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DELAYED FISSION  
OF THE  $^{238}\text{U}$  MUONIC ATOM

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**DELAYED FISSION  
OF THE <sup>238</sup>U MUONIC ATOM**

## 1. INTRODUCTION

In many measurements<sup>/1-4/</sup> the prompt and delayed components of the time distributions of fission events with respect to the  $\mu$ -stop moment have been clearly revealed. The delayed component is interpreted as induced by nuclear  $\mu$ -capture while the prompt component is assigned to fission events following nuclear excitation induced by radiationless transitions of the muon on its atomic orbits. It would be desirable to obtain an experimental verification of the interpretation. The physical problems could be formulated as follows: 1) do the prompt fission events really indicate fission of the nucleus of a muonic atom, 2) is the delayed component induced only by nuclear capture of  $\mu^-$ , and 3) what is the chance for muon to be emitted from the excited fission fragments as it was suggested by Zaretski<sup>/5/</sup>.

Very recently the interest in the second query has been stimulated by two experimental observations. Firstly, in the excitation curve for photofission of  $^{238}\text{U}$  a narrow resonance at 6.2 MeV has been found and its dipole nature,  $(I, K)=(1, 0^-)$  established<sup>/6/</sup>. It is possible that in a muonic atom this fission channel corresponds to the energy of radiationless  $2p \rightarrow 1s$  muonic transition, and

the shape isomer of  $^{238}\text{U}$  nucleus may be selectively excited by such a transition state.

Secondly, the population of the shape-isomeric state with an extremely high isomeric ratio has been proposed by Bloom<sup>/7/</sup> to explain the difference in the mean-lives of the electronic and fission decay modes for the muonic  $^{238}\text{U}$  atom. Kaplan et al.<sup>/8/</sup> have recently reported the value of 0.01 per  $\mu$ -capture as the upper limit of the gamma-decay probability of the muonic  $^{238}\text{U}$  atom in its shape-isomeric state.

In the present experiment we search for the fission decay branch of this atom.

## 2. EXPERIMENTAL SET-UP

The basic idea of the present experiment was to discriminate the radiationless transition fission against the delayed fission arising from nuclear muon capture by detecting the electrons from free decay of muon after fission.

The mean-life of the muon captured by the fission fragments should be about 100 nsec, while the partial mean-life for free decay of the bound muon is about  $3 \mu\text{sec}^{12/}$ ). Therefore in such an approach the fission of muonic atoms will be detected with an efficiency of several per cent only.

The measurements were made using the separated  $\mu^-$ -beam of the Dubna 680 MeV synchrocyclotron. The system of counters used is shown schematically in fig. 1. The counter telescope 1234 registered the  $\mu$ -stop moment while the electron passage was detected by the fourth and fifth counters operating in coincidence (time resolution being set 5.7 nsec).

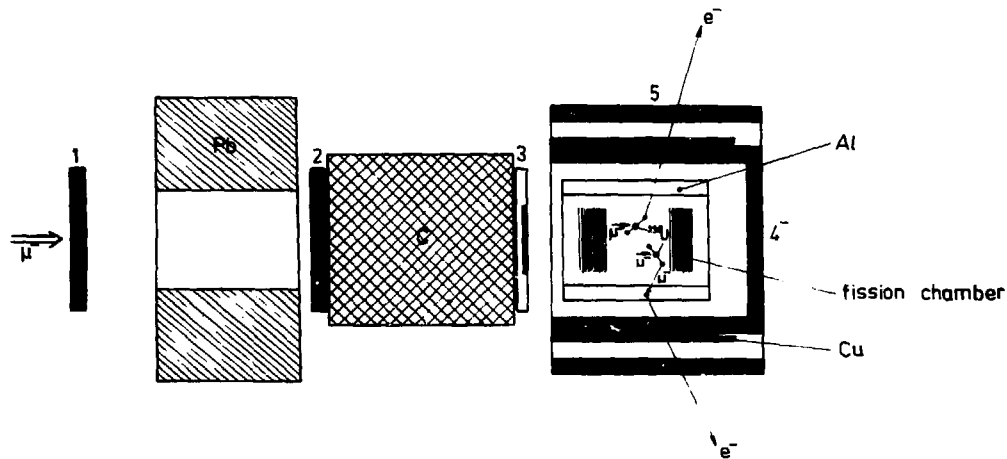


Fig. 1. Detection system for observation of muon-induced fission. The muon stop number is recorded by the conventional 1234 telescope, while the subsequent fission and muon-decay events are detected by the multi-plate ionization chamber and the surrounding scintillation detector. The aluminium is used to allow detection of the possible events in which the muon is liberated after a fission event.

Fission events were registered in the fast multi-plate ionization chamber /9/ containing one gramm of  $^{238}\text{U}$ .

The time resolution for the prompt reaction ( $\pi^-$ , f) was 3 nsec.

Two cases of muon free decay are illustrated in fig. 1: the decay of muon in the atomic orbit of the fission fragment, and the decay of the converted muon captured in the aluminium cylinder surrounding the uranium targets.

To be sure we observe the free decay of the muon which caused the preceding fission, the time interval between the successive muons entering the counter telescope should be controlled. All events registered in the course of the experiment were classified into two groups according to the time interval between the successive muons, viz.  $< 5 \mu\text{sec}$  and  $> 5 \mu\text{sec}$ . Only events in the second group were treated as true ones in the analysis of results.

The block-diagram of the experimental set-up is shown in Fig. 2. Eight time distributions were stored simultaneously in two ADC: the distributions of fission events and electrons with respect to the  $\mu$ -stop moment for double,  $[\mu, f]$  or  $[\mu, e]$ , and triple,  $[\mu(e), f]$  or  $[\mu(f), e]$ , coincidences.

The primary beam intensity was  $1.9 \cdot 10^4$  muons/sec, from which  $\approx 1.5 \cdot 10^4$  muons, sec were separated in time from one another by more than  $5 \mu\text{sec}$ . The rate of the 1,2,3 and 1,2,3,4 coincidences was  $5.5 \cdot 10^3$  and  $3.5 \cdot 10^3$ , respectively. The single count in the fission chamber was 1.5 events/sec and in the double coincidences,  $[\mu, f]$  it was 0.12 event/sec. The appropriate rates for

Block-diagram of the experimental set-up

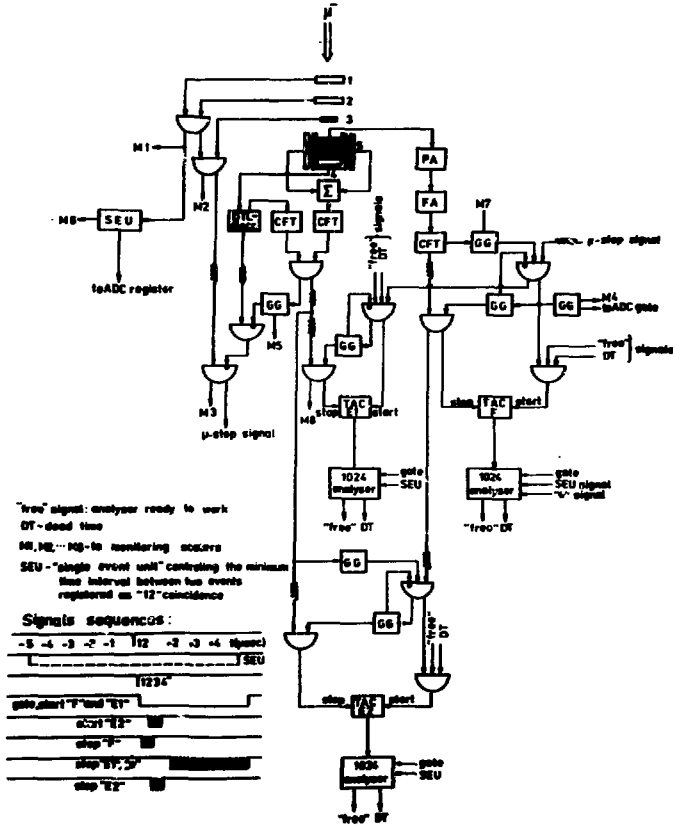


Fig. 2. Block-diagram of the experimental set-up for the observation of muon-induced fission.



electron counter were 400 events/sec and 90 events/sec, respectively.

The rate of the triple coincidences  $[\mu(e), f]$ , was 0.0005 events/sec.

### 3. RESULTS

The measured spectra are shown in fig. 3.

The double coincidence  $[\mu, f]$  and  $[\mu, e]$  spectra are presented in a semilogarithmic scale and the triple ones,  $[\mu(e), f]$  and  $[\mu(f), e]$ , in the linear histogram form.

The characteristics of both  $[\mu, f]$  spectra are identical to those presented in ref. <sup>/3/</sup> for  $^{238}\text{U}$ . The electron distributions contain also the prompt component indicating the admixture of electrons in the primary beam. The delayed part is composed of several exponents, the main one with a mean-time of about 800 nsec which is characteristic of the  $\mu$ -capture in aluminium <sup>/10/</sup>. The long tailing component is due to  $\mu$ -capture in light materials present in the chamber and scintillation counters.

The triple coincidence spectra represent the two-dimensional time distribution of electrons and fission events with respect to the  $\mu$ -stop moment, projected on both time axes.

The open block-histogram spectra refer to events in which more than one muon arrived during the period of 10  $\mu$ sec. The  $[\mu(f), e]$  spectrum, predominantly of a random character, is the result of chance coincidences with electrons from free decay of other muons, except the one giving the  $\mu$ -stop signal, entering the system in the 10  $\mu$ sec interval.

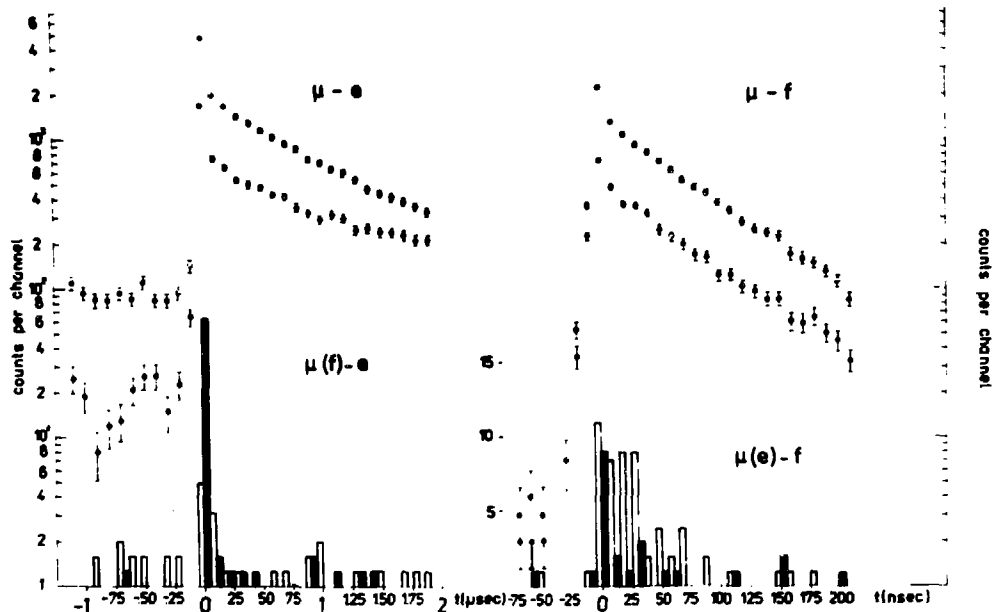


Fig. 3. Data from a preliminary experiment dealing with the search for the conversion process (left-hand part) and delayed fission of the muonic atoms of  $^{235}\text{U}$  (right-hand part). Open circles and open-block histograms refer to events in which more than one muon arrived during the period of  $10 \mu\text{sec}$ ; full circles and full-block histograms refer to events for which only one muon arrived during the period of  $10 \mu\text{sec}$ .

In distinction, both full-block histogram spectra show an evident correlation with the  $\mu$ -stop moment, which excludes the possibility of the observed fission events being correlated with randomly occurring electrons, and vice versa.

Thus, the long tailing component in the electron distribution can be explained (irrespective of the nature of delayed component in the fission spectrum) as the effect of conversion of the muons from the highly excited fission fragments.

The trivial explanation of the delayed component in the fission spectrum appearing as the result of chance coincidences between the fourth and fifth counters, registering prompt gamma-rays from fission induced by nuclear  $\mu$ -capture, can be fully rejected. The relative probability of such coincidences occurring would be of the order of  $10^{-5}$ - $10^{-6}$ , while the relative probability of the observed effect is  $10^{-3}$ .

We see two processes which could be responsible for the observed delayed fission events. The first is the spontaneous fission of the isomer, and the second the fission of the nucleus excited in the beta-decay of muon in the 1s orbit of the  $^{238}\text{U}$  muonic atom. Of course the second explanation is rather exotic but, nevertheless, it should be checked. This requires measuring of the  $[i(\mu), e]$  spectrum. In the case of the second interpretation only the prompt distribution is acceptable.

In view of the very poor statistics, we can only try to estimate the order of magnitude of the mentioned effects.

From the 26 events gathered in our triple coincidence  $[\mu(f), e]$  spectrum, eight events can be attributed undoubtedly to free decay of the converted muon. The mean-life ratio for  $\mu$ -capture in Al and fission fragments was assumed to lie in the limits of 4-8. Thus very roughly, the probability of the conversion process can be estimated as:

$$P_{\mu}^f \approx (0.03 \text{ to } 0.10).$$

In the  $[\mu(e), f]$  fission spectrum the prompt and delayed parts are approximately of the same intensity. As the yield of prompt fission was found<sup>/3/</sup> to be 0.002 per  $\mu$ -capture, this is also the yield of delayed fission observed in the present measurement.

So, the probabilities of decay of the compound  $^{238}\text{U}$  nucleus, excited in the radiationless muonic transitions, by prompt and delayed fission channels are approximately the same. Accepting the value of 0.2 as the probability of radiationless transitions<sup>/11/</sup>, we obtain:

$$P_{\mu}^f(\text{prompt}) = P_{\mu}^f(\text{delayed}) = 0.01.$$

This value is simultaneously the lower limit of the isomeric ratio:

$$\xi = Y(\text{is})/Y(\text{gs}) > 0.01, \quad (\text{gs}) \quad 0.01,$$

since the gamma-decay branch and muon capture from the isomeric state complete with the decay by a fission channel.

The isomeric ratio for spontaneously fissioning isomers observed up to date is of the order of  $10^{-3}$  -  $10^{-5}$ . The interpretation of the large value of  $\xi$  obtained in the present experiment would probably require including of the resonance mechanism of the compound nucleus excitation in the radiationless muonic transitions.

If the observed delayed fission would be the effect of a direct nuclear excitation in the free decay of a muon, then the probability of such a process should according to our result be of the order of 0.1. This is based on the probability of 0.02 of the muon free decay in the 1s orbit of the  $^{238}\text{U}$  muonic atom. In present estimation the partial mean-life for free decay of the bound muon was put  $\tau_{\mu}(\text{free}) = 3000$  nsec, after ref./12/, and  $\tau(\text{capture}) = 81.5 \pm 1.5$  nsec was used in accordance with ref./13/.

In order to make the interpretation of the nature of delayed fission in muonic atoms  $^{238}\text{U}$  more convincing, the distribution  $\{f(\mu), e\}$  must be measured and sufficient statistics gathered to define the mean-life of the observed decay. Besides, the measurement should be repeated for other isotope, say  $^{235}\text{U}$  or  $^{232}\text{Th}$ .

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