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INTERNAL COMPTON EFFECT

by

E. FUSCHINI, C. MARONI, P. VERONESI
(Istituto di Fisica dell'Università — Bologna)

1963

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Internal Compton Effect (*).

E. FUSCHINI, C. MARONI and P. VERONESI
Istituto di Fisica dell'Università - Bologna

(ricevuto il 3 Agosto 1962)

Summary. — In this paper an experimental check on the internal Compton effect (I.C.E.) is presented. The experiment, performed using a ^{137}Ba source, consists of the measurement of the differential cross-section of the effect at 30°, 45°, 60°, 90°, 120°, 150° and 180° angles. The results are in satisfactory agreement with the theoretical calculation of Spruch and Goertzel.

1. – Introduction.

The internal Compton effect is a nuclear transition through which the excited nucleus decays emitting a γ-ray and an orbital electron simultaneously (more frequently a K-electron). The transition probability for I.C.E. was investigated by several authors. An earlier theory, due to COOPER and MORRISON (1), is valid for high-energy electric-dipole transition, but does not take into account the gamma-electron angular correlation. If one considers the process as an internal bremsstrahlung of the conversion electron, one can apply the theory formulated by CHANG and FALKOFF (2) for the internal bremsstrahlung in the β-decay. The theory of Chang and Falkoff was applied to the experiment of BROWN and STUMP (3) who firstly showed the presence of a continuous γ-spectrum in connection with internal conversion in the decay of ^{137}Cs.

(*) This work was supported by Euratom-C.N.E.N. contract.
(1) E. P. COOPER and P. MORRISON: *Phys. Rev.*, **57**, 862 (1940).
(2) C. S. W. CHANG and D. L. FALKOFF: *Phys. Rev.*, **76**, 365 (1949).
(3) H. B. BROWN and R. STUMP: *Phys. Rev.*, **90**, 1061 (1953).

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Later, a theory of the I.C.E. has been worked out by SPRUCH and GOERTZEL [4]. The γ-electron angular correlation is calculated in the Born approximation and for magnetic transition.

The I.C.E. for electric and magnetic transition was considered by JAKOBSON [5]. This theory is valid for nonrelativistic energies and does not take the γ-electron angular correlation into account. Finally MELIKIAN [6] has extended the Spruch and Goertzel theory to electric transitions.

Experimentally the γ-electron angular correlation is studied in the work of BROWN and STUMP. The experimental results show an isotropic behaviour and does not agree with the theoretical prevision. Another experiment has been made by LINDQVIST, PETTERSSON and SIEGBAHN [7]; the γ-electron angular correlation is found to be consistent with the theory of Spruch and Goertzel.

2. – Theory.

In the theory of Spruch and Goertzel for magnetic transition, the relative differential probability of the I.C.E. is calculated.

The relative differential probability $\partial^2 B_k(L, q, \theta)/\partial\Omega_\gamma \partial q$ is the ratio of the probability of the effect (for K-electron, magnetic multipole of order L, per unit photon energy interval and per unit solid angle of γ-ray) to the probability of a conversion transition of the nucleus.

The theory of Spruch and Goertzel gives:

$$\frac{\partial^2 B_k(L, \theta, q)}{\partial\Omega_\gamma \partial q} = \frac{e^2 m^2}{\pi^2 W^{2L-1}(W+2m)^{L+1}} \frac{P}{q} \cdot Q^{2L} \cdot H \cdot F\,, \tag{1}$$

where

$$H = (E')^{-2}\left[WP^2(1-\mu^2) + q^2E'\right] - \\ - (mE')^{-1}\left[qP^2(1-\mu^2)(mq+P^2-Pq\mu)Q^{-2}\right] + \frac{q}{m^2}\, qE' - P^2q^2(1-\mu^2)Q^{-2}\,,$$

$F = [(Q^2 - W^2)^2 + (2mW\alpha Z)^2]^{-1}$.

W = energy of the transition,

$E = W + m - q$ = energy of the electron,

[4] L. SPRUCH and G. GOERTZEL: *Phys. Rev.*, **94**, 1671 (1954).

[5] A. JAKOBSON: *Soviet Physics J.E.T.P.*, **2**, 751 (1956).

[6] E. G. MELIKIAN: *Soviet Physics J.E.T.P.*, **4**, 930 (1957).

[7] T. LINDQVIST, P. PETTERSSON and K. SIEGHAHN: *Nucl. Phys.*, **5**, 47 (1958).

P = momentum of the electron,

q = energy and momentum of the γ-ray ($c = 1$),

θ = angle between electron and photon direction,

$\mu = \cos\theta$,

$E' = E - P_\mu$,

α = fine structure constant,

Z = nuclear charge,

$Q = P + q$,

$e^2 = \alpha$,

L = order of multipole of the nuclear transition,

$m = 1$.

In the theory of Chang and Falkoff for the internal bremsstrahlung the probability that a β-particle emitted with energy W_e and momentum P_e will radiate a quantum of energy q, per unit photon energy interval and per unit solid angle of β-ray, is given by:

$$\frac{\partial^2 B(W_e, q, \theta)}{\partial q\, \partial \Omega_\gamma} = \frac{\alpha P}{4\pi^2 P_e q}\left[\frac{W_e + W^2}{W_e(W - P\cos\theta)} - \frac{1}{(W - p\cos\theta)^2} - 1\right], \qquad (2)$$

where P and W are, respectively, the momentum and the energy of the electron after the photon emission.

The formulas (1) and (2) have been numerically calculated for the magnetic transition of ^{137}Ba resulting from the β-decay of ^{137}Cs, whose well known decay scheme is shown in Fig. 1. In Fig. 2 the behaviour of (1) and (2), for different γ-energy values, is reported.

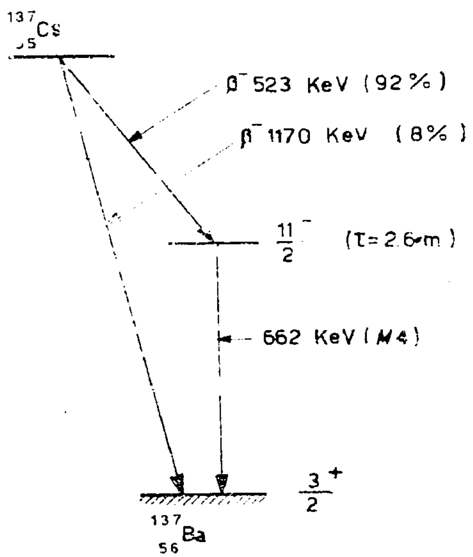

Fig. 1. – Decay scheme of ^{137}Cs.

The curves of Fig. 2 show that the angular correlation is considerably peaked for small angles.

The experiment of Brown and Stump shows isotropy in the $90° \div 160°$ angular interval; the experiment of LINDQVIST, PETTERSSON and SIEGBAHN was performed at angles larger than 90°.

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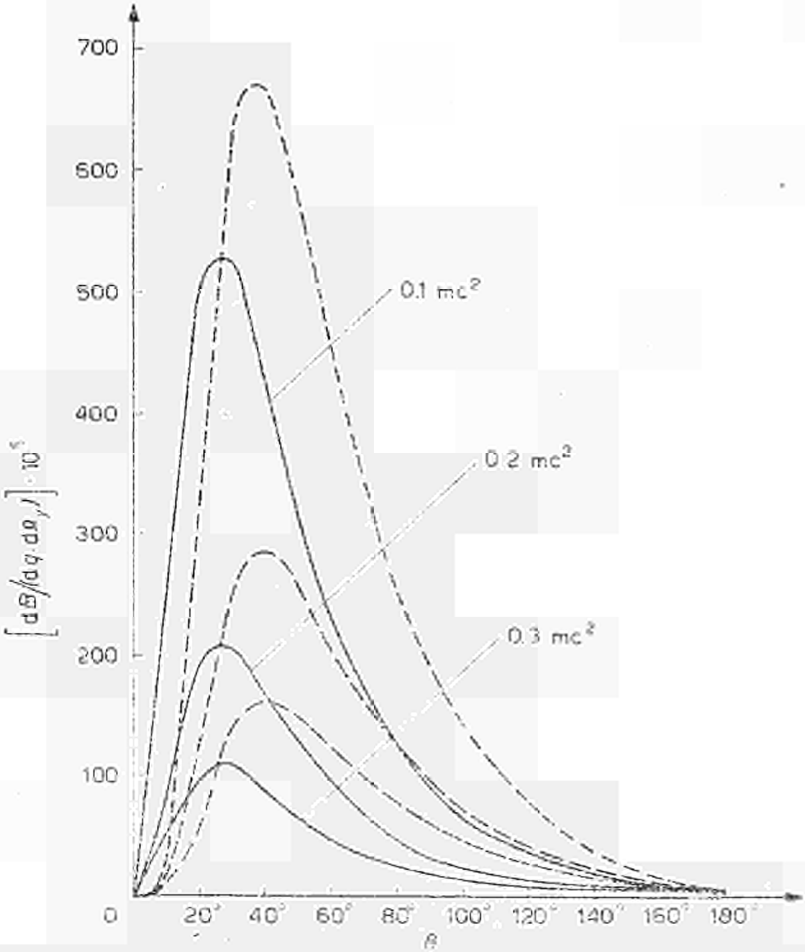

Fig. 2. – Differential cross-section of I.C.E.; the solid line corresponds to Spruch and Goertzel's theory; the dashed line corresponds to Chang and Falkoff's theory. The parameter is the energy of γ-rays.

An experiment of angular correlation at angles smaller than 90° can be hence a good test of the theory.

This is the purpose of the present experiment.

3. – Experimental method and apparatus.

From an experimental point of view the I.C.E. on the K-shell is studied detecting in coincidence the photon and the electron of the effect. (Obviously the photon energy plus the electron energy should be equal to the transition energy minus the binding energy of the electron in the K-shell.)

Other processes, as pointed out by LINDQVIST, PETTERSSON and SIEGBAHN, can take place in a β-γ coincidence measurement:

1) External Compton effect produced by the 666 keV γ-rays of the source
2) Conversion electron–X-ray coincidence.
3) Internal and external bremsstrahlung of the electron by the β-decay of ^{137}Cs.
4) I.C.E. on L-shell.
5) β-γ coincidences from ^{134}Cs always present in the source as a small contamination of the order of $(3\div4)\%$.
6) External bremsstrahlung of the conversion electron.

In principle some of the spurious events can be excluded, by a convenient choice of energy-channels.

For this, good energy resolution is required, mainly with respect to electrons. In the experiment of LINDQVIST *et al.* this condition was satisfied using a magnetic spectrometer. In our experiment we have followed a slightly different method, based on the detection of the X-ray following the K-electron emission. By a β-γ-X coincidence we can exclude events involving only two particles in the final state, like 1), 2), 3). Event 4) is excluded by selecting X-ray with a single-channel analyser. The presence of the event 5) has been evaluated and measured directly. The contribution to the counting rate was found to be significant only at large angles. This contribution was taken into account for the correction of the experimental data. The event 6) arises from the source thickness and from the air between source and β-counter.

The first contribution is negligible because of the small thickness of the source (~ 50 μg/cm^2), but rough evaluations show that the contribution of air is of the same order of magnitude as the effect under consideration. The counting rate due to the air could be eliminated working in vacuum, but the vacuum apparatus introduces some difficulties in the geometry.

By inserting a 3 mm thick Pb layer between γ ang β counters, the air contribution is made negligible. The experimental set-up is shown in Fig. 3; S is a 20 μCurie ^{137}Cs source, deposited on a thin carbon-coated mylar film, to insure electrical conductivity.

The electron detector, C_β, is a 1 in. diameter × 2 mm thick antracene crystal, optically coupled to a 12 cm long lucite light pipe.

The γ detector, C_γ, is a NaI(Tl) crystal 1 in. $\frac{3}{4}$ in diameter and $\frac{1}{2}$ in. thick. C_X, the X-ray counter, is a 1 in. diameter × 3 mm thick crystal of NaI(Tl) with Be window. The photomultipliers are 6810 A.

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C_X and C_β are in fixed positions with relative angle of 90°; C_γ can be rotated around C_β from 30° to 180°. The electronics is of fast-slow coincidence

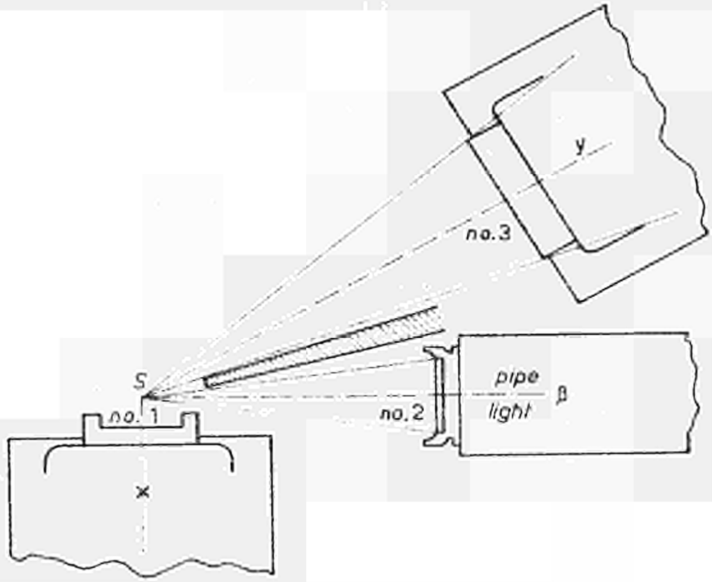

Fig. 3. – Experimental set-up.

tipe with a resolving time of 15 ns: the pulse analysis was performed by single-channel analysers D_X, D_γ and D_β.

4. – The experiment.

In the first part of the experiment we have looked for the presence of the effect.

In this preliminary measurement the angle between C_β and C_γ was 30°.

The single-channel analysers D_X, D_γ and D_β were set in order to accept, respectively, the photoelectric peak of ^{137}Ba X-rays, the gammas of energy between 50 and 150 keV and a range of about 70 keV in the energy-spectrum of the electrons.

In these conditions the energy spectrum of the electrons was taken; Fig. 4 shows the experimental result. The peak position agrees with the expected value.

The long tail at the bottom of the spectrum is due partly to energy spread caused by air and partly, mainly in the lower part of the spectrum, to back-scattering of the electrons of I.C.E. on the β detector.

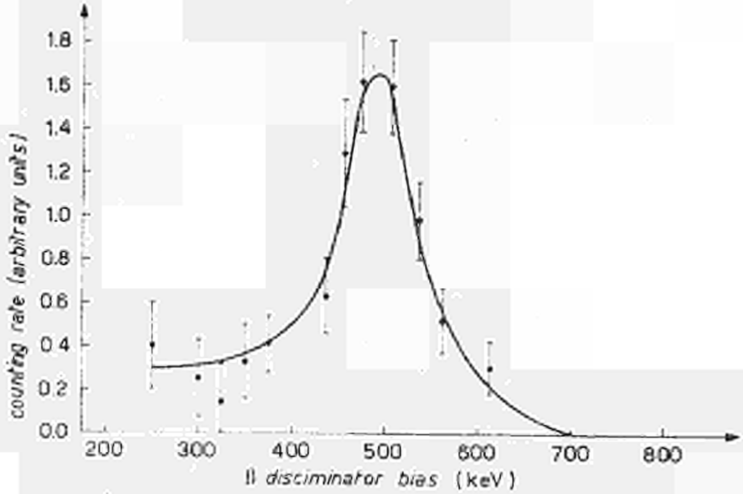

Fig. 4. – Coincidence spectrum of the electron.

Such a conclusion agrees with an experimental test done by taking similar spectrum of conversion electrons and by comparison with the results of other authors (8,9). The second part of the experiment dealt with β-γ angular cor-

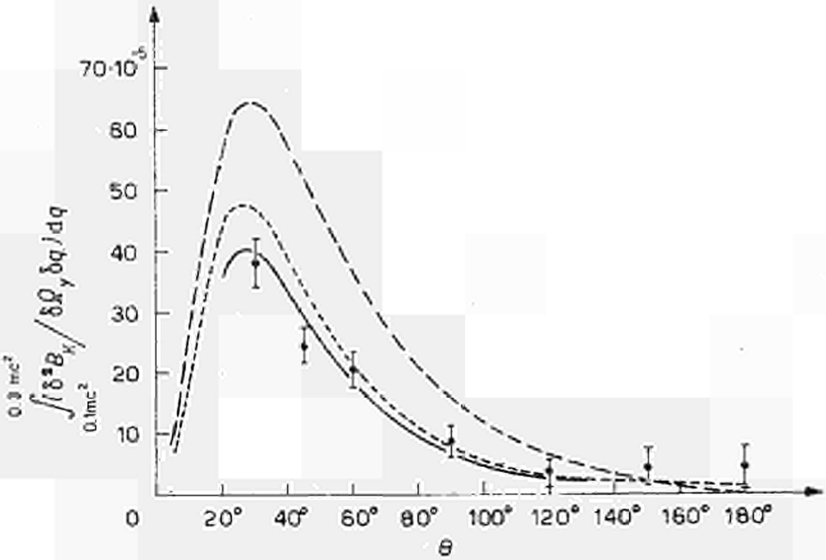

Fig. 5. – Angular correlation of the I.C.E.; solid line: Spruch and Goerzel's theory corrected for the geometry; dotted line: Spruch and Goertzel theory for pointform geometry; dashed line: Chang and Falkoff's theory for pointform geometry.

(8) W. Bothe: *Zeits. Naturf.*, **4a**, 542 (1949).

(9) G. Bertolini, F. Cappelloni and A. Rota: *Nucl. Instr. and Meth.*, **9**, 107 (1960).

relations. We detected the X-β-γ coincidences with a γ-ray energy range between 50 and 150 keV. In this case D_β works as an integral discriminator with a bias at about 445 keV.

The measurements were taken at 30°, 45°, 60°, 90°, 120°, 150°, 180° angles.

The experimental results are reported in Fig. 5. The dotted and dashed lines represent the behaviours of

$$\int_{0.1\,mc^2}^{0.3\,mc^2} \frac{\partial^2 B_k}{\partial\Omega_\gamma \partial q}\, dq\,,$$

(where $0.1 \div 0.3\, mc^2$ is the γ-energy range accepted by our apparatus) according to the theories of Spruch and Goertzel and Chang and Falkoff, respectively. The solid line shows the attenuation effect due to the geometrical arrangement.

The experimental and theoretical data are compared and underlined in the Appendix.

The results are in satisfactory agreement with the Spruch and Goertzel formula.

* * *

We are thankful to Mr. V. LEPRONI for the calculations at 650 IBM computer and to Mr. G. BUSACCHI and C. QUARANTINI for their assistance with the electronic equipment.

APPENDIX

If we take $\partial^2 E/\partial\Omega_\gamma \partial q$ as the absolute differential probability of I.C.E., we have for C_E, the measured coincidence rate,

$$C_E = I\,\frac{\Omega_\beta}{4\pi}\,\Omega_\gamma\,\frac{\Omega_X}{4\pi}\,\varepsilon_X\varepsilon_\beta\varepsilon_\gamma\varepsilon_c \int_{0.1\,mc^2}^{0.3\,mc^2} \frac{\partial^2 E}{\partial\Omega_\gamma \partial q}\, dq\,, \tag{A.1}$$

where:

I is the source intensity;

Ω_β, Ω_γ, Ω_X, ε_β, ε_γ and ε_X are solid angles and efficiencies of the detectors and ε_c is the efficiency of the coincidence circuit.

By assuming (IC) as the probability of the internal conversion we receive for C_{IC}, the β-X coincidence rate measured with the γ-detector off,

$$C_{IC} = I(IC)\,\frac{\Omega_\beta}{4\pi}\,\frac{\Omega_X}{4\pi}\,\varepsilon_X\varepsilon'_\beta\varepsilon'_c\,, \tag{A.2}$$

where, now, ε'_β is the efficiency for the detection of conversion electrons and ε'_c is the efficiency of the coincidence circuit without γ imput.

The ratio between (A.1) and (A.2) gives:

$$\frac{C_E}{C_{IC}} = \frac{\varepsilon_\beta}{\varepsilon'_\beta}\frac{\varepsilon_c}{\varepsilon'_c}\varepsilon_\gamma\Omega_\gamma\int\limits_{0.1\,mc^2}^{0.3\,mc^2}\left(\frac{\partial^2 E}{\partial\Omega_\gamma\,\partial q}\Big/\mathrm{IC}\right)\mathrm{d}q\,.$$

Bearing in mind that

$$\frac{\partial^2 E}{\partial\Omega_\gamma\,\partial q}\Big/\mathrm{IC} = \frac{\partial^2 B_K}{\partial\Omega_\gamma\,\partial q}\,,$$

and assuming

$$\frac{\varepsilon_\beta}{\varepsilon'_\beta} = \frac{\varepsilon_c}{\varepsilon'_c} = \varepsilon_\gamma = 1\,,$$

we obtain

$$\int\limits_{0.1\,mc^2}^{0.3\,mc^2}\frac{\partial^2 B_K}{\partial\Omega_\gamma\,\partial q}\,\mathrm{d}q = \frac{1}{\Omega_\gamma}\,\frac{C_E}{C_{IC}}\,.$$

RIASSUNTO

Si riferisce su un esperimento eseguito per mettere in evidenza l'effetto Compton interno. L'esperimento consiste nella misura della sezione d'urto differenziale dell'effetto agli angoli di 30°, 45°, 60°, 90°, 120°, 150° e 180°. La misura è stata condotta usando come sorgente un preparato di ^{137}Ba. I risultati sono in soddisfacente accordo con le previsioni teoriche di Spruch e Goertzel.