measurements were made on the three-photon annihilation radiation.

The ratio of the cross sections for the two-photon and three-photon annihilation processes, respectively, was obtained from the expression,

$$\sigma_2/\sigma_3 = N_2 f_3(\epsilon_{0.33})^3/N_3 f_2(\epsilon_{0.51})^2,$$

where N_2 and N_3 are the genuine doubles and genuine triples per single, respectively; f_3 is the fraction of all three photon sets intercepted by the three counters; f_2 is the fraction of all two-photon sets intercepted by two symmetrically spaced counters; $\epsilon_{0.33}$ and $\epsilon_{0.51}$ are the intrinsic efficiencies of the detectors for 0.33-Mev and 0.51-Mev photons, respectively.

Random accidentals arising from the two-photon annihilation process accounted for the largest portion of the spurious triples rate. The total triples rate was also corrected for accidentals of the second kind and those spurious triples arising as a result of the scattering of the two-photon annihilation radiation in the aluminum converter. The effect on the spurious triples rate of bremsstrahlung radiation emitted by the positron in slowing down was considered and found to be negligible.

Care was taken to eliminate spurious triples arising from counter-to-counter scattering. The sides of the crystals as well as the photo-multipliers were protected by $\frac{1}{16}$-in. lead sheet. In addition, a baffle system of $\frac{1}{4}$-in. lead sheet was arranged so that one counter could not "see" another counter.

Aluminum foil of such thickness as to stop even the most energetic electron recoil from the aluminum converter was put on the face of each crystal.

When equal weights were assigned to fourteen separate runs, the mean of the ratio of the cross sections was found to be

$$\sigma_2/\sigma_3 = (2.0\pm0.4)\times10^2, \quad \epsilon_{0.33} = \epsilon_{0.51};$$
$$\sigma_2/\sigma_3 = (3.3\pm0.7)\times10^2, \quad \epsilon_{0.33} = 1.18\epsilon_{0.51},$$

depending on the assumption made concerning the efficiency of the detector for 0.33-Mev gamma-radiation relative to the efficiency for the 0.51-Mev radiation, the latter being determined by coincidence-counting of the two-photon annihilation radiation.

There are two reasonable assumptions for extrapolation of the value to $\epsilon_{0.33}$ from the measured efficiency $\epsilon_{0.51}$. In the first, $\epsilon_{0.33} = 1.18\epsilon_{0.51}$, the efficiency varies directly as the Compton cross section, Compton scattering being the only process of importance for light materials in this energy range. In the second assumption, $\epsilon_{0.33} = \epsilon_{0.51}$, the increased "absorption" for the 0.33-Mev gamma-rays is compensated for by the greater ease with which the larger pulses from the 0.51-Mev gamma-radiation are detected.

Positive results were also obtained in the auxiliary experiments. The number of genuine triple coincidences obtained with the source out of the plane of the crystals was zero within the error of the experiment. The absorption experiment gave evidence that the three-photon annihilation radiation was softer than the two-photon annihilation radiation.

Work is continuing on the problem. The measurements are to be repeated with more efficient detectors and with a coincident circuit having a resolving time $<5\times10^{-8}$ sec. As an additional check on the existence of the effect it is planned to use Na^{22} as a source of positrons and to measure the quadruple coincidence rate in four counters.

I wish to thank Professor C. G. Montgomery for his constant encouragement and interest in this investigation. I am also indebted to Dr. Aadne Ore for valuable discussions.

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[‡] Assisted by the joint program of the ONR and AEC.

[1] J. A. Wheeler, Ann. N. Y. Acad. Sci. **48**, 219 (1946).

[2] J. Pirenne, Thesis, University of Paris (1944), Chapter III. See also Arch. sci. phys. et nat. **28**, 273 (1946), and **29**, 121 (1947).

[3] I. Pomeranchuk, Doklady Akad. Nauk S.S.S.R. **60**, No. 2, 213 (1948).

[4] A. Ore and J. L. Powell, Phys. Rev. **75**, 1696 (1949).

[5] E. M. Lifshitz, Doklady Akad. Nauk S.S.S.R. **60**, No. 2, 211 (1948).

[6] We are indebted to Professor C. T. Lane for this copper.

Detection of X-Rays by Means of NaI(Tl) Scintillation Counters*

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In connection with proposed research on nuclear isomerism we have been interested in investigating the possibility of detecting individual x-ray quanta by means of scintillation detectors. Using NaI(Tl) crystals[1] with uncooled RCA 5819 photo-multiplier tubes, we have been able to detect individual x-ray quanta in the range of 5- to 80-kev energy with an efficiency approaching 100 percent. X-rays of 2-kev energy have been detected with an efficiency between 50 and 80 percent.

The x-rays used in this experiment were produced as follows. In the range of 15 to 80 kev by monochromatizing x-rays from an Mo target with a Bragg single-crystal spectrometer; in the range of 5 to 20 kev by using the fluorescent radiation of various elements excited by Mo x-rays; at 2 kev by using the continuous radiation from a V target, filtered by the Be window of the x-ray tube and the oil covering the NaI crystal.

The NaI crystals were cleaved under oil into $\frac{1}{2}$ in. to $\frac{1}{4}$ in. parallelopipeds and used according to a technique previously described.[1] A thin (0.0005 in.) Al reflector was set over the crystal. In the detection of low energy x-rays a hole was cut into the reflector to allow the entrance of the x-rays.

With this arrangement we have found, from the widths of the pulse height distributions, 1.0 to 1.5 photo-electrons emitted from the photo-cathode of the 5819 tube for each kilo-electron-volt dissipated in the crystal. This figure agrees with previous estimates.[1] With 8-kev fluorescent x-rays from Cu, for example, we have observed the pulse height distribution shown in Fig. 1a, the width of which corresponds to approximately 12 photo-electrons on the average from the photo-cathode. Since all of the x-rays are absorbed in the crystal and since there seem to be hardly any pulses of zero pulse height, we can be quite sure that each 8-kev x-ray quantum results in a detectable pulse and hence the detection efficiency is close to 100 percent. This follows also from

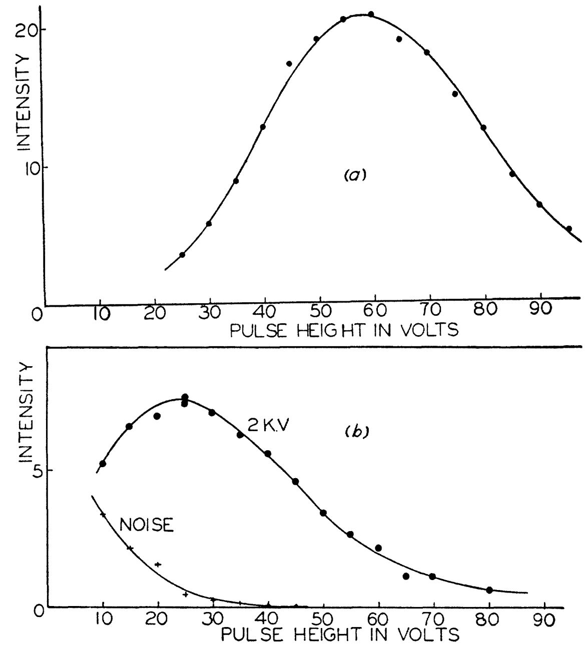

FIG. 1(a). Pulse height distribution due to 8-kev fluorescent x-rays from Cu (1.5-volt channel width). (b). Pulse height distribution due to 2-kev x-rays and due to photo-multiplier noise.

statistical considerations. With 2-kev x-rays the pulse height distribution shown in Fig. 1b was obtained, on which we have plotted also the noise pulse height distribution. The interpretation of this curve in terms of detection efficiency must await further calculations and measurements, but rough considerations indicate a detection efficiency of greater than 50 and less than 80 percent. This high detection efficiency of NaI(Tl) crystals for low energy x-rays sees to differ markedly from the sharp drop in the detection efficiency of anthracene crystals for low energy electrons[2] (<15 kev). Part of the latter effect may perhaps be due to a low light-collection efficiency in that experiment.

The average pulse height, which we identified with the peak pulse height for all energies except for 2 kev, varied linearly (within the experimental error) with the x-ray energy from 2 to 411 kev. For the measurement at 411 kev we used the gamma-ray[3] from Au^{198}. The linearity test was made in three different overlapping energy ranges, indicated by (a), (b), and (c) in Fig. 2. In each energy range different pulse height distributions were measured with a definite photo-multiplier tube voltage—about 700 volts for (a) and (b) and 800 volts for (c). One particular crystal was used during one day, so that the crystal surface would not deteriorate during one set of measurements. The pulse height distributions were not measured with the same amplifier gain, but in Fig. 2 the gain of all points is arbitrarily normalized to 1000.

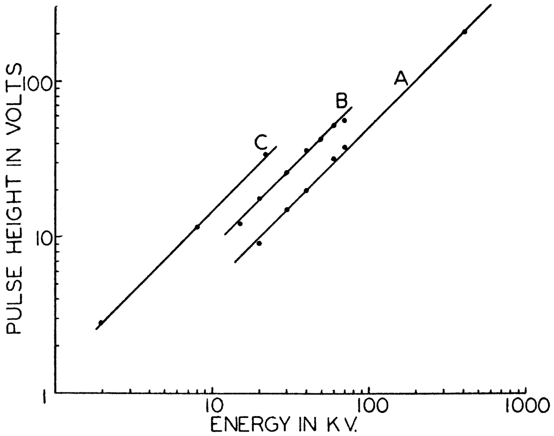

FIG. 2. Average pulse height (normalized to a gain of 1000) *vs.* incident x-ray energy for three different experimental arrangements, showing the proportionality of NaI(Tl) from 2 kev to 411 kev.

At incident x-ray energies above 33 kev, the binding energy of the *K*-electrons in iodine, two peaks were seen in the pulse height distribution. Figure 3 shows the distribution obtained with 44-kev x-rays. The peak at the higher energy corresponds to the full energy of the incident x-ray: both the iodine photo-electron and the iodine *K* x-ray energy are absorbed in the crystal. The peak at the lower energy is caused by the occasional escape of the iodine *K* x-rays from the front face of the crystal. That this interpretation is correct is demonstrated by the fact that at different energies of the incident x-rays (above 33 kev) the energy difference between the two peaks remains constant and approximately equal to the iodine *K* x-ray energy.

This "escape" peak is also observed in gas proportional counters,[4] where it is of the same order of magnitude as the main peak and where both the K_α and K_β escape peaks can be resolved because of the much larger number of pulse-forming electrons available. In the present case the escape probability is at most $\frac{1}{3}$ for incident x-rays just above 33 kev and decreases rapidly for higher energies, in agreement with rough theoretical considerations. This escape of the iodine *K* x-rays will, of course, lower the over-all detection efficiency for the incident x-rays unless the pulse height discriminator bias is made low enough to detect the lower energy peak. We have also placed additional crystals close to the detector crystal and have observed the capture of most of the escaping radiation.

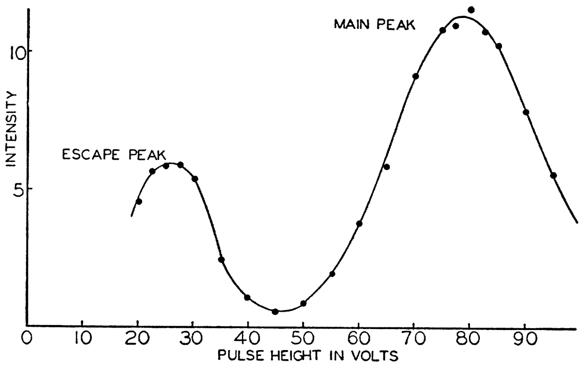

FIG. 3. Pulse height distribution due to 44-kev x-rays, showing small peak due to escape of I *K*-x-rays.

These and other experiments will be described elsewhere in the near future. We wish to thank Dr. J. A. McIntyre, Mr. W. Anderson, and Mr. L. Rieser for their help with this work.

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[1] R. Hofstadter and J. A. McIntyre, Nucleonics **7**, No. 3, 32 (1950).

[2] W. J. Ramler and M. S. Friedman, Rev. Sci. Instr. **21**, 784 (1950).

[3] J. W. M. DuMond, Cal. Inst. Tech., Report No. 3, March 30, 1948, unpublished.

[4] S. C. Curran, *et al.*, Phil. Mag. **40**, 929 (1949), and earlier; D. West and P. Rothwell, Phil. Mag. **41**, 873 (1950).

Binding Energy of the Triton*

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AS is well known, low energy two-body nuclear data can be described satisfactorily in terms of a shape-independent approximation.[1] On the other hand, predictions of high energy $n-p$ scattering data and of the triton binding energy depend on the assumed shape of the interaction potential. We have investigated in a limited way the dependence of the binding energy of H^3 on the range of the tensor force part of such a potential.

A nuclear interaction potential, consisting of central and tensor terms, was assumed as given below:

$$V(r) = -V_0\{[1-\tfrac{1}{2}g+\tfrac{1}{2}g(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)]\exp(-r/r_c)/r/r_c \\ +\Gamma S_{12}\exp(-r/r_t)/r/r_t\}.$$

It has met with success in describing low energy scattering processes and in accounting for the properties of the deuteron. Singlet and triplet wells can be obtained from such a potential, and charge independence of nuclear forces can be preserved.[2]

Calculations have been carried out to determine more accurately the shape of this well by using, instead of scattering data, the experimental value of the binding energy of H^3 to set the range of tensor forces. Whereas scattering data are in general insensitive to variations in tensor range, the binding energy may be expected to be reasonably sensitive.

The central force range r_c was obtained from singlet scattering data, primarily on $p-p$ scattering. The constant g was fixed by consideration of the difference between singlet and triplet well depths in $n-p$ scattering. From r_c and assumed values of r_t, the constants Γ and V_0 were set by use of two-body data, and an upper limit to the triton binding energy was computed by the Ritz method.