Two-Photon Decay of the 6.05-MeV State of ^{16}O

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A triple-coincidence, five-parameter technique was employed to search for two-photon emission in the decay of the ^{16}O(6.05-MeV) state. Data were event-recorded and analyzed in parallel with events associated with decay of the ^{16}O(6.13-MeV) and the ^{16}O(7.12-MeV) states. Our measured branching ratio is $N_{\gamma\gamma}/N_{\pi} = (2.5 \pm 1.1) \times 10^{-4}$.

Several experiments have been performed to search for two-photon emission in nuclear transitions. Most prominent have been investigations involving the decay of the first excited 0^+ states of ^{16}O, ^{40}Ca, and ^{90}Zr,[1-4] for which decay by single-photon emission is rigorously forbidden. Since the primary decay mode is internal conversion and/or pair emission, these cases are optimal for the observation of a competing second-order process such as two-photon emission.

Recent investigations on ^{40}Ca and ^{90}Zr have both reported the observation of two-photon decay, although each case involves experimental difficulties which introduce some ambiguity into the final result. The data of Beardsworth *et al.*[2] on ^{40}Ca contained evidence for an interfering γ-γ cascade in the region of interest, and the data of Asano and Wu[1] on ^{90}Zr required correction for a background line from ^{214}Bi which could not be resolved from the two-γ sum peak. Although ^{16}O should present the most favorable case from an experimental point of view, the picture here was confused since an upper limit was established[3] in the most recent experiment which was at least an order of magnitude below previously reported positive results.[4]

We have made a measurement of the two-photon branch of the ^{16}O(6.05-MeV) state using a multiparameter technique, which enabled us to collect sufficient information to provide positive identification of the decay mode. An important feature of the technique was the recording of the complete particle-γ-ray pulse-height matrix which made it possible to compare the two-dimensional γ-γ coincidence spectra gated by particle groups populating the 6.05-, 6.13-, and 7.12-MeV levels. The 6.13-MeV level, which decays by a single 6.13-MeV γ ray, identified the spectrum expected from cross-talk coincidences, and the 7.12-MeV level, which has a previously measured decay branch $7.12 \to 6.13 \to 0$, provided a direct check of the real-time system operation.

States in ^{16}O were populated using the reaction $^{19}F(p,\alpha)^{16}O$, and the proton energy, 1.89 MeV, was chosen to take advantage of the resonance at 1.88 MeV which preferentially populates the 6.05-MeV state over the 6.13-MeV state. The experimental configuration is shown in Fig. 1. Reaction α particles were detected with good resolution (44 keV) so that α-particle groups populating the ^{16}O 6.05- and 6.13-MeV states were clearly resolved. The γ radiation was detected in two 4-in.$\times$4-in. NaI detectors 180° apart which were positioned at 90° with respect to the incident beam. Alburger and Parker[3] have shown the importance of shielding the two γ-ray detectors from each other, and a 3-cm-thick Hevimet shield was used to insure that the observed radiation came from the target. A plastic cone was inserted in the aperture in the shielding to stop electrons from decay of the pair-emitting 6.05-MeV state. Lead, 0.3 cm thick, was used to attenuate low-energy γ rays preferentially. The target was biased at 300 V to prevent knockout electrons from reaching the detector.

Triple coincidences were detected with a conventional fast-slow system. For each event, five signals were recorded: energy signals from each of the three detectors and two time-to-amplitude converter (TAC) pulses measuring the time differences between the particle signal and the signals from each of the NaI detectors. Valid events were analyzed by a Tennelec multiplexer–stretcher–analog-to-digital converter (ADC) system interfaced to a mini-computer. The data were event-recorded on magnetic tape and subsequently analyzed off-line. The coincidence requirement was circumvented 1% of the time to permit accumulation of a singles particle spectrum. By summing the total spectrum, determining the portion due to population of the 6.05-MeV state, and comparing the result to an external scaler which recorded the total number of particles detected, the total population of the 6.05-MeV state was de-

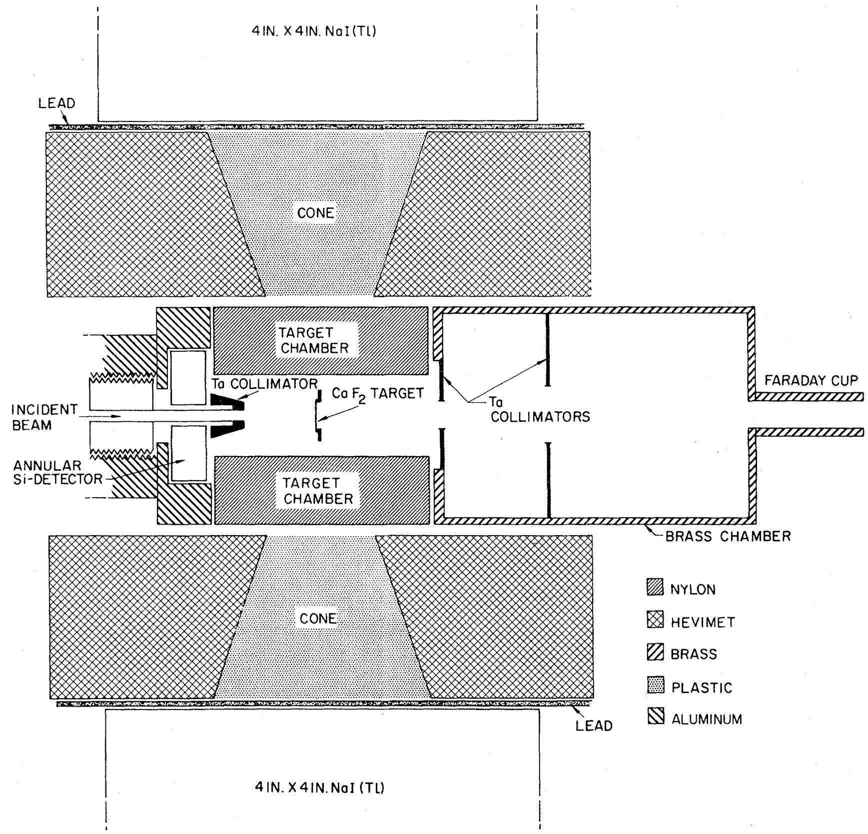

FIG. 1. Scaled drawing of target-detector geometry.

duced. A similar procedure was followed for the 6.13- and the 7.12-MeV states. A pulser functioned as a continuous monitor of the operation of the system as well as providing a means of determining the system live time, typically 90%. Time resolution was typically 30 nsec and determination of random-event background was accomplished in a straightforward manner by gating the γ_1-γ_2 two-dimensional spectra with the random-coincidence portion in one TAC spectrum and the (real + random) coincidences in the other TAC spectrum.

Pulse pile-up can be a problem in fast-slow systems. In the present system, the stretcher-ADC system contained pile-up rejection circuitry with a pulse-pair resolution of 0.3 μsec which eliminated most of these events. Analysis of pulser-tagged events revealed that the probability for pile-up to occur in one of the three energy channels was less than 0.1%. The detection efficiency was determined by two methods. The reaction $^{19}F(d,\alpha)^{17}O$ was used to populate several levels in ^{17}O, and a direct measure of the triple-coincidence efficiency was obtained by observing the $3.055 \rightarrow 0.87 \rightarrow 0$ γ cascade. This was cross-checked by particle-γ double-coincidence measurements on the decay of the 3.84-, 3.055-, and 0.87-MeV states in ^{17}O and the 6.13-MeV state in ^{16}O. The double-coincidence measurements additionally provided a calibration of detector efficiency as a function of γ-ray energy. The triple-coincidence efficiency was determined to be $(3 \pm 0.8) \times 10^{-4}$ for the simultaneous detection of two 3-MeV γ rays and was only slightly energy dependent over the region of importance since both γ-ray energies must sum to 6 MeV. The measured result is in agreement with a calculation of the expected efficiency from the known geometry and published γ-ray detection efficiencies. Total running time for the experiment was four weeks, with a typical run being 12 h.

The data, random background subtracted, is shown in Fig. 2. Observation of the $7.12 \rightarrow 6.13 \rightarrow 0$ cascade decay of the 7.12-MeV level provided a continuous monitor of the operation of the system. The measured branching ratio, (0.13

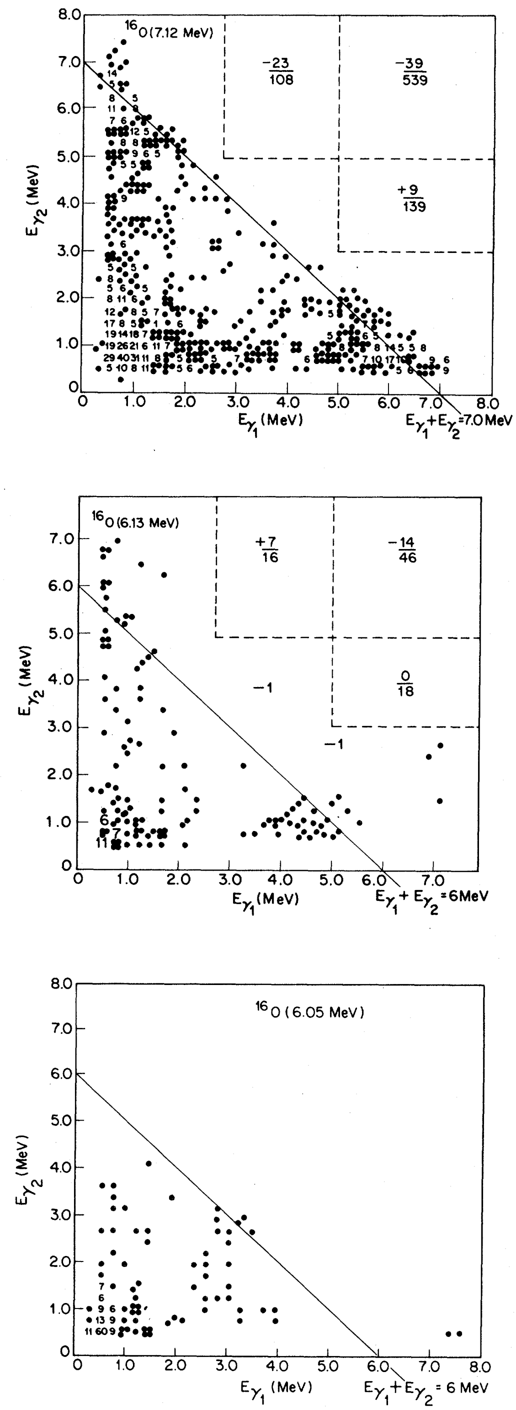

FIG. 2. E_{γ_1} versus E_{γ_2} spectra for γ rays in time coincidence with α particles populating the 7.12-, 6.13-, and 6.05-MeV states. Random events have been subtracted. The ratio A/B enclosed in a rectangular area represents the number of events after/before subtraction of random events in that area. Negative numbers indicate a surplus of random events. Each of the two -1's represents a random event at that point.

$\pm 0.05)\%$, is in agreement with a previous measurement of Wilkinson, Alburger, and Lowe,[5] $(0.07 \pm 0.014)\%$. The general features of this spectrum, Fig. 2(a), are as expected. The spectrum is reasonably symmetric with respect to E_{γ_1} and E_{γ_2}. Note that in the region of $E_{\gamma_1}=E_{\gamma_2}$ there are very few events. These possibly result from pair production in one detector with the annihilation radiation being detected in the other detector. The general features correspond to that which would be expected[3] on the basis of Heitler's[6] treatment of annihilation in flight.

In Fig. 2(b) is displayed E_{γ_1} versus E_{γ_2} for γ rays in coincidence with particles populating the 6.12-MeV state. Real events in this spectrum, corresponding to a high-energy γ ray in coincidence with a low-energy γ ray, probably result from the mechanism alluded to in the previous paragraph. Note the absence of events with $E_{\gamma_1} \approx E_{\gamma_2}$.

Figure 2(c) displays E_{γ_1} versus E_{γ_2} for γ rays in coincidence with particles populating the 6.05-MeV state. The general features of this spectrum are considerably different from those of the previous two. As opposed to the 6.13-MeV spectrum, there are no events in the region $E_{\gamma_1} = 5$ MeV, $E_{\gamma_2} = 1$ MeV. Therefore, the possibility that the events observed are a result of single γ rays which create cross-talk between the two NaI detectors can be excluded. Such events would not be expected in any case, since the α-particle group populating the 6.05-MeV level was completely resolved from the nearby group populating the 6.13-MeV level, and the primary decay mode of the 6.05-MeV level is by pair emission. Positron annihilation in flight could result in a real coincidence which would look like two-photon decay. However, the most probable positron energy is around 2.5 MeV (equal energy to each member of the pair) so positron annihilation in flight should contribute primarily to that region. This is not observed in the spectrum of Fig. 2(c). In fact, a calculation which folds together the peak shape and efficiencies of the NaI detectors and the energy distribution expected for two-photon decay, $F(E) \propto E^3(E_0 - E)^3$, can account for the entire spectrum observed except for a small region in the lower left-hand corner which results from the spillover of 0.511–0.511-MeV coincidences. We therefore believe that the observed events are genuine two-photon decay events, since no alternative explanation is viable. In Fig. 2(c), an analysis of the region corresponding to $E_{\gamma_1} + E_{\gamma_2} > 3$ MeV leads to the result $N_{\gamma\gamma}/$

$N_\pi = (2.5 \pm 1.1)\times 10^{-4}$ for the decay branch.

The most recent attempt to measure $N_{\gamma\gamma}/N_\pi$ was the work of Alburger and Parker.[3] They observed γ-γ coincidences only with no coincidence requirement on the particles and their quoted upper limit is 1.1×10^{-4}, somewhat below our number. However, it does not appear that the two are significantly conflicting.

Several calculations have been attempted to predict two-photon decay branching ratios. In a recent calculation, Bertsch[7] used a model of the states with spherical and deformed components and evaluated the matrix elements employing the dipole sum rule. Agreement was found with the reported measurement of Beardsworth *et al.*[2] His revised number[8] of 3×10^{-4} for ^{16}O is also in good agreement with our results.

In conclusion, this appears to be the first measurement of two-photon emission in $0^+ \to 0^+$ nuclear transitions free of contaminating or interfering effects. The events attributed to two-photon decay display the expected characteristics and no alternative explanation for these events is viable.

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Hot Spots in Laser Plasmas

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Spontaneously generated magnetic fields can substantially reduce the thermal conductivity in pellet atmospheres and give rise to localized hot spots, which may lead to the ablation of anomalously fast ions.

Magnetic fields have been observed in laser-target experiments and are believed to be thermoelectrically generated as a result of nonparallel density and temperature gradients in the absorption region.[1] In laser-fusion experiments they may grow through a lack of spherical symmetry in the laser irradiation, as is considered in this paper, or from instabilities in an otherwise uniform illumination.[2]

The electron thermal conduction, essential for the efficient transfer of heat into the compression region, may be drastically reduced by the large value of $\Omega\tau$ generated; this may give rise to "hot spots"—regions where heat is deposited by the laser but prevented from escaping by large confining magnetic fields. By virtue of ion acceleration in the large associated electric fields, these hot spots may be the origin of the suprathermal fast ions observed to carry away an anomalous proportion of the absorbed energy in ablative kinetic energy. Three other mechanisms are possible: (1) The magnetic fields generated in the absorption region and convected outwards may cause substantial acceleration of the lower-density plasma through the $\vec{J}\times\vec{B}$ force. Although in our simulations the magnetic pressure is generally lower than the plasma pressure we do not rule out this effect on longer time scales. (2) Flux-limited electron thermal conduction (to within a few percent of the free-streaming limit[3]) may increase the temperature in the absorption region without requiring lack of spherical symmetry. The authors of Ref. 3 mention $\Omega\tau$ effects as an alternative flux-limiting process,[4] which appears very plausible because of the dependence of conductivity on the square of $\Omega\tau$. (3) Suprathermal electrons, generated where the effect on the local average tem-