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π^- AND μ^- MESON-INDUCED FISSION

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March 4, 1953

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ABSTRACT

Meson-induced fission has been studied in uranium-loaded Ilford C-2 emulsions exposed to the π^- and μ^- meson beams of the University of Chicago cyclotron. 3762 π^- endings were studied including 17 fission events. 3573 μ^- endings were studied including 8 fission events. The probability of a π^- meson ending in fission is found to be $(4.5 \pm 1.5) \cdot 10^{-3}$ in C-2 emulsion containing 0.052 gm $\cdot$ cm^{-3} of uranium. The corresponding probability for μ^- mesons is found to be $(2.0 \pm 0.8) \cdot 10^{-3}$. Assuming the atomic capture probability is proportional to Z, it is found that (40 ± 20) percent of π^- captures in uranium produce fission and about 20 percent of μ^- captures produce fission.

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INTRODUCTION

The probability that a π^- meson stopping in uranium-loaded emulsion will cause a fission event is the product of the atomic capture probability for uranium and the probability that a meson capture by the uranium nucleus causes fission. By "atomic capture probability" we mean the probability that a meson will be captured into an orbit about a given nucleus in a mixture of nuclei. Subsequently the meson will undergo a nuclear capture. Experimental data on π^- capture in uranium-loaded emulsion can be used to calculate the Z-dependence of the atomic capture probability assuming that essentially all π^- captures in uranium lead to fission. Conversely, one could assume a theoretical value of the atomic capture probability and calculate the probability of fission by π^- capture. π^- capture in uranium-loaded emulsions was previously studied by Al-Salam.[1] The present investigation takes advantage of the much improved conditions of observation made possible by the use of the meson beam at Chicago.

The present study also includes the study of μ^- capture in uranium-loaded emulsions. The atomic capture probability of negative μ mesons should be approximately the same as that for negative π mesons since they have similar e/m. Comparison of the μ^- data to the π^- data then makes possible an estimate of the probability of fission when a μ^- meson is captured by uranium.

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1. S. G. Al-Salam, Phys. Rev. 84, 254 (1951)

EXPERIMENTAL DETAILS

200 micron Ilford C-2 emulsions were loaded with uranium. The plates were presoaked in water for about 30 minutes, then soaked in a solution of uranium acetate for an hour and a half. The plates were allowed to dry for three hours and then exposed for one hour to slow π^- mesons from the external meson beam of the University of Chicago cyclotron. The plates were soaked in developer at 8° C and developed at 29° C. Total elapsed time from the uranium solution soaking to fixing was about seven hours. The plates for the study of μ^- capture were treated as above except that they were exposed to the slow μ^- beam of the cyclotron.[2]

The emulsions were scanned at a magnification of 270X. Fission events were studied at 1400X. Fields of view were taken sufficiently far apart to eliminate the possibility of overlap. The concentration of uranium in the emulsion was determined by counting the uranium alphas in a given volume. Allowance was made for the gradation of uranium density with depth. Only the top 2/3 of the emulsion was scanned.

APPEARANCE OF EVENTS

The plates were relatively free of background tracks except for uranium alphas. A fission event appears as a "hammer" track at the meson ending. The two prongs are co-linear and approximately equal in length. The fission track is about 26 μ long and somewhat heavier than the uranium alpha tracks which are about 22 μ long. The fission events are fairly characteristic in appearance, however, in each case the event was carefully checked in detail at high magnification.

RESULTS OF π^- INDUCED FISSION

A total of 3762 π^- endings were studied. Seventeen fission events were seen. One fission was accompanied by the ejection of a third particle at 27° to the fission track. This third track lay completely in

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2. W. F. Fry, Phys. Rev. 85, 676 (1952)

the emulsion with a total range of 309 μ, corresponding to an alpha particle of 25 Mev. The measurements of the fission events are given in Table I. The probability of a π^- meson ending in fission is found to be $(4.5 \pm 1.5) \cdot 10^{-3}$ in C-2 emulsion containing 0.052 gm · cm^{-3} of uranium before development. The error is estimated from the statistics and the uncertainty in uranium concentration.

RESULTS OF μ^- INDUCED FISSION

A total of 3573 μ^- endings were studied, including 8 fission events. Measurements of the fission events are given in Table II. The probability of a μ^- meson ending in fission in C-2 emulsion containing 0.052 gm · cm^{-3} of uranium before development is found to be $(2.0 \pm 0.8) \cdot 10^{-3}$.

DISCUSSION OF π^- INDUCED FISSION

From the π^- data we have calculated the dependence of the atomic capture probability upon the atomic number of the capturing nucleus, using the known composition of Ilford C-2 emulsion. The percentage weight/atomic weight for each element was weighted by Z^n to find the probability of capture by uranium. It is found that n = 1/2 or 1/3 agrees with our data, assuming that essentially all π^- mesons cause fission when captured by uranium. Fermi and Teller[3] calculated that n = 1. If on the other hand, one assumes that the atomic capture probability is proportional to Z, one finds that (40 ± 20) percent of π^- captures by uranium lead to fission. It is interesting to note that under this assumption about 20 percent of μ^- captures by uranium lead to fission. This is in agreement with the upper limit set by Galbraith and Whitehouse.[4]

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3. E. Fermi and E. Teller, Phys. Rev. 72, 399 (1947)
4. W. Galbraith and W. J. Whitehouse, Phil. Mag. 44, 77 (1953)

DISCUSSION OF μ^- INDUCED FISSION

The prong distribution for 1516 μ^- endings is given in Table III. The distribution is in agreement with that obtained by Morinaga and Fry[5] in a study of μ^- stars on plates exposed under similar conditions. Morinaga and Fry estimate that this prong distribution corresponds to a π^- contamination of less than 3 π^- per 1000 meson endings. One would expect about 0.02 fissions per 1000 endings from this π^- contamination. We observed about 100 times this number of fissions per 1000 endings. Hence we conclude that most of the fission events on the μ^- plates were induced by μ^- mesons.

The study of μ^- stars in emulsions by Morinaga and Fry[5] showed that μ^- capture frequently gives rise to a nuclear excitation of 25 Mev. The calculations of Tiomno and Wheeler[6] gave nuclear excitations of the order of 15 Mev. The compound nucleus formed when a μ^- meson is captured by ${}_{92}U^{238}$ is ${}_{91}Pa^{238}$. In estimating the fission threshold of ${}_{91}Pa^{238}$, we note that the fission parameter Z^2/A for ${}_{91}Pa^{238}$ has nearly the same value as that for ${}_{90}Th^{234}$. The photofission threshold for ${}_{90}Th^{234}$ has been measured and found to be 5.4 Mev.[7] In addition, the μ^- meson must supply the mass difference between ${}_{91}Pa^{238}$ and ${}_{92}U^{238}$ which is about 2 Mev. Therefore a fission event represents a nuclear excitation of about 8 Mev or more.

The observed number of fissions per μ^- ending in emulsion of a given uranium loading appears to be about one-half the number of fissions per π^- ending, although the uncertainties are large. π^- capture would give an excitation energy of the compound nucleus of about 140 Mev. As the nucleus evaporates particles it loses excitation; after each evaporation there is a certain probability that fission will take place, until finally the excitation of the nucleus is below the fission threshold. μ^- capture leaves the compound nucleus with a much lower excitation than in the case of π^- capture, perhaps of the order of 15 Mev. Fewer particles need to be evaporated before the excitation is below the fission threshold. Hence in this interpretation the overall probability of fission in the case of μ^- capture would be smaller.

5. H. Morinaga and W. F. Fry, to be published.
6. J. Tiomno and J. A. Wheeler, Rev. Mod. Phys. 21, 153 (1949)
7. H. W. Koch, J. McElhinney and E. L. Gasteiger, Phys. Rev. 77, 329 (1950)

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Table I

Measurements of π^- Induced Fissions

Event Number	Total Range of Fission Track in Microns	Ratio of Ranges of Fission Fragments
1*	29	1.2
2	26	1.0
3	30	1.3
4	19	1.0
5	26	1.0
6	26	1.0
7	33	1.0
8	24	1.0
9	23	1.1
10	27	~1.1
11	29	1.3
12	24	1.1
13	24	1.5
14	24	1.1
15	24	1.2
16	28	1.1
17	27	1.2

*Third particle emitted from the fission.

Table II

Measurements of μ^- Induced Fissions

Event Number	Total Range of Fission Track in Microns	Ratio of Ranges of Fission Fragments
1	29	1.2
2	25	1.1
3	24	1.3
4	23	1.0
5	27	~1.1
6	27	1.2
7	25	1.3
8	25	(uncertain)

Table III

Prong Distribution of 1516 Stars on μ^- Plates

Number of Prongs	Number of Events
0	1459
1	43
2	6
3	6
4	2

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