partly by β^+ emission and partly by electron capture. It was assumed for V^{48} that 58 percent of the disintegrations were by β^+ emission and 42 percent by electron capture.[1] For Mn^{52}, 35 percent of the disintegrations were taken to be β^+ emission.[1] No effort was made to measure the 23-minute Mn^{52} isomer. For Co^{56} the disintegration rate was arbitrarily multiplied by four, since it is reported that K capture is at least three times as abundant as positron emission.[2] Thus the Fe cross section is a lower limit.

Corrections were made for the energy spread in the incident beam, as determined from the range distribution. The β^+ activities were corrected for the fact that the momentum of the incident deuteron sometimes carried the resultant struck nucleus out of the target foil.

The excitation functions are shown in Fig. 1. Individual experimental points could not be presented, as their identity was lost in the process of making corrections for the energy distribution of the deuteron beam. This process consisted of an inverse folding operation, carried out numerically on an IBM Card-Programmed Calculator. The vertical errors shown on the excitation function curves were estimated from the reproducibility of the shape of the excitation function. The horizontal errors represent the uncertainty in the energy of the incident deuterons. The uncertainty in the absolute cross-section scale, deriving principally from uncertainties in absolute β^+ counting efficiency, is estimated at ±10 percent. No estimate is included for the possible errors in the values taken for β^+/K-capture.

The shelf at the low-energy end of the titanium curve is thought to represent a contribution from the $Ti^{47}(d,n)$-V^{48} reaction, which could not be avoided without the use of targets depleted in Ti^{47}.

Half-lives measured during the course of this experiment were:

$$T_{\frac{1}{2}} \text{ of } Mn^{52} = 5.60 \pm 0.01 \text{ days},$$

$$T_{\frac{1}{2}} \text{ of } V^{48} = 16.25 \pm 0.17 \text{ days},$$

$$T_{\frac{1}{2}} \text{ of } Co^{56} = 77.2 \pm 0.80 \text{ days}.$$

Some indications were given by the form of the experimental data that a small dip in the excitation function for the $Ti^{48}(d,2n)V^{48}$ reaction may be present at about 16 Mev. The evidence that has been accumulated is insufficient to settle this point at present, but it is hoped that further work may clear it up. We also plan to carry out a measurement of that part of the $Cr^{52}(d,2n)Mn^{52}$ excitation function leading to the 23-minute Mn^{52} isomer, in order to provide a Cr excitation function that will be more directly comparable to those given for Ti and Fe, which represent the total $(d,2n)$ cross section rather than just part of it.

---

[1] Good, Peaslee, and Deutsch, Phys. Rev. **69**, 313 (1946).

[2] L. G. Elliott and M. Deutsch, Phys. Rev. **64**, 321 (1943).

PHYSICAL REVIEW VOLUME 95, NUMBER 3 AUGUST 1, 1954

n-γ Coincidences Produced by Inelastic Scattering of Neutrons

P. Shapiro, V. E. Scherrer, B. A. Allison, and W. R. Faust
Naval Research Laboratory, Washington, D. C.

(Received February 18, 1954; revised manuscript received May 5, 1954)

Scintillation spectrometer analysis of the gamma-ray spectrum arising from interaction of 3.2-Mev neutrons with chromium shows several gamma rays including a very pronounced 1.43-Mev line. Coincidence observations indicate that there are a negligible number of gamma rays in cascade with the 1.43-Mev line. Thus the residual nucleus is left in the 1.43-Mev state by emission of a neutron which carries off the remaining portion of the energy. The energy distribution of this group of inelastically scattered neutrons as deduced from the coincidence pulse-height distribution of recoil protons in a stilbene detector has a maximum at 1.5 Mev.

THE particular level structure of chromium is such that inelastic scattering of neutrons yields relatively simple spectra that permit the spectrum of both scattered neutrons and gamma rays to be deduced. Spectral distribution of gamma rays shows several different energy lines and is in agreement with results of Peacock and Deutsch[1] on the decay of Mn^{52}. γ-γ coincidence observations[2] of Cr excited by 3.2-Mev neutron bombardment indicate that few gamma rays are in coincidence with the strong 1.43-Mev line. This indicates that chromium is left in the 1.43-Mev excited state by emission of a group of inelastically scattered neutrons of energy $E_n = [(52/53) \times 3.2 - 1.43] \cong 1.71$ Mev. To verify that this supposition is correct the spectral distribution of neutrons in coincidence with the 1.43-Mev gamma ray have been observed.

DESCRIPTION OF EXPERIMENTS

Figure 1 illustrates the basic experimental arrangement of which various modifications were made by substitution of one type of scintillation detector for

---

[1] W. C. Peacock and M. Deutsch, Phys. Rev. **69**, 306 (1946).

[2] Scherrer, Allison, and Faust, Phys. Rev. **94**, 791 (1954).

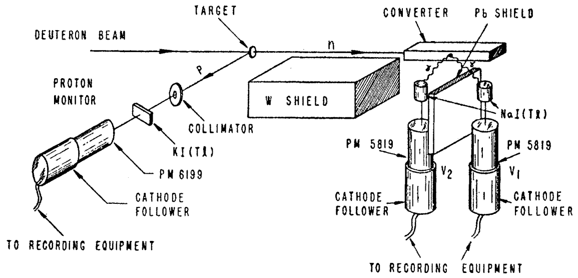

FIG. 1. Schematic arrangement of chromium radiator and detectors.

another or complete removal of one or the other detectors. Neutrons were obtained from the *d-d* reaction which was produced in a Cockcroft-Walton accelerator by 350-kev deuteron bombardment of a thick deuterium target formed by the adsorption of deuterium onto aluminum. The reaction was monitored by counting the protons from the companion reaction, $H^2(d,p)H^3$, in a KI(Tl) scintillation counter. As shown in Fig. 1, a chromium radiator was placed at 0° relative to the deuteron beam and about 25 cm from the target. Detectors used in the inelastic scattering experiments were placed about 10 cm below the chromium radiator and were partially shielded by a 10 cm×10 cm by 20 cm block of tungsten interposed between the accelerator target and detectors. The neutron detector used was a 7.5 cm diameter by 1.25 cm thick crystal of stilbene mounted on a K1197 photomultiplier. A single crystal of NaI(Tl), 12.7 cm in diameter and 5.1 cm thick in conjunction with a K1198 photomultiplier served as a gamma-ray spectrometer. NaI(Tl) crystals used in γ-γ and n-γ coincidence arrangements were 5.0 cm in diameter by 5.1 cm thick mounted on 5819 photomultiplier tubes. All of these detectors were used in conjunction with the usual amplifiers and pulse-height distributions were recorded on a twenty-channel analyzer.

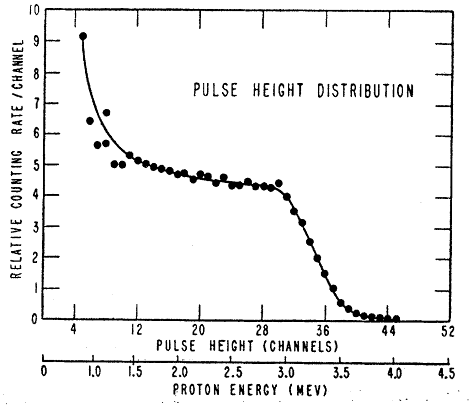

FIG. 2. Pulse-height distribution produced by accelerator neutrons falling on a stilbene crystal.

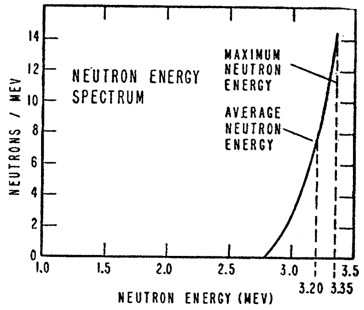

FIG. 3. Energy distribution of accelerator neutrons as deduced from Fig. 2.

The stilbene crystal which was used as a neutron spectrometer will count gamma rays or neutrons with about the same sensitivity. However, the absence of gamma rays in coincidence with the 1.43-Mev gamma ray makes it possible to count only neutrons in the stilbene if one records only those pulses which are in coincidence with the 1.43-Mev gamma ray.

Calibration of the neutron spectrometer was performed by observing the pulse-height distribution produced by neutrons leaving the target at 100°. At this angle the neutrons are nearly monoenergetic and have an energy of 2.46 Mev. Comparison of this distribution was made with that produced by the known electron distribution from gamma-ray sources. Absolute energy calibration was performed by using the calibration point at 2.46 Mev and utilizing data of Taylor *et al.*,[3] to calculate the energy corresponding to any arbitrary given recoil proton pulse height.

The energy distribution of neutrons incident on the radiator was determined from pulse-height distributions taken with the stilbene detector at the nominal position of the radiator. The pulse-height distribution produced by neutrons leaving the accelerator at 0° when the machine is operated at 350 kv is shown in Fig. 2. The pulse-height distribution shown in Fig. 2 was then corrected approximately for the photomultiplier statistics and the finite resolution of the pulse-height

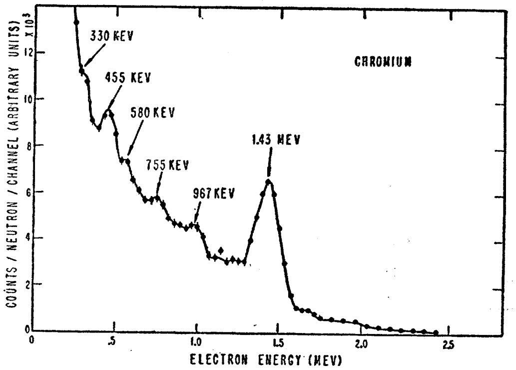

FIG. 4. Pulse-height distribution of gamma rays from chromium radiator.

---

[3] Taylor, Jentschke, Remley, Eby, and Kruger, Phys. Rev. 84, 1034 (1951).

analyzer using the method of Owen and Primakoff[4,5] assuming a Gaussian response. The half-width of the Gaussian was taken to be proportional to the square root of the pulse height and the constant of proportionality was determined by observing the Compton distribution in the crystal from known gamma-ray lines and correcting this data to the theoretical Compton distribution. The neutron spectrum $N(E)$ was then calculated from the corrected pulse-height distribution $P(E)$ by use of the well-known formula[6]

$$-dP/dE \propto \sigma(E)N(E)/E,$$

and the resulting spectrum is shown in Fig. 3. The end point agrees with that calculated from the known accelerator voltage and Q of the reaction.

Experiments were performed to obtain the pulse-height distribution of chromium gamma rays produced by the inelastic scattering of 3.2-Mev neutrons. The large NaI crystal described above was used as a detector. Because of the size of this crystal all secondary radiation was absorbed and most pulses appeared near the primary gamma-ray energy. Figure 4 shows the pulse-height distribution obtained in this manner. These results indicate chromium gamma rays at 1.43, 0.97, 0.75 Mev, with perhaps other possibilities.

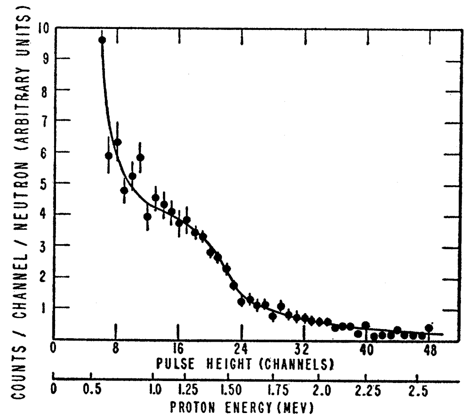

FIG. 5. Pulse-height distribution produced by neutrons from chromium radiator falling on a stilbene crystal.

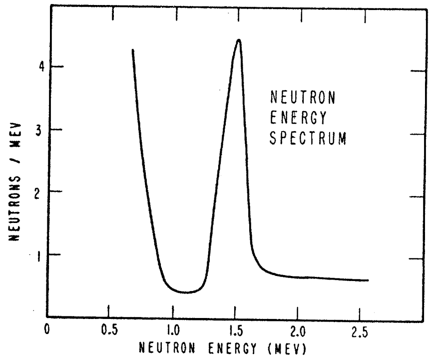

FIG 6. Energy distribution of neutrons from inelastic scattering of 3.2-Mev neutrons by a chromium radiator.

A γ-γ coincidence experiment was performed next. Two NaI(Tl) detectors were placed in the detector positions as indicated in Fig. 1. Pulses from one detector operated a single channel pulse-height analyzer which was adjusted so that only those pulses arising from the strong 1.43-Mev photopeak produced an output. The single channel output pulses operated the gating circuit on the twenty-channel analyzer which recorded the coincidence pulses from the second NaI(Tl) detector. Results of this experiment were essentially null indicating that few gamma rays are in coincidence with the 1.43-Mev line.

n-γ coincidences were observed by the same technique as used for the γ-γ coincidences. Here, however, one of the NaI(Tl) detectors was replaced by the stilbene detector described previously. The NaI(Tl) detector was adjusted so that the photopeak of the 1.43-Mev line was in the single channel, and the "coincidence" pulse-height distribution produced by the stilbene detector was recorded on the twenty-channel analyzer. The pulse-height distribution is shown in Fig. 5, and the neutron energy spectrum calculated from the pulse-height distribution is shown in Fig. 6.

DISCUSSION

The energy spectrum of inelastically scattered neutrons as calculated from data of Taylor *et al.*, has a maximum in the vicinity of 1.5 Mev, which should be compared with the value of 1.7 Mev mentioned previously. This discrepancy is ascribed to an inadequate knowledge of the pulse-height distribution produced by protons below 2 Mev; the error made by extrapolating Taylor's data to zero energy is of the order of 20 percent. The experiment does, however, show a fairly homogeneous group of neutrons near the expected energy and verifies that the strong 1.43-Mev chromium gamma ray arises from inelastic scattering of fast neutrons.

---

[4] G. E. Owen and H. Primakoff, Phys. Rev. **74**, 1406 (1948).

[5] G. A. Morton, Advances in Electronics **IV**, 97 (1952).

[6] M. J. Poole, Proc. Phys. Soc. (London) **A65**, 453 (1952).