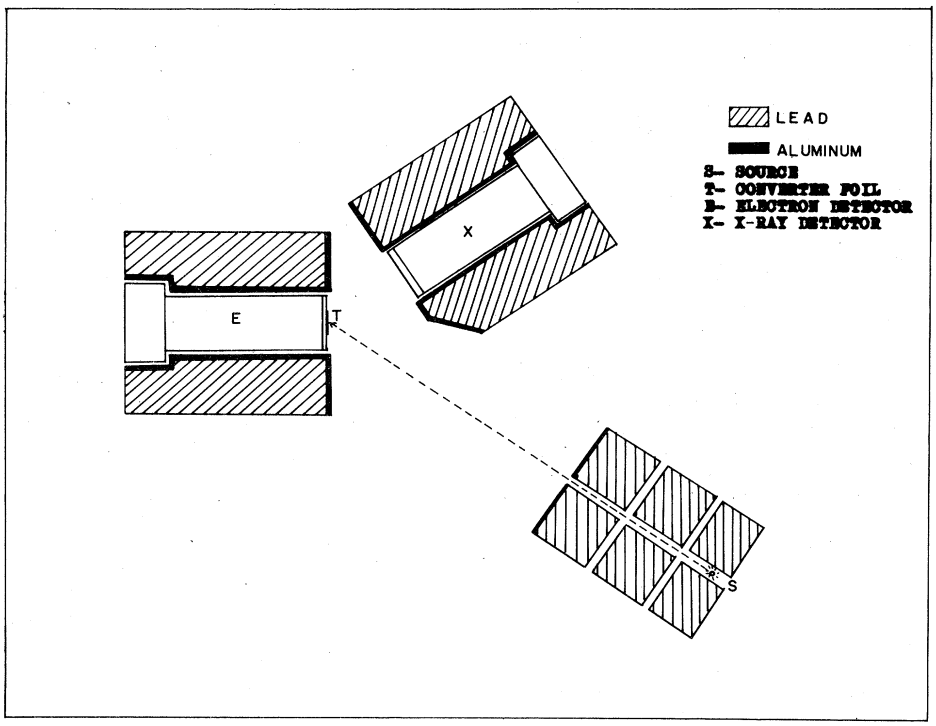

FIG. 1. Schematic diagram of the experimental setup.

meter and 55-mm length. The radiation leaving this collimator passed through another collimator with a collimating hole of 8-mm diameter and 70-mm length. Then it passed through a third collimator of collimating hole 6 mm and of length 70 mm, and finally hit the target foil under investigation which was placed on the face of the plastic scintillator. The two detectors were housed in a 40-mm thick lead shielding with aluminum linings to avoid crystal-to-crystal scattering. The distance between the source and the plastic detector was 45 cm. The K x-ray detector was kept at a distance of 8.8 cm from the target and at an angle of 120° with respect to the incident photon beam so as to reduce the gamma background of the direct beam. The two detectors and the source were all in the same plane. High-purity (99.9%) target foils of tin, tantalum, gold, lead, and thorium, each with diameter of 1.98 cm and respective thicknesses of 11.25, 13.5 12.0, 9.8 and 12.02 mg/cm^2 were used.

A conventional fast-slow coincidence assembly was used to handle the two outputs from each of the two detectors. Slow coincidence output was used to gate a 1024-channel analyzer. The resolving times in the fast and slow channels were 100 nsec and 1.5 μsec, respectively. The energy selection in the case of K x rays was achieved with a single-channel analyzer. A biased amplifier was used in the x-ray channel after the main amplifier in order to bias the crystal noise and thus reduce false coincidences. Between the slow and fast channels a suitable delay was introduced using a delay generator. All the electronic units were operated on an ac line voltage stabilizer. The experiment was carried out in an air-conditioned room in which the temperature was not allowed to vary by more than ±1 °C in relation to the normal temperature of 24 °C.

III. MEASUREMENTS

Photoelectron and K x-ray channels were first energy calibrated using standard gamma and x-ray sources. Singles spectra were then recorded with the experimental foil (target) mounted on the plastic scintillator for a known interval of time. The coincidence spectrum was then stored in the multichannel analyzer by gating the x-ray channel to accept K x rays from the target material under investigation while the single-channel analyzer in the photoelectron channel was operated in the integral mode. Front faces of the lead shielding housing the two detectors were covered with aluminum sheet of sufficient thickness to absorb lead K x rays originating from the shielding. Typical singles spectra of electron and K x-ray channels for ^{46}Sc gamma rays in tin target are

displayed in Figs. 2 and 3. Typical coincidence spectra for ^{46}Sc and ^{60}Co gamma rays in tin target are displayed in Figs. 4 and 5, respectively. As is evident from the coincidence spectra, a tail in the left portion indicates the unsuppressed Compton contribution. This was corrected using an aluminum target of almost equal dimension instead of the target under investigation. The contribution due to photoeffect in aluminum at these photon energies is very small and also it cannot be revealed by coincidence as the K x-ray energy was very low. So the recorded coincidence spectrum in the case of the aluminum target gives purely the scattering contribution which was less than 2% of the total coincidence events. This was subtracted from the target spectrum to give the final spectra which are also displayed in Figs. 4 and 5 (broken line). This technique was first used by Titus[7] in the case of singles spectrum.

The chance coincidence rate was measured by standard techniques and was used to correct the coincidence rate. Coincidence spectra for tin, tantalum, gold, lead, and thorium target foils were obtained with the K x-ray channel gated to accept 25.84-, 59.10-, 70.68-, 77.00-, and 95.79-keV x rays, respectively. Reproducibility was checked in all the cases. Figure 6 shows the linearity between the coincidence peak pulse hight and the photoelectron energy. An additional coincidence run was taken with thorium foil on the plastic detector, the source having been removed from the source position to account for the random coincidence rate due to natural activity of the thorium foil. The experiment was repeated for the ^{60}Co isotope. During the course of measurements, the storage time for coincidence spectra varied from 16 to 30 h, in which time sufficient coincidence events were recorded with a statistical uncertainty less than 2%. Since the target foil was placed on the face of the plastic scintillator itself, photoelectrons were detected in almost 2π geometry.

IV. SPECTRUM ANALYSIS

In order to calculate K-shell photoionization cross sections, we have to find out the total number of photoelectrons or K x rays released during the interaction. As can be seen from Figs. 4 and 5, the photoelectron peaks due to 889.2- and 1120.4-keV photons (Fig.4) and 1173.2 and 1332.5 keV photons (Fig.5) are not well resolved. This is due to the poor resolution of the plastic detector for electrons. To find out the number of photoelectrons under each peak, the spectrum analysis was made as follows. Generally the statistical processes in the detector following the energy transfer to the electrons, broaden the line corresponding to the total energy, and the full energy peak can be approximated (without background) as a Gaussian.[8,9] The scatter of the Gaussian is of course related to the resolution

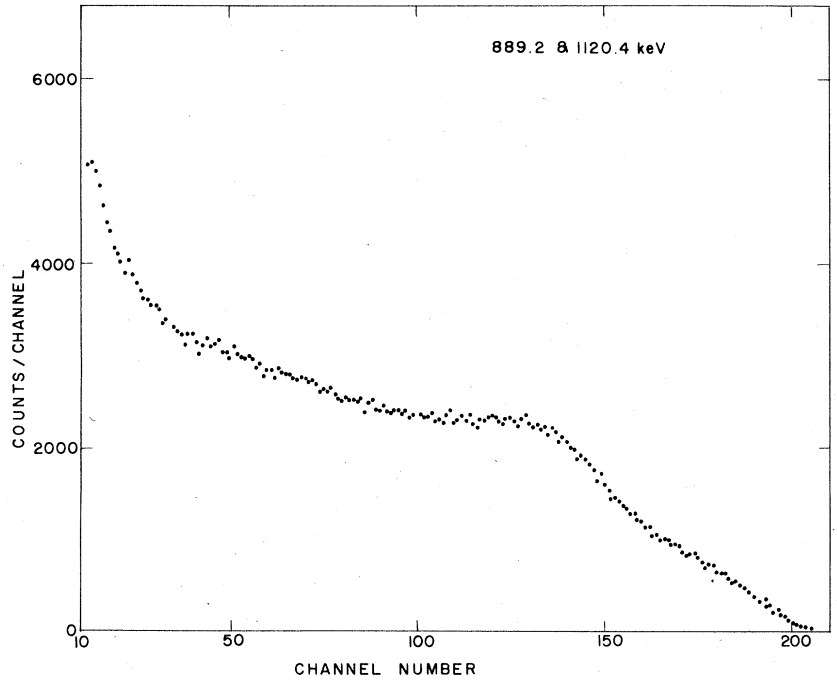

FIG. 2. Typical singles spectrum of electron channel in tin.

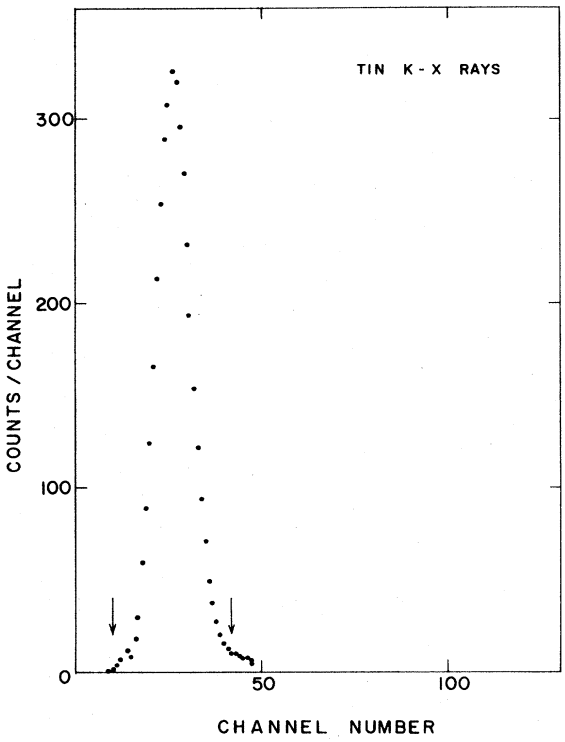

FIG. 3. Typical singles spectrum of x-ray channel in tin.

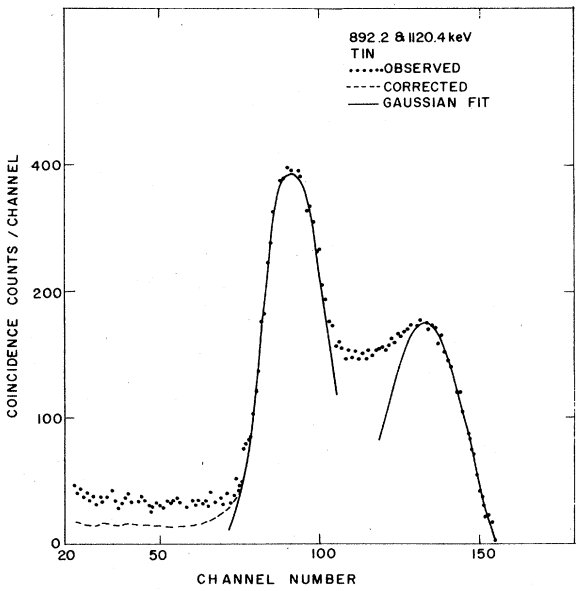

FIG. 4. Typical coincidence spectrum in tin for ^{46}Sc gamma rays.

of the detector. Therefore the Gaussian curve fitting was followed to estimate the number of coincidence counts under each peak. The parameters required for a simple Gaussian fit are

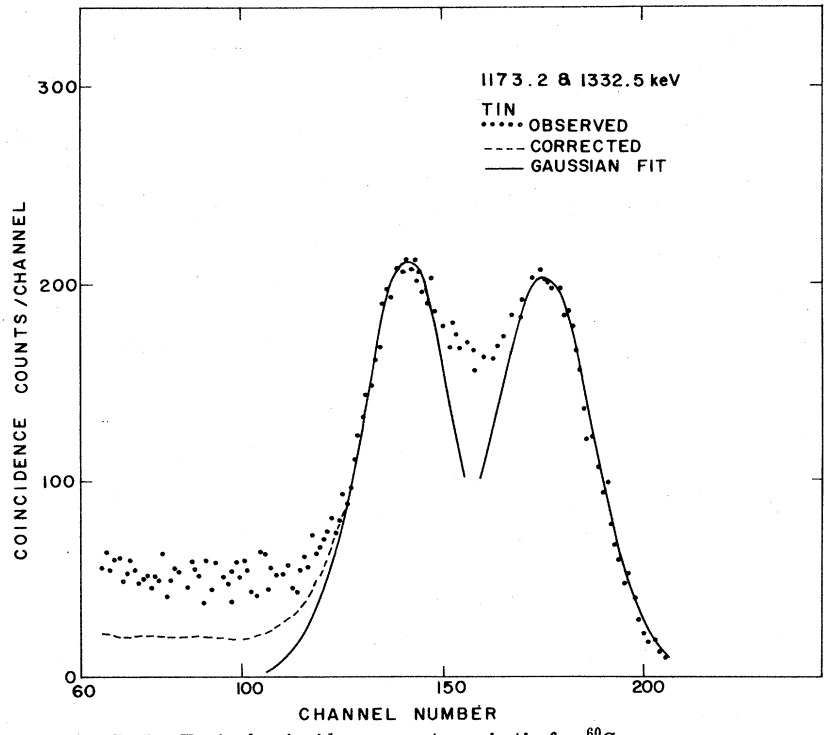

FIG. 5. Typical coincidence spectrum in tin for ^{60}Co gamma rays.

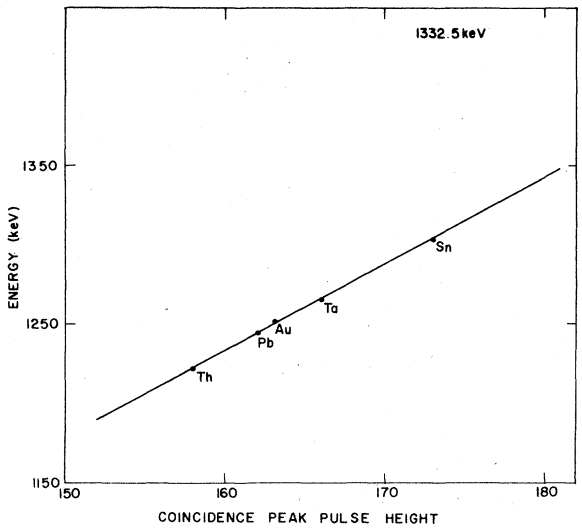

FIG. 6. Plot of coincidence peak pulse height against photoelectron energy.

the pulse height (or channel), amplitude of the peak (peak count rate), centroid of the peak (peak channel), and the peak width or full width at half maximum (FWHM). Except FWHM, all other parameters were experimentally known here. For a precise value of the centroid, the count rate was squared and the accurate channel value was determined.[10] The Gaussian width is energy dependent and therefore for the present energies, these Gaussian widths were interpolated and extrapolated from the experimentally measured Gaussian widths for monoenergetic photons 514, 661.6, 765.8, and 1115.5 keV (Fig.7). With these values, Gaussian fits were made to 889.2-, 1120.4-, 1173.2- and 1332.5-keV peaks (best fits). This fit is shown by the solid line in Figs. 4 and 5. Then the area under each peak was estimated to give the number of K-shell photoelectrons.

V. RESULTS AND DISCUSSION

The number of coincidence counts so estimated was corrected both for the chance coincidence rate and self-absorption in the target material. In the case of thorium foil, random coincidences due to the natural activity of the foil were also taken into account. It is known that photoelectrons have an angular distribution which has a very small backward component. Photoelectrons emitted in the forward direction only were detected in the experiment. The fraction that goes undetected for the lowest photon energy, 889.2 keV in tin and thorium targets, was found to be very much less ($<0.56\%$) according to Pratt *et al.*[11] and hence neglected. This corrected number N_k was then used to calculate the K-shell photoionization cross section σ_k using the relation

$$\sigma_k = N_k / NSw_k\epsilon_k\Omega \,, \tag{1}$$

where N is the total number of atoms present in the target foil, S is the gamma flux impinging on the target, w_k is the K x-ray fluorescence yield, ϵ_k is the photopeak efficiency of the x-ray detector for K x rays, and Ω is the fractional solid angle subtended by the x-ray detector at the target which is also called the geometry factor.

The total number N of atoms present in the target was estimated as follows. The mass m of the target foil was determined using the electrical balance and N was calculated according to the relation

$$NA = mL \,, \tag{2}$$

where L is the Avogadro number and A the atomic weight of the target material. The photon flux

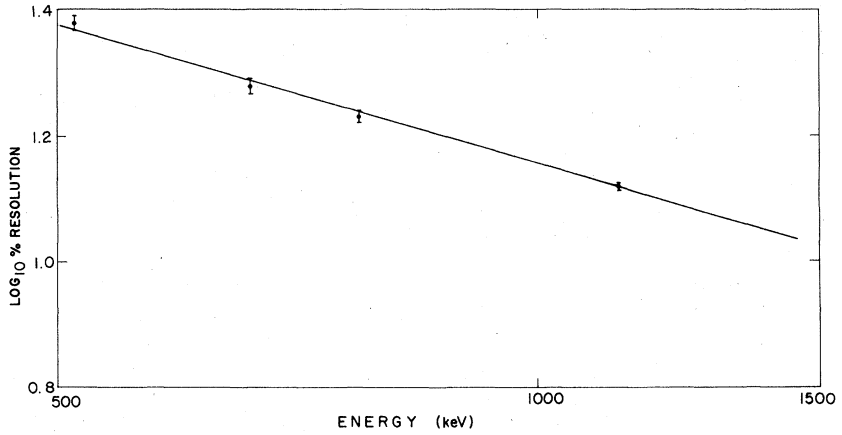

FIG. 7. Plot of percentage resolution of the plastic scintillator against electron energy.

TABLE I. K-shell photoionization cross sections (barns/atom). First line: present values. Second line: Schmickley and Pratt (Ref. 17). Third line: Scofield (Ref. 2).

Element / Energy (keV)	Tin	Tantalum	Gold	Lead	Thorium
889.2	0.701 ± 0.038	3.73 ± 0.19	5.27 ± 0.27	6.20 ± 0.30	9.23 ± 0.48
	0.735	3.90	5.53	6.50	9.68
	0.738	3.92	5.53	6.50	9.70
1120.4	0.434 ± 0.026	2.33 ± 0.14	3.28 ± 0.18	3.87 ± 0.22	5.80 ± 0.30
	0.457	2.45	3.46	4.07	6.10
	0.460	2.46	3.47	4.08	6.11
1173.2	0.399 ± 0.023	2.17 ± 0.13	3.00 ± 0.18	3.50 ± 0.20	5.36 ± 0.29
	0.417	2.24	3.16	3.72	5.57
	0.421	2.25	3.17	3.73	5.59
1332.5	0.308 ± 0.018	1.70 ± 0.10	2.40 ± 0.14	2.79 ± 0.16	4.25 ± 0.24
	0.328	1.76	2.48	2.92	4.38
	0.332	1.77	2.50	2.94	4.40
				3.24 ± 0.13 [a]	

[a] Bleeker *et al.* (Ref. 5).

S that was incident on the target foil was measured as described elsewhere.[12] In the case of ^{46}Sc, a short-lived isotope, decay correction was made while estimating the incident photon flux. The detector efficiency in both photoelectron and K x-ray cases was nearly 100%. The efficiency of the K x-ray detector ϵ_k was estimated using the absorption coefficients of NaI (Tl) crystal given by Davisson[13] for the effective K x-ray energies[14] of the targets used. This was found to be 100% and hence ϵ_k in relation (1) was taken as unity. The values of w_k were taken from the literature[15] and were available to an accuracy of 1%. The fractional solid angle Ω subtended by the K x-ray detector from the center of the target foil was approximately computed with an error of about 3%, using the formula of Jaffey[16] for the extended source or uniformly spread source, coaxial to the aperture of the crystal. K-shell photoionization cross sections so calculated are tabulated in Table I along with the theoretical cross sections and the only one measured cross section available in literature for comparison. The main sources of error in the present method come from the fractional solid-angle correction and the estimated number N_k. The error associated with the estimation of the number of photoelectrons (N_k) was about 4% because of Gaussian fit. The fractional solid-angle correction was associated with an error of about 3%. Statistical uncertainty was less than 2%. The error involved in the estimation of gamma flux S was less than 1% and that with N was less than 0.2%. Chance coincidence rate was less than 2% of the total coincident events. As such, the overall error (root-mean-square value) in the measured cross sections is not more than 6% in any case except in the case of tantalum at photon energy 1120.4 keV and gold at 1173.2 keV where it is 6%.

As it can be seen from the Table, there are no measured K-shell photoionization cross sections to compare with our results except in lead at 1.33 MeV. Therefore the present measurement is the first at these energies. It is also clear from the Table that the theoretical values of Schmickley and Pratt[17] and of Scofield[2] are in good agreement with the present experimental values.

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