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PROPOSAL

# STUDIES OF FISSION OF HEAVY NUCLEI INDUCED BY MUONS, PIONS AND PROTONS

Dubna-CERN-Copenhagen Collaboration

Dz. Ganzorig, T. Krogulski*), V.D. Kuznetsov and S.M. Polikanov (Dubna)

G. Tibell, P.G. Hansen, B. Jonson and L. Westgaard (CERN)

J. Pedersen (Univ. Copenhagen)

## SUMMARY

After preliminary experiments at Dubna on muon-induced fission and on the production of high-spin isomers in $\pi^-$ capture, we propose a continuation of this programme at the CERN Synchro-cyclotron. This programme should start with a study of muon-induced fission with an improved detector system, which is already being developed. Subsequent experiments would search for the possible formation of beta-delayed fission activity and for high-spin isomers decaying by fission.

Contact man: G. Tibell

*) On leave from the Institute for Nuclear Research, Swierk, near Warsaw, Poland.

## 1. INTRODUCTION

The recent development of the theory[1] of the nuclear energy surface has led to a better understanding of the fission process. The calculations show the important role of shell effects at larger deformations, leading to a second minimum of the potential-energy well at the saddle point of a heavy nucleus. Within the framework of this theoretical approach, various experimental facts can be understood, notably the resonances in the excitation function of fission below and near the fission barrier and also the previously observed occurrence of spontaneously fissioning isomers.

The identification of a rotational band in the $^{240}Pu$ fission isomer observed by Specht et al.[2] strongly supports the hypothesis of shape isomerism. But there is still a strong need for a more direct experimental verification of the assumed larger deformation of the nuclear charge.

In this respect, the study of the fission of muonic atoms seems of interest. As it was pointed out by Wheeler[3], then calculated first by Zaretski and Novikov[4] and recently in a refined way by Leander and Möller[5], the binding energy of the muon in its 1s orbit changes considerably with the nuclear deformation (Fig. 1). It leads to changes in the potential barrier which make the isomeric state in the presence of a muon quite different from that for the bare nucleus. If this can be checked experimentally, the existence of shape isomeric states could be regarded as a proved fact.

During the last few years an experimental programme has been developed at Dubna in $\mu^-$-induced nuclear fission. As a first stage the systematics of the absolute yields of prompt and delayed fission for heavy isotopes from thorium to plutonium has been obtained[6]. Also the muon mean lives in these isotopes have been measured. These experiments form the basis for a planned experiment to search for the shape-isomeric states excited in muonic radiationless transitions. The basic idea is to discriminate between the radiationless-transition fission and delayed fission arising from nuclear muon capture by detecting the electrons from the free decay of the muon after the fission.

A preliminary experiment has recently been performed at Dubna with the indication of a positive result (see Subsection 3.1 and Fig. 3).

Another sensitive check on Strutinski's model may be obtained from studies of the fission phenomena for isotopes far from the stability line.

Using reactions with high-energy protons one can try to look for delayed-fission activity excited in nuclear beta decay of the parent nucleus. Indications of such a process, which is analogous to the delayed emission of protons and $\alpha$-particles[7,8], was reported in Dubna for heavy-ion reactions[9].

The recent discovery in Dubna[10] of the $\pi^-$-induced selective excitation of high-spin metastable states in heavy nuclei may be used to look for the de-excitation of such states by spontaneous fission. Measured mean lifetimes could be compared with the model predictions for such light isotopes, in which the two-humped barrier practically disappears so that only one, relatively thin, barrier is viewed from excited states in the first well.

Since the improved CERN Synchro-cyclotron will offer very good conditions for this research, we are now proposing to continue the experiments at CERN. In the following, the main features of the experimental techniques and of the scientific programme are outlined.

## 2. EXPERIMENTAL TECHNIQUES

The main experimental problems will be encountered in connection with the study of muon-induced fission, and for this reason only the technique for this experiment will be discussed in detail.

To a large extent the apparatus, shown in Fig. 2, will be the same as that used in the earlier Dubna work. The main new features will be the following:

a) The new, fast multi-plate ionization chamber, which is now under construction, will contain about 25 g of $^{238}U$. It will work with an efficiency of at least 50% and have timing characteristics defined by a FWHM $\leq$ 4 nsec for prompt coincidences $\mu$-f. The chamber will be divided into five sections independently coupled to separate preamplifiers. The chamber is designed to permit also the detection of a muon converted from the fission fragments; this improves the over-all efficiency, as was found in our preliminary experiment (see Fig. 3), by 30%.

b) A cylindrical scintillation counter will be used in coincidence with a Čerenkov counter for detecting the electrons. The high-energy electrons originate from the beta decay of a muon, either captured by fission fragments, or converted and stopped in the aluminium cylinder surrounding the fissile material. The Čerenkov detector has the shape of a box surrounding the fission chamber and the scintillation counter. It is expected that the efficiency of this detector system will be near 90% corresponding to an improvement of a factor of two to three over the scintillation counter used in the first experiments.

c) The electronics (see the block diagram of Fig. 4) should develop timing signals from all the detectors and combine them to obtain the main three signals indicating the time of appearance of a $\mu$-stop, a fission event and an electron passage through the counter. All three time distributions between any two of them must be measured, with and without the presence of the third event.

In addition, it is necessary to make a special record of all events in which more than one muon arrives during the period of interest. It is also foreseen to operate the chamber in a pulsed proton (or $\pi^-$, $^3$He) beam with a timing ranging from seconds to minutes.

## 3. GENERAL SCIENTIFIC PROGRAMME

### 3.1 Muon induced fission

As has been pointed out by Wheeler[3], the change of the binding energy of the muon in a 1s orbit as a function of the nuclear deformation causes the fission barrier to increase substantially. Such an increase for the two-humped barrier means a considerable isomeric shift and a change of the mean lifetime of the spontaneously fissioning isomer. For these reasons the early experiments concentrated on the so-called prompt fission[6], which most probably is induced by the radiationless muonic transitions 2p-1s, so that the corresponding energy of about 6 MeV is transferred directly to the nucleus. In this process only dipole fission channels $(I,K^{\pi}) = (1,0^-)$ and $(1,1^-)$ can be involved.

In the excitation curves recently measured for photofission a pronounced resonant structure was revealed[11], and it is discussed in terms of the fission channels mentioned above.

The data available until now have stimulated the question of whether the shape-isomeric states can be excited in a resonance manner by the radiationless muonic transitions[12].

Kaplan et al.[13] tried to find the γ-decay branch of the shape-isomeric state in a muonic $^{238}U$ atom, and gave an upper limit of 1% per μ-capture. The search for the fission decay branch during the last year performed at Dubna has given an indication of a positive result with the effect being of the order of 0.2% per μ-capture (i.e., comparable with the prompt fission yield). At the present moment, however, this observation can also be interpreted as the delayed fission of a muonic atom induced by the free decay of a muon in its orbit.

The experiments now in preparation should attempt to explain the origin of the delayed events and should aim for much better statistics permitting a good determination of the mean decay period, which in itself should be useful in elucidating the origin of the delayed events. The measurement should also be repeated with other targets, especially $^{232}Th$ and $^{235}U$.

In the experiment, three time distributions will be measured between μ-stop and (i) fission event, (ii) electron appearance and, finally, (iii) between the last two events. The last distribution will definitely indicate whether we are dealing with a new type of nuclear fission induced by the free decay of a $\mu^-$, as only a prompt distribution will allow such an interpretation. In any other case we shall be able to state that we observe the delayed fission of the nucleus of a muonic atom excited in a radiationless transition of $\mu^-$.

If the time distribution between μ-stop and the appearance of an electron should confirm the result obtained in the experiment quoted above, then more accurate data on the probability of muon conversion from the fission fragments should be obtained. It could also serve as a check of Primakoff's formula on the $\mu^-$-capture probability for such fission fragments which are nuclei far from the stability line.

### 3.2 High-energy proton induced fission

It has been reported at Dubna[9] that in heavy-ion reactions the beta-delayed fission of light Np and Am isotopes had been observed. Speculatively, the nature of this activity may be explained analogously to delayed-proton[7] or delayed-alpha radioactivity[8]. Through the use of a high-energy proton beam (and, in the future, the $^3$He beam foreseen at CERN) with uranium targets, we could try to search for activities of this kind by measuring the time distribution of the fission events in our chamber relative to the bursts of a pulsed proton beam. A wide region of lifetimes, from a fraction of a second to many minutes, should be explored in this relatively simple measurement.

### 3.3 $\pi^-$-capture induced fission

The other approach to the problems of fission of nuclei far from the stability line is to use the $\pi^-$-capture mechanism to excite high-spin metastable states[10] in these nuclei and to search for a delayed-fission activity using the fission chamber. The experimental technique should be as discussed in Subsection 3.2.

## 4. INITIATION OF THE PROGRAMME

The search for shape-isomeric states excited in muonic atoms seems to be the logical choice for the first experiment in the programme sketched above. Based on our knowledge of the data rates and of the experimental conditions at CERN, we ask for a preliminary allocation of 20 shifts for testing and for preliminary data taking. Of these 20 shifts, 10 would be devoted to:

a) tests of the muon beam and the choice of the intensity, the collimation and the focusing for the experiment;

b) testing the chamber and the Čerenkov counter;

c) background measurements.

The beam conditions which we will ask for, are the following: minimum 100,000 μ/sec intensity of primary beam of 50 MeV energy and a duty factor better than 25%.

If this first step is successful, one could, after a period reserved for modifications, carry out the first, preliminary measurement, again estimated at 10 shifts.

After these two testing periods we intend to return with a request for more beam time for data taking; our present estimate of the time needed is about 50 shifts over a period of 10 months after the start of the data-taking period.

The fission chamber with its preamplifiers and other electronics, as well as the Čerenkov counter, will be taken to CERN from Dubna. The telescope counters and the scintillation counter in the electron detector, standard electronics needed, as well as the data acquisition system, will be supplied by CERN.

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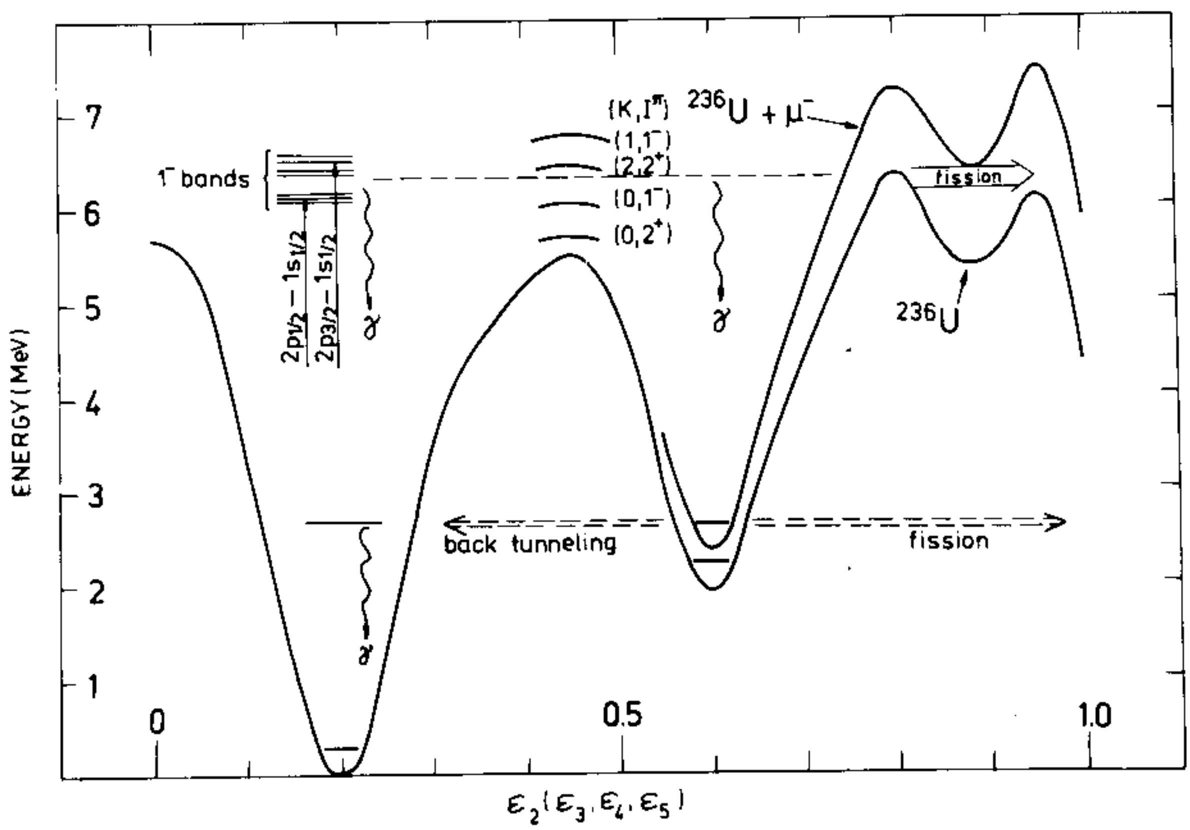


Fig. 1 The deformation energy, minimized with respect to higher multipoles, for the nucleus $^{236}U$ (lower curve) and for the muonic atom $^{236}U + \mu^-$ (upper curve) [5].

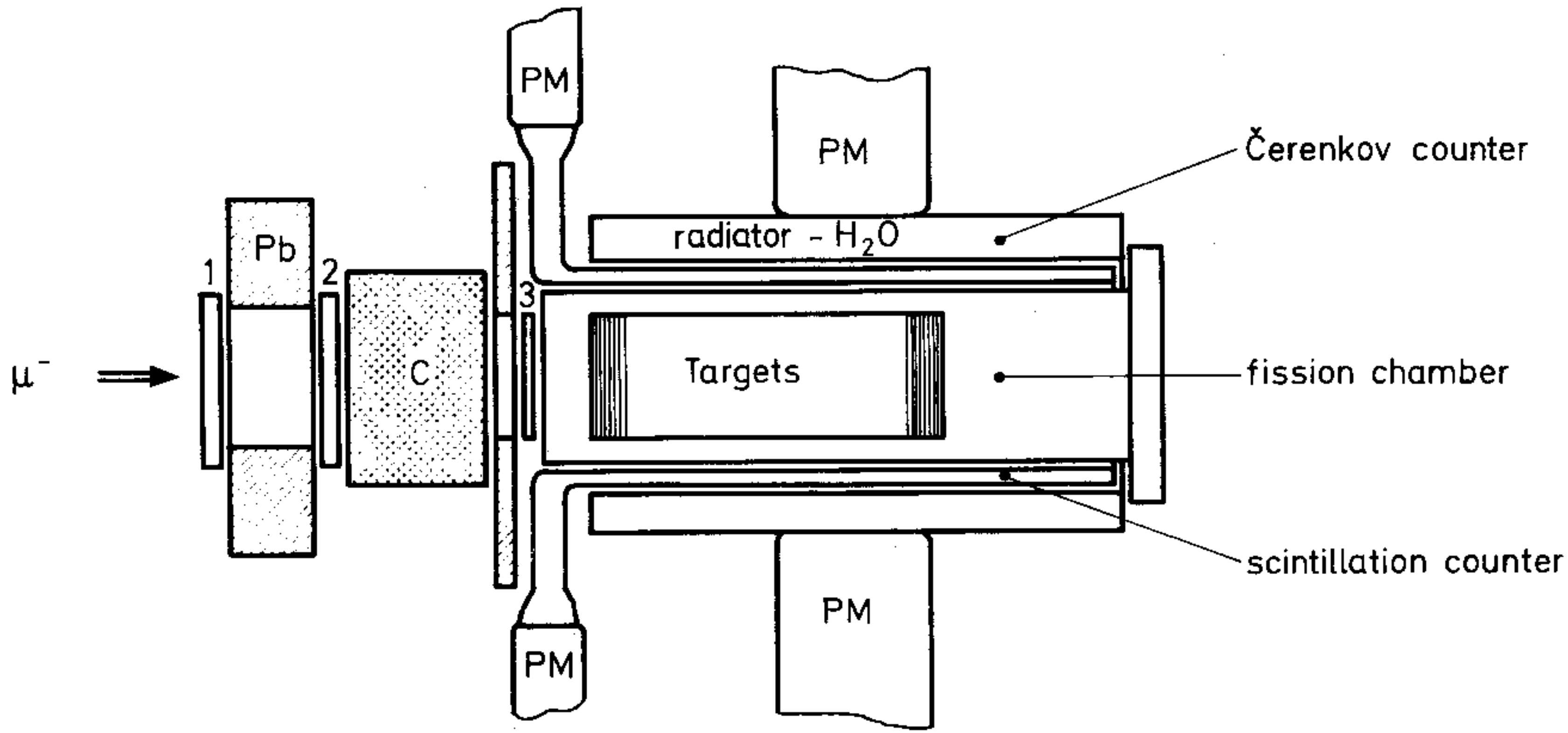


Fig. 2 Detection system for the observation of muon-induced fission. A muon stop event is recorded by the 123 telescope, while subsequent fission and muon-decay events are detected by the multi-plate ionization chamber and its surrounding scintillation and Čerenkov detector.

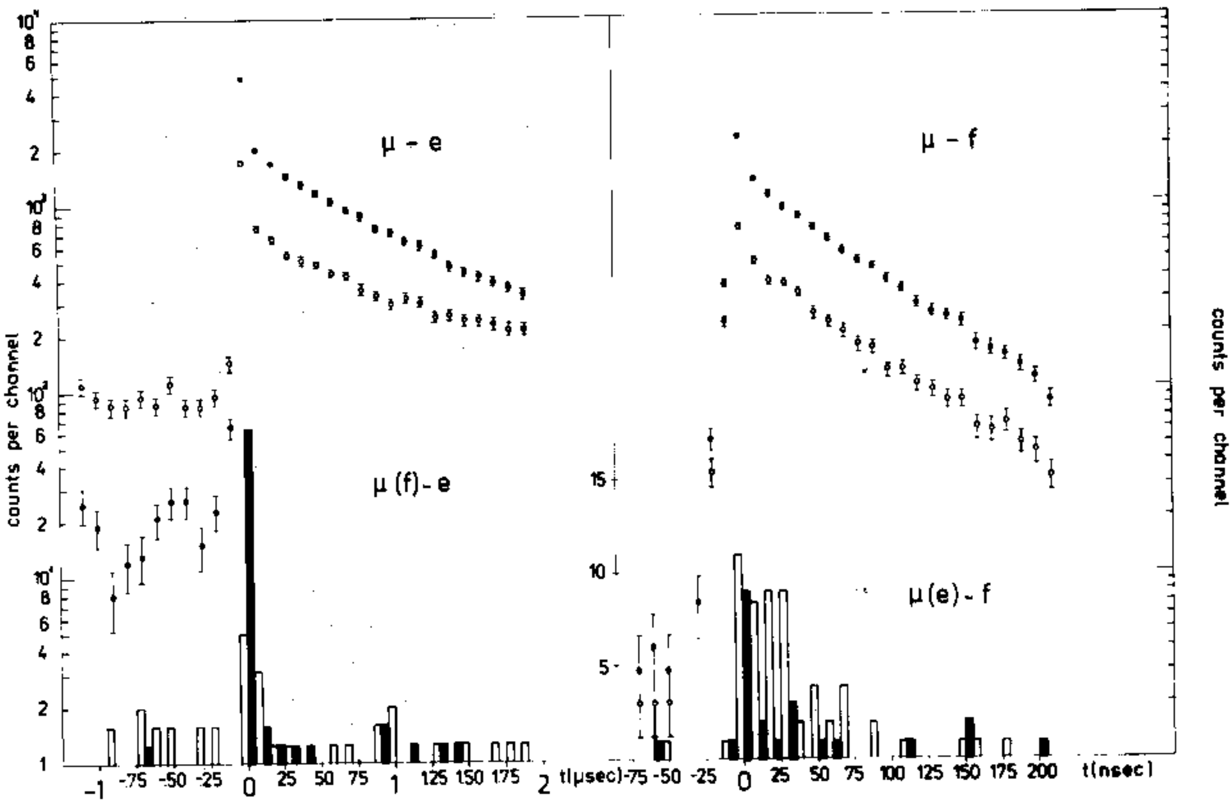


Fig. 3 Data from a preliminary experiment dealing with the search for the conversion process (left-hand part of the figure) and delayed fission of the muonic atoms of $^{238}U$ (right-hand part). Open circles and open-block histograms refer to events in which more than one muon arrived during the period of interest; filled circles and full-block histograms refer to events for which only one muon arrived during the period of interest.

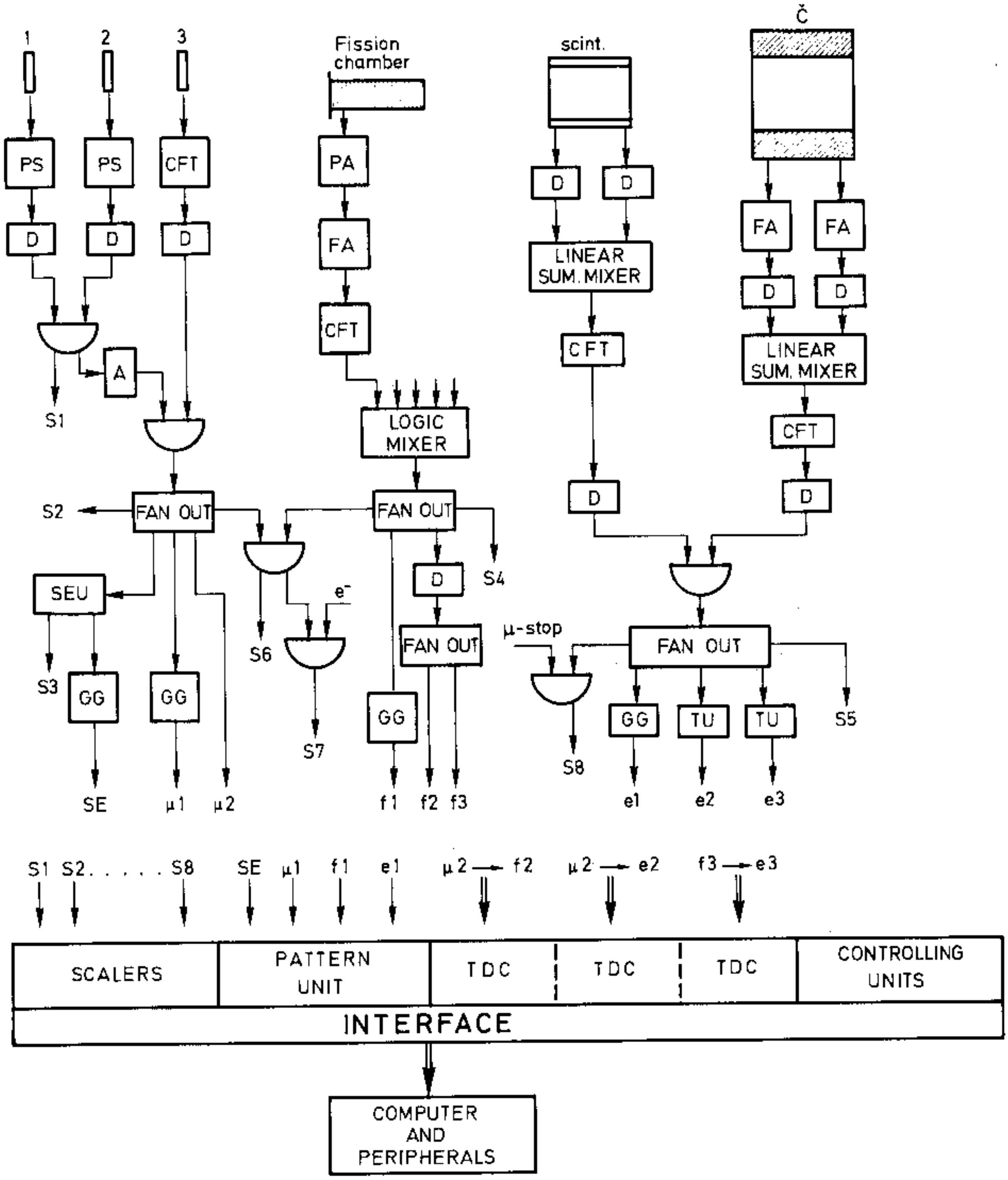


Fig. 4 Block diagram of the experimental set-up for the observation of muon-induced fission.