A0025/77
JUN, 1977

EXPERIMENTAL EVIDENCES OF SPONTANEOUS AND LOW-ENERGY INDUCED EMISSION OF HEAVY IONS FROM EVEN-EVEN HEAVY NUCLEI(*)

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ABSTRACT

During the course of an experiment to measure the spontaneous fission half-life of ^{238}U, it became evident that the ^{238}U is also a spontaneous emitter of heavy ions in the mass range from 20 up to 70. Other experimental facts reported in literature, such as the systematic observation of an abnormal isotopic abundance of neon and argon found in radioactive minerals, and the small etch pit track-diameters found recently in a very ancient man-made uranium-glass, seem to support our findings. Besides, a set of improved experiments with "visual" detectors carried out in our laboratory have shown that the emission of such heavy ions from uranium can also occur with low-energy incident photons and particles. Although these results may cause considerable scepticism, we wish to discuss in the present paper some experimental results which led us to the conclusion that some even-even heavy nuclei are emitters of heavy-mass fragments other than ordinary fission fragments.

(*) This work was supported in part by the Brazilian Comissão Nacional de Energia Nuclear.

1. INTRODUCTION

The present paper reports a series of experiments which provide physical evidences that heavy even-even nuclei, besides undergoing the well-known phenomenon of fission, are also capable, by spontaneous or induced processes, to decay by emission of heavy ions in the range of atomic masses from 20 up to 70.

Since 1959, this type of nuclear disintegration has been observed in our laboratory whenever we carried out low-energy photofission experiments of uranium using a special nuclear emulsion technique[1-5]. According to this improved detection technique[6-10], fission fragment tracks, as well as very heavy ion tracks, are recorded with 100% discrimination against the intense background of alpha particles. The method allows the recording of tracks resulting from an ionization above 1.5 MeV/μm only. This cutoff has been verified experimentally, and it is illustrated in Figure 1.

During the studies of photofission of uranium induced by near threshold fission-energy bremsstrahlung and monoenergetic photons, we systematically observed, besides the usual peak from normal photofission fragment tracks, an abnormal, small, but clear peak due to shorter track-ranges in all track-range distributions. At that time, we were not able to find an explanation for the origin of such unusual shorter tracks. The conclusion that the short track-ranges originate from a disintegration of the excited ^{238}U nuclei by heavy ions less massive than ordinary fission fragments became evident later, in 1973, when we developed plates which had been already exposed during eight years with densely uranium-loaded emulsions to measure the spontaneous fission decay constant of ^{238}U[11,12]. From the high population of tracks collected in this experiment, we again observed track-ranges shorter than ordinary spontaneous fission fragment tracks. Then, for the first time, the origin of such unusual short length tracks was explained as being due to nuclear spontaneous disintegration of uranium by heavy ions.

Since we interpreted these results as a nuclear phenomenon that had previously escaped our observation, we decided, therefore, to conduct a set of crucial experiments to confirm our previous conclusion. The main feature of these experiments was to develop methods for identifying and differentiating clearly the recording of binary fission from emission of single ions by means of marked--origin of fragments. With this aim in mind, we used the techniques of mica sandwiches of thin uranium layers, and the loading of nuclear emulsion with about 1μm diameter UO_2 grains.

The purpose of the present paper is to describe and to discuss the results obtained from such experiments.

2. REVIEW OF PREVIOUS EXPERIMENTS

In the late fifties, we started to develop in our laboratory new nuclear emulsion techniques for fission studies[7,8]. In the case of uranium fission, the method consists basically in preparing nuclear emulsion pellicles loaded quantitatively with complex solutions of an uranium salt in such a way that the recording properties of the nuclear emulsion are not altered during the loading, storage and processing stages, and, at the same time, the exact amount of loading element may be known. After storage for a long period of time or irradiating with photons and particles for induced fission studies, a special developing technique is applied in order to obtain very legible fission tracks in spite of an intense background of alpha particle tracks. To impede the fading of the latent image, the nuclear emulsion pellicles are vacuum packed between two sheets of sealable plastic and stored at low temperature. The method used allows development of very legible fission tracks, and, at the same time, does not record any alpha particle tracks at all. Details of this technique can be found in previous publications[3,9,10].

To measure with any great degree of accuracy the spontaneous fission half-life of ^{238}U by an integral recording method such as loaded nuclear emulsion, for statistical reasons very long exposures are necessary in order to collect the desired number of fission-tracks in the bulk of the emulsion. We were able to conduct a prolonged exposure experiment[11], using total exposures up to 12,500 mg-days of uranium per square centimetre of dry pellicle. In this way we obtained a sufficiently high population of tracks (up to about 10^4 per square centimetre) in the processed plates (see Figure 2). For discrimination and precise counting of tracks from spontaneous fission, we made detailed range-track distributions of all track-ranges recorded under our experimental conditions. The track-range distributions showed a very surprising result: the appearance of a new peak, together with the characteristic peak of spontaneous fission tracks from ^{238}U (see Figure 3-a and b). The recorded long tracks, measured with reasonable accuracy, have a mean range of about 23 μm and correspond to ordinary fission tracks. Both the heavy and light fission fragments contribute to the total length of the long track-ranges, and by counting these tracks a spontaneous fission half-life of $(6.0 \pm 0.4) \times 10^{15}$ y has been obtained. On the other hand, the new peak was attributed by us to tracks from heavy ions with a mass number of less than 70, since they are not related to the tracks originating from ordinary fission processes. By microscopic inspection of the ionization and careful analysis of the range distributions of these short tracks, we concluded that the shorter track-ranges have their origin in a spontaneous nuclear disintegration of ^{238}U, a case of emission of large nucleon-clusters of intermediate masses in the region from neon to nickel.

Our experimental method does not allow us to identify the charge and the mass of the recorded ions. However, the measured ranges of the short length tracks closely with the calculated energies and ranges of heavy ions in emulsion for some probable spontaneous decay modes. In addition, the calculated mean ionization of these ions at such energies indicates that these heavy ions are on the average less ionizing than an ordinary fission fragment, only by a factor of two, and therefore adequate to be recorded by means of our nuclear emulsion discriminination technique (cf. Figure 1).

The possibility that short range tracks could be caused perhaps by other mechanisms and/or by an instrumental experimental error was ruled out[12]. We considered, for instance, bacterial contamination of the plates, recording of alpha particle tracks in local high sensitivity regions by an uneven sensitivity in the nuclear emulsion, nuclear recoils from the interaction of cosmic ray particles at sea level with both the uranium and the components of the emulsion, nuclear recoils from secondary reactions induced by natural alpha radioactivity together with possible contamination of thorium and beryllium, etc. All these mechanisms have shown to be unlikely in explaining the recorded short track-ranges, and it was our conclusion that the short length tracks seem to support the evidence of a spontaneous emission of heavy ions from ^{238}U.

In a recent re-determination by Thiel and Herr[13] of the ^{238}U-spontaneous fission decay constant using a 126 year old uranium glass, it was also observed that two peaks in the track-diameter distributions were very similar to the peaks we had found in the track-range distributions obtained by the nuclear-track emulsion method (see Figure 4). According to Thiel and Herr, the uranium-glass sample was never heated above 50°C for a long period of time, and, therefore, no correction due to thermal track fading had to be applied. From nuclear-particle-track identification studies in glasses[14-17], it has been shown that the diameter of the etched particle tracks increases with the mass and energy of the incident particle, at a constant etching rate. Although the uranium-glass sample used by Thiel and Herr[13] may have particle-recording properties slightly different from common glasses used in laboratory practice, and in spite of the radiation damage from nuclear fragments occurring in different internal faces of the glass, it is possible that the shorter track-diameters could be the result of a spontaneous emission of heavy ions from ^{238}U.

Based on the classical WKB method for penetration of potential barriers, and assuming previously the existence of heavy-nucleon-clusters within the nucleus, we performed rough calculations[11,12] to obtain the half-life of this possible spontaneous process. These calculations showed, within the limits of great uncertainties, the possibility of a few spontaneous emissions of heavy ions from ^{238}U, with mass number ranging from 20 to 70, whose yields are compatible with our findings.

Experimental evidence which supports our heavy-ion decay hypothesis is the highly abnormal isotopic abundance (in relation to the atmosphere) of neon and argon found in radioactive minerals[18-21]. The explanation for the origin of this unusual isotopic abundance is still not very clear[21,22]. However, assuming that the excess of ^{22}Ne and ^{38}Ar observed in gases contained in uranium minerals comes from the spontaneous emission of such isotopes from ^{238}U, the half-life for these processes can be easily estimated from data available in literature, and the results are, within the large error margin involved, consistent with our observations (see Table 1).

The first observation of these unexpected shorter tracks in nuclear emulsion plates led us to search for the same short tracks on uranium-loaded plates used previously in both spontaneous fission and low-energy photon-induced fission experiments[4,23]. We observed systematically the same range-track distributions with the same clear peak related to the shorter length tracks (see Figure 3-c). This observation seems to indicate also the emission of heavy ions from uranium induced by low-energy photons.

In addition, radiochemical studies of thermal neutron induced fission on ^{235}U, to search for true ternary fission[24-27], have indicated a few cases of abnormal yield of intermediate nuclides in the mass range from 20 up to 70 which may originate not from tripartition but from some heavy-ion decay modes of the excited compound ^{236}U nuclei.

Another experimental observation possibly related to short track-ranges observed in emulsion as reported above, is the recording of unpaired tracks by means of mica sandwiches in high-energy particle-induced fission experiments[28-31]. The origin of such single fragments has not been clearly explained, and it may be the result of a low-energy excitation mechanism (which takes place in a non-negligible percentage of all high-energy particle-induced reactions) leading to the emission of nuclear fragments of high mass asymmetry, thus resulting in the recording of unpaired particle-tracks.

3. DESCRIPTION AND RESULTS OF THE PRESENT EXPERIMENTS

The above listed considerations on a possible low-energy photon- and particle-induced emission of intermediate-mass fragments from heavy nuclei, led us to conduct a set of three different experiments to obtain confirmation of such processes.

3.1. Low-Energy Photon-Induced Process

We exposed nuclear emulsion pellicles loaded with a uranium complex solution to the low-energy photon beams produced at the reactor "Saphir" of the EIR (Würenlingen, Switzerland). The target emulsions were prepared following the usual procedures as described before[10]. The 8.86 MeV monochromatic gamma-rays flux was obtained by neutron radioactive capture reactions on a nickel target placed near the core of the reactor, in such a way as to obtain a collimated and very high intense beam. The irradiated plates were submitted to the same discriminating development technique previously used in spontaneous fission studies[11]. In this way, very legible heavy-fragment tracks were recorded and, at the same time, neither alpha particle tracks nor the electron background due to soft gamma-rays were to be seen. The scanning consisted in measuring all track-ranges found in a given area. About 400 track-ranges were selected under microscope inspection with total optical magnification of 1300X. Track-range measurements were improved by taking into account only those tracks with dip equal to or less than 2µm. The track-range distributions obtained by two observers in two different plates can be seen in Figure 5. We observed again a clear peak related to short track-ranges, besides the more pronounced peak of photofission fragment tracks of uranium. Apart from some possible angular distribution, the percentage of short track-ranges amounts, on the average, to 30% of the total number of recorded tracks, which corresponds, roughly, to a total cross section of (10 ± 3) mb for the production of heavy ions from uranium induced by 8.86 MeV photons.

More convincing results would be obtained in an experiment which allows one to individualize the emitted fragments from a common point origin. In such an experiment, fission events would be clearly differentiated from single heavy-particle emission by the recording of the two collinear fragment tracks as a result of moving away of fission fragments in opposite directions. For this purpose, the near 4π-geometry mica-target-mica-sandwich technique is very adequate[32]. Accordingly, an event due to ordinary binary fission looks like a spatial coincidence of paired tracks, one in each of the mica sheets.

Clean, freshly cleaved sheets of muscovite mica (4cm x x 4cm x 0.01cm) were selected and pre-etched in 49% hydrofluoric acid during three hours at room temperature in order to produce large diamond-shaped pits of "fossil" tracks so as to distinguish them from tracks produced after irradiation (the density of fossil tracks was about 380/cm^2). To make a sandwich, one of the mica sheets was covered on one side with a thin layer of uranium-oxide

(20μg of U/cm^2) by means of the "parlodion ignition" method as described by Yagoda[33]. This method gives quite uniform extra-thin films of uranium and causes, during the prolonged heating stage, the total thermal annealing of any primordial track inside the mica. Moreover, the thinness of the uranium film is such that self-absorption of heavy nuclear fragments is negligible. To keep the two sheets of mica forming a sandwich close together, they were enclosed between two sheets of a heat-sealable plastic and vacuum packed. To ensure a perfect realignment of the tracks after etching, the mica foils were previously held together, near one edge, with a common stapler. Six of such mica sandwiches forming a stack were exposed orthogonally to an intense flux of 8.86 MeV monoenergetic gamma-rays obtained by neutron radioactive capture reactions on nickel in the reactor "Saphir" (total dose was about 10^{12} photons/cm^2). After irradiation, the mica foils were slightly opened and partially immersed in a diluted nitric acid solution so as to remove the thin uranium layer. Etching proceeded with 49% hydrofluoric acid at room temperature during different time intervals from 12 min up to 50 min. Observation of tracks under a microscope was made in a given area by two observers using total magnification of 400X. Under the conditions of the present experiment, the track density was low enough to avoid the possibility of overlapping of tracks originating from different events. Collinearity, equal dip and location in each sheet of the mica were the criteria used for identification of paired tracks of binary photofission events. Besides the large amount of correlated tracks expected (about 10^4 paired tracks/cm^2), we also observed many single, uncorrelated tracks. From the analysis of the results as reported in Table 2, we concluded that the unpaired tracks have their origin from the emission, by the excited ^{238}U, of single heavy ions with an amount of energy transfer sufficient to be recorded under the present experimental conditions. To be sure of the above conclusion, we studied the spatial recording (dip angle distribution) of such single-etched tracks, and the results are comparable with those obtained from tracks on single mica foils irradiated with ^{252}Cf-fission fragments in 2π-geometry (see Figure 6). The relatively small number of unpaired tracks (4-10%) as compared with the number of shorter length tracks observed in loaded nuclear emulsion plates of the previous experiment (30%), can be explained by a number of causes. First, mica has a particle-detection threshold higher than our nuclear emulsion detection technique, so that ions of mass number less than about 30 would not be recorded[34]. Second, the detection efficiency of mica sandwiches (which results from the critical angle of incidence and the track geometry) is slightly lower than that of nuclear emulsion pellicles, because, in this case, track-ranges are recorded over the whole volume. Finally, some anisotropy of track-recording in micas might also contribute to some extent towards losses in the registration of single heavy-mass fragments. Apart from the above considerations, we wish to emphasize, however, that both the preceding experiments give physical evidence of the emission of heavy ions with masses less than about 70 from ^{238}U excited by 8.86 MeV photons.

3.2. Thermal-Neutron-Induced Process on ^{235}U

As has been earlier suggested by de Carvalho *et al.*[1], another technique which provides the recording of both fission fragment tracks from a common point origin is the use of loaded emulsion with grains of uranium oxide of about 1μm diameter. By means of such a technique, the emission of single heavy fragments from uranium would be totally differentiated from ordinary binary fission by the recording of one-prong-like events. We were successful in conducting an experiment in which we exposed loaded emulsions with grains of uranium oxide to different doses of thermalised neutrons from an americium-beryllium neutron source.

Extra-fine uranium oxide (UO_2) powder was dispersed in a diluted gelatin solution and filtered. After drying in a lucite tray, homogeneity and grain size were controlled by inspection under an optical microscope. Successive filtering and drying of the solution were necessary until we got complete homogeneity and grains of average size as small as 1μm diameter. After remelting the gelatin pellicle, a portion of emulsion (Ilford-K0) in gel form was melted together at about 50°C until complete homogeneity was obtained. After drying in a lucite tray we obtained a large pellicle pie of about 200μm thick. The proportion of chemicals was adjusted in such a way that a final 2X gelatin dilution of the emulsion was obtained. Such a degree of gelatin dilution provides improvement in track-range measurements as well as a better uniformity of the grain dispersion within the emulsion. By fixing with hypo an aliquot of the pellicle pie, it was possible to study the grain-diameter distributions at different depths in the emulsion. The observed distributions can be seen in Figure 7. In addition, it was observed that the grains were uniformly dispersed in the whole volume of the emulsion in a concentration of 5×10^9 grains/cm^3. Irradiation followed, with thermal neutrons of total doses varying from 2×10^9 neutron/cm^2 up to 1.3×10^{10} neutron/cm^2. Since some de-sensitization of the emulsion was expected, use of the gradation developing technique[6] was needed in order to achieve the best conditions for processing(*). As the sensitized AgBr grains have, after development, a size of about 0.5 m , and in view of the actual diameter-distributions of the uranium grains have, after development, a size of about 0.5μm, and in view of the actual diameter-distributions of the uranium grains (see Figure 7), some tracks do not show the point-origin of fragments. However, the consistency of this track-recording method was verified by counting all track-ranges recorded on a given area in different plates. We observed a quite linear increase of the track density with the increasing of the thermal neutron flux. Moreover, binary fission events with marked-origin were carefully analysed and the track-range distributions of the light and heavy fission fragments are shown in Figure 8. Further, we wish to emphasize the recording of tracks of one fragment (one-prong-like events) which originates from an uranium grain. The range of these tracks is compatible with those of heavy fragments in the mass region from neon up to nickel possibly emitted by the excited ^{236}U nuclei (see Figure 9). Unfortunately, there was no means of identifying the charge and the mass of these heavy ions by analysis of the tracks themselves. However, as mentioned in the introductory part of this paper, the rate of energy loss experienced by such ions, which would have initial kinetic energy of about 1.5 MeV/nucleon, is sufficient to be recorded by our detection technique. In addition, the observed track-profiles indicate a monotonical decrease of track-width with increasing residual range. It was also observed that the one-fragment tracks amount to 30% of the total number of

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(*) Under the conditions of the present experiment, very legible tracks were to be seen by using the following developing procedure: boric acid 10g , sodium sulfite 5g, potassium bromide 0.5g, amidol 1g and water to make 1 litre; develop at 6°C during 8 h.

recorded tracks. This result is comparable with the one obtained from the 8.86 MeV photon-induced process as reported in the present paper.

4. CONCLUSION

We have performed some improved experiments with visual track-detectors in order to see unusual events which can be ascribed to the emission of single heavy fragments from even-even uranium isotopes excited by either low-energy photons or thermal neutrons as incident particles. The experiments described above were motivated by a previous observation of the same type of phenomenon which can occur spontaneously. The short range tracks observed in emulsion plates irradiated with low-energy photons, as well as unpaired tracks detected in uranium mica sandwiches, seem to support evidences of heavy fragments in the mass range 20 up to 70 emitted from the excited ^{238}U nuclei. Besides, as we have also observed one-prong-like events with marked-origin from thermal-neutron-induced fission of ^{235}U, it is probable that the excited ^{236}U nuclei are also emitters of heavy ions with energy of about 1.5 MeV/nucleon, but less massive than ordinary fission fragments.

It is hoped that future work along these lines, from other laboratories as well, will furnish more experimental data which may confirm the phenomena described above.

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Table 1 - Estimated Half-lives for the Production of Isotopes of Rare Gases in Excess Found in Minerals which Contain Uranium (*).

Sample	Age (10^6 year)	Percent of Uranium Content	Excess of Rare Gas (10^{-9} cm^3/g)	Isotope	Half-life (year)
Samarskite (a)	330	5.48	47	^{21}Ne	2.5×10^{16}
			400	^{22}Ne	3.0×10^{15}
Betafite (a)	293	9.39	125	^{21}Ne	1.4×10^{16}
			2700	^{22}Ne	6.5×10^{14}
Hatchettolite (a)	293	2.39	57	^{21}Ne	8.0×10^{15}
			2500	^{22}Ne	2.0×10^{14}
Pitchblende (a)	230	69	2130	^{21}Ne	4.8×10^{15}
			4700	^{22}Ne	2.2×10^{15}
Pitchblende (a)	230	18.8	1270	^{21}Ne	2.2×10^{15}
			1000	^{22}Ne	2.8×10^{15}
Monazite (a)	1950	0.146	732	^{21}Ne	2.5×10^{14}
			440	^{22}Ne	4.2×10^{14}
Pitchblende (b)	215	44	136	^{21}Ne	4.5×10^{16}
	650				1.4×10^{17}
Monazite (b)	460	0.2	8.7	^{21}Ne	7.0×10^{15}
Euxenite (b)	60	6	8	^{21}Ne	2.9×10^{16}
	600				2.9×10^{17}
Pitchblende (b)	215	44	20	^{38}Ar	3.0×10^{17}
	650				0.9×10^{18}
Euxenite (b)	60	6	0.095	^{38}Ar	2.5×10^{18}
	600				2.5×10^{19}
Monazite (b)	535	0.3	0.6	^{38}Ar	1.7×10^{17}

(*) The half-lives reported in this Table were calculated on the assumption that the excess of neon and argon isotopes comes from the spontaneous emission of such isotopes from ^{238}U. Accordingly, $T_{1/2}$(year) $\approx 6.5 \times 10^{14}$ C_U $t/\Delta V$, where C_U is the percent of uranium content in the sample, t is the age of the sample in units of 10^6 year, and ΔV is the excess of the rare gas isotope in units of 10^{-9} cm^3/g.

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Table 2 - Number of Paired (Correlated, Coincident) and Unpaired (Single, Uncorrelated) Tracks Observed in Mica Sandwiches with thin Uranium-layer Exposed to an Intense Flux of 8.86 MeV Monoenergetic Gamma-rays.

Sandwich Number	Etching Time(*) (min)	Area of Scan (mm^2)	Total Number of Paired Tracks(**)		Number of Unpaired Tracks						Percent of Unpaired Tracks
					On the Mica Surface without the Uranium-film		On the Mica Surface with the Uranium-film		Total		
			Observer 1	Observer 2	Obs. 1	Obs. 2	Obs. 1	Obs. 2	Observer 1	Observer 2	
8	12	9	832 (99%)	816 (97%)	29	23	18	12	47 (98%)	35 (73%)	5.4
2	12	8	952 (100%)	948 (99%)	13	10	35	29	48 (100%)	39 (81%)	4.8
2	42	8	979 (100%)	978 (100%)	12	11	43	41	55 (100%)	52 (95%)	5.3
1	30	10	975 (100%)	970 (99%)	31	30	21	20	52 (100%)	50 (96%)	5.1
3	15	10	822 (100%)	803 (98%)	37	33	6	6	43 (94%)	39 (75%)	5.3
3	30	10	1024 (99%)	1034 (100%)	30	36	8	8	38 (86%)	44 (100%)	4.1
4	50	10	1117 (100%)	1105 (99%)	65	70	51	51	116 (95%)	121 (99%)	9.8
5	12	8	1109 (98%)	1130 (100%)	56	64	5	6	61 (87%)	70 (100%)	5.8
5	30	8	1221 (100%)	1195 (98%)	56	54	1	1	57 (100%)	55 (97%)	4.5

(*) Etching in 49% hydrofluoric acid at room temperature.

(**) The figures in parenthesis are individual counting efficiencies.

FIGURE CAPTIONS

Fig. 1. Rate of energy loss by ionization of heavy ions in standard emulsion as a function of energy. Initial kinetic energy, T_0, of selected ions are indicated near the curves. T is the kinetic energy as the ions move towards the end of their range. All curves have been obtained following Heckman et al. [Phys. Rev. 117, 544 (1960)]. From the measured total track-length of fission fragments (cf. Fig. 3), a cut off of about 1.5 MeV/μm has been deduced for our nuclear emulsion discrimination technique. Therefore, ions which have charge, mass, and energy above about 30 MeV-^{16}O will be recorded.

Fig. 2. Number of spontaneous fission fragment tracks recorded per square centimetre as a function of total exposure for different nuclear emulsion plates loaded with uranium. The straight line is a least squares fit of the experimental points. The uncertainty of track density is only slightly larger than the point size.

Fig. 3. Range distributions of tracks recorded in uranium-loaded emulsion plates. a) and b) refer to spontaneous fission experiments (ref. 11); c) shows the result obtained with an emulsion plate that had been previously used in low-energy photofission experiments (Ref. 4).

Fig. 4. Comparison between track-diameter distribution (upper scale) in glass (Ref. 13) and track-range distribution (lower scale) in emulsion (Ref. 11) obtained from ^{238}U-spontaneous fission experiments. The histograms were constructed in such a way that both the origin and the abscissa of the more prominent peaks coincide. Both histograms are normalized to the same number of tracks.

Fig. 5. Range distributions obtained from tracks recorded in uranium-loaded emulsion plates exposed to an intense monochromatic photon beam of 8.86 MeV. Both histograms are normalized to the same number of tracks, and they represent the results of two independent measurements. The monochro

matic gamma-rays flux was obtained by neutron radioactive capture reactions on a nickel-target (main line energy of 8.86 MeV). The total dose was about 10^{11} photons per square centimetre. The emulsion plates (Ilford-K0) were loaded with 10^{19} uranium nuclei per square centimetre.

Fig. 6. Dip angle distribution of unpaired tracks recorded in mica sandwiches of thin uranium layers, irradiated with 8.86MeV monochromatic gamma-rays (full line). For comparison is also shown the result obtained from ^{252}Cf-fission fragments recorded on single mica foils in 2π-geometry (dashed line). Both histograms are normalized to the same number of tracks.

Fig. 7. The smoothed diameter distributions of grains of uranium oxide dispersed within the whole volume of a nuclear emulsion 190μm thick diluted 2X gelatin. The curve marked C_1 refers to distributions obtained from measurements made at different depths varying from 25μm up to 120μm. The curve marked C_2 was obtained at a depth of 165μm. Measurements were taken under optical microscopes with high resolution calibrated eyepieces (one scale division = 0.6μm) after fixing the emulsion without development.

Fig. 8. Track-range distributions of heavy and light fission fragments obtained from thermal-neutron-induced fission of ^{235}U (top). Both fission fragment tracks are differentiated by means of the technique of marked-origin of fission fragments with uranium grains. The histograms were obtained from events of binary fission with marked-origin selected according to the following criterion: short tracks with ranges between 8μm and 16μm and, at the same time, long tracks with ranges between 13μm and 21μm. Those events whose difference between the two track-ranges was less than 1μm were disregarded. The distributions of the difference between and the sum of the long and the short track-ranges of the same event are plotted at bottom. Mean values and standard deviations of the distributions are as follows: heavy fragment, $\bar{R}_H$ = 11.26μm with σ_H = 1.64μm; light fragment, $\bar{R}_L$ = 16.36μm with σ_L = 1.74μm; difference, $\bar{D}$=5.17μm

with σ_D = 2.19μm; sum (total length of binary fission events), $\overline{S}$ = 27.57μm with σ_S = 2.39μm.

Fig. 9. Track-range distributions of "one-fragment tracks" and fission fragment tracks (total length, cf. Figure 8) recorded in an emulsion plate loaded with grains of uranium oxide and exposed to thermal neutrons. Both types of events are in the same scanning area. Dilution of the emulsion with 2X gelatin was used to improve track-range measurements. Such a degree of dilution causes an increase of track-ranges due to a lower rate of energy loss by ionization of ions in the emulsion (cf. Figures 3 and 5). The well-detected peak centered at 17μm corresponds to one-prong events which originate from uranium grains. These events seem to be indicative of the emission of heavy ions in the mass range 20 up to 70 from the excited ^{236}U.

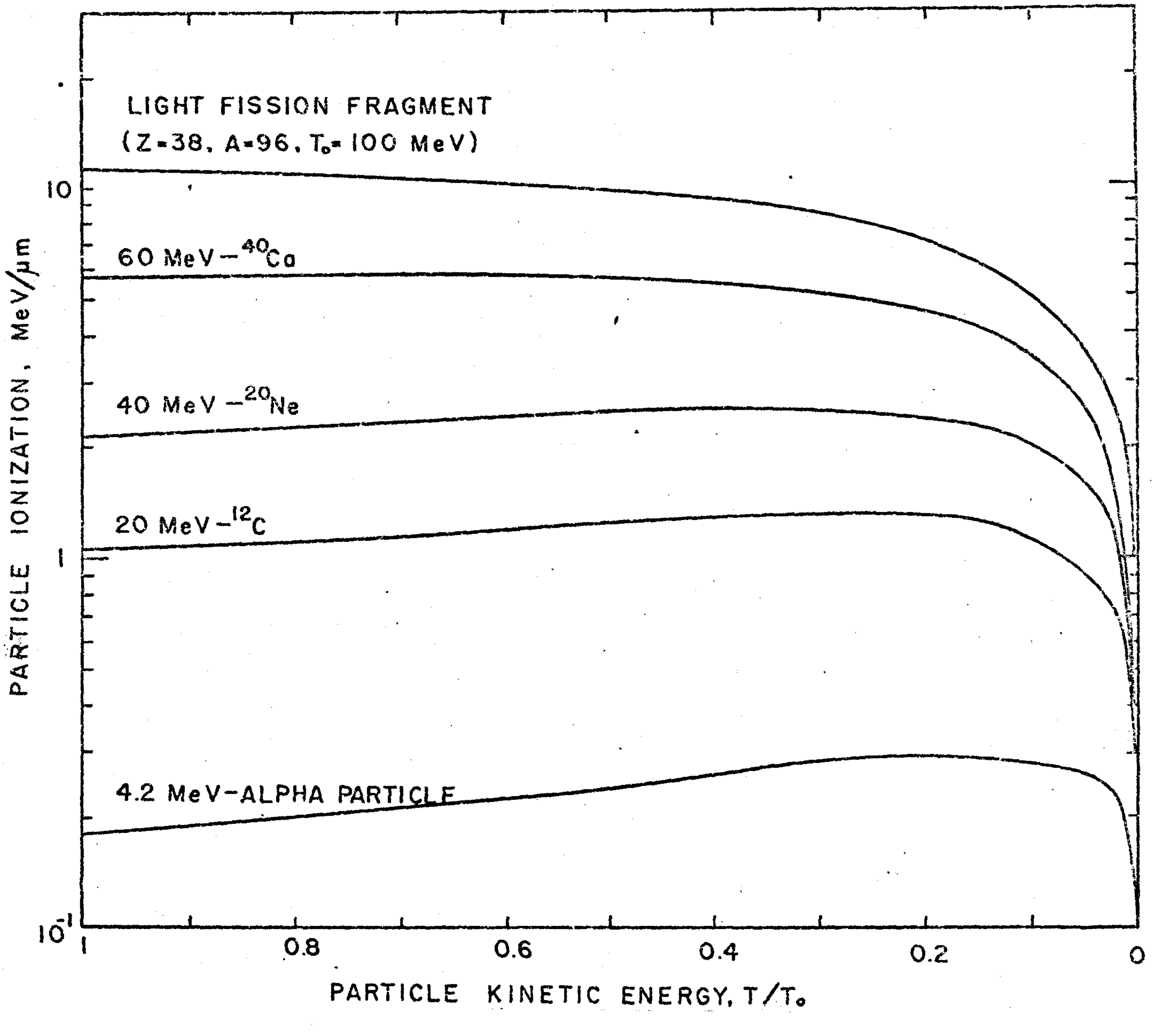
LIGHT FISSION FRAGMENT
(Z=38, A=96, T₀=100 MeV)
60 MeV-⁴⁰Ca
40 MeV-²⁰Ne
20 MeV-¹²C
4.2 MeV-ALPHA PARTICLE
PARTICLE IONIZATION, MeV/μm
10
1
10⁻¹
1
0.8
0.6
0.4
0.2
0
PARTICLE KINETIC ENERGY, T/T₀

Figure 1

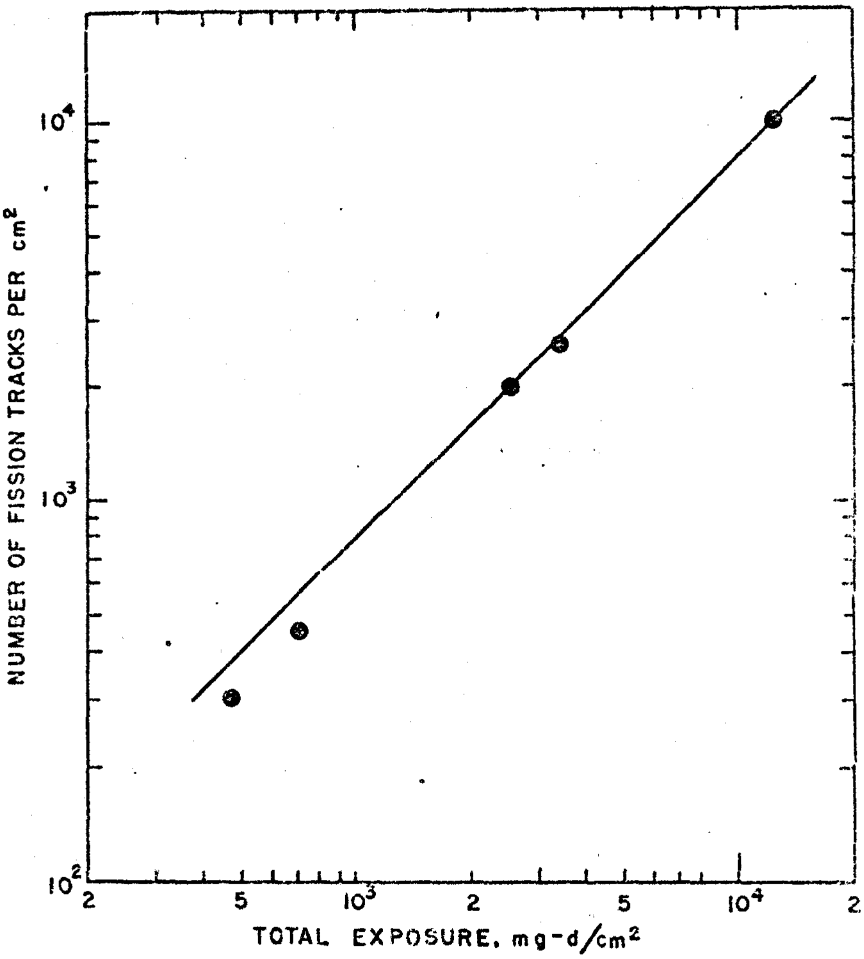

Figure 2

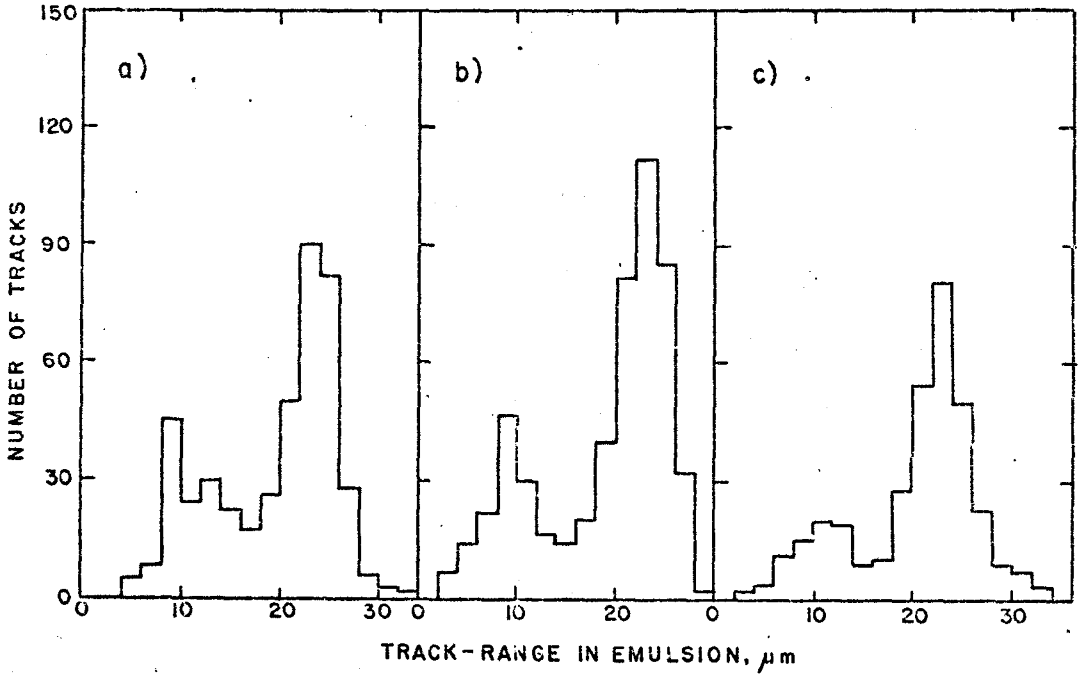

Figure 3

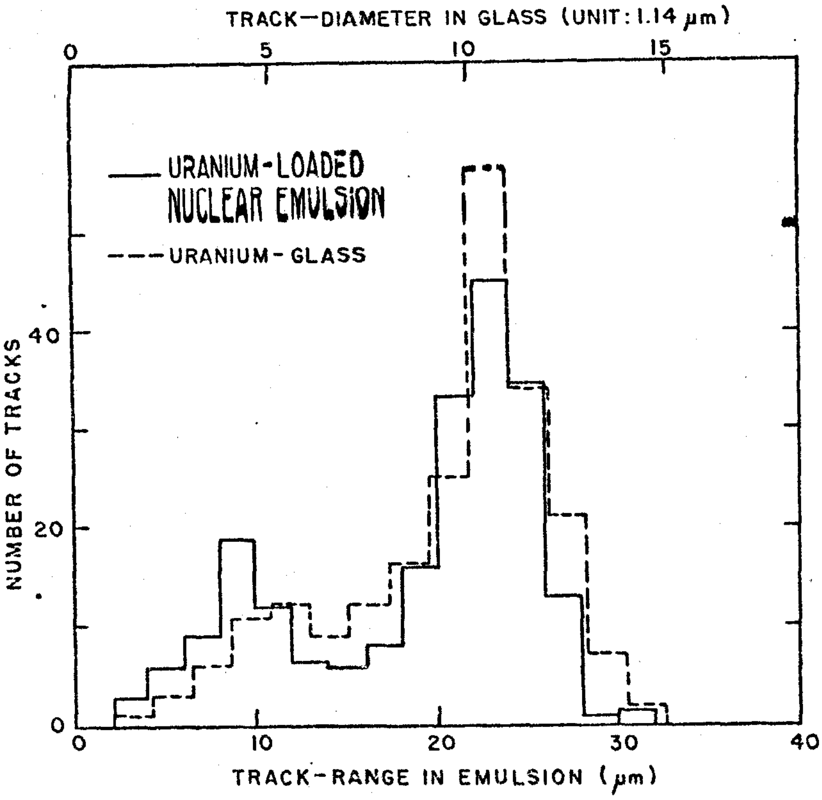

Figure 4

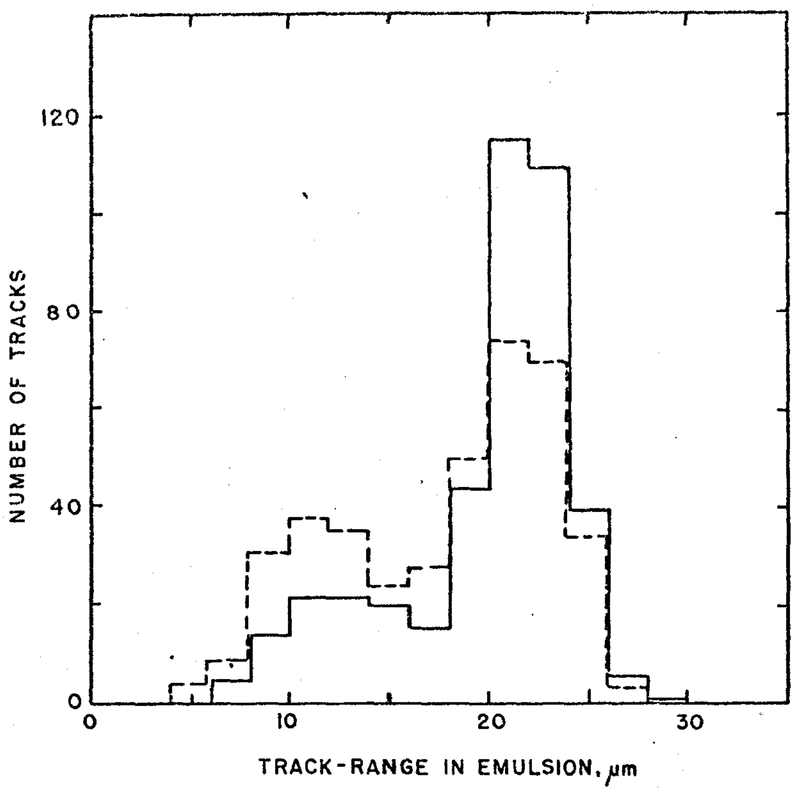

Figure 5

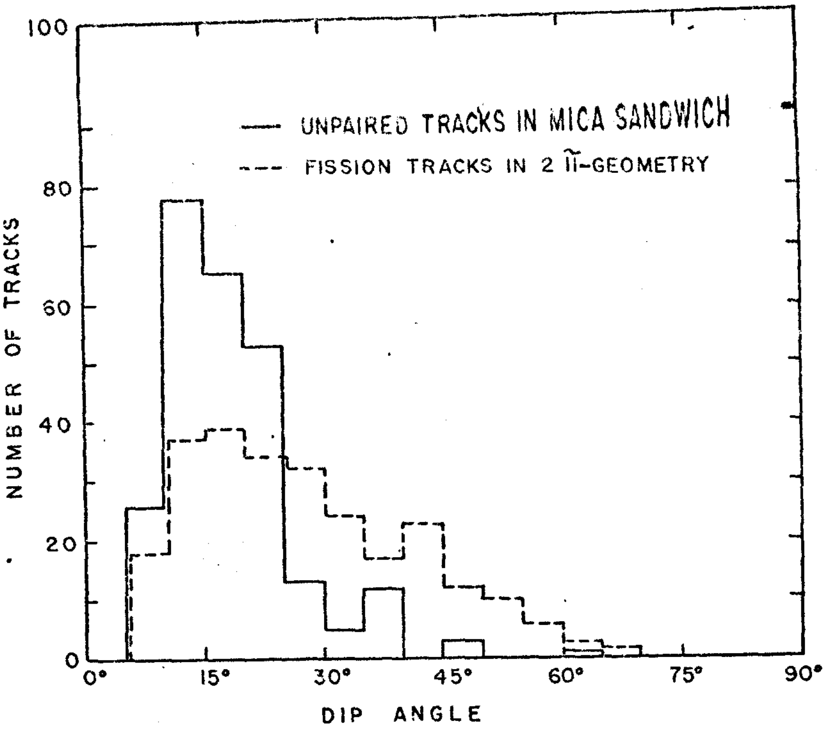

Figure 6

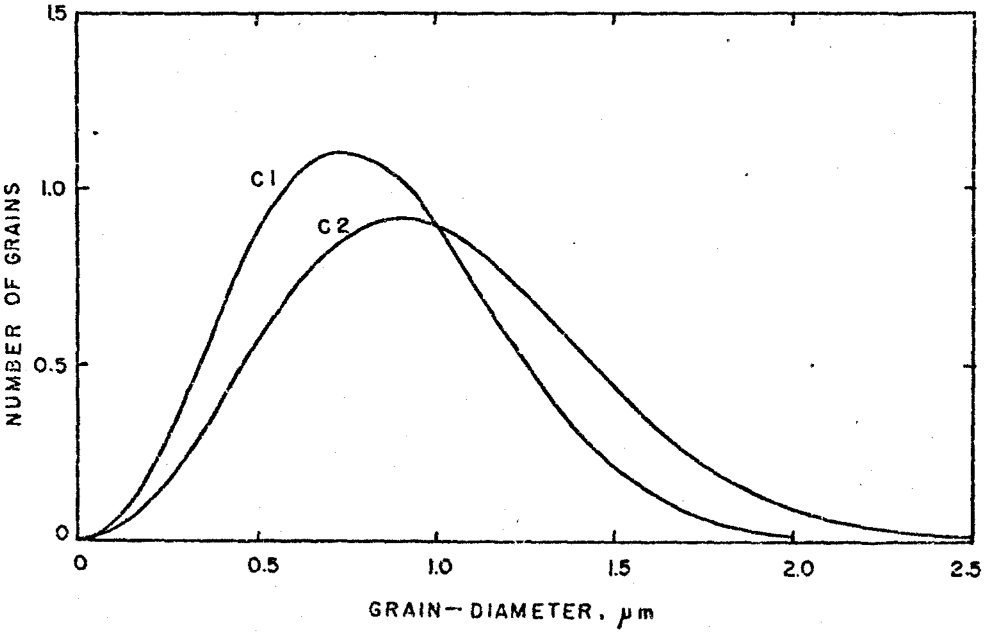

Figure 7

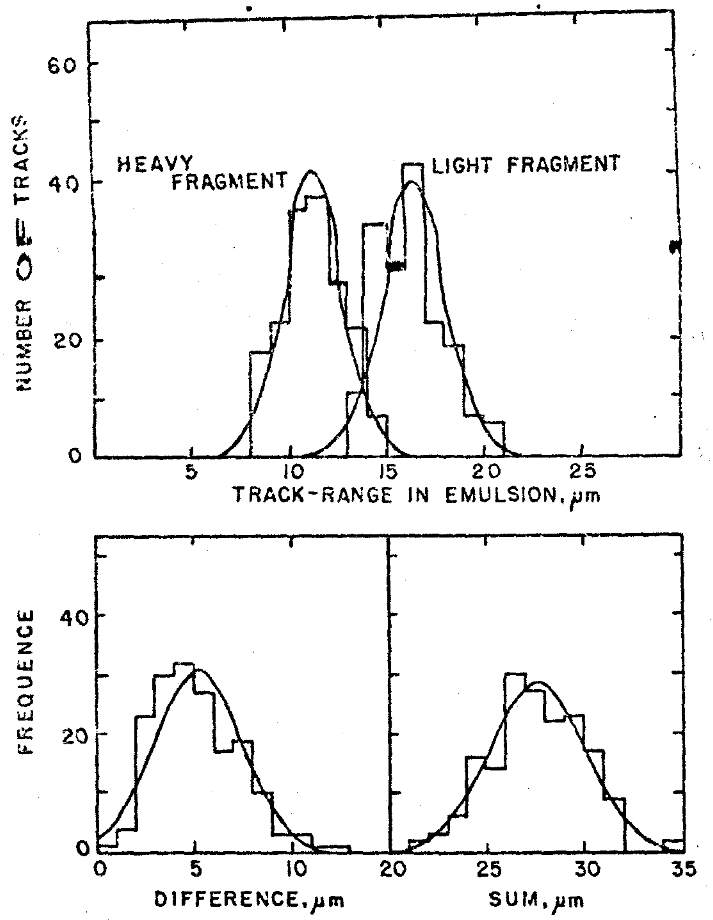

Figure 8

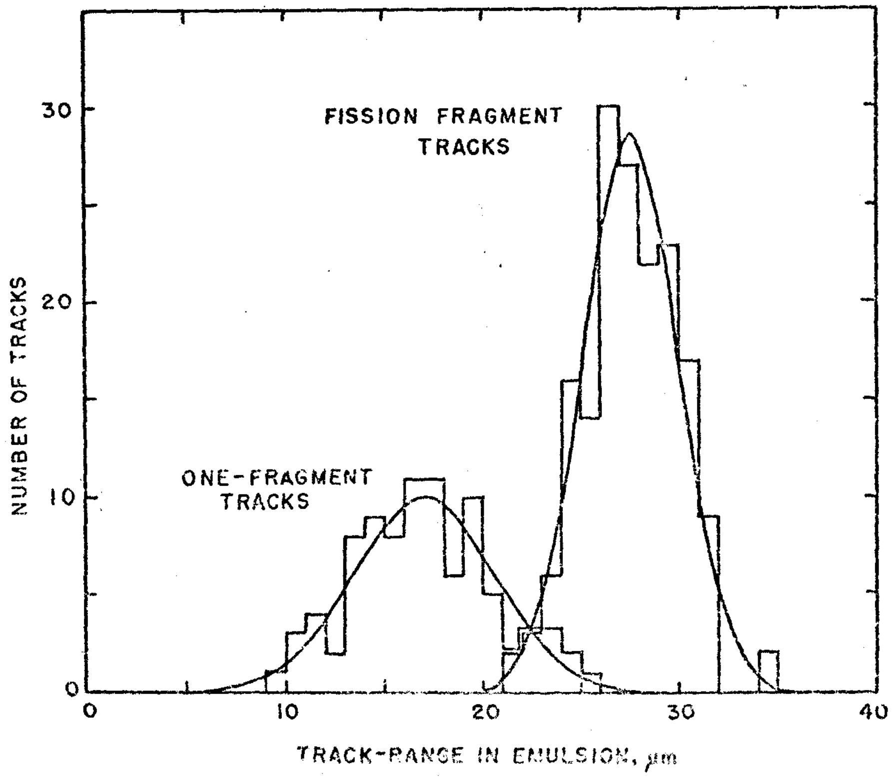

Figure 9