THE

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 72, NO. 3 AUGUST 1, 1947

Directional Properties of Fission Neutrons*

ROBERT R. WILSON**
Los Alamos Scientific Laboratory, Santa Fe, New Mexico

(Received April 2, 1947)

An experiment has been performed to measure the correlation between direction of neutron and fragment in the fission process. The results are consistent with the isotropic evaporation of neutrons from the moving fragments.

THE simplest picture of the emission process of fission neutrons is that these are evaporated from the moving fission fragments. If this is true, and if the evaporation velocity is comparable with that of the fragments, then one would expect the neutrons, when measured in the laboratory system, to be emitted predominantly in the direction of the fragments. The present experiment was designed to detect and measure the directional correlation of the fission fragments and the emitted neutrons.

Figures 1 and 2 show the experimental arrangement. The direction of the fission fragments was determined by the thin collimator placed over the U_{235} foil which was one mg/cm^2 thick. The collimator consisted of a grid of closely spaced $\frac{1}{16}$ in. holes drilled in a $\frac{1}{8}$ in. thick block of aluminum. The holes were drilled over a square area one inch to the side which corresponded to the area of the foil. The fission fragments penetrating the collimator were detected by the ionization chamber formed from the collimator and the ion collection plate $\frac{3}{8}$ in. away. It was possible to rotate this system with respect to a neutron counter which consisted of a bundle of ten proportional counters $1\frac{1}{2}$ inches long and

TABLE I. Counting rate of the numbers of neutrons emitted at angles 0 and $\pi/2$ in the laboratory system.

Angle	Time min.	$\frac{\text{Recoils}}{64}$	$\frac{\text{Fissions}}{1024}$	$\frac{\text{Coincidences}}{4}$	Coincidences per $2.56\cdot 10^4$ fissions	Accidental counts per $2.56\cdot 10^4$ fissions	True coincidence counts per $2.56\cdot 10^4$ fissions
0°	23	472	1941	41.0	2.11	0.29	1.82
$\pi/2$	14	273	1093	6.7	0.61	0.27	0.34
π	5	91	403	8.5	2.11	0.26	1.85
$3\pi/2$	6	108	573	3.5	0.61	0.25	0.36

Av. of number of neutrons emitted per fission at 0° and π; $n(0)=(1.83\pm 7\%)/2.56\cdot 10^4$.
Av. of number of neutrons emitted per fission at $\pi/2$ and $3\pi/2$; $n(\pi/2)=(0.34\pm 16\%)/2.56\cdot 10^4$
$n(\frac{1}{2}\pi)/n(0)=0.18\pm 0.03$.

---

[*] This document is based on work performed in 1945 at Los Alamos Scientific Laboratory of the University of California under Contract No. W-7405-eng-36 for the Manhattan Project, and the information contained therein will appear in Division V of the Manhattan Project Technical Series as part of the contribution of the Los Alamos Laboratory.

[**] Now at Cornell University.

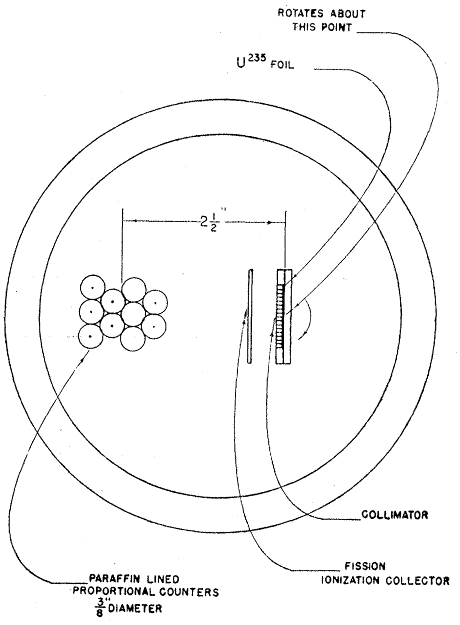

FIG. 1. Plan view of counter arrangement.

$\frac{3}{8}$ in. in diameter. The three-mil wires along the axis of all counters were connected in parallel to a fast amplifier (Model 500). The inside of each cylinder was coated with paraffin. The sensitive area of the counter was very nearly a square one-inch to the side. The front of the neutron counter was $1\frac{7}{8}$ in. from the center of the U_{235} film. The geometry was such that if the neutrons were emitted exactly in the direction of the fission fragments, then no neutrons would be counted by the proportional counter at angles greater than 45° with respect to the direction of the fragments. Argon at 60 cm Hg plus CO_2 at one cm Hg was used to fill the chamber and was thus the counting gas for both the ionization chamber and the proportional counter. A negative potential of 1000 volts was applied to the collimator and the cylinders so that electrons were collected in each case. A typical number-bias curve for the proportional counter is shown in Fig. 3.

The fission pulses from the ionization collection plate and the neutron pulses from the wire were amplified separately and then led to a coincidence counter. The number of fissions, the number of neutrons, and the number of coincidences were all counted simultaneously when the foil was irradiated by the nearly pure thermal neutron flux of the water boiler. The resolving time of the coincidence system was 0.25μ sec. as determined by placing a strong source of fast neutrons at various distances from the proportional counter and then measuring the accidental counts.

The first run was made to determine the counting rate of the number of neutrons per fission in the direction of the fission fragments (0°), to the counting rate of neutrons per fission emitted perpendicular (in the laboratory system) to the fragment direction. The fission counter bias was set as low as possible so that all fragments were registered. Table I summarizes the data. The neutron counting rate observed perpendicular to the fragment direction was about one-fifth of that observed in the direction of the fragments.

The second run was made to try to determine the effect of the energy of the fission fragment counted both on the number of neutrons emitted in the direction of the fragment (0°) and the opposite direction (π). The energy of the fragment was varied by changing the fission counter bias. A typical number-bias curve is shown in Fig. 4. The gain of the amplifier was different

TABLE II. Influence of the fission fragment energy on the numbers of neutrons emitted at angles 0 and π.

Angle	Fission counter bias in volts	Time min.	$\frac{\text{Recoils}}{64}$	$\frac{\text{Fissions}}{1024}$	$\frac{\text{Coincidences}}{4}$	Coincidences per $2.56\cdot10^4$ fissions	Accidental counts per $2.56\cdot10^4$ fissions	True coincidence counts per $2.56\cdot10^4$ fissions
0	0	10	250	796	15	1.88	0.35	1.53±0.20
0	0	10	240	742	12	1.62	0.34	1.28±0.24
0	40	10	239	356	7.75	2.18	0.34	1.84±0.33
0	50	10	238	106	2	1.9	0.34	1.6 ±0.6
π	0	10	218	682	10.5	1.55	0.30	1.55±0.24
	40	10	230	318	4.0	1.26	0.33	0.93×0.25
	50	10	239	55	0	0	0.35	−±100%

TABLE III. Angular distribution of the neutrons emitted from fission fragments.

Angle	Time min.	$\frac{\text{Recoils}}{64}$	$\frac{\text{Fissions}}{1024}$	$\frac{\text{Coincidences}}{4}$	Coincidences per $2.56\cdot10^4$ fissions	Accidental counts per $2.56\cdot10^4$ fissions	True coincidences counts per $2.56\cdot10^4$ fissions
0	10	331	729	16.25	2.23	0.47	1.76 ± 0.28
$\pi/16$	12	501	883	14	1.58	0.59	0.99 ± 0.21
$\pi/8$	12	417	868	7	0.81	0.49	0.32 ± 0.15
$3\pi/16$	11	450	780	6	0.77	0.57	0.20 ± 0.16
$\pi/4$	13	576	910	6.25	0.68	0.61	0.07 ± 0.13
$3\pi/8$	12	525	824	5	0.61	0.66	-0.05 ± 0.13
$7\pi/16$	13	595	905	9.75	1.07	0.64	0.43 ± 0.17
π	12	556	831	13	1.56	0.65	0.91 ± 0.22
π	10	487	775	11.75	1.51	0.68	0.83 ± 0.22
$3\pi/2$	10	439	809	5	0.62	0.62	0.00 ± 0.12
2π	12	518	779	12.25	1.58	0.60	0.98 ± 0.23

at that time. The data are summarized in Table II. The statistics are poor, as can be seen from the large standard errors given in the last column. The energy of the fragment has no evident effect on the number of neutrons per fission emitted in the forward direction. There is a slight indication that fewer neutrons are emitted from the low energy fragment because there seem to be fewer recoils in the backward direction at the higher biases. This effect may be instrumental.

A third run was made to obtain a curve of the numbers of neutrons emitted per fission at various angles. Table III shows the data, and the standard errors listed in the last column indicate that the results are too rough to plot. Furthermore, the sensitivity of the neutron counter seemed to change during the course of the run. However, anything really unusual might have been noticed even with such rough data.

The first run was made under good conditions, so let us see what conclusions can be drawn from it about the process of neutron emission. Assume the simplified picture that the fission fragments all have the same velocity and that the neutrons are evaporated isotropically with respect to the moving fragment and with a uniform velocity.

The ratio of the number of neutrons emitted in the forward direction to those emitted at 90° in the laboratory system can be calculated to be

$$N(\tfrac{1}{2}\pi)/N(0)=r(r^2-1)^{\frac{1}{2}}/(r+1)^2, \qquad (1)$$

where $r=v_n/v_f$, and v_n is the speed of the emitted neutron with respect to the fragment, and v_f is the speed of the fragments.

Now the proportional counter is sensitive to the energy of the neutrons. The speed of a neutron emitted at 0° is (v_n+v_f), while that of a neutron emitted at an angle $\pi/2$ is $(v_n^2+v_f^2)^{\frac{1}{2}}$.

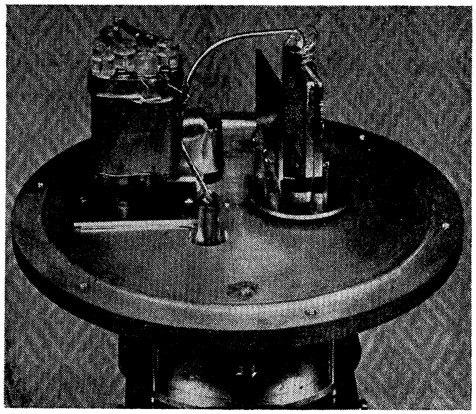

FIG. 2. View looking down on the chamber with enclosing shell removed. The rotating fission collimator and counter are to the right; the neutron counter is to the left; and the preamplifier is below.

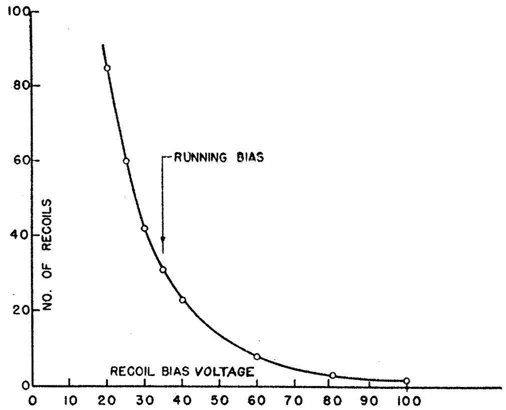

FIG. 3. A typical number-bias curve for the recoil proportional counter.

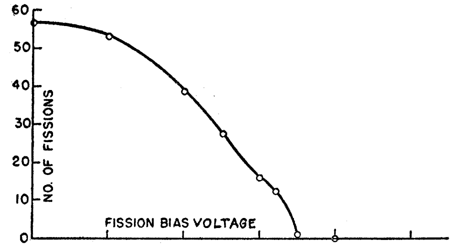

FIG. 4. A typical number-bias curve for the fission counter.

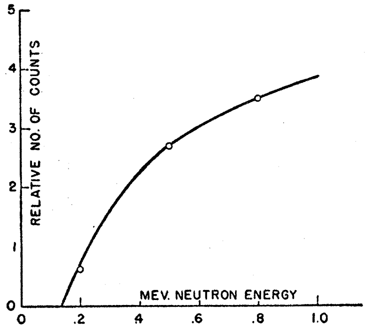

FIG. 5. Energy response of the recoil proportional counters.

The energy sensitivity of a neutron counter of the same dimensions and gas filling was taken at a different time, using the lithium (p, n) neutrons obtained from a Van de Graaff generator. The curve is shown in Fig. 5, and for our purpose the sensitivity can be approximated roughly by $K'(E_n)^{\frac{1}{2}}$. If we make this correction to Eq. (1) we get

$$n(\tfrac{1}{2}\pi)/n(0)=r(r-1)/(r+1)^2 \qquad (2)$$

where $n(\frac{1}{2}\pi)/n(0)$ is the ratio of the numbers of neutrons counted at angles $\pi/2$ and 0. In Fig. 6 is plotted $n(\frac{1}{2}\pi)/n(0)$ as a function of r, and we can read a value of $r=1.8\pm0.2$ corresponding to the experimental value $n(\frac{1}{2}\pi)/n(0)=0.18\pm0.3$ If the average energy of a fission fragment is 70 Mev, and the average atomic weight is 100, the velocity v_f is the same as that of a neutron of 0.7 Mev; hence the energy of evaporation would be $0.7\times(1.8)^2\approx 2$ Mev. Had we assumed that the detector was insensitive to energy the evaporation energy would be about one Mev. The crudeness of the experiment and its interpretation are apparent.

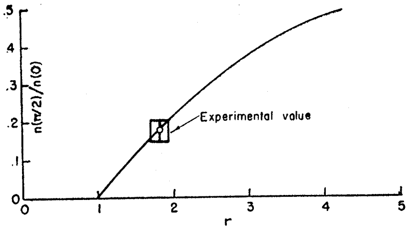

FIG. 6. Theoretical ratio of neutron counts at right angles to fission direction to neutron counts in the direction of the fission fragment as a function of r, the ratio of the speed of the emitted neutron with respect to the fragment to the speed of the fragment.

I had hoped to split the neutron counter into two equal parts and count coincidences between these neutron counters when they were on opposite sides of a piece of uranium exposed to thermal neutrons and when the two counters were on the same side. This would give information about the mechanism of emission of fission neutrons as well as of the quantity $\langle\nu^2\rangle_{\text{Av}}-\langle\nu\rangle_{\text{Av}}^2$, where ν is the number of neutrons per fission. However, the very brief time available for the experiment did not permit this extension.

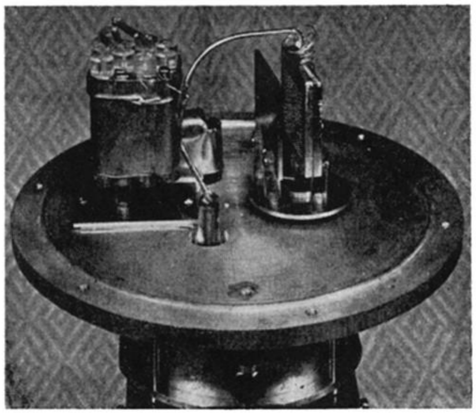

FIG. 2. View looking down on the chamber with enclosing shell removed. The rotating fission collimator and counter are to the right; the neutron counter is to the left; and the preamplifier is below.