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MUON-INDUCED FISSION

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There exists now a big family of elementary particles, but only a few of them are "reasonably stable" (Table 1). "Reasonably stable" means that the lifetimes are essentially longer than fission time. However, most of the listed particles having been attached to nuclei decay via strong interaction in a short time. Only two of them could survive inside nuclei for a relatively long time. These are the Λ^0 hyperon and the negatively charged muon. Being attached to a fissioning nucleus either Λ^0 or μ^- should rearrange its orbits following the elongation of the nucleus. Therefore, these particles could to some extent serve as probes in the study of the dynamics of fission. At the same time the collective motion of nucleons itself might be affected by the presence of either Λ^0 or μ^-.

Table 1

"Reasonably stable" elementary particles

Particle	Interaction*) with nuclei	Lifetime (s)
μ^-	E, W	2.2×10^{-6}
π^-	E, S	2.6×10^{-8}
K^-	E, S	1.2×10^{-8}
Λ^0	W	2.5×10^{-10}
Σ^-	E, S	1.5×10^{-10}
Ξ^-	E, S	1.7×10^{-10}
Ω^-	E, S	1.3×10^{-10}
X^-, X^0 ($M > 10^2$ GeV) (?)		$> 10^{17}$

*) E: electromagnetic interaction,
S: strong interaction,
W: weak interaction.

Owing to its mass 207 m_e, the negatively charged muon behaves like a heavy electron. Its atomic orbits are compressed by the factor m_μ/m_e. For instance, in the case of heavy elements a muon in 1s orbit spends a lot of time inside the nucleus. Negatively charged muons interact with the matter through the following stages:

i) Slowing down;

ii) Formation of muonic atoms;

iii) Decay via weak interaction.

The two first stages proceed for no longer than 10^{-12} s. Muonic atoms of heavy elements decay by muon capture with a lifetime of about 80 ns. The residual nuclei are excited up to an energy sufficiently high to undergo fission. However, this process would not be of interest to us. It seems more attractive to study fission induced by the radiationless muon transition[1,2]. This process is

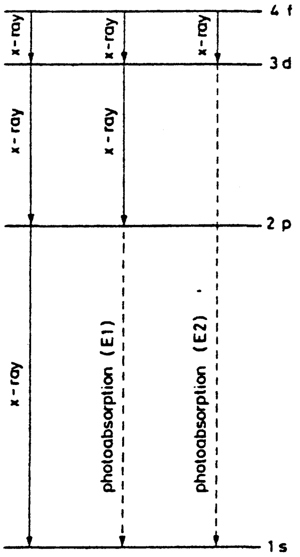

Fig. 1 Radiationless transitions in muonic atoms

Table 2

The probability of radiationless transitions for ^{238}U

Transition	Energy (MeV)	$\Gamma_{r\ell}/(\Gamma_{r\ell} + \Gamma_{\gamma})$
2p → 1s	6.2	0.24
3d → 1s	9.5	0.15
3p → 1s	9.5	0.5

nothing more than the absorption of virtual photons (Fig. 1). Recently, Teller and Weiss$^{3)}$ have calculated the probability of the radiationless transitions for ^{238}U, treating giant resonances (GQR, GDR) as the entrance channels. They have concluded that the 2p → 1s, 3d → 1s, and 3p → 1s radiationless transitions should be quite probable for ^{238}U (Table 2).

In recent experiments at SIN$^{4)}$ the probability of the 3d → 1s radiationless transition for ^{238}U has been measured. For this purpose, the intensity of the 3d → 2p and 4f → 3d radiative transitions was compared both for the single spectrum and gated by the 2p → 1s X-rays. The fraction of missing X-rays (3d → 2p) which corresponds to the total yield for the 3d → 1s transitions appeared to be about 20%. The contribution of the radiative transition 3d → 1s is small. Thus we can arrive at the conclusion that the probability of the radiationless 3d → 1s transition is near 20%. In the light of this result some old estimates of the probability of the 2p → 1s radiationless transition for ^{238}U $^{5)}$ should be revised. The value obtained at SIN is in a reasonably good agreement with the calculation done by Teller and Weiss$^{3)}$.

Another series of experiments includes the observation of prompt fissions in coincidence with muonic X-rays$^{6-8)}$. The results for ^{238}U obtained at SIN$^{6)}$ manifest evidently the role of the 3d → 1s radiationless transition for fission (Table 3). The 2p → 1s and the 4 → 1 radiationless transitions resulting in fission cannot be ruled out at the present level of accuracy. In experiments at TRIUMF$^{8)}$ it has been found that about 60% of all prompt fissions for ^{238}U are caused by the 2p → 1s radiationless transition.

Table 3

Ratios of muonic X-ray intensities for prompt and delayed fission. The normalization was made to the 6-5 transition.

Transition $n_i \rightarrow n_f$	Intensity ratios $I_{pr.f.}/I_{del.f.}$
8 → 7	1.01 ± 0.25
7 → 6	1.03 ± 0.16
6 → 5	1.0
5 → 4	1.02 ± 0.11
4 → 3	0.88 ± 0.13
3 → 2	0.26 ± 0.15
2 → 1	0

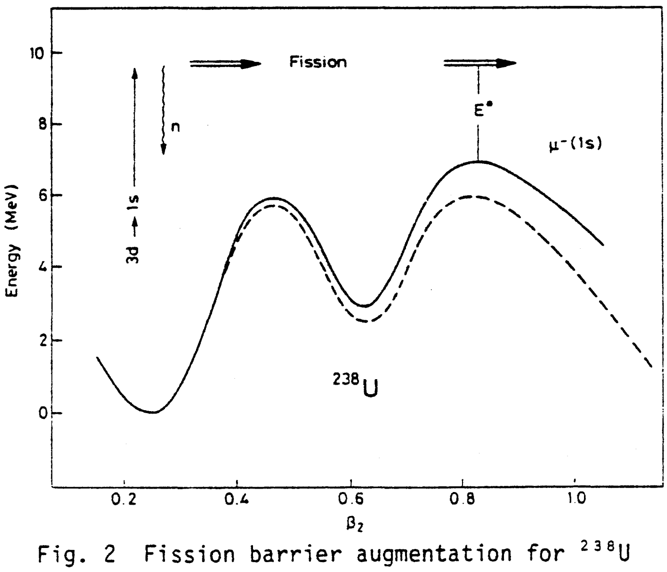

Fig. 2 Fission barrier augmentation for ^{238}U

By using SIN results the value $\Gamma_n/\Gamma_f = 40$ was deduced. That is 10 times larger than Γ_n/Γ_f measured for ^{238}U in experiments with γ-rays. One of the possible explanations for such significant suppression of the fission channel could be the augmentation of the outer fission barrier in the presence of a negatively charged muon[9]. This effect is illustrated in Fig. 2.

In earlier experiments at CERN[10] it has been shown that preferentially muonic atoms of heavy fragments are formed through fission induced by the radiationless transitions. Muonic atoms of heavy fission fragments showed themselves by electrons emitted in muon beta-decay (Fig. 3). The Rochester group has arrived at the same conclusion by the observation of neutrons evaporated after the muon capture by heavy fission fragments[11]. The fact that muons stick to heavy fission fragments indicates clearly that the separation of fission fragments proceeds slowly (Fig. 4). The results obtained at CERN[10] have also demonstrated muon conversion. This mode of de-excitation of fission fragments is naturally characteristic only for muon-induced fission. The muon-binding energy is equal to 5.8 MeV and 3.3 MeV for heavy and light fission fragments, respectively. More likely muons are ejected from muonic atoms of light fission fragments, but that would mean that muons are attached to light fragments with a non-negligible probability.

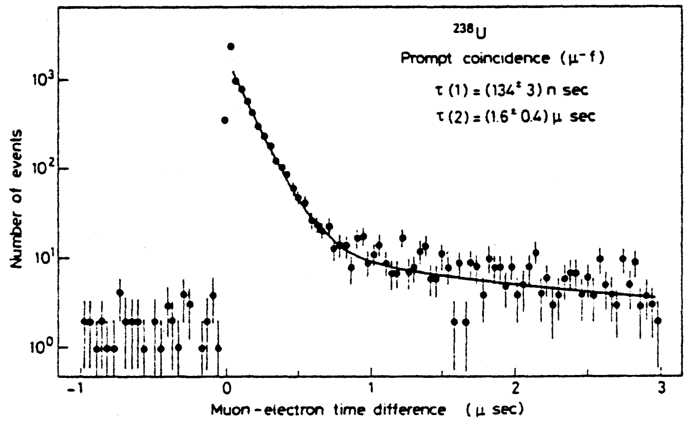

Fig. 3 Time distribution of electrons emitted at muon decay (taken from Ref. 10)

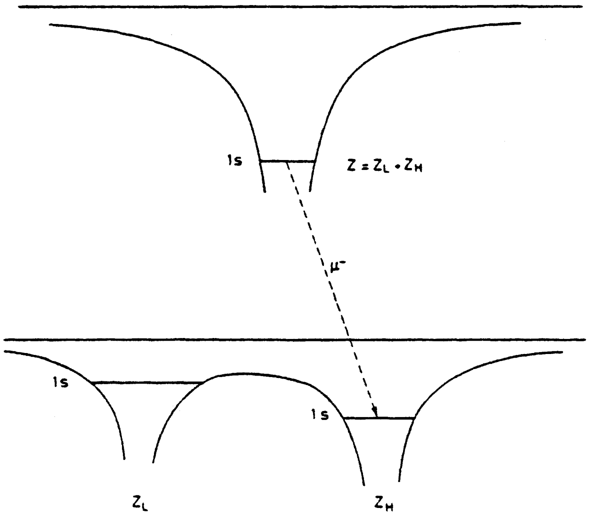

Fig. 4 Muon attachment to heavy fission fragments

Our present knowledge of muon interaction with fissile nuclei enables us to think of some new experiments in this field. These are the topics of possible interest:

1. Quadrupole photofission.
2. Muon attachment to fission fragments.
3. Muon conversion.
4. Muonic atoms of shape isomers.
5. Parity violation.

The observation of quadrupole radiationless transitions reveals some new opportunities for studying quadrupole photofission not covered by dipole photoabsorption. That is certainly an advantage which one gains in experiments with muons, but at the same time the excitation energy cannot be varied. Measurements of the energy spectrum of fission fragments hopefully could provide us with some new facts.

It has been mentioned in some papers[12-14] that by studying muon attachment to light fission fragments one could learn more about nuclear viscosity. It is reasonable to suggest that at sufficiently fast separation of fission fragments a muon can stick to the light fission fragment. However, it is not clear what accuracy is needed to disentangle viscosity effects from any others.

It seems interesting to study muon conversion in more detail. In fact, this could provide us with some new information concerning electromagnetic radiation from fission fragments. In particular, high-spin isomers with energy larger than the muon binding energy might be studied.

Until now all the attempts to produce muonic atoms of shape isomers have not given sufficiently convincing results. Most likely the lifetime of the shape isomer of ^{238}U in the presence of a muon is very short. Hopefully by choosing Pu or Cm as targets a more favourable situation might be achieved for the observation of the fission mode of the decay of shape isomers.

Finally it seems relevant to mention also that the observation of fission induced by the 3d → 1s radiationless transition makes it possible to study some effects in connection with the parity violation in electromagnetic interactions. It is known that the closeness of the 3d and 3p levels might result in mixing of states of the opposite parity. Probably this effect might show up in measurements of the polarization of muons attached to fission fragments in respect to momenta of fission fragments.

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