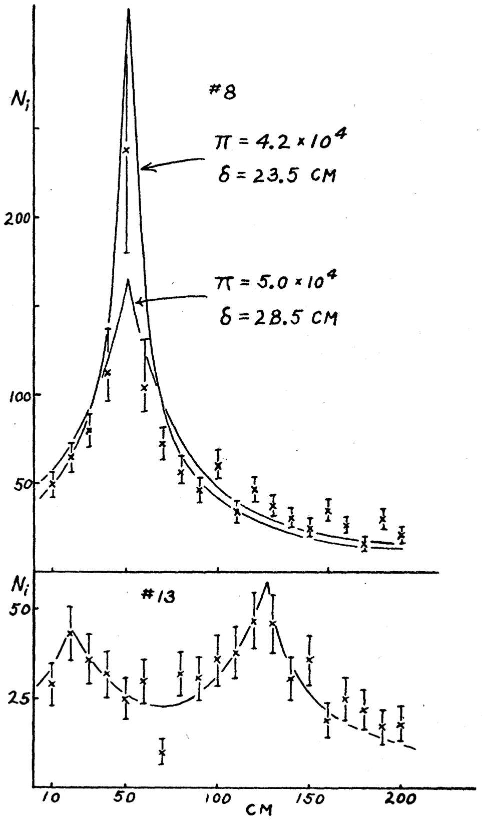

FIG. 3. Individual showers. Event 8 is the largest event observed. In 13, a curve compounded from two showers indicates the effect of superposition; this event is believed to be a close hit because of its size, the fact σ is nearly twice $(\overline{N_i})^{\frac{1}{2}}$, and the systematic character of the "fluctuations."

3 and 4 were the largest of their type and confirm (at least in the case of distant events) the prediction[1] that the fluctuations in N_i expected in this experiment are $1.15\sqrt{N_i}$ (the 1.15 arises from the transition effect).

An event such as 13 is particularly difficult to interpret except in terms of separated cores generated by different π^0 mesons.

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* Supported in part by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.

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The Neutron-Electron Interaction*

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AFTER it was pointed out by Foldy[1] that approximately 4000 ev (well depth for e^2/mc^2 range) of the neutron-electron interaction could be attributed to the neutron moment, it was clear that more accurate measurements were necessary in order to isolate the electrostatic dissociation effect arising from the meson charge distribution. At this time an experiment was already under way at Brookhaven designed to increase the experimental accuracy by means of mirror reflection of neutrons. Previous measurements had utilized the variation of scattering cross section with angle[2] or with wavelength[3] to detect the form factor behavior of the electron scattering. The observed effects in each case were small and of the same order of magnitude as various corrections. Since the form factor is exactly unity for mirror reflection, however, the neutron-electron scattering is observed at its maximum value. Fortunately, the use of a balancing technique makes the critical angle for total reflection a sensitive measure of the neutron-electron interaction.

The experimental arrangement used was one in which the critical angle is measured for total reflection of long wavelength neutrons at the interface of bismuth and liquid oxygen. As the nuclear scattering (per unit volume) of oxygen and bismuth differ by only two percent while the electron scattering is much stronger in bismuth, the index of oxygen relative to bismuth is to a large extent determined by the electron scattering amplitude. A highly collimated neutron beam, Fig. 1, filtered through graphite, was incident on the interface at an adjustable angle of the order of a few minutes of arc. The critical angle was measured by techniques developed for other mirror experiments.[4] The measurement consists essentially of an observation of the incident angle at which the reflected intensity drops suddenly, this angle being the critical angle for the cut-off wavelength (6.7A) of the incident filtered neutrons. In order to determine the critical angle accurately, the experimental points (Fig. 1) are compared to a calculated curve that takes into account the finite reflectivity beyond the critical angle and the resolution of the incident neutron beam (about 0.25 minutes of arc). The final value, based on several measurements similar to that illustrated in Fig. 1, is 3.64±0.04 minutes.

The equation relating the critical angle to the coherent bound scattering amplitude a is

$$\frac{\pi}{\lambda^2}\theta_c^2 = N_{\mathrm{Bi}}a_{\mathrm{Bi}}\left\{\frac{N_{\mathrm{O}}a_{\mathrm{O}}}{N_{\mathrm{Bi}}a_{\mathrm{Bi}}}-1\right\}+\{N_{\mathrm{Bi}}Z_{\mathrm{Bi}}-N_{\mathrm{O}}Z_{\mathrm{O}}\}a_e, \qquad (1)$$

where N is the number of nuclei per cm^3, λ the neutron wavelength, and the subscripts O, Bi, and e refer to oxygen, bismuth, and the electron. This equation consists of three parts: the first involving the measured critical angle, the second the coherent amplitudes, and the last the neutron-electron interaction. Since the nuclear amplitudes of oxygen and bismuth are nearly equal, the two terms on the right-hand side of the equation are of the same order of magnitude. In order to reach reasonable accuracy in the electron amplitude, the coherent nuclear amplitudes must be measured with much higher accuracy. These amplitudes are obtained from the free atom cross sections by application of the reduced mass factor and subtraction of incoherent scattering.

It is not necessary to measure the absolute values of the free atom cross sections of oxygen and bismuth, for it is only the ratio that enters into the result in a sensitive way. This ratio was measured by transmission for neutrons of average energy 8 ev: these neutrons being produced by a boron difference measurement for a pile neutron beam. Two nearly identical beams were

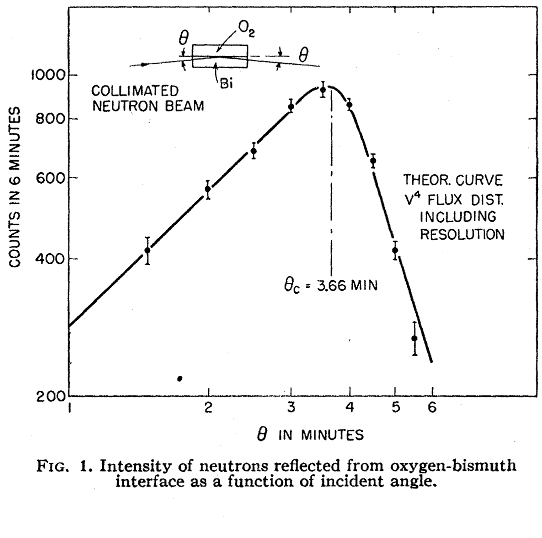

FIG. 1. Intensity of neutrons reflected from oxygen-bismuth interface as a function of incident angle.

used, and the intensity was measured after passage through samples of oxygen and bismuth, one in each beam. The intensities were again measured after the samples were alternated. In this method the cross-section ratio was corrected for several tenth-percent effects still present at an energy of 8 ev: the crystal interference, paramagnetic scattering, residual neutron-electron scattering, and Doppler effects. A small correction was also made for the incoherent scattering of bismuth, measured by transmission for long wavelength neutrons.[5]

The numerical results, $\theta_c = 3.64 \pm 0.04$ minutes and $N_0 a_0 / N_{\mathrm{Bi}} a_{\mathrm{Bi}} = 1.0204 \pm 0.0008$, when substituted into Eq. (1), give $a_e = 1.40 \times 10^{-16}$ cm, corresponding to a well depth of 3860 ± 370 ev. The errors include statistics as well as uncertainty in the various constants in Eq. (1). Assuming the legitimacy of the Foldy effect, we conclude that the electrostatic meson dissociation effect can be no more than a few hundred volts. There have been several recent discussions[6] of possible explanations for the magnitude of the observed effect, but none of these seems able to account satisfactorily for the measured result. We wish to express thanks to G. W. Johnson, H. R. Muether, and R. C. Garth, who have been of great assistance at various stages of the work.

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The Gamma-Ray Cascade Following Decay of Sc^{46}[†]

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THE report by Nag *et al.*[1] that a 12-μsec state exists in Ti^{46} and their assignment of this lifetime to the first excited level in Ti^{46} seem in disagreement with other reports on the angular correlation[2–4] reported for the well-known cascade in Ti^{46} following the negatron decay of Sc^{46}. We have re-investigated the question of $\gamma - \gamma$ delay in Ti^{46} with the particular idea that perhaps the delayed coincidences found by Nag, *et al.*[1] resulted from a weak and previously unidentified gamma-ray in Ti^{46} following β-decay of Sc^{46} to a third excited level in Ti^{46}. Our present results do not support this possibility.

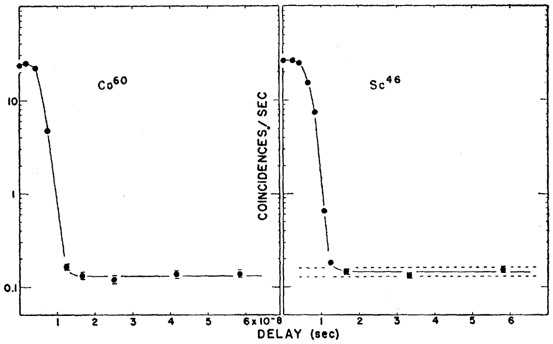

FIG. 1. Delayed coincidence curves for Co^{60} and Sc^{46} (raw data). The curve on the left is used to determine the effective resolving time of the apparatus from the accidental coincidence rate on the "tail" of the Co^{60} curve, assuming a prompt cascade. The curve on the right shows the Sc^{46} delayed coincidences. The dotted lines indicate the upper and lower limits for the calculated accidental coincidence rate expected for Sc^{46} on the basis of the Sc^{46} single counting rates and the measured resolving time; these limits reflect the uncertainty in the measured resolving time.

A conventional delayed coincidence arrangement with a resolving time of 1.3×10^{-8} sec, employing stilbene phosphors with 5819 multiplier tubes, was used. Integral discriminators were employed in slow channels for energy selection. The source was obtained from Oak Ridge with further chemical purification at this laboratory.

The procedure involved the use of Co^{60} and Na^{22} as "prompt" standards. The delayed coincidence curve of the prompt events was obtained and the effective resolving time of the equipment calculated from the accidental coincidence rate (i.e., the "tail" of the prompt standard curve). The Sc^{46} delayed coincidence curve was then obtained and the coincidence rate of the "tail" compared with that calculated as the accidental rate using this measured resolving time and the single counting rates. As indicated in Fig. 1, the coincidence rate on the "tail" of the Sc^{46} curve is the same as the calculated accidental rate within the statistical errors. Further, this result was obtained with the discriminators on the amplifiers set to accept pulses which correspond to events with at least as low an energy as 130 kev. The 137-kev gamma-ray of Re^{186} was used for calibration. We find, therefore, no evidence for a state in Ti^{46} following the β^--decay of Sc^{46} with a lifetime greater than 1.5×10^{-9} sec. The results of Nag *et al.*[1] remain unexplained.

[†] Supported by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commision.

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Allowed Final States for Annihilation into Three Photons[*]

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LANDAU[1] and Yang[2] have discussed the consequences of rotational invariance for annihilations into two photons, and Peaslee[3] and Michel[4] have pointed out selection rules for annihilations into two and three bosons. Here we study in more detail the consequences of invariance under rotations and reflections for annihilations into three photons, limiting ourselves to the symmetrical case in which three photons of equal frequency are emitted in a plane at 120° from one another.

TABLE I. Transformation properties of *RRR*, ··· *LLL* under D_{3h}.[a]

E	*RRR*	*RRL*	*RLR*	*LRR*	*RLL*	*LRL*	*LLR*	*LLL*
C_3	*RRR*	*LRR*	*RRL*	*RLR*	*LRL*	*LLR*	*RLL*	*LLL*
σ_h	−*LLL*	−*LLR*	−*LRL*	−*RLL*	−*LRR*	−*RLR*	−*RRL*	−*RRR*
$\sigma_v^{(1)}$	*LLL*	*LRL*	*LLR*	*RLL*	*LRR*	*RRL*	*RLR*	*RRR*

[a] E = identity. C_3 = rotation by 120° about axis normal to the plane of the photons. σ_h = reflection in plane of the photons. $\sigma_v^{(1)}$ = reflection in plane containing the normal to the plane of the photons and the first momentum vector.

The boson nature of the photons allows the use of *RRR*, *RRL*, *RLR*, *LRR*, *RLL*, *LRL*, *LLR*, and *LLL* as a complete set of final states, where a right (*R*) or a left (*L*) circular polatization is associated with each of the three momentum vectors: since the creation operators for bosons commute, the order in which the photons are created is not significant. These eight final states are used to construct a complete set of states which are irreducible representations of the symmetry group D_{3h} of the annihilation.[5]