EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/81-62
26 June 1981

A NEW MEASUREMENT OF THE MUON TRANSFER RATE FROM MUONIC HYDROGEN TO ARGON

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ABSTRACT

We have studied the transfer reaction

$$\mu p + Ar \rightarrow \mu Ar^* + p$$

occurring in gas (p = 2-4 atm). The transfer rate has been measured by detecting the X-rays from the electromagnetic cascade of μAr^*. We obtain

$$\Lambda_{1s}^{Ar} = (3.67 \pm 0.72) \times 10^{11}\ s^{-1} ,$$

in agreement with previous measurements performed with the same technique.

(Submitted to Nuovo Cimento)

1. INTRODUCTION

Transfer processes have been extensively discussed in the last few years from the theoretical point of view for their intrinsic interest and also as a possible tool in order to study properties of ordinary matter, such as the chemical bond and the structure of surfaces[1]. In this approach, the transfer reaction to noble gases is the simplest process and it would be useful to have clear experimental results in order to test methods of calculation for application to more complicated systems.

The rate of transfer reaction from the 1s state of μp atoms to argon:

$$(\mu p)_{1s} + Ar \rightarrow \mu Ar^{*} + p$$

has been measured several times[2-5], using two different methods:

i) measurement of the time distribution of the typical muonic γ-rays in argon[3-5];

ii) measurement of the time distribution and yield of the decay electron[2-4].

The results obtained using the two methods are in strong disagreement (as shown later in table II). In this respect, it is useful to have a new measurement. Furthermore, recent theoretical calculations[6] show that the rate from the 2S metastable level is much larger than from the 1S level, the ratio R of the two ranging from 40 to 80 depending on the energy of the μp system[7]. On these grounds it has been suggested[6] to use the transfer reaction as a method to measure the interesting parameters of the 2S level in muonic hydrogen, i.e. the initial population and the lifetime.

For these reasons we performed an experiment devoted to the study of the transfer reaction of muons to argon. The first results of this experiment have been reported elsewhere[8]. In this paper we discuss the experimental method and apparatus, we report a new value of the transfer rate from the 1S state, and we give a short discussion of the limitations of our experiment for the detection of transfer from the excited states.

2. EXPERIMENTAL METHOD

On the basis of the processes summarized in fig. 1, the time distribution of the typical muonic γ-rays produced in the de-excitation of the μAr^* system can be written as

$$\frac{dn}{dt} = A\ e^{-\lambda_1 t} + B\ e^{-\lambda_2 t}\ , \qquad (1)$$

where A and B are coefficients depending on the initial population n_1, n_2 of the 1S and 2S levels in muonic hydrogen, $\lambda_1 = \lambda_0 + \lambda_{1S}^{Ar}$ is the disappearance rate of the μp_{1S} level and $\lambda_2 = \lambda_0 + \lambda_S + \lambda_{2S}^{Ar} = \lambda_0 + \lambda_S + R\lambda_{1S}^{Ar}$ is the disappearance rate of the μp_{2S} level (for further explanation of the notation see fig. 1). The values of A, B, and λ_2 depend on n_1, n_2, R, and λ_S (the rate of Stark de-excitation of the 2S level). A few measurements at different values of the pressure P and argon concentration C_{Ar} should enable the value of these parameters to be deduced.

3. EXPERIMENTAL APPARATUS

The apparatus was constructed in such a way as to get a clear electronic signal for muons actually stopping in the gas and a good time resolution for the γ-rays. The experimental set-up is shown in fig. 2.

The target was a stainless-steel vessel*) of special shape; its walls were 3 mm thick, but the entrance window had a thickness of only 1 mm. The target vessel was able to support a pressure of 10 atm. The conical part of the target vessel, downstream from the entrance window, contained the last beam moderator (a beryllium disk 20 mm thick) and a proportional counter (α) working with the same gas filling as that of the target.

The proportional counter was used to measure the energy loss ΔE of the incoming muons in order to select muons having a residual range shorter than the allowed path in the target gas.

The shape of the elliptical part of the target vessel was chosen to optimize the ratio of muons stopping in the gas to muons impinging on the target walls for

*) 17% Cr, 13% Ni, 2% Mo, 1% Li, 2% Mu, 65% Fe.

a properly selected threshold on the α signal. The shape was selected by a Monte Carlo calculation, taking into account the energy resolution of the proportional counter and the multiple scattering of muons in the entrance window, in the beryllium moderator, and in the gas[9].

To evacuate and fill the target vessel a system was built in stainless steel, which had a turbomolecular pump to evacuate the target vessel and a palladium purifier to guarantee the purity of the hydrogen filling.

A collimator and a beam telescope (plastic counters 1, 2, 3) were mounted upstream from the entrance window.

Counters A_1-A_9 are plastic scintillators completely surrounding the vessel. These counters were used both to veto the muons passing through the vessel and to detect the muon-decay electrons. Counters X_1-X_8 are 4 in. × 4 in. NaI(Tl) crystals, each viewed by an XP-2040 or 2041 photomultiplier (PM), and they were used to detect the muonic X-rays. All dynodes of the PM seeing the X counters were separately stabilized to hold the gain constant.

A $(1\cdot 2\cdot 3)\cdot\alpha\cdot\overline{\Sigma_i A_i}$ (=STOP) coincidence signalled the stopping of the muon inside the target. Only those muons giving a signal in counter α larger than a preset value were accepted. The counter α was calibrated with the electrons contaminating the beam.

The STOP signal opened a 10 μs wide gate during which X-ray signals (pulses in the NaI crystals) and electron signals (pulses in counters A_1-A_8) were recorded. To reduce accidental background, all STOP signals that were preceded within 8 μs by another incoming particle $(1\cdot 2\cdot 3)$ were ignored.

A pulse of any of the eight NaI counters during the gate interval caused the following quantities to be recorded on magnetic tape:

i) the amplitude of all the X-ray pulses within the gate;
ii) the time of all the X-ray pulses within the gate;
iii) the time of arrival of the decay electron (if any);
iv) the amplitude of the α counter pulse.

The times and the amplitudes of the X-ray pulses were measured by eight TDC + ADC channels. The TDCs were started by the STOP signal. The proportional chamber α worked very well when the target was filled with a mixture of argon and 5% of propane; the selection efficiency for muons actually stopping in the gas can be deduced from fig. 3. In the hydrogen runs the chamber was working badly and consequently the selection was not so efficient.

The time resolution for the X-ray was 4 ns FWHM (fig. 4); the amplitude resolution at 644 keV (K_α line of μAr) was better than 12% FWHM and the average efficiency was (including solid angles) approximately equal to 0.1% per counter.

4. EXPERIMENTAL RESULTS

We first performed several calibration runs with the target vessel filled with argon (+5% of propane)[8]. After that we performed several runs with the target vessel filled with pure hydrogen, and with a mixture of hydrogen and argon at different values of the pressure P and of the argon concentration C_{Ar} (see table I).

As we are interested in measuring the fast component of the X-ray time distribution we need to know the background time distribution immediately after the μ stop time. In this interval contributions due to the decay or nuclear capture of muons stopped in the target walls cannot be neglected.

In run 1, performed without the proportional chamber to increase the background yield, the time distribution of the X-rays, in the energy interval corresponding to the K lines of muonic argon, can be fitted using an expression

$$\frac{dn_\gamma}{dt} = A_1\, e^{-\lambda_1 t} + A_2\, e^{-\lambda_2 t} + A_3 \,, \qquad (2)$$

where A_3 represents a flat accidental counting rate, $\lambda_1 = \lambda_{nc}^{Be} + \lambda_0$ is the disappearance rate of muons stopped in the beryllium moderator and $\lambda_2 = \lambda_{nc}^{T} + \lambda_0$ is the disappearance rate of muons stopped in the target walls.

The numerical values obtained in the fit

$$\lambda_{nc}^{Be} = (0.20 \pm 0.05) \times 10^6\ s^{-1} \,, \qquad \lambda_{nc}^{T} = (5.30 \pm 0.35) \times 10^6\ s^{-1} \,,$$

are in reasonable agreement with the known values, taking into account the composition of the stainless steel used to build the target vessel (see section 1). To deduce Λ_{1S}^{Ar} the fit to the other runs was carried out by using a similar expression

$$\frac{dn_\gamma}{dt} = A_1\, e^{-\lambda_1 t} + A_2\, e^{-\lambda_2 t} + A_3 \ , \tag{3}$$

where $\lambda_2 = \lambda_{nc}^{T} + \lambda_0$ was a fixed parameter deduced from the fit on run 1 and $\lambda_T = \lambda_0 + \lambda_{1S}^{Ar} = \lambda_0 + \rho p c_{Ar}\, \Lambda_{1S}^{Ar}$. The contribution due to muons stopped in the beryllium moderator has been avoided because the presence of the proportional chamber excludes these events from the trigger. The fit was extended from 50 ns to 9 μs after the μ-stop time.

The results and the experimental conditions of the different runs are listed in table I. The weighted mean of the measured values of Λ_{1S}^{Ar} is

$$\Lambda_{1S}^{Ar} = (3.67 \pm 0.72) \times 10^{11}\ s^{-1} \ .$$

Once we had fitted the delayed part of these time distributions we analysed the earlier part of them (10-50 ns), looking at some significant differences between the experimental data and the extrapolation of the fits previously obtained. The first limit T_1 = 10 ns of the analysed time interval was chosen in order to avoid any contribution from the prompt peak (see fig. 4). We were not able to find any significant differences.

5. DISCUSSION OF THE RESULTS

Let us first quote once more the value of the nuclear capture rate in argon λ_{nc}^{Ar} obtained in the analysis of the argon runs[8]:

$$\lambda_{nc}^{Ar} = (1.41 \pm 0.11) \times 10^{6}\ s^{-1} \ .$$

Taking into account the other measured value[10] the weighted value for λ_{nc}^{Ar} is

$$\lambda_{nc}^{Ar} = (1.27 \pm 0.06) \times 10^{6}\ s^{-1} \ . \tag{4}$$

The value of Λ_{1S}^{Ar} obtained in this experiment is reported in table II together with the results of other experiments. The table shows a good agreement between the values obtained by the γ-method, but they do not agree with the results obtained by the e-method.

One may remark now that both experiments based on the decay electron measurement[2,4] were performed before an experimental value for the nuclear capture rate in argon was available.

Both experiments used as a fixed parameter λ_{nc}^{Ar}, assuming for it a numerical value obtained by interpolating[11] the measured values for neighbouring elements ($\lambda_{nc}^{Ar} = 1.86 \times 10^6\ s^{-1}$ in ref. 1 and $\lambda_{nc}^{Ar} = 1.69 \times 10^6\ s^{-1}$ in ref. 3). These values are very different from the experimental values mentioned above [see expression (4)]. However, the value of Λ_{1S}^{Ar} is in both experiments[2,4] weakly dependent on the value assumed for λ_{nc}^{Ar}, as can be seen by looking at the analytical expression used in the fits or looking directly at the published experimental data.

Anyway we believe that the results obtained by measuring the X-ray time distribution give a more direct and hence a more reliable value of Λ_{1S}^{Ar}. The weighted mean of the value obtained for the transfer rate by the γ-method is

$$\Lambda_{1S}^{Ar} = (3.48 \pm 0.40) \times 10^{11}\ s^{-1}\ .$$

This value is in reasonable agreement with the smooth[7] or linear[12] dependence on Z of the transfer rate that has been found theoretically (see fig. 5).

As far as the transfer rate from the metastable 2S level and the parameters (initial population and decay rate) of the μp_{2S} system are concerned we cannot deduce anything from our measurement because, with the measured value of Λ_{1S}^{Ar}, under our experimental conditions the maximum contribution to the X-ray yield due to the μp_{2S} system can be ∿ 3%.

Owing to the inefficiency of the proportional chamber we were able to collect only a few thousand good events, and the lack of statistics makes us unable to get any results on the transfer process from the metastable 2S level.

Recently the value of the μp_{2S} lifetime (τ_{2S}) has been measured at the Schweizerisches Institut für Nuklearforschung (SIN). The result[13] is $\tau_{2S} = 600$ ns at 1 Torr of pressure. A linear extrapolation would yield $\tau_{2S} = 0.3$ ns at 3 abs. atm, much below our time resolution.

Acknowledgements

We wish to thank E. Zavattini and G. Fiorentini for useful discussions and criticisms, B. Minieri for having done the Monte Carlo simulation of the experiment and G. Gorini for his help.

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Table I

Experimental results

Run	Total pressure (abs. atm)	Argon concent. (‰)	Proport. chamber	λ_{1S}^{Ar} (10^6 s^{-1})	Λ_{1S}^{Ar} (10^{11} s^{-1})
1	2.3	0	off		
2	2.0	1	on	0.92 ± 0.56	3.61 ± 2.20
3	4.0	1	on	1.94 ± 0.85	3.81 ± 1.67
4	3.0	1	on	1.44 ± 0.52	3.77 ± 1.36
5	3.0	2	on	2.71 ± 0.86	3.55 ± 1.12

Table II

Comparison of experimental values of the transfer rate Λ_{1S}^{Ar} measured using the γ or e techniques

Experiment	Λ_{1s}^{Ar} (10^{-11} s^{-1})	Method
S.G. Basiladye et al.[1)]	1.20 ± 0.19	e
A. Alberigi-Quaranta et al.[2)]	3.20 ± 0.60	γ
A. Bertini et al.[3)]	1.46 ± 0.14	e
G. Backenstoss et al.[4)]	3.28 ± 0.78	γ
This experiment	3.67 ± 0.72	γ

Figure captions

Fig. 1 : Schematic diagram of processes following the stop of negative muons in a mixture of hydrogen and argon

$\lambda_0 = 4.54 \times 10^{-5}\ s^{-1}$: free muon decay rate

λ_S: 2S → 1S de-excitation rate due to external Stark effect

λ_{nc}^{Ar}: nuclear capture rate in argon

$\lambda_{1S}^{Ar} = \rho\ C_{Ar} P \Lambda_{1S}^{Ar}$: transfer rate to argon from the μp_{1S} system

$\lambda_{2S}^{Ar} = \rho\ C_{Ar} P \Lambda_{1S}^{Ar} = R \lambda_{1S}^{Ar}$: transfer rate to argon from the μp_{2S} system

$C_{Ar} = P_{Ar}/P$: argon concentration

P: total pressure in abs. atm

$\rho = 1.274 \times 10^{-3}$: ratio between the atomic density of hydrogen at 1 abs. atm and normal temperature and atomic density of the liquid hydrogen (4.32×10^{22} atom/cm^2)

Fig. 2 : Schematic view of the apparatus: 1, 2, 3 = beam telescope; 4 = NaI(Tl) crystals (counters X_1-X_8); 5 = proportional counter (counter α); 6 = stainless-steel vessel; 7 = anticoincidence shield (counters A_1-A_9).

Fig. 3 : Effect of the discrimination of the proportional counter signal: K_1 is proportional to the number of events recorded in an energy window around the K_α line (644 keV). K_2 is the ratio between the number of events in the K_α peak and the total number of events surviving the cut.

Fig. 4 : Time distribution of the prompt γ-ray peak in the runs 4 + 5.

Fig. 5 : Values of the measured transfer rates versus Z [6].

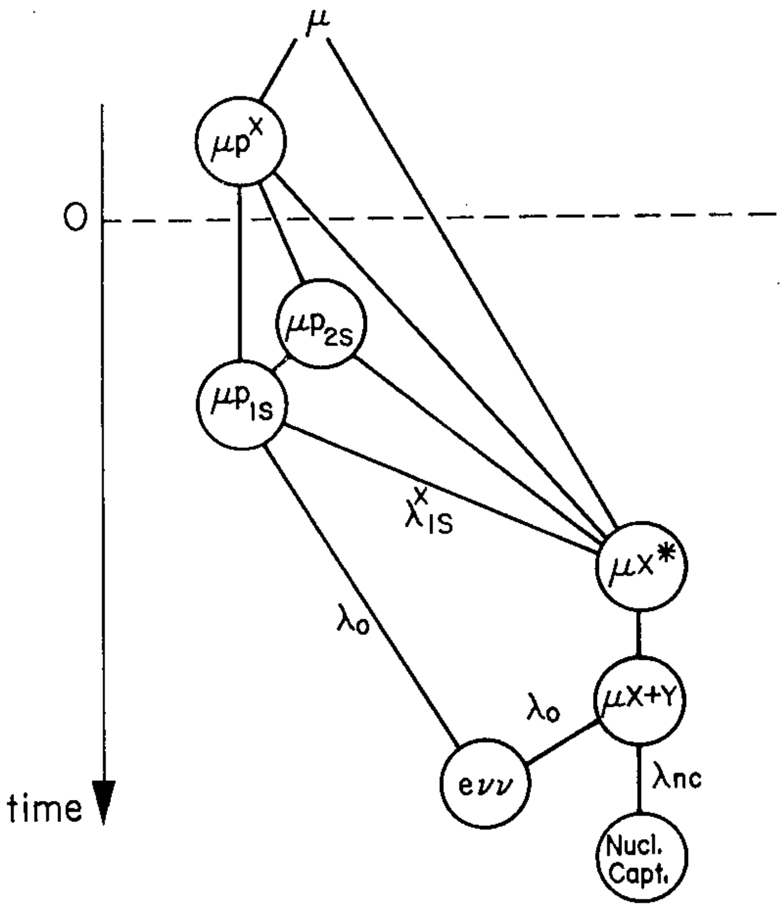
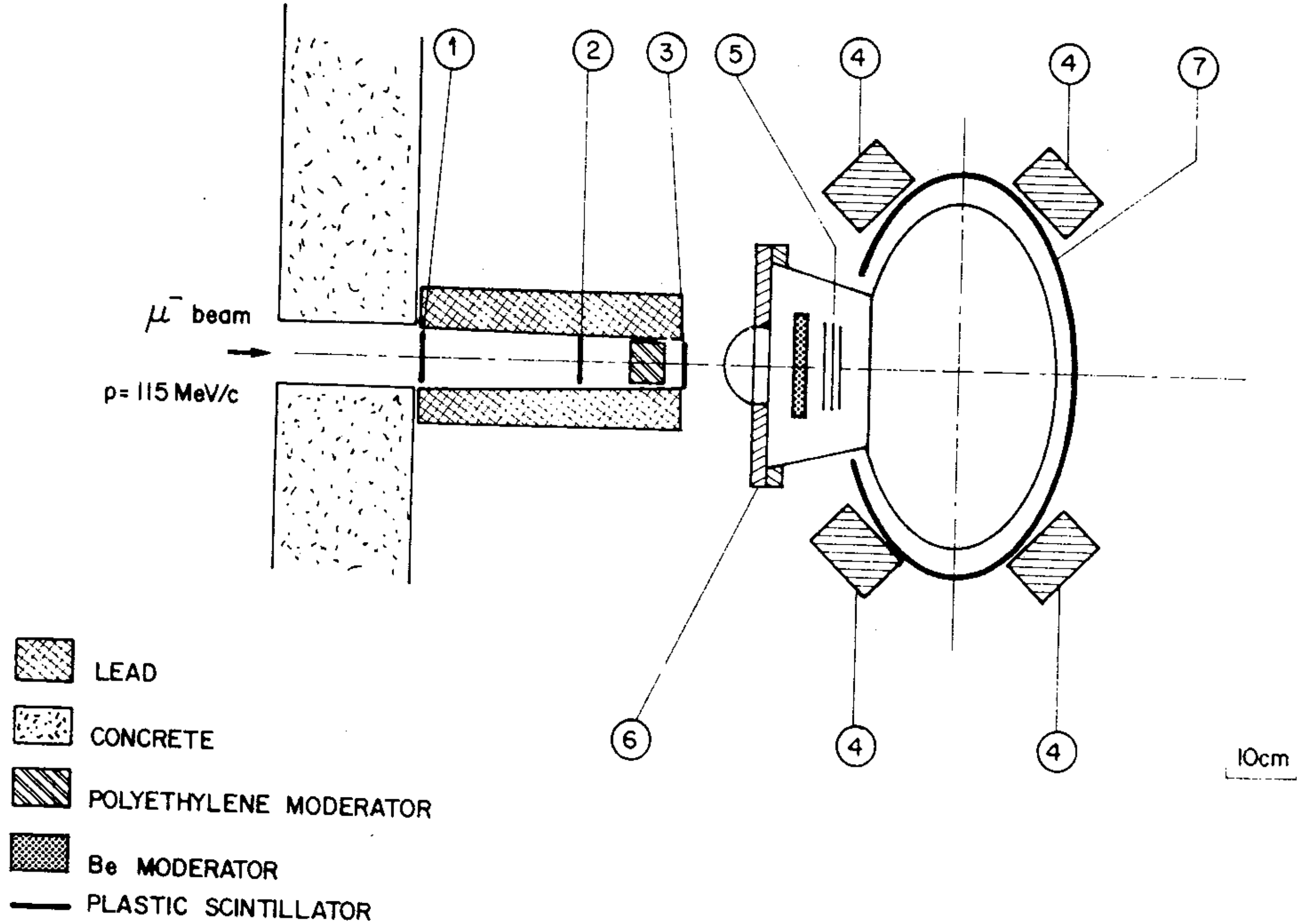
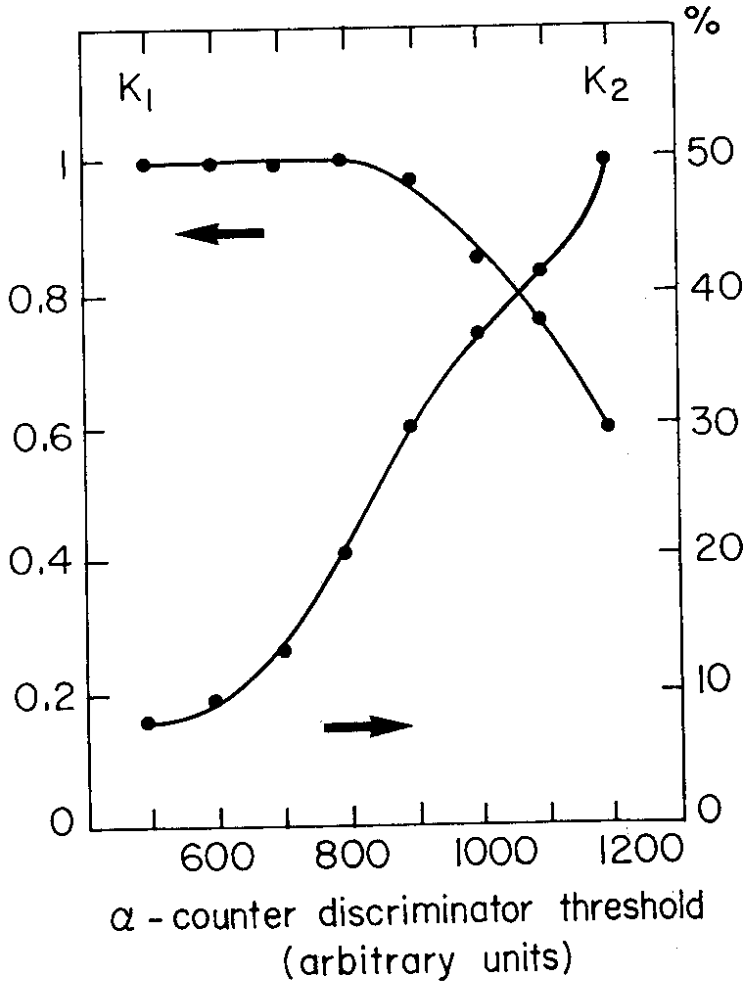


Fig. 1



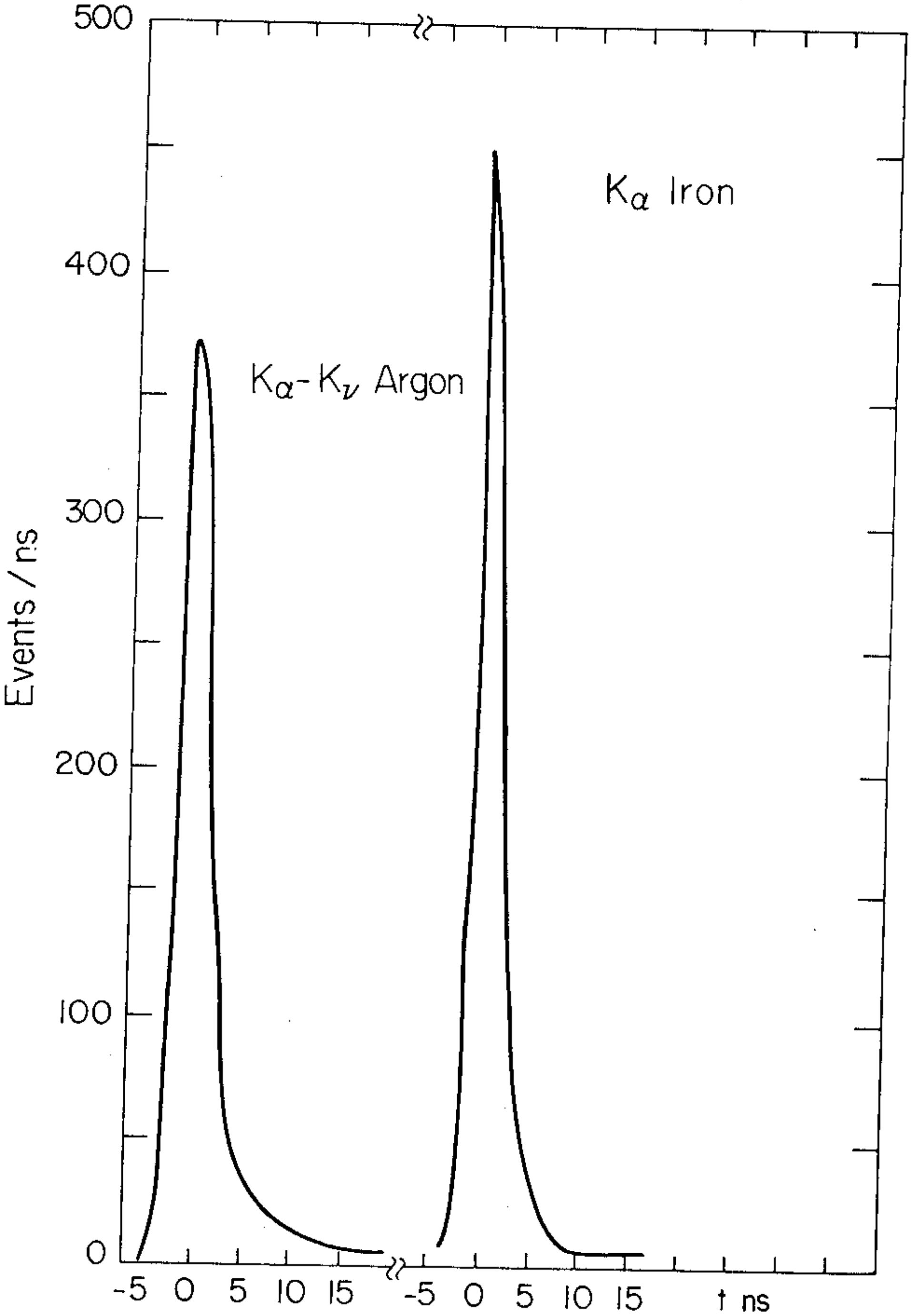
μ⁻ beam
p= 115 MeV/c
1
2
3
4
5
6
7
10cm
LEAD
CONCRETE
POLYETHYLENE MODERATOR
Be MODERATOR
PLASTIC SCINTILLATOR

Fig. 2



%
K1
K2
1
0.8
0.6
0.4
0.2
0
50
40
30
20
10
0
600
800
1000
1200
α - counter discriminator threshold
(arbitrary units)

Fig. 3



500
400
300
200
100
0
Events / ns
Kα Iron
Kα-Kν Argon
-5 0 5 10 15
-5 0 5 10 15
t ns

Fig. 4

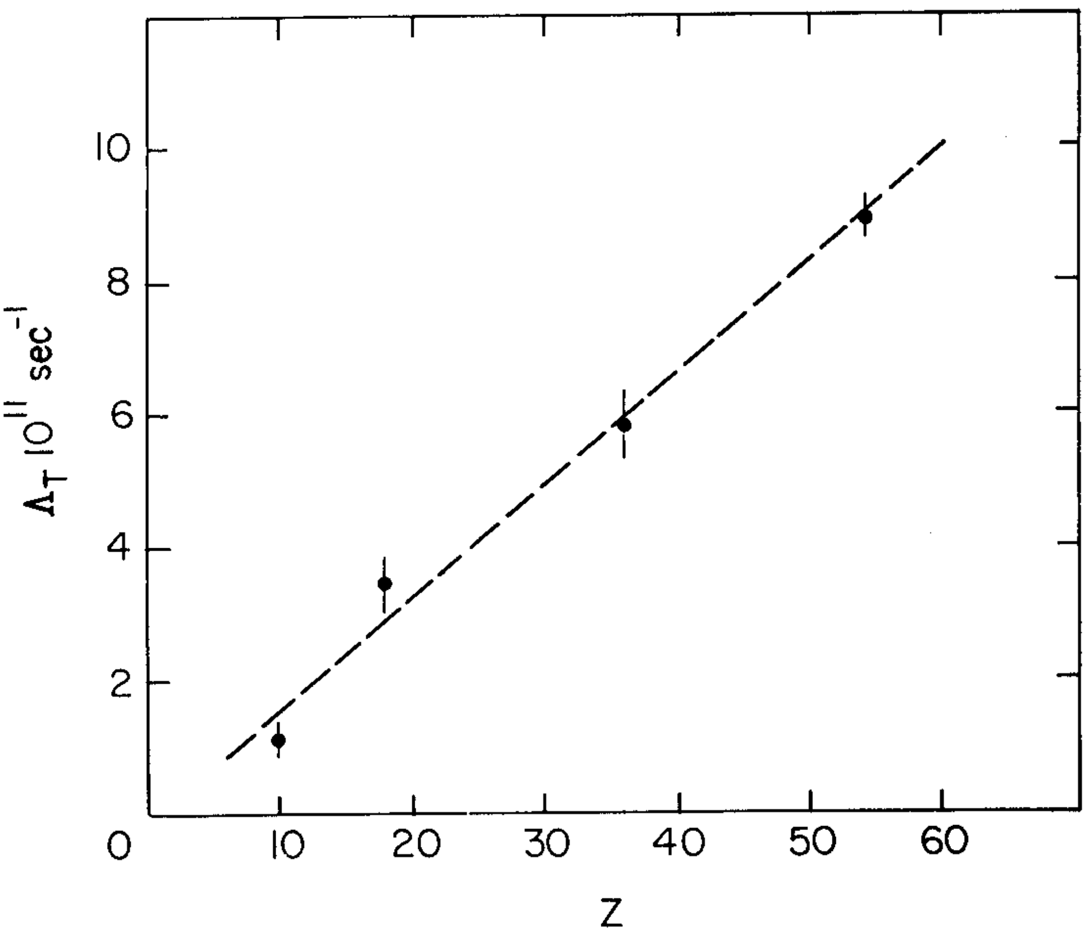


Fig. 5