

DETECTOR CROSS REGISTRATION IN RECENT DOUBLY RADIATIVE np CAPTURE MEASUREMENTS

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The detection of γ -ray scattering in the recent Grenoble and Chalk River measurements of the doubly radiative np capture cross sections is investigated. Calculations show that such processes can account for about $(75 \pm 25)\%$ of the coincident events in all the measurements.

Recently Dress et al.¹⁾ reported a branching ratio of 10^{-3} for the two-photon to one-photon decay following np radiative capture. This value is several orders of magnitude larger than expected from conventional electromagnetic theory²⁻⁴⁾. Subsequently similar experiments have been performed in two different laboratories^{5,6)} yielding results which indicate that the branching ratio is $\leq 10^{-4}$. One of these⁵⁾ showed experimentally that the so-called two-photon events could be due to cross scattering involving the 2.223 MeV photon emitted in the single radiative np capture. For brevity, we refer to all such events as "cross talk".

It remains to calculate the magnitude of the various types of cross talk. In the experiments^{1,5)} two photon

events in which either γ -ray has less than a threshold energy $E_c \approx 600$ keV were rejected. This condition vetoed two obvious sources of cross talk; Compton backscattering of the 2.223 MeV γ -ray and positron annihilation in one detector followed by detection of a 511 keV photon in the second detector. Other possible sources of cross talk not rejected by the electronics are shown in fig. 1; (a) Doppler shifted 511 keV γ -rays due to annihilation of positrons in flight (APF); (b) the summing in one detector of an annihilation photon

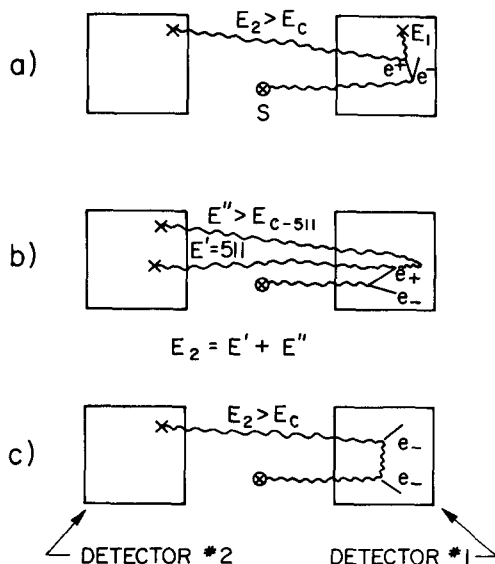


Fig. 1. Three mechanisms of cross talk considered in this work: (a) annihilation of positrons in flight; (b) annihilation of positrons at rest; and (c) multiple Compton scattering. The total energy deposited in both detectors must be 2223 keV. The cut-off energy E_c is ≈ 600 keV.

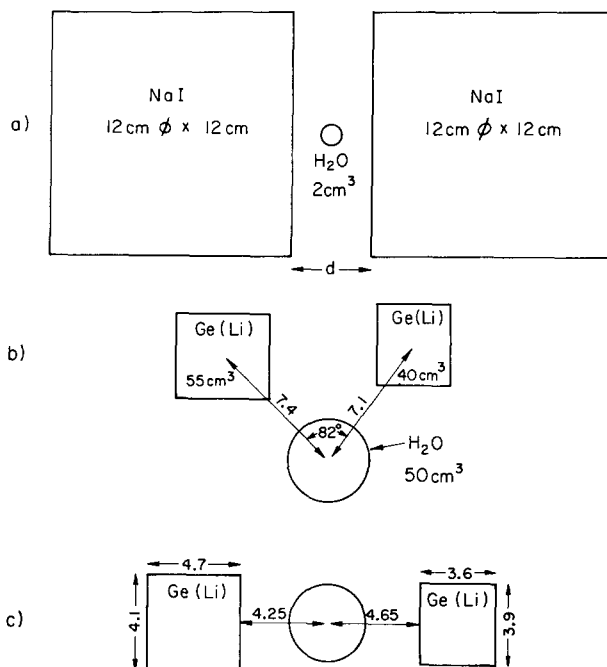


Fig. 2. (a) The three experimental arrangements at Grenoble referred to in the text as G5, G15 and G25, had d equal to 5, 15 and 25 cm respectively. (b) Chalk River experiment referred to as CR90 in text. (c) Chalk River experiment referred to as CR180 in text. The same detectors and source are used in (b) and (c).

and a Compton backscattered annihilation photon originating in the other detector from annihilation of positrons at rest (APR); and (c) multiple Compton scattering (MCS).

We have considered the effects of these three processes in the Grenoble¹⁾ and Chalk River⁵⁾ experiments. The experimental arrangements are shown in fig. 2. In the Grenoble measurements only the distance, d , separating the two NaI detectors was varied; the detectors were at 180°. We shall refer to the three measurements with d 5, 15, and 25 cm as G5, G15, and G25 respectively. In geometries used in the Chalk River measurements the angles subtended at the target by the two detectors were 90° and 180°. These geometries are referred to as CR90 and CR180. In all these measurements, except CR90, APF was the only significant source of cross talk accounting for about $(75 \pm 25)\%$ of the observed coincidence events. MCS was the major source of cross talk in CR90, accounting for about $(65 \pm 15)\%$; APF accounts for another $(23 \pm 8)\%$.

Annihilation of positrons in flight

Alburger⁷⁾ suggested that APF (see fig. 1a) may be an important source of cross talk in the Grenoble experiment. The ratio of coincident (or "two-photon") to single counts due to APF can be expressed as

$$(N_{2\gamma}/N_{\gamma})^{\text{APF}} = 2(N_{\pi}/N_{\gamma}) P_{f1}(1 - P_{E1}) R_{E1} P_{E2} \varepsilon_{E2}, \quad (1)$$

where (N_{π}/N_{γ}) is the ratio of e^+e^- pairs produced by the 2.223 MeV γ -ray to the single 2.223 MeV photons in the photo peak; P_{f1} is the probability that the positron annihilates in flight, and produces two photons with $E_1, E_2 > E_c$; $1 - P_{E1}$ is the probability that the photon with energy E_1 does not leave the

first detector (D1) without interacting at least once; R_{E1} is the photofraction of this photon in D1; P_{E2} is the probability that the second photon (with energy E_2) escapes D1 without loss of energy; ε_{E2} is the photopeak efficiency of the second detector (D_2); and the factor of 2 takes account of the possibility that the roles of the two photons with energies E_1 and E_2 respectively can be interchanged. For a more detailed calculation we should replace P_{f1} by the differential probability $P_{f1}(E_1, E_2)$ and integrate over E_1 and E_2 . The energy distribution of the positron created by the incident 2.223 MeV γ -ray can be estimated from Øverbø et al.⁸⁾ A mean energy of ≈ 1.1 MeV is expected. The angular distribution of these positrons with respect to the incident photon is nearly isotropic⁹⁾. The probability of annihilation in flight can be estimated from Heitler¹⁰⁾ and Kantele and Valkonen¹¹⁾. The energy and angular distribution of the photons following positron annihilation in flight have been reported by Kendall and Deutsch¹²⁾. For 2.223 MeV incident γ -rays the most probable result is for $E_1 \approx E_2 \approx 0.8$ MeV, and a reasonable value for P_{f1} is 3%. The error in P_{f1} due to the approximation used is expected to be $\leq 33\%$.

The interaction probability $1 - P_E$ is calculated using $P_E = e^{-\mu_E l}$ where μ_E is the total linear attenuation coefficient of a photon of energy E in the material and l is the distance travelled by the photon. We used the values given by Heath¹³⁾ for the attenuation coefficients for NaI, and values given by Storm et al.¹⁴⁾ for Ge. The mean free path of a 2.223 MeV photon in NaI is about 6 cm. This implies that on the average the positron is created and annihilated around the center of the NaI detectors. However the factor $P_{E2} \varepsilon_{E2}$

TABLE 1
Summary of results.

Measurement	$(N_{2\gamma}/N_{\gamma})_{\text{calculated}}$				$(N_{2\gamma}/N_{\gamma})_{\text{expt}^c}$	cal/expt. (%) ^d
	Annihilation in flight ^a	Annihilation at rest	Multiple Compton scattering ^b	Total		
G5	$13.5 \pm 4.5 \times 10^{-5}$	4×10^{-9}	$< 10^{-7}$	$13.5 \pm 4.5 \times 10^{-5}$	$19 \pm 1.9 \times 10^{-5}$	$(71 \pm 7) \pm 24$
G15	$4.2 \pm 1.4 \times 10^{-5}$	3×10^{-10}	$< 10^{-7}$	$4.2 \pm 1.4 \times 10^{-5}$	$6.0 \pm 1.0 \times 10^{-5}$	$(70 \pm 11) \pm 23$
G25	$2.0 \pm 0.7 \times 10^{-5}$	6×10^{-11}	$< 10^{-7}$	$2.0 \pm 0.7 \times 10^{-5}$	$2.8 \pm .45 \times 10^{-5}$	$(71 \pm 12) \pm 24$
CR90	$2.7 \pm 0.9 \times 10^{-6}$	1×10^{-7}	$7.6 \pm 1.7 \times 10^{-6}$	$10.3 \pm 2.6 \times 10^{-6}$	$11.7 \pm 1.1 \times 10^{-6}$	$(88 \pm 9) \pm 22$
CR180	$1.4 \pm 0.5 \times 10^{-6}$	3×10^{-8}	$< 10^{-8}$	$1.4 \pm 0.5 \times 10^{-6}$	$1.72 \pm 0.38 \times 10^{-6}$	$(81 \pm 17) \pm 29$

^a The error allows for the 33% uncertainty in the factor P_{f1} in eq. (1).

^b The error is the statistical error in the Monte Carlo result.

^c Values for the Grenoble measurements deduced from eq. (4).

^d Errors in brackets are experimental.

in (1) favors a smaller l . We used $l = 3$ cm in calculating P_{E_2} for the Grenoble experiments, and used $l = 6$ cm for P_{E_1} since the photon with E_1 can escape in any direction. For the Chalk River measurement we assumed the positron was annihilated at the center of the approximately 4 cm diam. $\times$ 4 cm long Ge(Li) detectors, i.e. $l = 2$ cm. The factor R_{E_1} was calculated with the aid of a Monte Carlo program using the appropriate attenuation coefficients. In this program photons with energy greater than 150 keV are treated realistically. However photons lost through the photoelectric effect and those degraded through Compton scattering to an energy less than 150 keV are assumed to have been detected in the photopeak. Thus the program has a tendency to overestimate the photofraction, R , or the photopeak efficiency ε of the detector. We find that for the NaI detectors our program was able to reproduce published values for ε and $R^{13,15}$ to within 10%. On the other hand, the calculated efficiencies for the Ge(Li) detectors are about a factor of two larger than the measured efficiencies¹⁶). This indicates that the calculated photofraction must be reduced by the same factor. The value for the pair to single ratio, N_π/N_γ , was also calculated by the Monte Carlo program. For the Ge(Li) detectors, this ratio was normalized to the measured efficiency. Putting all factors together, we have

$$\begin{aligned} (N_{2\gamma}/N_\gamma)_{\text{Grenoble}}^{\text{APF}} &= 2 \times 0.23 \times (0.03 \pm 0.01) \times 0.78 \times \\ &\quad \times 0.63 \times 0.47 \times \varepsilon_{E_2} \\ &= \varepsilon_{E_2} \times (3.2 \pm 1.1) \times 10^{-3}, \end{aligned} \quad (2a)$$

and

$$\begin{aligned} (N_{2\gamma}/N_\gamma)_{\text{Chalk River}}^{\text{APF}} &= 2 \times 0.80 \times (0.03 \pm 0.01) \times 0.50 \times \\ &\quad \times 0.15 \times 0.50 \times \varepsilon_{E_2} \\ &= \varepsilon_{E_2} \times (1.8 \pm 0.6) \times 10^{-3}. \end{aligned} \quad (2b)$$

The order of values in eq. (2) is the same as the symbols in eq. (1). The efficiency ε_{E_2} depends on the experimental geometry. For G5, G15 and G25 the efficiencies are 4.2%, 1.3% and 0.63% respectively. For CR90 and CR180 they are 0.15% and 0.075% respectively. The calculated values for $N_{2\gamma}/N_\gamma$ are listed in the second column of table 1.

Annihilation of positrons at rest

The ratio $N_{2\gamma}/N_\gamma$ due to APR (see fig. 1b) can be expressed as

$$(N_{2\gamma}/N_\gamma)^{\text{APR}} = 2(N_\pi/N_\gamma) P_{E'} \varepsilon_{E'} (1 - P_{E_1}) P_{E''} \varepsilon_{E''}, \quad (3)$$

where $E_1 = E' = 511$ keV and E'' is the energy of the backscattered photon, E_1 . The factor $P_{E'} \varepsilon_{E'}$ represents the probability that one of the annihilation photons is counted by D2 and the factor $(1 - P_{E_1}) P_{E''} \varepsilon_{E''}$ expresses the probability that the other annihilation photon is Compton backscattered in D1 and then deposits E'' in D2. In evaluating eq. (3) we ignore the slight angular anisotropy of the Compton scattered 511 keV γ -ray, and make use of the fact that the interaction of the 511 keV photon with detectors is dominated by Compton scattering and that $E'' \approx 170$ keV. The calculated values for $(N_{2\gamma}/N_\gamma)^{\text{APR}}$ are given in column 3 of table 1. Clearly cross talk from this type of event is negligible in the experiments considered.

Multiple Compton scattering

As mentioned earlier cross talk due to single Compton scattering of the 2.223 MeV γ -ray has been experimentally rejected by setting $E_c \approx 600$ keV. However, the γ -ray can be scattered through a large angle and at the same time retain a relatively large portion of its energy by suffering successive small angle scatterings (see fig. 1c). We have calculated the effect using the Monte Carlo program mentioned earlier. As expected the ratio $N_{2\gamma}/N_\gamma$ due to MSC is extremely sensitive to the experimental arrangement. In fact it has an exponential dependence on the average of the angle

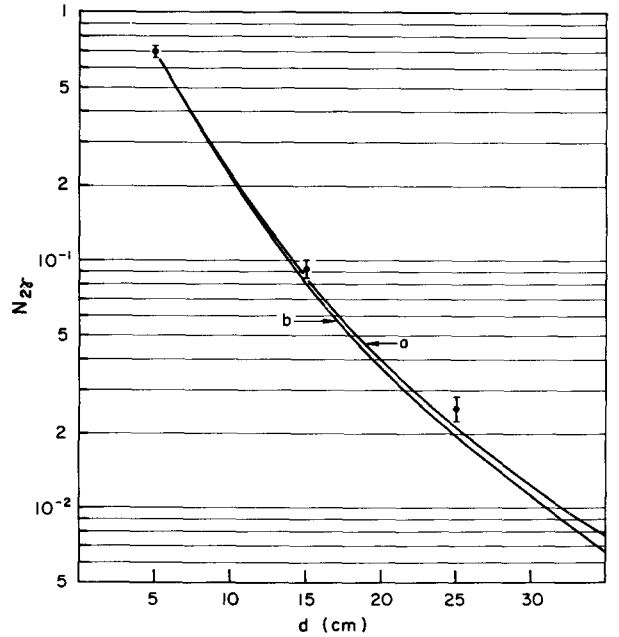


Fig. 3. Expected d dependence of two-photon counts due to (a) doubly radiative np capture, and (b) cross talk carried by annihilation of positrons in flight. Data points are from ref. 1.

required for the scattering of the γ -ray from D1 to D2. This average angle is 180° for all the measurements except CR90, which has an average angle of about 130° . This fact is reflected in the calculated values for $N_{2\gamma}/N_\gamma$, listed in column 4 of table 1. Only in CR90 was MCS an important cause of cross talk.

The total calculated coincident to single ratio due to cross talk is given in column 5 of table 1, and may be compared to the measured ratio given in column 6. The experimental ratios for CR90 and CR180 are obtained from Earle et al.¹⁶⁾ and those for the Grenoble measurements are obtained from the relation

$$(N_{2\gamma}/N_\gamma)^{\text{expt}} = \frac{\varepsilon_{E_1} \varepsilon_{E_2}}{\varepsilon_E} \frac{\sigma_{2\gamma}}{\sigma_\gamma}, \quad (4)$$

where $E_1 + E_2 = E = 2.223$ MeV, and $\sigma_{2\gamma}/\sigma_\gamma = 1.05 \times 10^{-3}$ is the ratio of (the supposedly) doubly radiative to single radiative cross-section, reported in ref. 1. The efficiencies¹³⁾ in eq. (4) are those measured for a source on axis, midway between the two detectors. We have used the mean energy division¹⁾, $E_1 = 800$ keV and $E_2 = 1420$ keV. The errors assigned to the deduced Grenoble ratios are estimated from the errors given in fig. 2 of ref. 1. It should be pointed out that, contrary to the assertion made there, the variation of the coincident counts with the separation d is consistent with cross talk. This is illustrated in fig. 3, where the coincident counts as expected (a) from double photon decay and (b) from cross talk due to APF are plotted as functions of d . The counts are normalized to that of G5.

The result of the present study is summarized in column 7 of table 1, where the calculated coincident count is given as a percentage of the observed count. The error in the bracket is experimental. A systematic

error of $\approx 33\%$ may be present in the theoretical result primarily owing to the uncertainty in P_{fl} . The mean calculated to experimental ratio is $(76 \pm 11) \pm 24\%$. We have thus shown that almost all of the coincident events seen in the five measurements discussed can be understood in terms of cross talk between the detectors and that there is no evidence for real doubly radiative events in np capture.

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