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FISSION OF MUONIC ^{232}Th AND ^{238}U

Dz. Ganzorig[1)], P.G. Hansen[2)*)], T. Johansson[2)**)], B. Jonson[2)***)], J. Konijn[2)†)], T. Krogulski[1)††)], V.D. Kuznetsov[1)], S.M. Polikanov[1)], G. Tibell[2)**)] and L. Westgaard[3)]

ABSTRACT

Muon-induced prompt fission of ^{232}Th and ^{238}U, interpreted usually as being caused by muonic radiationless transitions, was observed in delayed coincidence with the decay electrons from muons bound to fission fragments. The measured lifetime indicates that the muon is captured preferentially by the heavy fragments. Muon conversion from highly excited fission fragments was also observed.

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1) Joint Institute of Nuclear Research, Dubna, USSR.

2) CERN, Geneva, Switzerland.

3) University of Oslo, Norway.

*) On leave from Institute of Physics, University of Aarhus, Aarhus, Denmark.

**) On leave from the Gustaf Werner Institute, Uppsala, Sweden.

***) On leave from Department of Physics, Chalmers University of Technology, Göteborg, Sweden.

†) On leave from IKO, Amsterdam, Netherlands.

††) On leave from the Institute of Nuclear Research, Swierk, Poland.

We report here on the first results of an experiment on the fission of muonic ^{232}Th and ^{238}U. The experiment is a continuation and extension of measurements in Dubna[1]. This paper concerns results on the fate of the muon in the process.

In studies of fission induced by muons, delayed events due to nuclear muon capture as well as fission events in prompt coincidence with the stopped muons have been observed[2-5]. The prompt events are usually interpreted as being due to nuclear excitation accompanying radiationless muonic transitions. Thus we have to do with the fission of *muonic atoms*, i.e. the fission of a nucleus with the muon in its 1s orbit in which the muon remains closely bound to the nucleus and can be used as a probe for the fission process. In this way one could, for instance, hope to obtain information on the fission dynamics. A first step has been to study the fate of the muon after fission. As part of this study, a search was also made for the phenomenon of muon conversion from highly excited fission fragments[6].

A schematic view of the detection system is shown in Fig. 1. The muon beam from the muon channel of the CERN Synchro-cyclotron (momentum about 100 MeV/c and intensity up to 2×10^4 muons/sec, measured as coincidences between counters 1 and 2) was slowed down in a 4 cm thick carbon moderator. A plexiglas Čerenkov counter vetoed telescope signals due to electrons present in the beam. The muon stop signal ($12\bar{Č}3$) was defined in time by the third counter. The fissile target material (natural uranium or thorium) was deposited on 100 aluminium foils, forming the electrodes of a parallel-plate, fast ionization chamber. The total amount of target material was about 25 g in both cases, with a thickness along the beam of about 600 mg/cm^2.

High-energy electrons from muon decay were detected in a telescope, consisting of a cylindrical plastic scintillator and a water Čerenkov counter. The amount of material between the targets and the electron detector implied a threshold for electron registration of about 10 MeV.

For triple events, muon(μ) - fission(f) - electron(e), the three time intervals μ-f, μ-e, and f-e were measured using time-to-digital converters and recorded event by event on magnetic tape. Each triple coincidence was tagged by an additional bit of information to distinguish between the cases when only one, or more than one, muon entered the detection system during a period of ±10 μsec, relative to the μ-stop time. On the other hand, we rejected such events where two electrons appeared within ±5 μsec relative to any particular electron event.

Histograms of the time distributions for double and triple coincidence events were accumulated on line, providing a possibility for checks and for later normalization of count rates. With 20,000 muons/sec in the primary beam and with a duty cycle of ≈ 60%, we had typically about 6000 12$\bar{3}$ coincidences/sec. With this intensity the number of doubles μ-f/sec was 5.0 and 0.5, the number of triples μ-f-e/sec 0.1 and 0.01, for uranium and thorium, respectively.

We present here the results concerning triple events for which the fission appears in prompt coincidence with the muon stop.

For such triple events where -5 nsec $< t(\mu\text{-f}) < +5$ nsec, we have projected the points from the two-dimensional distribution onto the $t(\mu\text{-e})$ axis, thereby building up the time distribution of muon disappearance after fission, which is promptly induced by muons stopped in the target. This distribution was fitted using a constant background, plus either one or two exponentials. Only in the uranium case, owing to the much larger number of events collected, was a statistically significant difference observed between using one or two exponentials (see Fig. 2).

For the dominant exponential the two targets gave the same result, within the errors, corresponding to a mean lifetime of

$$\tau_1(^{238}\text{U}) = (134 \pm 3)\ \text{nsec}, \qquad \chi^2/\nu = 1.17$$

$$\tau_1(^{232}\text{Th}) = (132 \pm 7)\ \text{nsec}, \qquad \chi^2/\nu = 0.51\ .$$

For the second component the result for uranium is $\tau_2(^{238}\text{U}) = (1.6 \pm 0.4)$ μsec.

We interpret the shorter mean lifetime to correspond to muon disappearance on the fission fragments and the longer one as being due to muons absorbed on light elements inside the fission chamber: Al from the foils and the walls or C and H from the methane gas. This latter observation can be understood assuming the muon to have been released, for instance, from highly excited fission fragments by the conversion process[6].

Making use of published data on charge and mass distributions of fission fragments, it is possible to determine if the present result corresponds to muons being attached to the heavy or the light fragments. This was done by using the so-called Primakoff plot[7)], which presents the muon disappearance rate as a function of the neutron excess parameter N/2A. Interpreting the measured mean lifetime as being due to absorption on light or heavy fragments, one can get normalized values of the muon capture rate for both kinds of fragments, which in Fig. 3 are represented by the shaded areas. Evidently, the interpretation that the muon goes along with the light fragment fails. Noting that for light fission fragments the neutron excess parameter lies in a well-tested region, we have no reason to doubt the applicability of Primakoff's formula in this case. Thus, we conclude from our results that the muon goes preferentially with the heavy fragment.

In order to test the reliability of our analysis of the time distribution, and thus qualify our conclusion about the fate of the muon, we have performed Monte Carlo calculations. A randomized function, the sum of three exponentials, was generated with variable weights for the different exponentials. The first two of these corresponded to the exponentials found in the measurement (Fig. 2), whereas the last was chosen to correspond to one of the two cases where either the muons move out, bound to the light fragments ($\tau \approx 220$ nsec), or where released muons would be recaptured on the heavy target ($\tau \approx 80$ nsec). As a result of these calculations, it was found that a 10% admixture of the 220 nsec component would have little influence on the 134 nsec lifetime, whereas it would decrease the longer component to about 1.1 μsec. On the other hand, a 20% admixture of the 80 nsec lifetime would decrease the lifetime of the 134 nsec component by about 10%. Thus our observations that the measured muon disappearance rate is about 10% higher than that predicted for heavy fragments (Fig. 2) might indicate some admixture of the 80 nsec component. The calculations performed have also shown that the main observed exponential characterized by $\tau = 134$ nsec cannot be the result of the superposition of the two other components, 80 nsec and 220 nsec.

The long component in the μ-e spectrum contains about 1% of all prompt fission events when the measured number of events is corrected for the large difference in muon absorption rates. This number gives us a lower limit for the total probability of releasing muons via the conversion mechanism from highly excited fragments.

Experimentally, an upper limit for this probability is defined by the possible admixture of the 80 nsec component in the measured spectrum (∿ 20% as discussed above), coming from muons recaptured in the target material.

Barit et al.[11)] calculated the total probability of the conversion process and the energy distribution of converted muons. The effective threshold for converted muons to escape from the target layers (2-5 mg/cm^2 thick) can be estimated to be about 500 keV. According to the distributions given in Ref. 11, this means that less than 75% of converted muons can be recaptured on the target. By comparing to our value for the long component (∿ 1%) we thus obtain an upper limit of 4% for the total probability of muon conversion.

The authors of Ref. 11 present values for the muon-conversion probabilities separately for light and heavy fragments, and find them to be in the ratio of about 30 to 1. Such a low probability for muon conversion from heavy fragments is compatible with the observed low probability for muon conversion in conjunction with a strong selection for muon attachment to heavy fragments.

Although qualitatively understandable the present experimental results concerning the fate of the muon, after muon-induced prompt fission, point to the need for more detailed calculations which should be able to predict i) the strong selection in favour of muon attachment to the heavy fragment, ii) the energy spectra and yields of muons released from fission fragments.

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Figure captions

Fig. 1 : Schematic view of the apparatus used in the experiment. The fission chamber contains a total of 100 Al foils on which the fissile target material was deposited.

Fig. 2 : Time distribution of events with the absolute value of $t(\mu\text{-}f)$ less than 5 nsec projected onto the $t(\mu\text{-}e)$ axis. The experimental data were fitted with the sum of two exponentials and a constant background.

Fig. 3 : Primakoff plot due to Filippas et al.[8] and Eckhause et al.[9] with the capture rate, corresponding to the present results, for light and heavy fragments in the fission of Th or U indicated as shaded areas. The other points are published experimental data, some of which are used in finding the parameters of the Primakoff formula. The crosses denote the values calculated according to Goulard and Primakoff[10] for fission fragments.

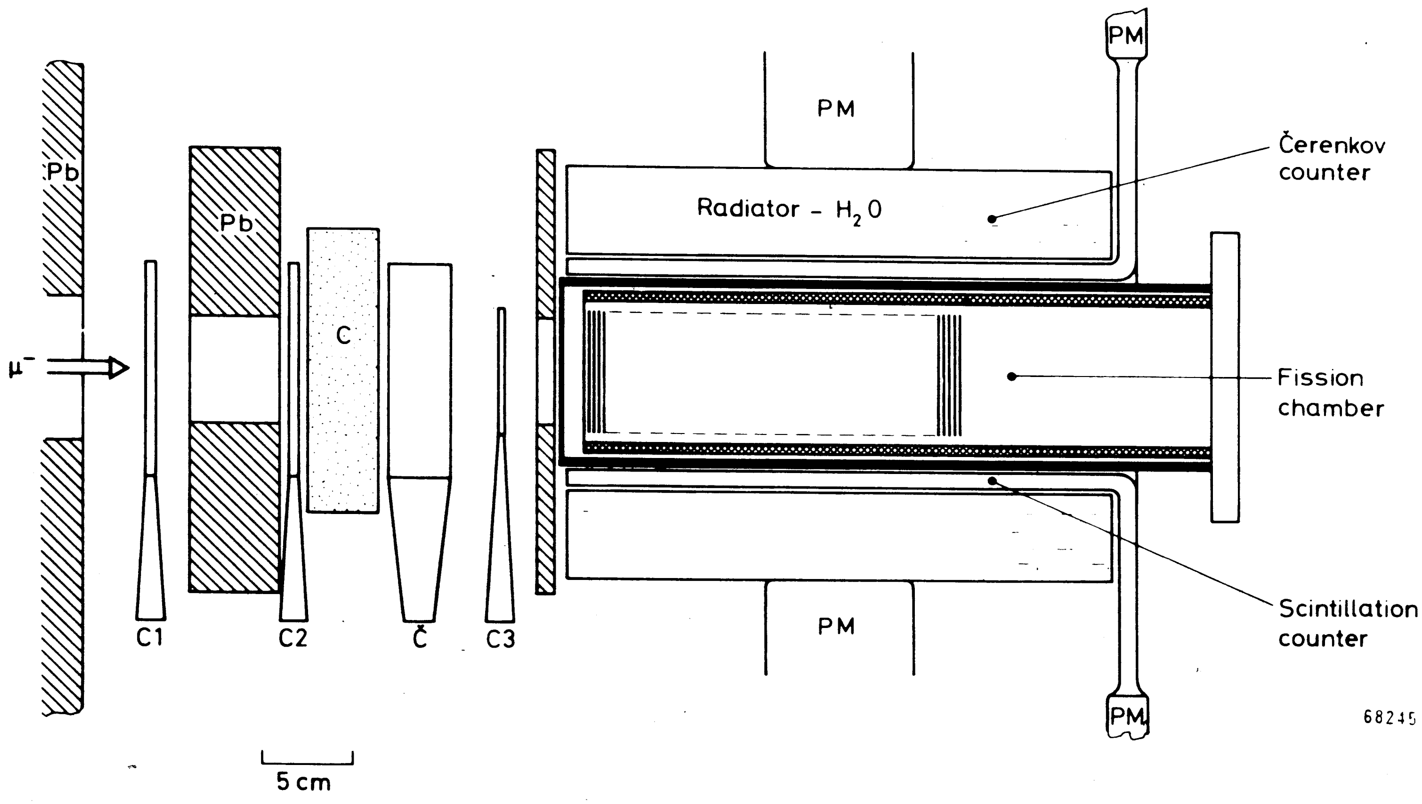
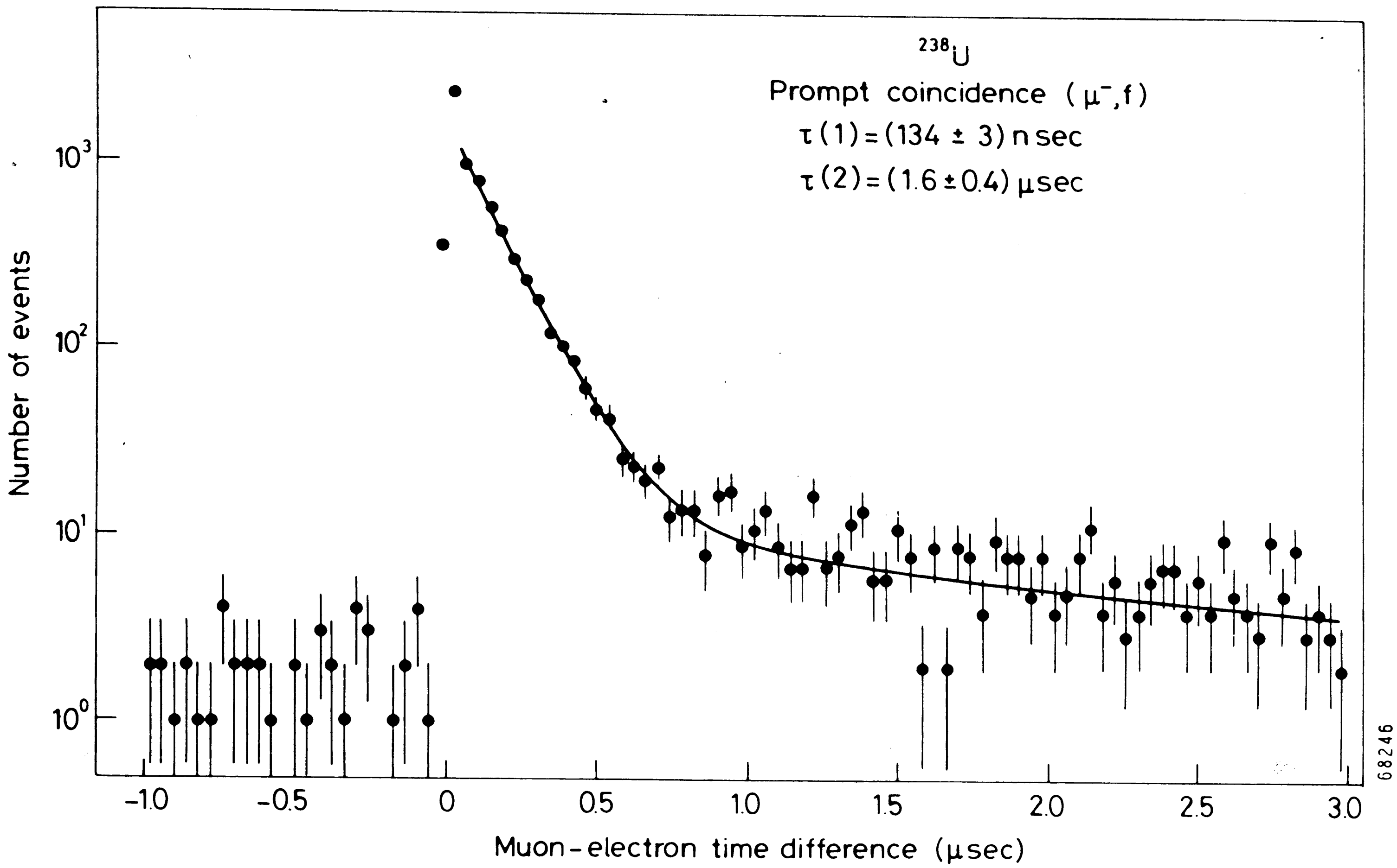
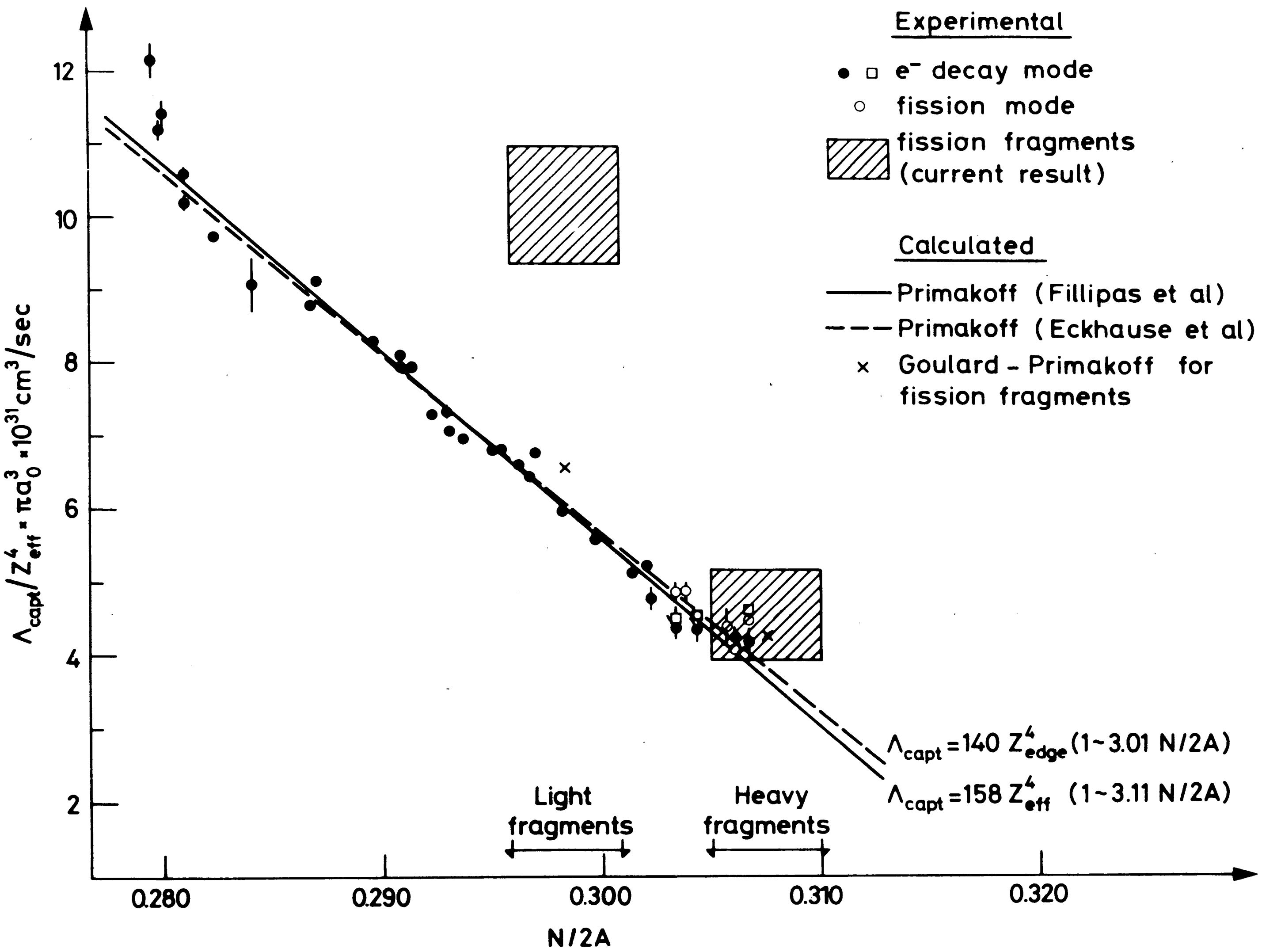

Pb
μ⁻
C1
Pb
C2
C
Č
C3
PM
Radiator - H_2O
PM
PM
PM
Čerenkov counter
Fission chamber
Scintillation counter
5 cm
68245

Fig. 1



^{238}U
Prompt coincidence (μ^-,f)
$\tau(1) = (134 \pm 3)$ nsec
$\tau(2) = (1.6 \pm 0.4)$ μsec
Number of events
10^3
10^2
10^1
10^0
-1.0
-0.5
0
0.5
1.0
1.5
2.0
2.5
3.0
Muon-electron time difference (μsec)
68246

Fig. 2



Experimental
e⁻ decay mode
fission mode
fission fragments (current result)
Calculated
Primakoff (Fillipas et al)
Primakoff (Eckhause et al)
Goulard - Primakoff for fission fragments
$\Lambda_{capt}=140\ Z^4_{edge}(1-3.01\ N/2A)$
$\Lambda_{capt}=158\ Z^4_{eff}\ (1-3.11\ N/2A)$
Light fragments
Heavy fragments
$\Lambda_{capt}/Z^4_{eff} = \pi a_0^3 \cdot 10^{31} cm^3/sec$
N/2A
12
10
8
6
4
2
0.280
0.290
0.300
0.310
0.320

Fig. 3

67400