Observation of Two-Photon Decay in n-p Capture*

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Coincident γ rays of total energy 2.22 MeV, the deuteron binding energy, were observed following the capture of subthermal neutrons by an H_2O target. The differential cross section, assuming a $1/v$ neutron energy dependence, increases from about 0.2 μb/keV at equal γ energies to about 1.0 μb/keV for a γ energy of 1600 keV. The branching ratio for emission of two γ rays, both in the γ-ray energy range from 600 to 1620 keV, to single 2.22-MeV γ rays was found to be $(1.05 \pm 0.16) \times 10^{-3}$.

We wish to report the observation of two photons in coincidence following the capture of subthermal neutrons by hydrogen in an H_2O target. The sum of the energies of the coincident photons was equal to the binding energy of the deuteron ($E_0 = 2.22$ MeV) within the experimental error of 1%. This work was undertaken in response to calculations by Adler[1] who considered the possibility of two photons being emitted in transitions from the n-p continuum to the ground state of the deuteron as a result of a possible nonorthogonality of the wave functions as suggested by Breit and Rustgi.[2] An earlier experiment failed to observe such events at the 1-mb level, as reported recently by Arnold, Chertok, Schröder, and Alberi.[3]

The present experiment consisted in recording pulse heights associated with coincident events in a 64×64 two-dimensional array. The detectors were a matched pair of 12-cm×12-cm NaI(Tl) crystals, mounted on selected RCA 4522 high-speed, high-resolution photomultiplier tubes. The detectors were contained in a graded iron and lead housing to provide magnetic shielding and to reduce the number of events not originating in the target volume, which was midway between the two crystals. The target was 2 cm^3 of distilled water sealed in a bag of 0.006-mm-thick Mylar, placed inside a container made of 2-mm-thick LiF enriched in lithium-6; thus any neutrons not captured by the water or Mylar were absorbed in the lithium with the emission of very few γ rays. This precaution shielded the crystals from scattered neutrons and practically eliminated all background radiation from neutron capture in surrounding materials. The neutron beam from the high flux reactor at the Institute Laue-Langevin, Grenoble, France, was about 8 mm in diameter with an intensity of about 10^6 neutrons/sec and a mean wavelength of about 10 Å. The beam was conducted to the target area by a 12-mm-i.d. glass tube, 5 m long, after being collimated to the desired size.

The electronic system was a standard slow-fast coincidence arrangement.[4] The fast signals were derived from a dual-discriminator system wherein a pulse large enough to rise above the noise level was used to gate a second discriminator, delayed with respect to the first, and set at a much lower level to be responsive to the first few photoelectrons reaching the anode of the photomultiplier. The fast signal from detector x was used to start a conversion cycle in a time-to-amplitude converter, and the delayed fast signal from detector y provided the stop pulse. Pulses in the range corresponding to actual coincidences, as determined by the two coincident photons from ^{60}Co, were used to gate the "slow" side of the circuit which carried the spectroscopic information. The full width at halfmaximum was 4.6 nsec, and the energy resolution was 7.3% for the 1.33-MeV ^{60}Co γ ray. A window 9.6 nsec wide furnished the coincidence requirement for the measurements. The system was checked using targets of carbon, H_2O, D_2O, Mylar, and the empty ceramic target holder. All visible peaks in the region of interest were identified as being due to either hydrogen or oxygen. A calibration was performed with sources of known energy and strength, and a search was made for continuously distributed coincident radiation from the 2.7-MeV transition in ^{24}Na and the 2.14-MeV transition in ^{144}Ce. No unusual ridges corresponding to such continuously distributed radiations in the two-parameter spectra were observed during these tests.

With the H_2O target in place, a number of prominent features were immediately evident: Referring to Fig. 1, peaks corresponding to coincident 511-keV photons from pair production in the material near the crystals, coincidences between the 511-keV radiation in one detector and the first- and second-escape peaks (at 1.71 and 1.20 MeV, respectively) in the other, and a much smaller peak due to random coincidences of the 2.22-MeV photopeaks in both detectors are visible. The *xy* pulse-height space was calibrated for each run using peaks corresponding to the first- and second-escape photons, as well as three pairs of small peaks due to capture in oxygen. The normalization was obtained from the random-coincidence peak at (E_0, E_0), thus correcting for any reactor power-level changes and dead-time problems in the conversion electronics.

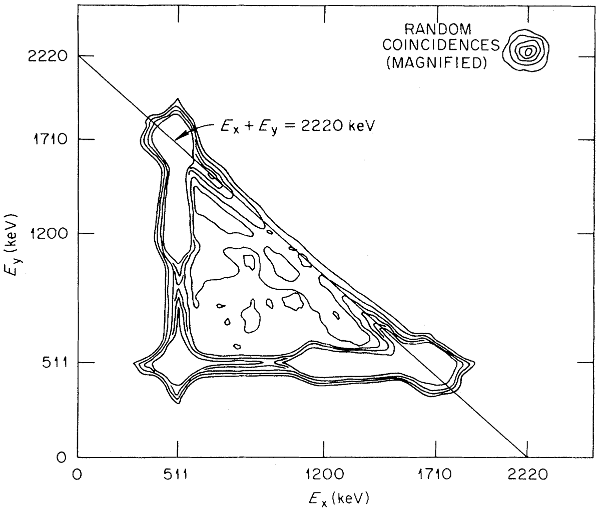

FIG. 1. Contours of yield for 16 h versus D_x and E_y. Contours of less than 1000 and more than 10 000 counts per channel have been suppressed in order to emphasize the ridge along $E_x + E_y = E_0$. The contours of random coincidences at (E_0, E_0) have been magnified to make the peak visible.

A diagonal ridge, running between the two first-escape peaks located at (511, 1710) keV and at (1710, 511) keV, was readily evident in the H_2O data, but absent in the other spectra. The top of the ridge was found to lie along line $E_x + E_y = E_0$ to within 1%. This unambiguously identifies the ridge as being due to *n-p* capture. The three explanations considered for this feature are (1) Compton backscattering from one detector into the other, (2) a tail of the coincident (511, 1710)-keV peaks, and (3) the simultaneous emission of two photons, possibly of the type first discussed by Göppert-Mayer,[5] or more recently by Adler.[1] Those events due to Compton backscattering may be avoided by excluding the region below a certain value corresponding to the maximum possible energy for a scattered photon consistent with the detector and target geometry. For a distance of 5 cm between the detectors and a target volume of 2 cm^3, possibly not centered, this maximum energy is about 600 keV. Accordingly, events below 600 and above 1620 keV were not included in the final results. The region between 600 and 1620 keV is, in principle, free of events due to Compton scattering. This hypothesis was checked experimentally in two ways: First, a run with low discriminator-bias settings was made. The 180° backscatter peak at 230 keV was easily visible, and contributions from the tail of this peak could not have been more than a few percent above 600 keV. Second, measurements were made at distances of 15 and 25 cm between the crystals, as well as at 5 and 3.7 cm. Figure 2 shows the integrated count rate with background subtracted in the range 600–1620 keV at 5, 15, and 25 cm separation normalized with respect to the rate obtained at 3.7 cm. The upper curve is the expected behavior if the source of both γ rays is the target volume between the crystals, and the lower curve is expected if the first detector is the source of the second photon. The data clearly favor the first case, so the explanation based on single or multiple Compton scattering with one detector as the source of the photon in the second detector must be excluded on experimental as well as on geometrical grounds. This agreement also confirms that the tails of the (511, 1710) and (1710, 511) keV peaks were correctly subtracted along the ridge $E_x + E_y = E_0$; as such, a contribution would lie along the lower curve.

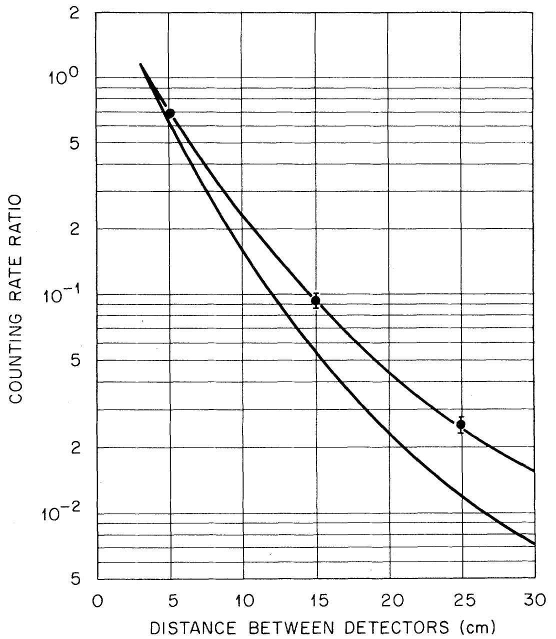

FIG. 2. Counting rate, relative to that at 3.7 cm, as a function of the distance between the detectors. The upper curve corresponds to the source of both photons at the target, and the lower curve would result if the source of the second photon were the first detector.

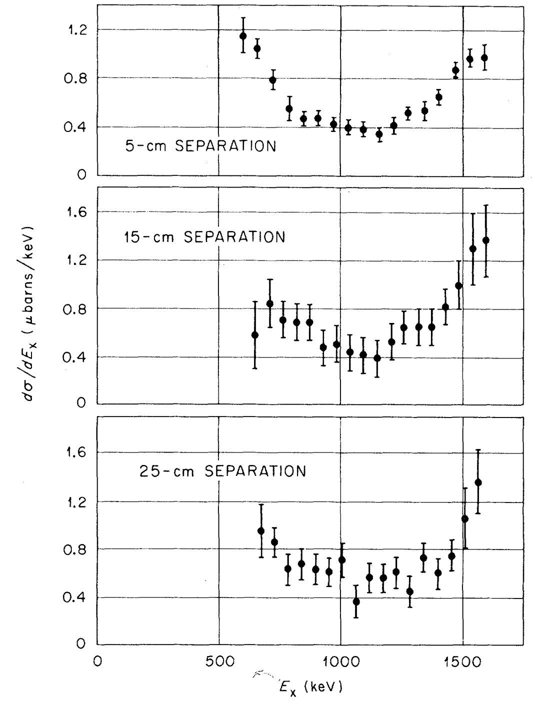

FIG. 3. Differential cross section for three different distances between the detectors plotted versus the energy of the photon incident on detector x.

If we assume that the presence of the ridge is the result of a two-photon process leading to the ground state of the deuteron, we are able to derive a cross section based on the value of the np-absorption cross section (σ_{abs}), on values of NaI(Tl) efficiencies given by Vegers, Marsden, and Heath,[6] on the detector geometry, and on the measured counting rates. We assume that σ_2 and σ_{abs} are both proportional to $1/v$, and that $\sigma_{abs} = \sigma_1 + \sigma_2$, where σ_1 and σ_2 are the cross sections leading to one and two γ rays, respectively. The counting rate for events leading to two γ rays was obtained by plotting cuts of the two-dimensional spectra taken approximately perpendicular to the kinematic ridge and removing background under the peak thus obtained by the usual stripping process. The uncertainty in this counting rate was due more to an uncertainty in removal of the background than to counting statistics. Figure 3 shows the differential cross section measured at three different detector separations. Note that if these differential cross sections are integrated one obtains twice the two-γ cross section. The ratio of the integrated two-γ cross section, in the range $600 < E_x < 1600$ keV, to the one-γ cross section was found to be

$$\sigma_2/\sigma_1 = (1.05 \pm 0.16) \times 10^{-3}, \tag{1}$$

where the error is a combination of counting statistics, errors due to background subtraction, and uncertainties in calibration, normalization, and detector efficiencies. The region outside of the indicated limits was inaccessible in this experiment because of interference by the first-escape peaks and the necessity of avoiding backscattered photons.

If we assume that $\sigma_{abs} = 334.2$ mb,[7] then we obtain

$$\sigma_2 = 350 \pm 50\ \mu\text{b}. \tag{2}$$

This value for σ_2 is approximately an order of magnitude larger than Adler calculates,[1] even in its limited energy range; thus it is unlikely that it can be due entirely to the speculated nonorthogonality of the wave functions.[2] It will be interesting to see if this result can be explained using the one-pion-exchange formalism as has worked so well in accounting for the interaction effect in the np-absorption cross section.[8]

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Recent Measurements of the Flux Excess from Solar Faculae and the Implication for the Solar Oblateness

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Direct observation of the excess brightness from photospheric faculae are presented. This excess brightness is, at times, large enough to produce an apparent oblateness that exceeds that reported by Dicke and Goldenberg. These results support the Chapman-Ingersoll facular explanation for the excess solar oblateness and support the findings of Hill *et al.* by offering a possible source for their excess equatorial brightness which, they showed, can produce an apparent, nongeometrical oblateness.

Dicke and Goldenberg[1,2] measured the shape of the sun using a special-purpose telescope at Princeton University in 1966. They found that the sun had an oblateness of approximately 5×10^{-5} and that this oblateness caused the perihelion advance of Mercury to no longer agree with the prediction of general relativity. Chapman and Ingersoll[3,4] proposed that photospheric faculae caused an excess equatorial flux that could have given the excess solar oblateness signal. These bright facular patches, which are associated with magnetic fields on the sun, were estimated to have an area and brightness sufficient to give approximately the equatorial-flux excess measured by Dicke and Goldenberg. Furthermore, the daily fluctuation in the Princeton oblateness signal was significantly correlated with a facular oblateness-type signal obtained by visually estimating the area of faculae on photographs of the whole sun. Since the actual facular-flux excess was not determined from the photographs, only the form of the fluctuations was used in the correlations with the Princeton oblateness signal. Depending on the unknown errors in the two signals, statistical estimates suggested that 35–100% of the excess oblateness could have been caused by faculae. Dicke[2,5,6] contested those results and devised statistical models in which the Chapman-Ingersoll facular signal only accounted for 14–17% of the excess solar oblateness. Most of the controversy has centered around statistical arguments and has not dealt with the estimated magnitude of the facular signal. This emphasis on the statistical discussion is due to the lack of quantitative measurements of the excess brightness from facular regions. Measurements of the contrast of a number of isolated faculae have been made[7] but these do not represent total excess brightness of any specific facular region.

The controversy might be settled by repeating