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VARIATIONS OF THE ABSORPTION COEFFICIENTS IN EXPERIMENTS WITH BETA-PARTICLES

E. VAPIREV, P. GROZEV, N. KRASTEVA, T. JORDANOV,
M. SEREZLIEVA, S. AMIN
University of Sofia, Faculty of Physics, 1164 Sofia, Bulgaria

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Abstract. Experiments have been performed for qualitative determination of the effect of geometry of the experiment on beta-ray absorption coefficients. It has been demonstrated that the reduction in a number of the beta-particles transmitted through absorbers is due mainly to the process of deflection from the initial direction. The influence of the geometry has been investigated for a ^{90}Sr(Y) source with a stilbene crystal and for a ^{147}Pm source with a silicon avalanche diode. An empirical relation for the number of beta-particles transmitted through an absorber which accounts for the geometry and the contribution of scattered electrons has been tested. The energy transfer for transmission and scattering has also been measured.

1. Introduction

In the process of transmission the beta-particles are reduced in number due to deflection from the incident direction (scattering) and energy shift below a threshold energy (absorption). The probability for a deflected beta-particle to be recorded by the detector depends on the relative position of source/absorber/detector or on the "geometry" of the experiment. The undefined geometry conditions in experiments, performed by different authors is a reason for the reported deviations of the measured absorption coefficients of the exponential dependence [1] as well as for the deviations of experimental data and empirical relations [2].

The purpose of the present investigation is: (*i*) the differentiation of the two main effects — scattering and absorption — to which the loss of electrons is attributed; (*ii*) search for a general relation which describes experimental observations on absorption of beta-particles at different source/absorber/detector positions.

2. Experimental

2.1. Experimental determination of the contribution to the reduction of the number of beta- particles in the process of transmission due to scattering and absorption

The experiment for measurement of the two effects for transmission is shown in Fig. 1.

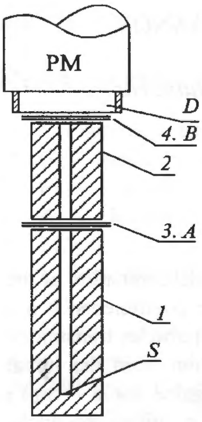

Fig. 1. Experiment for measurement of the contribution of the effects of scattering and absorption for the reduction of the number of beta-particles for transmission

D — scintillation detector (stilbene), *S* — source ^{90}Sr(Y), *1, 2* — plastic collimators, *3* — absorbers at position *A*, *4* — absorbers at position *B*

The detector is a stilbene crystal, ⌀30 mm, 10 mm thick, ≈ 1 mg/cm^2 Al window and the energy resolution for the 624 keV of ^{137}Cs is 14 %. The source (*S*) is ^{90}Sr(Y), 2.5×10^5 Bq, and is fixed in a plastic collimator (1), the internal diameter of the collimator is ⌀4 mm, collimation angle $\approx 2.5\,°$. A second plastic collimator (2) (⌀4 mm, collimation angle $\approx 5\,°$) is aligned above the first collimator at a distance 5 mm. The second collimator is at 5 mm distance from the detector window.

The plastic absorbers (*3, 4*) are placed at position *A* between the collimators and at position *B* between the second collimator and the detector.

The idea of the experiment is that for an absorber at position *A* all beta-particles which are deflected at an angle $\geq 5\,°$ from the initial direction do not reach the detector, or at position A the reduction of the number of beta-particles occurs due to both effects — scattering and energy shift below a certain electronic threshold (20 keV in this experiment).

For an absorber at position *B* all scattered beta-particles are recorded by the detector and the reduction occurs only (or predominantly) due to energy shift to lower energy.

The filters are plastic in order to reduce the effect of backscattering.

The experimental absorption curves for positions *A* and *B* are plotted in Fig. 2 in semilogarithmic scale. The effect of the position of the absorbers on transmission differs by an order of magnitude.

Definitely the dominant effect in the reduction of the number of beta-particles is the effect of scattering and hence the measured mass attenuation coefficients depend essentially on the relative position of absorber and detector.

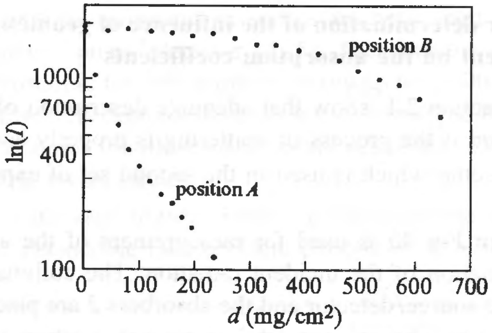

Fig. 2. Experimental absorption curves for positions *A* and *B*

The recorded beta-spectra (Fig. 3) confirm the conclusion that the reduction of the number of beta- particles is due predominantly to scattering in position *A* and predominantly to energy shift in position *B* for very thick absorbers.

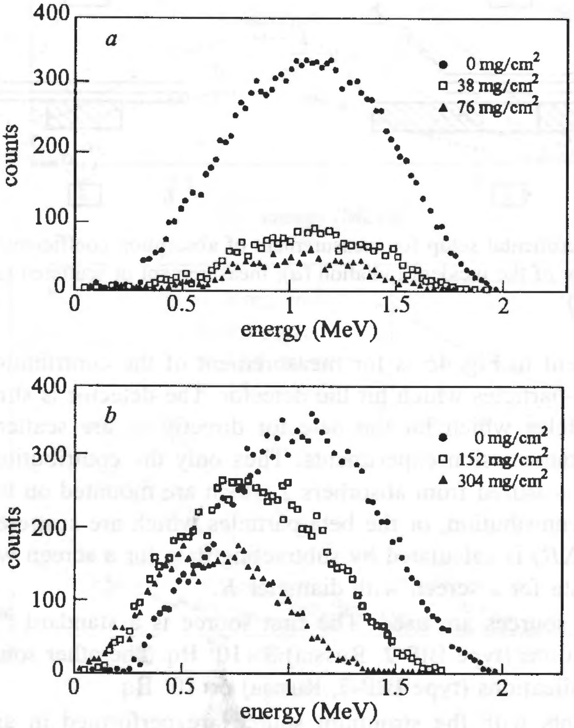

Fig. 3. Recorded beta-spectra for positions *A* (*a*) and *B* (*b*) for different absorber thickness

The beta-source is also thick and therefore the radiation from ^{90}Sr is almost totally absorbed and only the radiation from ^{90}Y reaches the detector.

2.2. Experiments for determination of the influence of geometry of the experiment on the experiment on the absorption coefficients

The experiments in section 2.1. show that adequate description of transmission experiments can be achieved if the process of scattering is properly accounted for.

The experimental setup which is used in the second set of experiments is shown in Fig. 4.

The arrangement in Fig. 4*a* is used for measurement of the absorption coefficient for the case of collimation of the incident radiation. The collimator *1* is fixed in the middle of the distance source/detector and the absorbers *2* are placed on the collimator. The middle position was chosen since it is a typical position in many experiments although the authors of [1] show that the absorption coefficient depends on the position absorber/detector. Since the major contribution to the absorption coefficient is from scattering, the value of the absorption coefficient decreases when the absorber is close to the detector and increases with the distance absorber/detector.

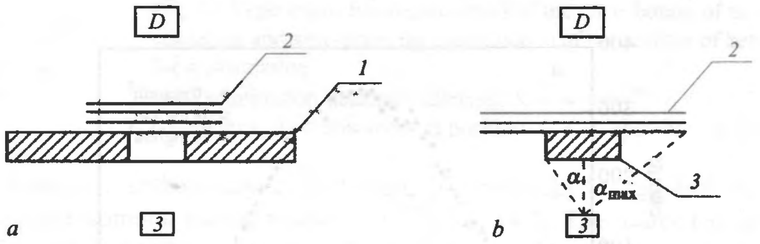

Fig. 4. Experimental setup for measurement of absorption coefficients for the case of collimation of the incident radiation (*a*); measurement of scattered radiation from α to α_{max} (*b*)

The arrangement in Fig. 4*b* is for measurement of the contribution of scattered in the absorber beta-particles which hit the detector. The detector is shielded by a screen *3* from beta-particles which hit the detector directly or are scattered at very small angles in usual transmission experiments. Thus only the contribution of the scattered beta-particles is measured from absorbers *2* which are mounted on the circular screen. The differential contribution, or the beta-particles which are scattered from a circular strip (R to $R + \Delta R$) is calculated by subtracting data for a screen with diameter R to $R + \Delta R$ from data for a screen with diameter R.

Two different sources are used. The first source is a standard ^{90}Sr(Y) source for industrial applications (type BIS-2, Russia) 3×10^7 Bq. The other source is ^{147}Pm, also for industrial applications (type BIP-7, Russia) 6×10^7 Bq.

The experiments with the strontium source are performed in air with a stilbene scintillation detector with a thin Al window and 10 % energy resolution for the 624 keV of ^{137}Cs [3]. The source and the detector are surrounded with plastic screens. All metal parts are covered with either plastic or thick paper in order to reduce background scattering. The source/detector distance is approximately 15 cm and the scattering from ≈ 18 mg/cm^2 air is inevitable. The absorbers are made from paper.

The experiments with the promethium source are performed in a vacuum chamber with a silicon avalanche "point" detector [4, 5]. The detector is with an active area 0.2 mm^2 and is spectroscopic for beta-particle energy up to ~ 300 keV, estimated energy resolution 1.5 %. The source/detector distance is ≈ 2.4 cm. The metal vacuum chamber is lined with plastic in order to reduce background scattering. The absorbers/scatterers are thin self-supporting mylar circles.

Both sources are with very high activity and therefore the scattering experiments are performed within reasonable measurement periods — 5 to 30 min per point.

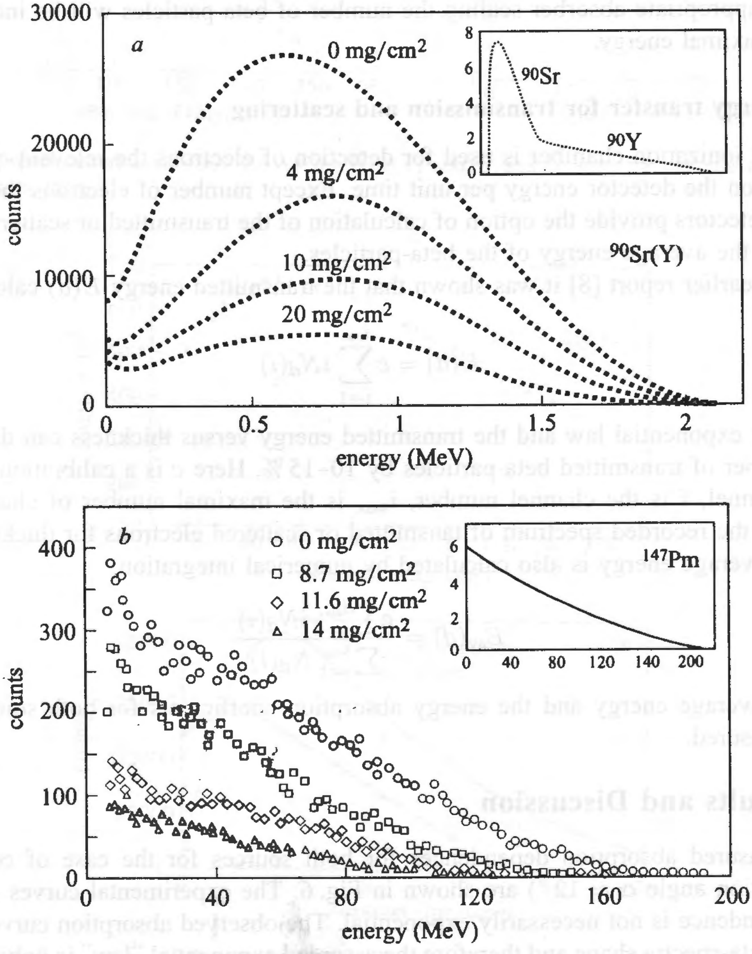

Fig. 5. Experimental spectrum of the used source ^{90}Sr(Y) measured with a stilbene detector (*a*), the spectrum of a thin ^{90}Sr(Y) source measured with a similar stilbene detector with 10 % energy resolution is plotted in the inset; (*b*) spectrum of the ^{147}Pm source measured with Si avalanche diode, the theoretical spectrum of ^{147}Pm is plotted in the inset [6]

The sources ^{90}Sr(Y) and ^{147}Pm were chosen because this pair has very different beta-spectra. The sources are thick and the emitted spectra are distorted and differ from the theoretical beta-spectra. The experimental spectra measured with stilbene detector and Si avalanche diode are shown in Fig. 5. A spectrum of thin ^{90}Sr(Y) measured with a detector with 10 % energy resolution is shown and the theoretical spectrum of ^{147}Pm is plotted in the inset [6].

The great difference in the end-point beta-energy is not a strong argument for choosing those sources since it has been shown that for appropriate scaling (e. g. in units of maximal range) beta-ray doses are independent of maximal energy [7]. It is expected that for appropriate absorber scaling the number of beta-particles will be independent of the maximal energy.

2.3. Energy transfer for transmission and scattering

When an ionization chamber is used for detection of electrons the relevant quantity is incident on the detector energy per unit time. Except number of electrons the spectroscopic detectors provide the option of calculation of the transmitted or scattered energy and also the average energy of the beta-particles.

In an earlier report [8] it was shown that the transmitted energy $E(d)$ calculated by

$$E(d) = c\sum_{i=1}^{i_{\max}} iN_d(i) \tag{1}$$

obeys an exponential law and the transmitted energy versus thickness can differ from the number of transmitted beta-particles by 10–15 %. Here c is a calibration constant, keV/channel, i is the channel number, $i_{\max}$ is the maximal number of channels and $N_d(i)$ is the recorded spectrum of tansmitted or scattered electrons for thickness d.

The average energy is also calculated by numerical integration:

$$E_{\mathrm{av}}(d) = \frac{c\sum_{i=1}^{i_{\max}} iN_d(i)}{\sum_{i=1}^{i_{\max}} N_d(i)} \tag{2}$$

The average energy and the energy absorption coefficients for both sources were also measured.

3. Results and Discussion

The measured absorption dependences for both sources for the case of collimation (collimation angle $\alpha \approx 12\,^{\circ}$) are shown in Fig. 6. The experimental curves show that the dependence is not necessarily exponential. The observed absorption curves depend on the beta-spectra shape and therefore the assumed exponential “law” is only a suitable approximation. At least two exponents are observed for both sources.

Averaged absorption coefficients μ_{col} (a fit over all experimental points) have been used in the further calculations.

The intensity of scattered radiation is shown in Fig. 7. Both curves are for emission angles from ^{90}Sr(Y) and ^{147}Pm sources between 12 ° and 65 ° (Sr) and 25 °

and 75 ° (Pm). The experimental data fit very well to the expression of the type $\mu_{\text{col}} d \exp(-\mu_{\text{col}} d)$. For ^{147}Pm the experimental data differ essentially for air and vacuum.

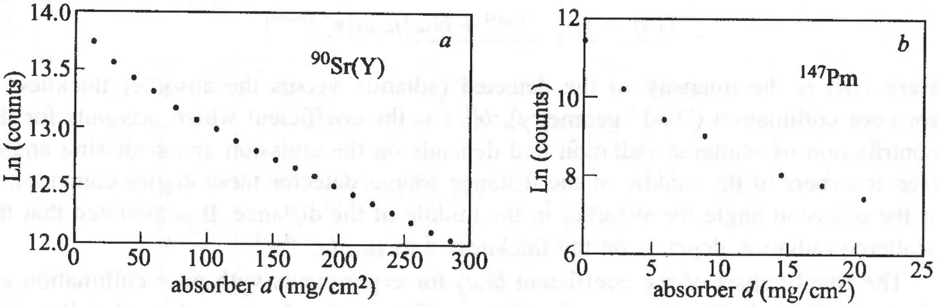

Fig. 6. Experimental absorption curves for ^{90}Sr(Y) and ^{147}Pm sources for the case of collimation ($\alpha \cong 12°$)

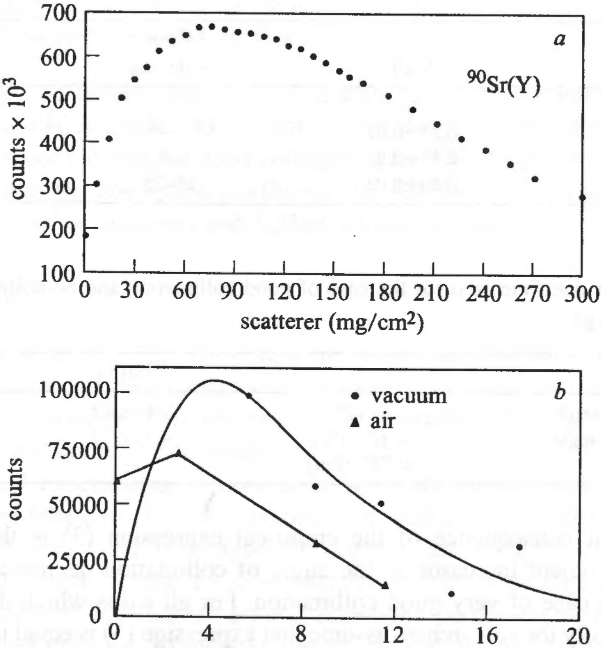

Fig. 7. Intensity of scattered radiation for emission angles from ^{90}Sr(Y) and ^{147}Pm sources between 12 ° and 65 ° (Sr) and 25 ° and 75 ° (Pm)

The detailed investigation of the intensity of the scattered radiation on the emission angle was possible only for the strontium source because of difficulties for exact geometry measurements in the vacuum chamber.

For geometries which differ from the case of good collimation we assumed that the experimental data can be fitted with an expression which accounts for transmitted and scattered radiation:

$$I(d) = I_0 \left[e^{-\mu_{col}d} + b(\omega)\mu_{col} d\, e^{-\mu_{col}d}\right] . \tag{3}$$

Here $I(d)$ is the intensity of the detected radiation versus the absorber thickness d for poor collimation ("bad" geometry), $b(\omega)$ is the coefficient which accounts for the contribution of scattered radiation and depends on the emission and scattering angles (for absorbers in the middle of the distance source/detector these angles coincide), ω is the emission angle for absorber in the middle of the distance. It is assumed that the scattered radiation depends on the thickness d as $\mu_{col} d e^{-\mu_{col}d}$.

The fitted values of the coefficient $b(\omega)$ for experiments with poor collimation are shown in Table 1. The average absorber coefficients for the case of good collimation and poor collimation are presented in Table 2.

Table 1. Contribution of the scattered radiation (coefficient $b(\omega)$) for different emission angles

^{90}Sr(Y) angle, deg	$b(\omega)$	^{147}Pm angle, deg	$b(\omega)$
0–12	0	—	—
12–22	0.23±0.02	—	—
22–40	0.45±0.03	—	—
40–65	0.50±0.03	25–75	0.8±0.05

Table 2. Absorber coefficients μ for the case of good collimation and no collimation for ^{90}Sr(Y) and ^{147}Pm, (cm^2/g)

		^{90}Sr(Y)	^{147}Pm
collimation angle	≈ 12°	7.85±0.2	243±20
collimation angle	≈ 65° (Sr)	4.40±0.1	—
	≈ 75° (Pm)	—	128±10

An important consequence of the empirical expression (3) is that the measured absorption coefficient increases as the angle of collimation decreases and its highest value is for the case of very good collimation. For all cases which differ from "good geometry" actually the researchers assume that expression (3) is equal to $I_0 \exp(-\mu_{exp} d)$ and the experimental value of the measured absorption coefficient μ_{exp} is less than μ_{col}.

The results from the experiments on energy transfer for ^{90}Sr(Y) are shown in Fig. 8 for transmission (*a*) and for scattering (*b*). The average energies are normalized to the average energy without any absorber, $E_{av}(0) = 0.820$ MeV, the average energy for ^{90}Sr(Y) for thin source is 196 keV (Sr) and 931 keV (Y) [6].

For transmission there is a slight increase of the normalized average energy due to absorption and scattering of the low energy electrons in the spectrum for thin absorbers.

Further the energy shift and scattering of the rest of the electrons prevail and the normalized average energy decreases.

The energy transfer for scattering (Fig. 8*b*) does not start from zero since there is inevitable scattering in the air.

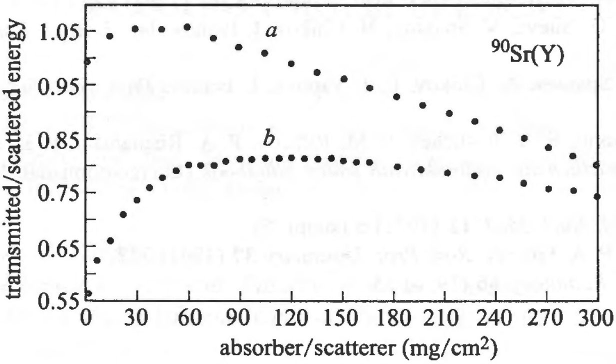

Fig. 8. Experimental results for the normalized average energy for ^{90}Sr(Y) for transmission (*a*) and for scattering (*b*)

The absorption coefficients for good collimation for ^{147}Pm for number of electrons and energy practically coincide 243±20 cm^2/g (number) and 248±20 cm^2/g (energy).

The absorption coefficients for good collimation for ^{90}Sr(Y) differ by approximately 25 % in reference to the absorption coefficient for number of electrons for good collimation 4.07±0.1 cm^2/g (number) and 5.22±0.15 cm^2/g (energy).

4. Conclusion

The experiments in section 2.1. show that the main contribution to the effect of reduction of the number of beta-particles in the process of transmission is scattering or deflection of beta-particles. This observation explains the effect of the influence of collimation on the absorption coefficient.

For the case of experiments without collimation the contribution of the scattered from the absorber beta-particles are accounted for with a relation of the type (3). The suggested dependence, which is the most important result of the report, is qualitatively similar to the Loevinger relation for dose calculation from point beta-ray sources [9].

Since the absorption coefficients depend essentially on the geometry of the experiment, the measured values in handbooks should be accompanied by information about the conditions of the experiments — degree of collimation and ratio of the distance (source-absorber)/(absorber-detector).

Acknowledgements

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