Dynamics of muon-induced fission of uranium nuclei

G. E. Belovitskiĭ and C. Petitjean[1]
Institute of Nuclear Research, Academy of Sciences of the USSR

(Submitted 22 June 1983)
Pis'ma Zh. Eksp. Teor. Fiz. **38**, No. 4, 212–215 (25 August 1983)

The emission of charged particles (p and α) from the ends of fragments has been observed by means of nuclear emulsions in the radiationless fission of uranium nuclei induced by muons.

PACS numbers: 25.85.Ge, 27.90. + b

The fission of nuclei can be induced by slow negative muons through two mechanisms: (a) nuclear capture of muons; (b) direct (radiationless) transfer to the nucleus of the energy of mesic-atom transitions.[1] These two fission mechanisms are called "delayed" and "prompt." In prompt fission the muon is entrained by one of the fragments, and (a) may be ejected from the excited fragment into the continuum through an internal-conversion process, (b) may undergo a $\mu \rightarrow e$ decay, or (c) may be absorbed by the fragment, with the result that particles are emitted (n, p, α).

There is the possibility that a study of prompt fission in which the muon remains in or in the immediate vicinity of the fissile nucleus throughout the process can yield information on the dynamics of the fission process. This question has been taken up in several theoretical papers.[2-6] Karpeshin *et al.*[6] assumed that the fission occurs adiabatically and solved the problem at the quasimolecular level. The probability for entrainment of a muon by a light fragment (W_L) was found to be 1.7%. Maruhn *et al.*[4] and Ma *et al.*[5] incorporated dynamic effects, finding $W_L \sim 10\%$. We thus see that the value of W_L and also several secondary processes accompanying the radiationless fission (in particular, the conversion of muons) are strongly affected by the fission dynamics.

Ganzorig *et al.*[7] and Schroder *et al.*[8] have measured W_L. Their results yield $W_L \leqslant 0.1$ and imply that most of the muons are entrained by heavy fragments, with a probability $W_H > 0.9$.

In this letter we report preliminary results of measurements of W_L by means of nuclear emulsions. The excitation energy of the uranium nucleus for radiationless fission is less than 10 MeV, so that an asymmetric fission is most probable. During the absorption of muons by fragments, charged particles (p, d, t, α) may be emitted. The stopping time of a fragment in an emulsion is $\sim 2\times 10^{-12}$ s, while the lifetime of the muon at the fragment is $\sim 10^{-7}$ s. The particles are therefore emitted from the ends of the fragments. By measuring the fragment ranges R_L and R_H one can determine which of the fragments has captured the muon ($R_L > R_H$). By comparing the numbers of these events with light and heavy fragments, one can determine W_L and W_H.

We used emulsions of two types, each 150 μm thick, developed by the Scientific-Research Institute of Chemical and Photographic Planning. Plates of type A detected protons with energies up to 20 MeV, while those of type K detected protons up to 100 MeV. The uranium was inserted into the emulsion just before the bombardment.

The plates were bombarded in the $\mu E4$ muon beam at the Schweizerishes Institut für Nuklearforschugn. The muon stopping density was $(4\text{–}8)\times 10^5$ cm^{-2}. The photographic were examined under a microscope at a total magnification of 900 ×.

Included in the analysis were 180 000 fission events in the plates of type A and 170 000 in the plates of type K. A total of 53 cases were observed in which the fission of uranium nuclei induced by muons was accompanied by the emission of a proton or an α particle from the end of a fragment.

Only half as many events were detected in the plates of type A as in the plates of type K, because of the lower sensitivity and the lower observation efficiency. Figure 1 shows photomicrographs of events involving the emission of protons and an α particle from the ends of fragments (see Ref. 9 for some other photographs). The nature of the particle (its mass, charge, and energy) was determined by measuring the ionization and the range. We will refer to all the singly charged particles as protons. Table I shows the distribution of events in terms of the type of fragment.

We can obviously write $W_L/W_H = N_L/KN_H$, where N_L and N_H are the numbers of cases in which protons are emitted from light and heavy fragments, while K is a correction for the difference in the probabilities for the emission of charged particles during the absorption of muons of different fragments.

Karpeshin *et al.*[6] have calculated the probability for the entrainment of muons of

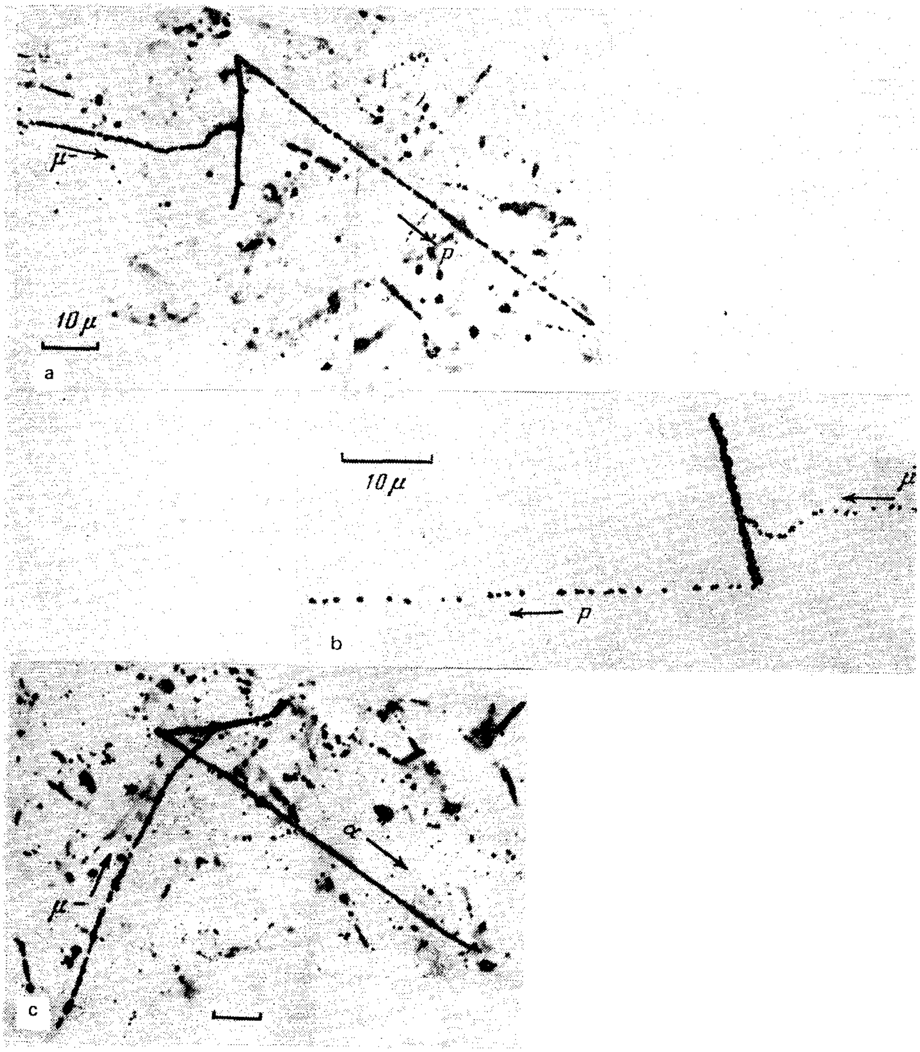

FIG. 1. Prompt muon-induced fission of uranium nuclei accompanied by the emission from the end of the heavy fragment of the following particles: a—A 5.6-MeV proton; b—a 12-MeV proton; c—a 19.2-MeV α particle.

fragments in the radiationless muon-induced fission of uranium nuclei. The effective values of Z of the fragments were found to be $Z_L = 41$ and $Z_H = 51$. Wyttenbach *et al.*[10] have used an activation method to measure the values of P_μ, which are the probabilities for (μpxn) reactions, where $x = 0, 1, 2, 3$, in the absorption of muons in 18 elements from Na to Bi. According to the results of Ref. 10, the correction factor is $K = P_\mu(Z = 41)/P_\mu(Z = 51) = 18\times10^{-3}/10.5\times10^{-3} = 1.7$. We then find $W_H = 0.93$ and $W_L = 0.07$.

Can the reaction probabilities P_μ found for stable nuclei be used for fragments or

TABLE I.

Type of fragment	Number of particles	
	p	α
Heavy	40	7
Light	5	1

nuclei with a large neutron excess? The value which we found for P_μ for heavy fragments is $(3.5 \pm 1.0) \times 10^{-3}$, while the value for stable nuclei with the same Z is 10.5×10^{-3}. This difference of a factor of about three can be easily explained by noting that the fragments contain several excess neutrons in comparison with the stable nuclei of the same charge. According to Ref. 10, an increase in the number of neutrons by two (^{63,65}Cu, ^{121,123}Sb) will cause P_μ to decrease by an identical factor for the two nuclei (the factor is ~1.6). This uniformity in the change in P_μ with a change in the number of neutrons could thus be expected even more confidently for fragments with a much smaller difference in charge. Since the fragments contain more than two excess neutrons, the change in P_μ for them should be greater.

The same effect—the decrease in the cross section for the (np) reaction with increasing number of neutrons in the isotopes of the given element—is observed for 14-MeV neutrons in all nuclei.

It should be noted that the average number of excess neutrons in the fragments after the emission of prompt neutrons is identical. This conclusion follows from the equal length of the β-decay chains for the light and heavy fragments. Furthermore, the average excitation energy of the fragments during the absorption of muons and the subsequent (pxn) emission exceeds 30 MeV. For this reason, we may ignore the effect of the structure factors of the particular fragments on the proton emission probability.

We conclude by estimating a lower boundary for W_L. We work from all 53 events in which we observed the emission of a proton or an α particle from a fragment, since the behavior for $(\mu\alpha xn)$ cases is apparently the same as for (μpxn) cases.[10] From the ends of the heavy fragments, 47 particles were observed; from this figure we find that the maximum possible number of particles was 61 at a confidence level of 0.95. Furthermore, if 6 events from the ends of light fragments are to be detected with a probability no greater than 10%, the average number of particles emitted from the light fragments would have to be four. This situation is possible if $W_L = 0.04$ and if the events obey a Poisson distribution. As a result, we find $0.04 < W_L < 0.1$.

We wish to thank Yu. P. Blazer and I. M. Frank for support of this study.

[1)] Switzerland SN-5254. Villingen.

---

[1] D. F. Zaretskiĭ, Trudy vtoroĭ mezhdunarodnoĭ konferentsii po atomnoĭ energii (Proceedings of the Second International Conference on Atomic Energy), Vol. 1, 1959, 4.

[2] Yu. I. Demkin *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **28**, 287 (1978) [JETP Lett. **28**, 263 (1978)].

[3] V. A. Karnaukhov, Yad. Fiz. **28**, 1204 (1978) [Sov. J. Nucl. Phys. **28**, 621 (1978)].
[4] J. A. Maruhn *et al.*, Phys. Rev. Lett. **44**, 1576 (1980).
[5] Z. Ma *et al.*, Nucl. Phys. **A348**, 446 (1980).
[6] F. F. Karpeshin *et al.*, Yad. Fiz. **31**, 47 (1980) [Sov. J. Nucl. Phys. **31**, 24 (1980)]; Yad. Fiz. **36**, 336 (1982) [Sov. J. Nucl. Phys. **36**, 195 (1982)].
[7] Dz. Ganzorig *et al.*, Phys. Lett. **77B**, 257 (1978).
[8] W. U. Schroder *et al.*, Phys. Lett. **43B**, 672 (1979).
[9] G. E. Belovitzky, C. Petitjean, *et al.*, SIN News Lett. **13**, 56 (1980).
[10] A. Wyttenbach *et al.*, Nucl. Phys. **A294**, 278 (1978).

Translated by Dave Parsons
Edited by S. J. Amoretty