THE

PHYSICAL REVIEW

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

SECOND SERIES, VOL. 71, NO. 6 MARCH 15, 1947

Long Range Alpha-Particles Emitted in Connection with Fission. Preliminary Report†

G. FARWELL,* E. SEGRÈ,** AND C. WIEGAND**
Los Alamos Scientific Laboratories, Los Alamos, New Mexico
(Received December 12, 1946)

Alpha-particles are emitted in coincidence (i.e., within 5×10^{-6} sec.) with fission by U^{235} and Pu^{239}. The maximum range observed corresponds to an energy of 16 Mev. About one alpha per 250 fissions is emitted by U^{235} and one alpha per 500 fissions by Pu^{239}. The investigation is being continued.

INTRODUCTION

L. W. ALVAREZ reported (verbal communication) that a foil of U^{235} irradiated with slow neutrons emits charged particles which are probably alpha-particles with a range of about 20 cm of air.

An experiment has been performed to determine the nature, energy, and abundance of particles other than fission fragments and neutrons which are occasionally emitted in connection with the fission process. We have found that these particles are emitted in coincidence (within 5×10^{-6} sec.) with fission in U^{235} and Pu^{239}, that they are alpha-particles, and that their maximum energy is about 16 Mev. About one alpha per 250 fissions has been detected for U^{235}, and one alpha per 500 fissions for Pu^{239}.

EXPERIMENTAL ARRANGEMENT AND RESULTS

A double chamber connected to twin linear amplifiers and counting circuits was used as a detector. The chamber was filled with argon and electrons were collected. A coincidence circuit registered events occurring simultaneously on each side of the chamber. The resolving time of the circuits was measured experimentally from the formula: $N_c=2N_AN_Bt$. N_c is the rate of accidental coincidence counts; N_A the counting rate of A side; N_B the counting rate of B side; t the resolving time.

With various single counting rates the resolving time was found to be from six to ten microseconds.

The chamber is shown in Fig. 1. It was so constructed that the sample foil acted as a high voltage electrode between two collecting electrodes which were connected to first amplifier tube grids. Thus the sample mounted on a thin metallic foil could emit particles into either side

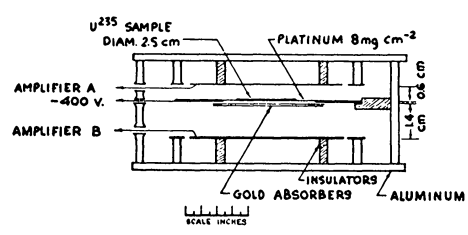
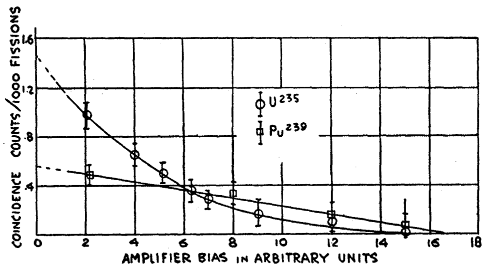


FIG. 1. Schematic diagram of ionization chamber.

† This report was filed on May 18, 1944; the press of other work prevented the continuation of this investigation at Los Alamos.
* Present address: Institute of Nuclear Studies, University of Chicago, Chicago, Illinois.
** Present address: Department of Physics, Radiation Laboratory, University of California, Berkeley, California.



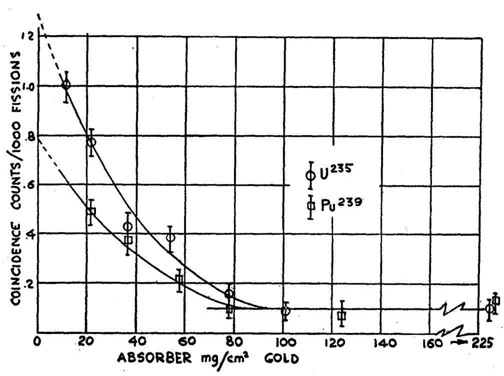


FIG. 2. (upper) Number of coincidences per 1000 fissions *versus* bias of the B chamber amplifier. Pressure in chambers 4 atmos. argon. Absorber between A and B chambers 8 mg/cm² Pt+5 mg/cm² Au for the U^{235} curve; 8 mg/cm² Pt +15 mg/cm² Au for the Pu^{239} curve.

FIG. 3. (lower) Number of coincidences per 1000 fissions *versus* absorber thickness between chambers A and B. Pressure in chambers 4 atmos. argon. Bias of the B amplifier 2.2 of the units used in Fig. 3.

or both sides. In our experiment the actual sample of uranium faced the chamber side which we will call A. The back of the foil faced into side B. The physical depth of side A was 0.6 cm and the physical depth of side B was 1.4 cm. A pressure of 4 atmospheres of argon was used, making an effective depth of 5.7 cm air equivalent on side B and of 2.3 cm air equivalent on side A.

The enriched sample used consisted of 0.220 mg of U^{235} electrodeposited on a thin platinum foil weighing 8 mg/cm². This foil was also backed with an additional layer of gold weighing 5 mg/cm² making an equivalent total of 12.2 mg/cm² of gold. With this arrangement, and the bias used, the natural uranium alpha-particles and fission fragments were not detected in side B.

The chamber was irradiated with slow neutrons from the cyclotron. Table I gives the ratios of the observed counting rates in the chambers as functions of the bias voltage. The fission rate on side A was maintained at about 4000 counts/min. The non-coincident counts on side B may perhaps be caused by an (n, p) reaction on a nitrogen impurity in the argon (tank argon was used); considerably less than 1 percent of nitrogen would account for the effect.

The data of the last column are shown graphically in Fig. 2. When the curve is extrapolated to zero bias, it indicates approximately 1.5 coincidence counts per 1000 fissions.

The next part of the experiment was the making of an absorption curve for the particles in coincidence with the fission counts. Various thicknesses of gold foils were used as absorbers. The bias of side B was maintained constant at 2.1 units; and the fission rate in side A was maintained at about 3500 counts/min. Table II gives the observed data on the counting rates as functions of the absorber thickness.

The data of the last column are shown graphically in Fig. 3.

We are now able to determine the number of penetrating particles emitted per fission. The extrapolated bias curve gives a coincidence rate of 1.5 per 1000 fissions. To this we apply a correction factor of 1.3, representing an extrapolation of the absorption curve from 12.2 mg/cm² of gold (the absorber thickness at which the bias curve was run) to zero absorber thickness. In addition we allow for the fact that chamber side B subtends a solid angle 2π seen from the fissionable material, hence half the particles are lost to possible observation. We have finally:

Number per 1000 fissions $= 1.5 \times 1.3 \times 2 = 4$ per 1000 fissions.

Having bias and absorption curves for the particle, we are able to calculate its range and

TABLE I. Ratios of counts in amplifiers A and B. A and B represent the single counting rates in chambers A and B. C is the coincidence counting rate.

Amplifier bias in arbitrary units	B/A	C/A
2.1	0.022	0.0010
4.0	0.0029	0.00066
5.2	0.0024	0.00045
6.3	0.0028	0.00035
7.0	0.0011	0.00029
9.0	0.0006	0.000163
12.0	0.00069	0.000103
14.7	0.0001	0.000025

specific ionization, which in turn identify the particle and its energy.

The range is obtained from Fig. 3, which shows that the particle of maximum range is stopped by 90 to 100 mg/cm^2 of gold. Using 3.9 mg/cm^2 of gold as the equivalent in stopping power of 1 cm of air, we estimate the maximum range of the particle in air to be about 23 cm. The range determination allows us to use the bias curve for the particle to show that its specific ionization is that of an alpha-particle.

The considerations leading to the conclusion that we are dealing with an alpha-particle are as follows: When collecting electrons in an ionization chamber of our type the pulse output of the chamber is determined by the product of the ionization charge and its displacement. Practically speaking the maximum pulse output from a particle of given energy is produced when the ionization track arises from a sample mounted on a negative electrode and when the track is parallel to that electrode. The total charge is then displaced the entire depth of the chamber. Referring to the bias curve of the alpha-particles of polonium of Fig. 4, we see that these particles of range 3.84 cm, energy 5.3 Mev, are able to produce a maximum pulse output corresponding to 14.5 of our units. This occurs when the electrons move through the whole depth of the chamber, which is 5.7 cm.

As a check we used the datum given above to calculate also the minimum output from the polonium alphas. This is obtained for a particle emitted perpendicularly to the electrode; the center of gravity of the ionization is taken to be at $\frac{3}{5}$ of the range of the particle. The chamber depth is 5.7 cm so the average charge is displaced 3.4 cm.

The minimum output should then have the

TABLE II. Absorption curves of particles.

Absorber gold mg/cm^2	B/A	C/A
12.2	0.032	0.0010
22.2	0.019	0.00077
37.2	0.0421	0.00043
53.2	0.039	0.00038
78.2	0.0365	0.00016
99.2	0.035	0.00009
124.2	0.055	0.000075
225	0.051	0.00010

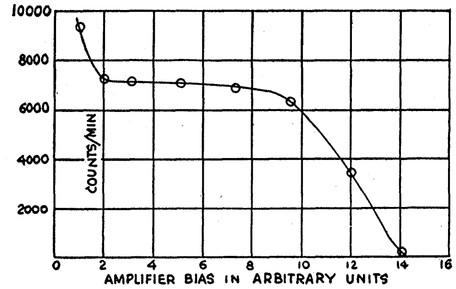


FIG. 4. Bias curve for alpha-particles from a Po sample facing downwards from the high voltage electrode in chamber B. Pressure in the chamber 4 atmospheres of argon.

ratio 3.4/5.7 to the maximum output, i.e., be $14.5(3.4/5.7)=8.7$ of our units. This is in agreement with the bias curve which breaks at a value between 8 and 9.

We have calculated the geometrical path in our chamber which would cause maximum pulse output from an alpha-particle whose range in air is 23 cm. Taking into account the part of the range spent in the absorber by such a particle, we find that the residual energy available for ionization in the gas is 11 Mev. Its trajectory is such that the average charge displacement is 2.8 cm. The largest pulses of polonium alphas should then be in a ratio $(5.3\times5.7)/(11\times2.8) = 0.98$ to the maximum pulses of the other particles.

Thus the assumption that the particle under observation is an alpha leads to the conclusion that the maximum pulse heights of Po alphas and the unknown particle are about the same.

From the bias curves of Po alphas and long range particles of Figs. 2 and 4 it is seen that both produced about the same maximum ionization pulse. It can, therefore, be concluded that the particle emitted in coincidence with fission of U^{235} (within a few micro-seconds) is an alpha of 23 cm of air range. From curves of Livingston and Bethe[1] this corresponds to an energy of about 16 Mev.

Long range alpha-particles were also observed in coincidence with Pu^{239} fission. A sample of about 2 mg of Pu^{239} was used for the experiment. A collimating screen, necessary to reduce the alpha-background on the fission side A, reduced the effective mass of the Pu^{239} to about 0.200 mg.

[1] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. 9, 266 (1937).

The sample was irradiated with neutrons from a Ra+Be source, with paraffin as a slowing medium. Fission counting rates of two to three hundred per minute were observed.

The absorption curve for the particles accompanying Pu^{239} fission is seen in Fig. 3. The maximum range of the particle appears to be about the same as that of the alphas from U^{235} fission, within the limits of the experimental error. The curves relevant to the Pu^{239} experiments are also reported in Figs. 2 and 3, together with the curves for U^{235}.

The difference in shape of the curves for U^{235} and Pu^{239} in Fig. 3 may be accounted for by the additional absorber used for Pu^{239}, which has the effect of eliminating the particles which made very small pulses on the U^{235} run. The same arguments used for U^{235} establish also that the ionizing particles emitted by Pu^{239} in coincidence with fission are α-particles.

The number of alpha-particles emitted in coincidence with Pu^{239} fission is computed from the data exactly as before. The result obtained is about 2 alphas per 1000 fissions.

This investigation will be followed up with the purpose of finding for both U^{235} and Pu^{239}:

(1) The energy distribution of the alphas.
(2) The possible presence of protons.
(3) The time relation of the emission of the charged particles to the fission.

ACKNOWLEDGMENT

This document is based on work performed under Contract W-7405-Eng-36 for the Manhattan Project at the Los Alamos Scientific Laboratories of the University of California.

The information covered in this document will appear in Division V of the Manhattan Project Technical Series as part of the contribution of the Los Alamos Scientific Laboratories.

PHYSICAL REVIEW VOLUME 71, NUMBER 6 MARCH 15, 1947

The Probability of K Ionization of Nickel by Electrons as a Function of Their Energy

LEONARD T. POCKMAN, DAVID L. WEBSTER, PAUL KIRKPATRICK, AND KEITH HARWORTH
Stanford University, California

(Received July 22, 1946)

Thin targets of Ni were bombarded with electrons at 12 to 183 kv and intensities of the $K\alpha$ doublet were measured in arbitrary units. The results were converted to absolute cross sections for ionization by comparison with Smick and Kirkpatrick's absolute measurements at 70 kv. At any voltage $V=UV_K$, where V_K is the K ionization voltage, the cross section is well represented empirically as

$$\Phi_K=7.3(e/V_K)^2U^{-0.837}\log_{10}U,$$

with e and V_K both in electrostatic units. Burhop's theory is confirmed with accuracy probably well within the limits of error imposed on it by the Born approximation and neglect of relativity, exchange and other minor factors. The effect of relativity is found by comparison of the cross sections for Ni with ones for Ag, previously measured in this laboratory. Relativity increases the cross sections by moderate percentages, which increase with voltage. Deduction of these percentages yields data for a hypothetical non-relativistic element; and Burhop's non-relativistic theory fits this element best. Smith's cross sections for helium are compared with these non-relativistic cross sections and with those for real nickel. At low U's the cross sections for helium are notably less than would be predicted by simple analogy with the other elements, presumably because of unusually great effects in helium, due to movement of the electron which remains in the atom.

I. INTRODUCTION

BECAUSE of the mathematical complexity of wave mechanics and the physical complexity of most real atoms, atomic hydrogen would be the best element for a test of theories of K ionization by electron impact. Experiments with atomic hydrogen are difficult; but silver, which has been studied both experimentally and theo-