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DELAYED FISSION
OF THE ^{238}U MUONIC ATOM

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1. INTRODUCTION

In many measurements[1-4] the prompt and delayed components of the time distributions of fission events with respect to the μ-stop moment have been clearly revealed. The delayed component is interpreted as induced by nuclear μ-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 μ^-, and 3) what is the chance for muon to be emitted from the excited fission fragments as it was suggested by Zaretski[5].

Very recently the interest in the second query has been stimulated by two experimental observations. Firstly, in the excitation curve for photofission of ^{238}U a narrow resonance at 6.2 MeV has been found and its dipole nature, $(I, K) = (1, 0^-)$ established[6]. 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}U nucleus may be se-
lectively excited by such a transition state.

Secondly, the population of the shape-
isomeric state with an extremely high iso-
meric ratio has been proposed by Bloom[7] to
explain the difference in the mean-lives
of the electronic and fission decay modes
for the muonic ^{238}U atom. Kaplan et al.[8]
have recently reported the value of 0.01
per μ-capture as the upper limit of the
gamma-decay probability of the muonic ^{238}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 transi-
tion fission against the delayed fission ari-
sing 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 μsec[12]). The-
refore in such an approach the fission of
muonic atoms will be detected with an effi-
ciency of several per cent only.

The measurements were made using the se-
parated μ^--beam of the Dubna 680 MeV synchro-
cyclotron. The system of counters used is
shown schematically in fig. 1. The counter
telescope 1234 registered the μ-stop mo-
ment while the electron passage was detected
by the fourth and fifth counters operating
in coincidence (time resolution being set
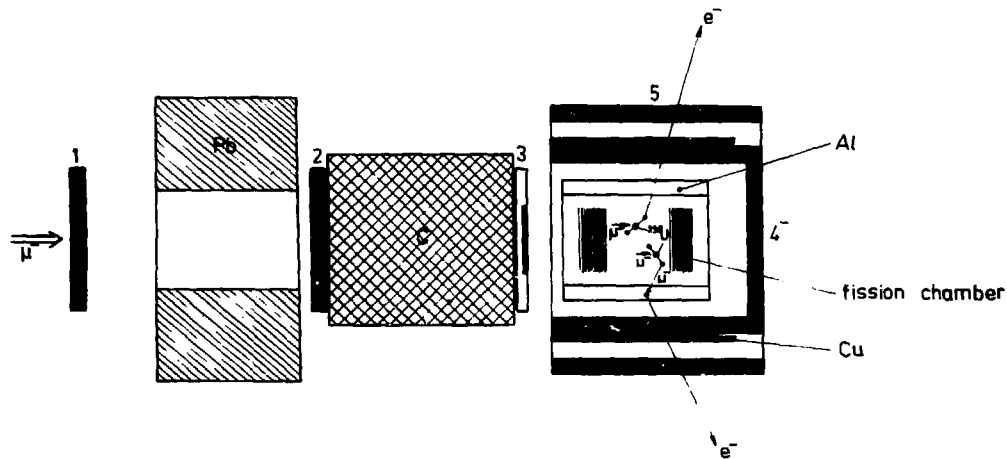5.7 nsec).

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Fig. 1. Detection system for observation of muon-induced fission.
The muon stop number is recorded by the conventional 1234 ̄ ele-
scope, 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 fis-
sion event.

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

The time resolution for the prompt reaction (π^-, 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. $< 5\ \mu$sec and $> 5\mu$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 μ-stop moment for double, $[\mu, f]$ or $[\mu, e]$, and triple, $[\mu(e), f]$ or $[\mu(f), e]$, coincidences.

The primary beam intensity was $1.9.10^4$ muons/sec, from which $\approx 1.5.10^4$ muons, sec were separated in time from one another by more than 5 μsec. The rate of the 1,2,3 and 1,2,3,$\overline{4}$ coincidences was 5.5×10^3 and 3.5×10^3, 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

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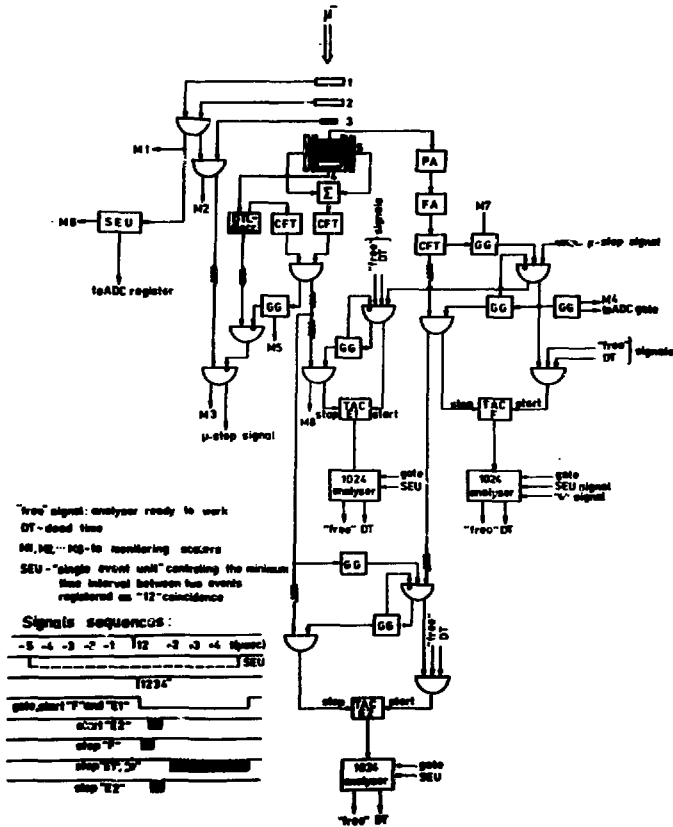
Block-diagram of the experimental set-up

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 $[\mu, e]$ spect-
ra 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. [3]
for ^{238}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 μ-capture in aluminium [10]. The long
tailing component is due to μ-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 μ-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 μsec. The $[\mu(f), e]$
spectrum, predominantly of a random charac-
ter, is the result of chance coincidences
with electrons from free decay of other
muons, except the one giving the μ-stop sig-
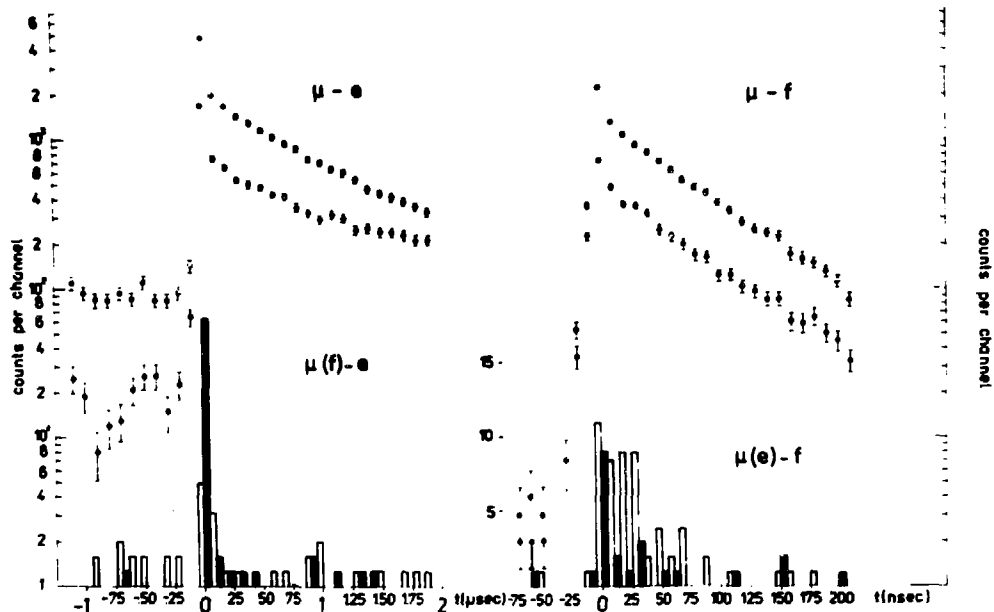nal, entering the system in the 10 μsec
interval.

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}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 μsec; full circles and full—block histograms refer to events for which only one muon arrived during the period of 10 μsec.

In distinction, both full-block histogram spectra show an evident correlation with the μ-stop moment, which excludes the possibility of the observed fission events being correlated with randomly occuring 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 μ-capture, can be fully rejected. The relative probability of such coincidences occuring 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}U muonic atom. Of course the second explanation is rather exotic but, nevertheless, it should be checked. This requires measuring of the $[\tilde{x}(\mu), e]$ 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 μ-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:

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

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 [3] to be 0.002
per μ-capture, this is also the yield of
delayed fission observed in the present
measurement.

So, the probabilities of decay of the
compound ^{238}U nucleus, excited in the radia-
tionless muonic transitions, by prompt and
delayed fission channels are approximately
the same. Accepting the value of 0.2 as
the probability of radiationless transitions [11],
we obtain:

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

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

$\xi = Y(\text{is})/Y(\text{gs}) > 0.01$,   (gs) 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 fis-
sioning isomers observed up to date is of
the order of $10^{-3} - 10^{-5}$. The interpretation
of the large value of ξ obtained in the
present experiment would probably require
including of the resonance mechanism of the
compound nucleus excitation in the radiation-
less muonic transitions.

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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}U muonic atom. In present estimation the partial mean-life for free decay of the bound muon was put τ_μ (free) $\approx$ 3000 nsec, after ref.$^{/12/}$, and τ (capture) = 81.5 ± 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}U more convincing, the distribution $[I(\mu), e]$ 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}U or ^{232}Th.

ACKNOWLEDGEMENTS

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