relative effect of tube amplification on R for phosphors of different efficiencies is of interest. The relation between slopes $(-s_1)$ and $(-s_2)$ at two amplifications for phosphor A and slopes $(-s_3)$ and $(-s_4)$ for phosphor B can be shown to be

$$s_1/s_3 = s_2/s_4 = n.$$

Hence the relation between the counting rate ratios R_A and R_B is

$$R_A = R_B^n.$$

From Fig. 2,

$$R_{\mathrm{CaWO_4}} = R^5_{\mathrm{NaI(Tl)}}. \quad (1)$$

If the time constants of the pulse are independent of the pulse amplitude, the percentage change in anode current resulting from a change in magnetic field would be constant for both phosphors.

In the case of $CaWO_4$ a 40 percent change in counting rate was observed when the field was changed from 0 to 1.5 gauss through the tube. Discrimination took place just above the dark current level. This corresponds roughly to the change that would result from positioning the tube axially with and against the earth's field. The 3 percent change predicted from expression (1) for this same field change with NaI(Tl) was not detectable with the experimental accuracy observed. The change in total current for the 1.5 gauss change was about 9 percent.

[1] The NaI(Tl) sample was obtained through the courtesy of R. Hofstadter, Princeton University, and the $CaWO_4$ sample was obtained from the Linde Air Products.

Radioactive Decay of the Neutron*

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March 6, 1950.

EXPERIMENTAL evidence concerning the instability of the neutron[1] has been obtained with the apparatus shown in Fig. 1. A beam of neutrons from the Oak Ridge uranium-graphite reactor passed longitudinally (perpendicular to paper) through an evacuated tank shown in section. An electric field was applied between an open-sided cylindrical electrode (+) and a plane electrode (−) such that positive particles appearing in this region of

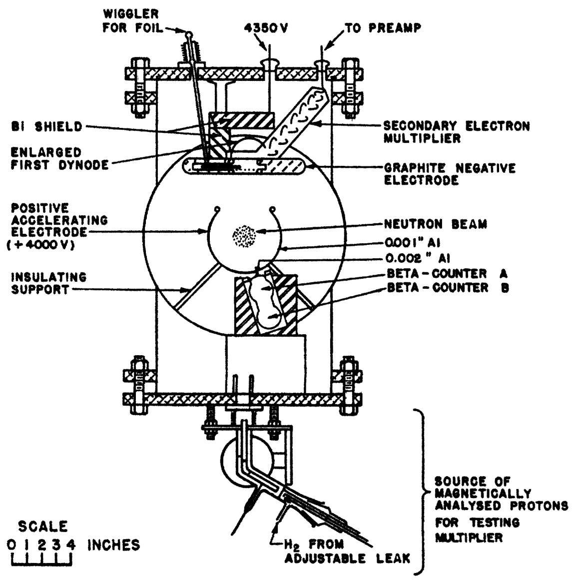

Fig. 1. Apparatus used for seeking beta-proton coincidences arising from neutron decay. The neutron beam is indicated in section at the center. A vertical electric field accelerates the protons upward and focuses them upon the secondary electron multiplier; the beta-particles register in the double beta-proportional counter below.

Table I. Coincidences with 0.25 μsec. delay.

Conditions	Transverse electric field	Genuine coincidence rate cpm	Field-sensitive genuine coincidence rate cpm	Remarks
Normal	on off	0.74 ±0.05 0.08 ±0.04	0.66 ±0.07	Conditions would allow neutron decay coincidences to appear.
Boron interrupting slow neutron beam	on off	0.13 ±0.03 0.03 ±0.03	0.10 ±0.04	B^{10} shutter known to leak about 10% of the slow neutrons through thin spots.
Cadmium in beam, eliminating slow neutrons and substituting strong source of capture gammas	on off	0.18 ±0.08 0.17 ±0.10	0.01 ±0.13	Pile power reduced until individual counting rates about equal to those in other tests. (Factor 1/7.)
3 sq. ft. Cd wrapped around vacuum tank	on off	0.73 ±0.08 0.19 ±0.07	0.54 ±0.11	Neutrons again present in beam. Local captures increased many fold.
0.0002 in. Al foil covering multiplier aperture	on off	0.05 ±0.04 0.05 ±0.04	0.00 ±0.06	Reassuring check; contributes little new.
H_2 gas in vacuum tank to 5 times base pressure	on off	0.73 ±0.05 0.06 ±0.04	0.67 ±0.07	No more field-sensitive coincidences than in 1, 4 or 8.
0.051 in. Al over AB counter window	on off	0.11 ±0.04 0.12 ±0.03	−0.01 ±0.05	Sufficient Al to stop betas of expected energy (0.8 Mev).
Repeat 1	on off	0.75 ±0.04 0.08 ±0.03	0.67 ±0.05	

the beam would be accelerated upward through 8 kv and would be focused upon the enlarged first plate of a secondary electron multiplier situated behind an aperture in the negative electrode. The aperture and the multiplier plates were 7.3 cm long in the direction parallel with the beam. The two-celled beta-proportional counter placed below the beam had an effective length of about 11 cm.

Triple coincidences were sought; namely, coincidences between discharges of counter A and counter B resulting from beta-particles emitted from neutrons in the beam, and pulses in the multiplier caused by the focused product protons.

Because of stray radiation the single counting rates were high (~75,000 per minute in A and B, and 1500 per minute in the multiplier). With an effective resolution time of 1.3 μsec., the random coincidence rate was almost equal to the expected genuine rate. Genuine coincidences were nevertheless observed. They could be divided into two classes:

(1) Coincidences which appeared when no special delays were were introduced in the circuits. These coincidences did not depend upon the presence of the electric field. They were probably caused by fast secondary electrons in the background radiation, which traversed the three detectors. They do not concern us further.

(2) Coincidences which appeared when 0.25 μsec. delay was inserted in the AB counter channel. These coincidences depended upon the presence of the electric field across the beam. A field plot had shown that 0.25 μsec. was approximately the minimum time required for a recoiling proton to be collected upon the multiplier.

Table I gives some observations made with the 0.25 μsec. delay in the AB channels. Random coincidence rates which have been subtracted were about 0.9 counts per minute throughout. A field-sensitive effect was present (column 5) which was the same under conditions 1, 4, 6, and 8, but which essentially vanished under conditions 2, 3, 5, and 7. Tests were also made with the reactor off, using a pure gamma-source (Co^{60}) to actuate the detectors to approximately the same individual rates as prevailed when the reactor was on; no significant field-sensitive effects appeared either in the coincidences or in the single counting rate of the multiplier alone.

Taken together, these observations indicate the existence of coincident events involving on the one hand the appearance of positive particles with low energy and of roughly protonic mass, and on the other hand the discharge of counters by something which could penetrate 0.003 inch of aluminum but failed to penetrate 0.054 inch of aluminum. In addition, the events depended upon the presence of slow neutrons in a manner unconnected with their capture gamma-rays, and they did not involve ionization processes in the residual gas.

The observations would be explained completely and without internal contradiction if neutrons in free flight transform spontaneously into protons with the emission of beta-particles having a maximum energy of less than about 0.9 Mev.

We are not yet in a position to give an accurate value for the half-life of the neutron because of difficulties in evaluating the collecting geometry, in which beta-proton directional correlations are involved. A half-life in the range 10–30 minutes would, however, be consistent with all of our observations.

E. F. Shrader, D. Saxon, and L. C. Miller have collaborated actively in the experiment in the past. We are indebted to W. H. Jordan for generous help in the electronics.

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[1] J. Chadwick and M. Goldhaber, Proc. Roy. Soc. **A151**, 479 (1935).

Radioactive Decay of the Neutron

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March 13, 1950

By using a thin magnetic lens spectrometer in conjunction with an electrostatic field, the positive particle from the radioactive decay of the neutron has been identified as a proton. The source of neutrons was a beam from the Chalk River pile from which the pile gamma-rays had been filtered by a 5-in. bismuth plug at the reacting core end of the collimator. Figure 1 shows a plan view of the apparatus mounted outside of the pile shield with the beam entering the aluminum vacuum tank through a 0.005-in. aluminum window and emerging through a 0.018-in. window into the beam catcher.

The high voltage electrode in the form of a hollow half-cylinder of 0.005-in. aluminum was held at a positive potential to ground

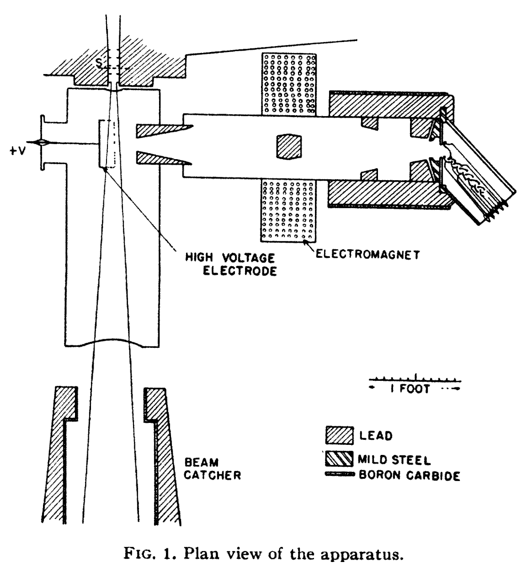

Fig. 1. Plan view of the apparatus.

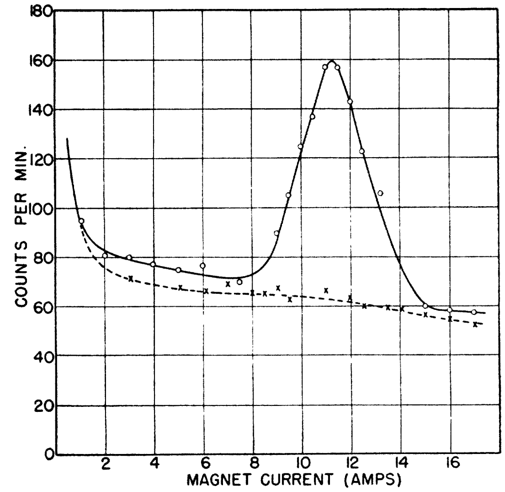

Fig. 2. Electron multiplier counting rate as a function of magnetic field for a potential of 15 kv on the high voltage electrode. The solid curve corresponds to the boron shutter "out" and the dotted curve to the boron shutter "in."

so that low energy positively charged particles such as protons resulting from the neutron decay were deflected through the entrance aperture into the thin magnetic lens spectrometer. The counter at the end of the spectrometer was an electron multiplier shielded from the magnetic field by mild steel shaped to deflect the field away from the beryllium-copper electrodes. A thin shutter of boron carbide power held between two 0.005-in. aluminum windows could be inserted in the beam at S in the pile shield to shut off the thermal neutrons without appreciably scattering the other components of the beam.

The procedure in the experiment was to set a definite voltage on the electrode and record the counting rate of the electron multiplier as the magnet current was varied. Figure 2 shows the results obtained with 15 kv on the electrode, and consists of two curves one with the boron shutter "out" and the other with the shutter "in." The peak on the "out" curve occurs at the correct magnetic field to focus protons of the energy received from the electrostatic field. With the boron shutter "in", the general features of the counting rate curve are similar except that the peak disappears. The difference in the counting rates observed between 2 and 7 amp. and above 15 amp. is probably due to gamma-rays from the capture of thermal neutrons scattered by the vacuum chamber windows and by the air between the vacuum chamber and beam catcher.

At accelerating potentials under 10 kv it would have been possible with the magnetic field available to observe the peak corresponding to singly ionized molecular hydrogen. No significant peaks other than that corresponding to protons were observed at any potential. The pressure in the vacuum tank was varied to see if any of the protons arose from spurious effects in the residual gas. No significant effect was observed with air or oil vapor between pressures of 7×10^{-7} mm and 5×10^{-6} mm of mercury, measured with an ionization gauge. Above the latter pressure the electrostatic field tended to break down under the stray magnetic field near the high voltage electrode. A gamma-ray source placed near the vacuum tank increased the background but did not affect the proton peak. It thus appears probable that the proton peak corresponds to the decay of neutrons, and is not due to other pile radiation or to any effect of the residual gas in the vacuum tank.

An estimate of the half-life of the neutron can be obtained from the number of protons striking the first surface of the electron multiplier, the efficiency of the collecting and focusing system and the density of neutrons in the beam.

To obtain the number of protons striking the first surface of the electron multiplier a set of curves similar to Fig. 2 was obtained at