Alpha-Particles Associated with Fission*

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The photographic emulsion technique has been applied to the study of the long range particles associated with the fission of uranium. Twenty such long range tracks were observed and studied. From the grain spacing along the tracks it was possible to show that the particles are not protons but are most likely alpha-particles. The maximum range observed for the long range alphas is about 40 cm of normal air. From the distribution in angle with respect to the fission tracks, it is shown that the alphas are not emitted from the fission fragments but are released as a part of the fission process.

In this work the photographic emulsion technique has been applied to the study of the long range particles associated with the fission of uranium.

Alvarez first observed these particles and Segrè, *et al.* have made a study of them with ion chambers arranged to give coincidences between the particles and the fission fragments. They have identified the particles as alpha-particles from measurements of the density of ionization near the ends of their range. Hughes has observed some of these alpha-particles in the cloud chamber, but his set-up did not permit him to observe the associated fission tracks.

The cloud chamber or photographic emulsion technique permits information to be obtained about the alpha-particles and their association with the fission process that cannot be easily obtained by the ion chamber method.

The photographic emulsion technique has been

TABLE I.

No.	Fission fragment tracks: One fragment, Length microns	One fragment, No. of grains	Other fragment, Length microns	Other fragment, No. of grains	Alpha-tracks, Length microns	Alpha-tracks, No. of grains	Angle of α with fission θ°	Deviation of fission tracks from 180° Δ°	Range of α in cm air*	Energy of α Mev
1	10.0	11	10.2	14	282	138	130	—	39.4	22.1
2	17.0	10	16.0	10	154	66	72	—	21.6	15.2
3	14.5	10	17.5	8	160	82	80	—	22.4	15.6
4	13.8	10	12.8	8	284	140	51	—	39.7	22.2
5	13.5	9	12.7	7	154	65	75	12	21.6	15.2
6	8.5	10	9.5	9	208	97	17	—	29.0	18.2
7	9.9	11	9.45	14	207	94	84	10	28.9	18.1
8	10.35	12	14.2	14	244	129	62	4	34.2	20.2
9	9.5	6	11.5	11	64.5	27	88	2	9.0	9.2
10	14.5	9	10.2	8	97	48	72	6	13.7	11.6
11	12.2	8	11.5	8	161	94	83	2	22.4	15.6
12	11.5	9	10.0	9	108	66	72	0	15.1	12.2
13	10.6	9	13.1	11	160	71	57	23	22.4	15.6
14	11.1	9	7.8	8	105	49	73	2	14.7	12.0
15	15.8	10	14.0	10	251	115	82	0	35.2	20.3
16	9.3	6	11.3	8	256	122	90	8	35.8	20.8
17	13.9	10	10.5	11	186	97	87	2.5	26.0	17.0
18	14.3	11	14.0	9	111	60	86	5	15.6	12.6
19	10.7	9	10.7	9	171	74	90	8	23.9	16.1
20	9.4	10	10.5	5	151	80	89	0	21.2	15.0

* The stopping power of the emulsion is taken as 1400 times that of air.

* This paper appeared as a report on the Manhattan Project in July 1944. The report is maintained in essentially the same form as originally written, without regard to more recent work which has been done on the project and to work which has now been published in this Journal; i.e., Pierre Demers, Phys. Rev. **70**, 974 (1946); G. Farwell, E. Segrè, and C. Wiegand, Phys. Rev. **71**, 327 (1947); Tsien San-Tsiang, Ho Zah-Wei, R. Chastel, and L. Vigneron, Phys. Rev. **71**, 382 (1947). D. L. Hill has made a rather extensive study of the range of these particles with a coincidence chamber arrangement.

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used in this case because it lends itself very well to a study of rare events of this type.

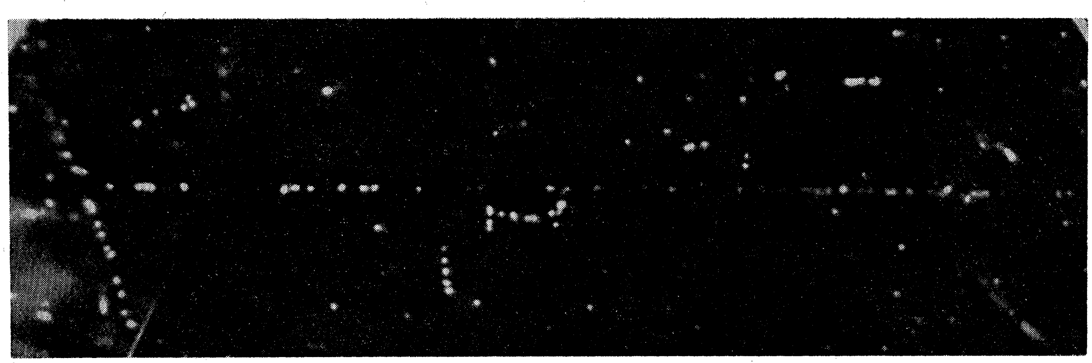
EXPOSURE OF PLATES

Eastman alpha-particle plates with an emulsion thickness of about 50μ were used. It was desirable to obtain as large a number of fission events in the emulsion as possible without too high a background. It was found that the plates could be soaked in a saturated water solution of uranyl acetate without damaging the emulsion. Plates soaked in this solution for 30 minutes were dried and then exposed near the edge of the reflector of the Clinton Pile for 1 or 2 sec. This gave of the order of 10^6 fission tracks on a $3'' \times 1''$ plate. Control plates (a) irradiated but unsoaked, and (b) soaked but not irradiated, were made as a check on natural alpha-particle tracks and recoil protons from the small percent of fast neutrons from this place in the pile. A single good plate which can be made in a few hours after the conditions of exposure have been determined furnishes material for a long and tedious examination under the microscope.

TRACK DATA

A plate area of about 10 cm^2 has been searched for long range alphas. In all cases to date in which both ends of the alpha-track are observed to lie in the emulsion, it has been found that the alpha-particle originates near the center of a fission track. So far twenty such tracks have been observed and measured. The data on these tracks are given in Table I. The lengths and number of grains are listed for each fission particle track and for the alpha-particles. The true angle between one fission fragment and the alpha-track is given as θ. This angle was determined from the horizontal projection angle and the depths of the track ends in the emulsion. The angular deviation of the fission track from a straight line is listed as $\Delta°$. Natural curvatures in the tracks make it impossible to expect any accuracy in these values. Most of the angles are, however, positive, as is to be expected for conservation of momentum.

In order to get a good microphotograph of a track, it should lie nearly in a plane perpendicular to the axis of the microscope. So far no track has fulfilled this condition for both the fission and alpha-particle. A few cases have, however, been photographed and are shown in Figs. 1 and 2. All these photographs have been made by piecing together sections of the track for which the grains were in approximate focus at one setting of the microscope. In Fig. 1b the track has been retouched in a few places where the grains were not in sharp focus.



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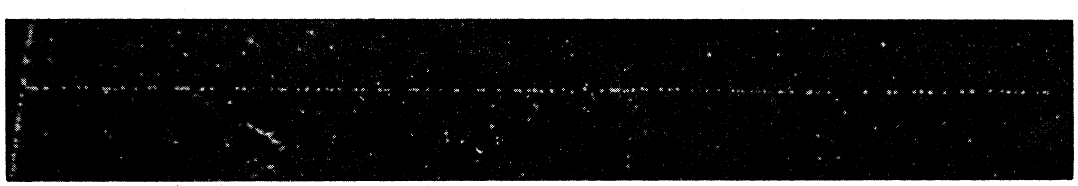

b

FIG. 1. Examples of long range alpha-tracks associated with fission.

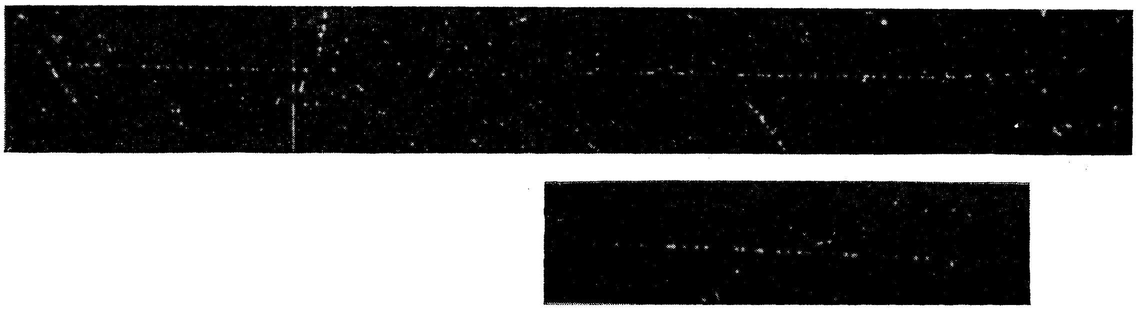

FIG. 2. Long alpha-track associated with fission (upper picture) as compared with a recoil proton track (lower picture). The difference between the two tracks can be seen by comparing their average grain spacings. The pictures are so placed that the ends of the tracks fall at the same distance from the left side of the page.

In Fig. 2 a short proton track has been included for comparison of grain spacing with the alpha-track. This point is discussed in the next paragraph.

EVIDENCE THAT PARTICLES ARE ALPHAS

Alpha-particle tracks can be distinguished from proton tracks by the relative grain spacings along the tracks. To check this, a plate was exposed to fast neutrons from the cyclotron and the grain spacings for long recoil proton tracks were measured. In Table II comparison is made of the grain spacing for two (α_1 and α_2) of our so-called long range alpha-tracks with the average spacing for 6 long proton tracks. Figure 3 shows the data of Table II in graphical form. It is evident that these long range particles are not protons, and hence it seems logical to assume that they are alpha-particles, although the evidence presented here does not exclude the possibility of their being identified with other light nucleii.

EVIDENCE FOR ALPHA-PARTICLES BEING EMITTED IN FISSION PROCESS

The fact that the alpha-particles originate near the center of the fission track does not in itself show that these alphas are liberated in the fission act; they may be ejected from one of the fission fragments left in a highly excited state.

The time scale given by the velocity and range of the fission particles is very short in a photographic emulsion. The time for a fission particle to travel 10 microns in the film is in the neighborhood of 10^{-12} sec. The alpha must then be coincident with fission within less than 10^{-13} sec. For alpha-particles of the high energy encountered here, however, even this short a time is long compared to the average lifetime before emission of the alpha-particle, and hence this gives no information regarding the nature of the process.

If the alpha-particles were emitted from the fission fragments after fission has occurred, one should expect in the center of gravity system a random angular distribution of the alphas with respect to the fission tracks. This would mean an angular distribution function $N(\alpha)d\alpha = \sin\alpha d\alpha$ in the center of gravity system from which the angular distribution function in the laboratory system can be calculated for a given energy and

TABLE II. Grain spacing of long range alphas compared to spacing of proton tracks.

Tracks	Grains per 20 microns as a function of distance from end of tracks in microns						
	0–20	20–40	40–60	60–80	80–100	100–150	150–200
α_1	14	14	13	13	11	10.2	8.8
α_2	10	14	13	11	13	8.4	8.8
Average of 6 proton tracks	10	9	6	6	5.5	3.4	3.4

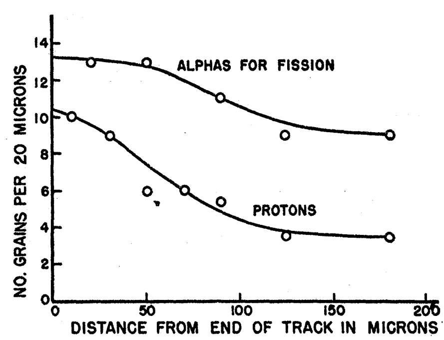

FIG. 3. Comparison of grain spacings for α-particles and protons.

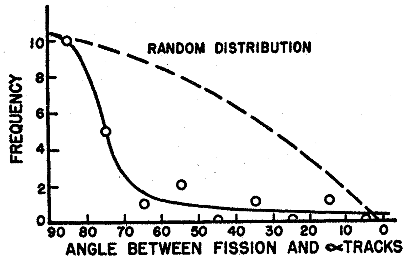

FIG. 4. Angular distribution of α-tracks.

mass of the alphas and the fission fragments. This was done by an approximate method for the more or less average case for which $E_f/E_\alpha=6$ and $m_f/m_\alpha=24$. It is found on this basis that in the laboratory system there is a preponderance of alphas emitted near 45° with its fission track, but when the emission for the two fission fragments is averaged, the distribution function is not very different from that in the center of gravity system, being slightly higher than the sine function at small angles.

If, instead of being emitted by a fission fragment, the alpha-particle is more or less pinched off between the two heavier fragments in the fission act, then it is to be expected that the angular distribution of the alphas will favor the direction normal to the fission track. This is readily seen when one considers the forces on the alpha-particle located in the region between two positively charged particles. The path which the alpha-particle will travel will be determined by the magnitude and direction of its initial velocity and on the magnitude of the charges carried by the fission fragments. If the initial velocity is small, the alpha will move down the potential valley of the two charged particles, in which case the alpha will make a large angle with the fission track. With a large initial velocity, however, any angle is possible.

The angular distribution of the twenty particles given in Table I is plotted as the solid line and points of Fig. 4. The dashed line is for random distribution. The observed distribution is sufficiently different from the random case to indicate quite definitely that many of the alphas at least are ejected in the fission act. This might be taken as the first evidence of the existence of three-particle fission, although this is certainly a very special case of such a process.

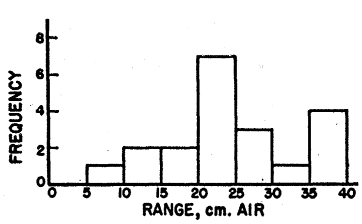

FIG. 5. Energy distribution of the α-particles.

RANGE AND ENERGY OF ALPHA-PARTICLES

We have not yet been able to make accurate stopping power determinations for the alpha-particle plates which we have been using, but this has been done previously for these plates. From the literature it seems that the stopping power of the plates relative to air is about 1400. Using this value and Bethe's energy-loss formula, the energy of the particles has been calculated. The range in air and the calculated energy are tabulated in the last two columns of Table I. An energy distribution for the twenty measured alphas is also shown in the block diagram of Fig. 5. The highest energy alphas ($\sim$22 Mev) which we find are higher than any of those reported so far by Alvarez, Segrè, or Hughes, and are much higher than any alphas previously observed to accompany any natural process.

RANGE DISTRIBUTION OF FISSION FRAGMENTS

The distribution in length of the normal fission tracks (total track) is plotted in the upper curve of Fig. 6. The range distribution for the fission tracks which are accompanied by alpha-emission is plotted in the lower curve of the same figure. It is seen that the average range of the latter is about 20 percent less than for normal tracks. This is to be expected if the

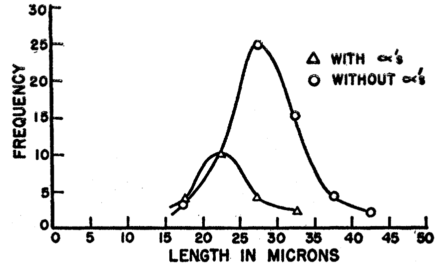

FIG. 6. Distribution in length of fission tracks (upper curve). Range distribution of fission tracks which are accompanied by α-emission (lower curve).

available energy is about the same in the two cases, and in one case the alpha takes off from 10 percent to 15 percent of the energy.

For the fission tracks listed in Table I, a distribution in range can be plotted for individual fragments, since the alphas mark the point of origin. Such a distribution curve is shown in Fig. 7. With only 40 tracks, the accuracy of the curve is necessarily low, but it is felt that the two groups are within the accuracy of the data to resolve. Two groups might be expected from the two energy groups associated with the light and heavy fragments as shown by Jentsche[1] and Flammersfeld, Jensen, and Gentner.[2]

[1] W. Jentsche, Zeits. f. Physik **120**, 165 (1943).
[2] A. Flammersfeld, P. Jensen, and W. Gentner, Zeits. f. Physik **120**, 450 (1943).

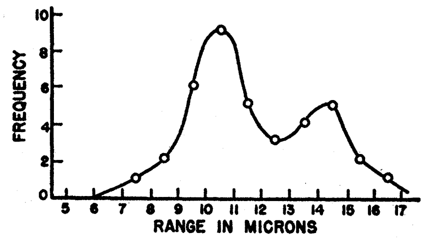

FIG. 7. Distribution in range of individual fragments in fission.

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Hyperfine Structure and Nuclear Moments of Columbium^{93}

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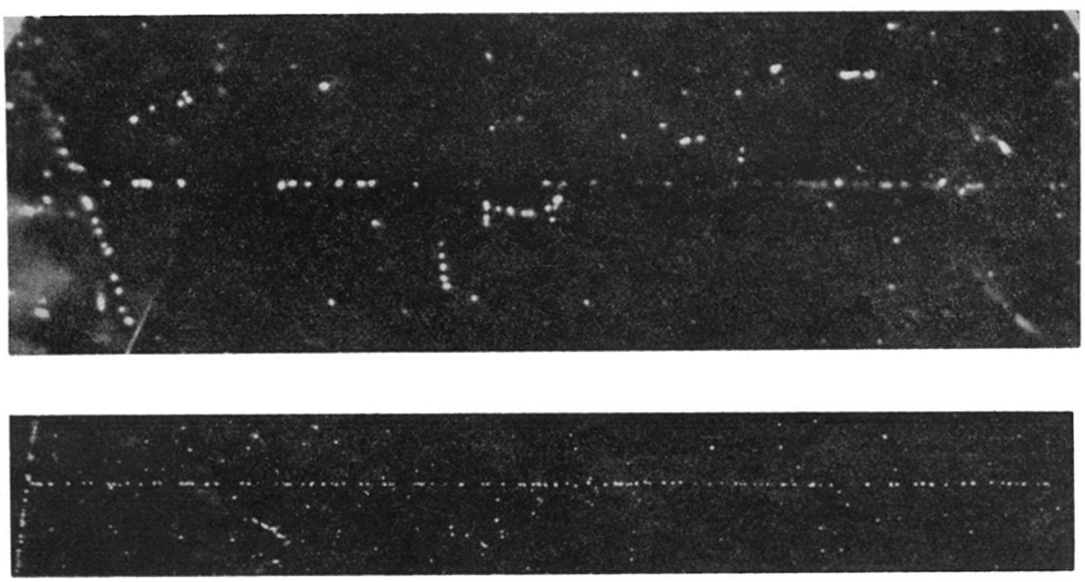
Measurements have been made on the hyperfine structure of 32 lines in the spectrum of CbI. Analysis of these structures supports the previously reported spin value of $4\frac{1}{2}$ units for the Cb^{93} nucleus and yields 32 hyperfine interval factors. These data, when used in conjunction with semi-empirical formulas for the coupling between the nucleus and an s electron in the configuration $4d^4\,5s$, lead to values for the nuclear g-factor and nuclear magnetic moment of 1.18 and 5.3 nuclear magnetons, respectively, for stable Cb^{93}. No nuclear electric quadrupole moment is detected.

INTRODUCTION

THE first published measurements and analysis of columbium hyperfine structure were by Ballard[1] who examined the intervals and intensities in ten visible lines. On a basis of this study he reported the nuclear spin as $4\frac{1}{2}$ units and the nuclear magnetic moment as 3.7 nuclear magnetons. Ballard's analysis was handicapped by a lack of information concerning the term structure of CbI, which was at that time very incompletely known. Subsequently, Meggers and Scribner[2] and Humphreys and Meggers[3] published very extensive classifications of the CbI lines and energy states, thus greatly facilitating a more detailed investigation of the hyperfine structure. We have measured the structure of 32 lines in the visible and by analysis of these data determined 32 hyperfine interval factors. Our analysis is in agreement with Ballard's value of $4\frac{1}{2}$ for the nuclear spin, but indicates a nuclear magnetic moment 43 percent larger than reported by him.

* Now at Western Maryland College, Westminster, Maryland.
[1] S. S. Ballard, Phys. Rev. **46**, 806 (1934).
[2] W. F. Meggers and B. F. Scribner, J. Research Nat. Bur. Stand. **14**, 629 (1935).
[3] C. J. Humphreys and W. F. Meggers, J. Research Nat. Bur. Stand. **34**, 477 (1945).



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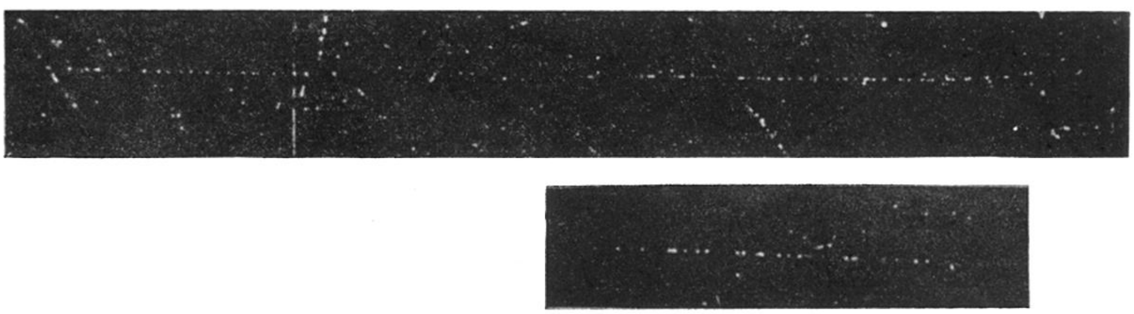

FIG. 2. Long alpha-track associated with fission (upper picture) as compared with a recoil proton track (lower picture). The difference between the two tracks can be seen by comparing their average grain spacings. The pictures are so placed that the ends of the tracks fall at the same distance from the left side of the page.