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A. Alberigi-Quaranta, A. Bertin, P. Dalpiaz(o), G. Matone(+), F. Palmonari, A. Placci(+), G. Torelli(x) and E. Zavattini(-): MEASUREMENT OF THE TRANSFER RATES OF MUONS FROM HYDROGEN TO XENON AND SOME OTHER MONOATOMIC ELEMENTS.

## 1. INTRODUCTION. -

A $\mu^-$ slowing down in hydrogen is quickly captured into an excited level around a proton[1], and it is very likely that in less than $10^{-9}$ sec it reaches the 1S state of the newly formed mesoatom. The radius of the Bohr orbit of such a neutral system is $a_\mu = \hbar^2/m_\mu e^2 = 2.56 \times 10^{-11}$ cm, which is very small compared to atomic dimensions; hence the $\mu p$ mesoatom, which has a life time of 2.2 $\mu$s, has the possibility of approaching very closely to the core of any atomic system.

When the hydrogen is isotopically pure (protonium), the $\mu p$ system interacts with it through the processes[2]:

i) elastic collision with a hydrogen molecule

$$(\mu p) + H_2 = (\mu p) + H_2 \tag{1}$$

ii) formation of mesonic molecules:

$$(\mu p) + H_2 = (\mu pp) + p$$

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The rate $\lambda_{pp}^{(x)}$ of this last reaction has been directly measured in liquind[3,4] and gaseous[5] hydrogen.

If a small amount of another element Y is present mixed to the protonium, then generally[3,6,7,8] also the following competing reaction takes place:

$$(3) \qquad (\mu p) + Y = (\mu Y)^{*} + p$$

i. e. the $\mu^-$ may leave the $\mu p$ atom to form a Y atom $(\mu Y)^{*}$ which within $10^{-10}$ sec, deexcites to its lowest level. Let us call $c_y \lambda_y$ the rate of reaction (3), where $c_y$ is the molecular concentration of the element Y in the protonium.

In the deexcitation process mesic gamma rays as well as Auger electrons can be emitted as it has been experimentally proved[3,9]. We wish to report here an experiment in which, by detecting the 2P-1S transition gamma rays (3.8 MeV, see ref (10)) emitted by the xenon mesoatom, the following measurements have been done:

i) measurement of the rate $\lambda_{Xe}$ of the reaction

$$(4) \qquad (\mu p) + Xe = (\mu Xe) + p$$

ii) measurement of the relative ratios $\lambda_Y / \lambda_{Xe}$, where Y stands for Ne, A, Kr.

The experiment has been performed at a hydrogen pressure of 26 atmospheres and at room temperature, using an already existing apparatus built to measure cross-sections of the process (1)[o].

We studied process (3) mainly in view of a future measurement of the $\mu^-$ nuclear capture rate in hydrogen at low density; in relation to this we wanted to clarify the two following points:

a) which is the degree of purity to which the protonium has to be kept;

b) the possibility of quenching very quickly the capture reaction $\mu^- + p = n + \nu$ by adding a small amount of Xe, to be able to measure the contribution to the neutron counting rate of all the background coming from anything but the protonium gas.

According to the theory[11], $\lambda_{Xe}$ should in fact be very high; on the other hand, the $\mu^-$ capture rate in Xe is very fast.

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(x) - All the values of the rates are referred to the density of liquid $H_2$, assumed as corresponding to $d = 4.22 \times 10^{-22}$ nuclei/cm$^3$.

(o) - "A. Alberigi-Quaranta et al., Elastic scattering ot mesoatoms on hydrogen: determination of the total spin state of the $\mu p$ mesoatom". To be published on Il Nuovo Cimento.

Section 2 is devoted to the explanation of the principle of our experiment. In section 3 the experimental apparatus will be described, whereas in section 4 we will discuss the measurements and the data analysis. In section 5 our results will be compared to those obtained by other groups and with the predictions of theoretical calculations.

## 2. DESCRIPTION OF THE METHOD. -

Let $N_o$ be the number of $\mu p$ systems present at the time t = 0 (given by the arrival of the muon) in a gaseous mixture of protonium (at a pressure P) and xenon (with a concentration $c_{Xe}$). The number of $\mu p$ atoms for $t \geq 0$, is

(5) $$N(t) = N_o e^{-\lambda_T t} = N_o e^{-t/\tau}$$

where

(6) $$\lambda_T = \lambda_o + \rho (\lambda_{pp} + c_{Xe} \lambda_{Xe}) = \frac{1}{\tau}$$

being $\lambda_o$ the decay rate of the free $\mu^-$, $\lambda_{pp}$ the rate of mesomolecular formation(x) and $\rho$ the hydrogen gas density in units of the liquid hydrogen density(+). If the transfer to xenon is followed by the emission of a $2P \rightarrow 1S$ transition gamma ray, the yield of these as a function of time is:

(7) $$dN_{Xe}(t) = N_o c_{Xe} \lambda_{Xe} e^{-\lambda_T t} dt$$

and their total number is:

(8) $$N_{Xe} = \frac{\rho N_o c_{Xe} \lambda_{Xe}}{\lambda_o + \rho (\lambda_{pp} + c_{Xe} \lambda_{Xe})}$$

To deduce $\lambda_{Xe}$ we measured for a known concentration $c_{Xe}$ of Xe the parameter $\lambda_T$ of equation (7), looking at the time distribution of the emitted 3.8 MeV gamma rays. From (6) we have

$$\lambda_{Xe} = (1/c_{Xe}) \times \left[ (\lambda_T - \lambda_o)/\rho - \lambda_{pp} \right]$$

If however another monoatomic element Y, with concentration $c_Y$ , is added to the protonium-xenon mixture, equation (7) is still valid if $\lambda_T$ is re-

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(x) - $\lambda_o = 4.55 \times 10^5 \ sec^{-1}$; $\lambda_{pp}$ is assumed to be $\lambda_{pp} = (2.2 \pm 0.13) \times 10^6 \ sec^{-1}$ from ref. (3) and (4).

(+) - $\rho = (2L/d) \times P = (2 \times 2.7 \times 10^{19}/4.22 \times 10^{22}) \times P = 1.28 \times 10^{-3} \times P$, where L is the Loschmidt number, and P is the gas pressure is abs.atms.

placed by

(6') $$\lambda_T = \lambda_o + \rho(\lambda_{pp} + c_{Xe}\lambda_{Xe} + c_Y \;_Y)$$

The total number $N^Y_{Xe}$ will now be given by

(8') $$N^Y_{Xe} = \frac{\rho N'_o c_{Xe} \lambda_{Xe}}{\lambda_o + \rho(\lambda_{pp} + c_{Xe}\lambda_{Xe} + c_Y \lambda_Y)}$$

If $c_{Xe}$ is such that $_o$ $c_{Xe}$ $_{Xe}$ and $_{pp}$ $c_{Xe}$ then one can write, for equal numbers of initial mesic atoms, $N_o = N'_o$.

(9) $$\frac{N_{Xe} - N^Y_{Xe}}{N_{Xe}} = \frac{c_Y \lambda_Y}{c_{Xe}\lambda_{Xe} + c_Y \lambda_Y} = \frac{1}{1 + \frac{c_{Xe}\lambda_{Xe}}{c_Y \lambda_Y}}$$

To determine the ratio $\lambda_Y/\lambda_{Xe}$ we measured the quantity $(N_{Xe} - N^Y_{Xe})/N_{Xe}$ after having added to the protonium-xenon mixture an amount of element Y such that $c_Y Z_Y \sim c_{Xe} Z_{Xe}$, since according to Gershtein(11) $\lambda_Y$ is almost proportional to the atomic number $Z_Y$.

## 3. EXPERIMENTAL APPARATUS. -

The target and counters arrangement is shown in fig. 1. The target was a 46 cm long, 12. 5 cm diameter stainless steel cylinder, whose wall and flanges were respectively 0. 2 cm and 0. 1 cm thick.

A telescope of counters (1, 2, 3, 5)(x) scaled the muons supplied by the CERN $\mu^-$ channel(+) and collimated by an iron collimator.

Five plates of brass, 0. 3 mm thick, 5 cm distant from one another, were placed inside the target in the region viewed by the NaI counter to reduce losses in the number of $\mu^-$ stopping in $H_2$ gas, due to multiple scattering. The gamma counter, a 9"x 7"NaI (Tl) crystal coupled with a 58 AVP PM, was placed on one side of the tank with its axis normal to the one of the target; it was shielded by a 5 cm thick lead wall.

The target was completely surrounded by counters in anticoincidence (ANTI - 5, 6, 7, 8, 9, 10, 11 = $\overline{\Sigma \text{ANTI}}$), each one 1 cm thick.

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(x) - Counters 1, 2, 3, 4 were respectively 1 cm, 0. 5 cm, 0. 3 cm, 2 cm thick; counter 5 was 1 cm thick, with a central hole of 10 cm diameter.

(+) - Citron et al., Proc. 1960 Conference on Inst. for High Energy Physics, p. 286.

A block diagram of electronics is given in fig. 2. A coincidence M = (1, 2) circuit monitored the number of particles at the entrance of the iron collimator. The time of arrival of muons was given by the $\mu^-$-STOP coincidence (1, 2, 3, $\overline{\Sigma \mathrm{ANTI}}$), whose signal was used as the START pulse for a time-to-pulse-heigth-converter (TPHC). The time at which a muon was transferred to a Xe atom was defined by the detection of the corresponding mesic gamma ray by mean of the NaI counter. The STOP command to the TPHC was taken from the last dynode of the NaI phomultiplier, after proper delay and amplification. We stored the TPHC pulses into a 1024 channels TMC Pulse Hight Analyzer (PHA), which recorded the distribution of the time intervals between the muon arrival and its transfer to a Xenon atom.

The PHA was triggered by the coincidence TRIGGER (see fig. 2) which insured us that:

i) the pulse coming from the NaI crystal was sharply discriminated in amplitude, to select 3. 8 MeV gamma rays. The limits of discrimination are shown in fig. 3 by the two vertical arrows.

ii) The pulse coming from the NaI crystal through the gated Discriminator was accepted only if contained in a time interval from 1 $\mu$sec before to 7 $\mu$sec after the $\mu^-$ STOP signal.

The output of this Discriminator was also interrupting the gate-on signal. Moreover this gate-on signal was interrupted both by a second monitor pulse and by a pulse coming from any of the ANTI coincidence counters.

The filling system scheme is drawn in fig. 4. The used hydrogen was protonium[(x)], an isotopically pure type of hydrogen, containing less than 3 ppm of deuterium. After a preliminary purification, it passed through a palladium filter[(o)] which ensured a residual concentration of elements other then hydrogen less than $10^{-8}$. The pure hydrogen at the output of the filter entered directly into the target through a short connection.

The mixture of hydrogen and noble gases were made using an auxiliary volume in contact with the target through a valve. All the filling system, built in stainless steel, was evacuated and kept for several days to a pressure of less than $10^{-5}$ mm Hg, before being filled with protonium.

## 4. MEASUREMENTS AND DATA ANALYSIS. -

The number of muons stopped in the hydrogen gas was $\sim 20\ \mathrm{sec}^{-1}$; this represented 2. 5‰ of the number of muons which could be stopped in 3 grams of polyethylene (width of the range curve at half maximum).

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(x) - Protonium was supplied by Air Liquide, Paris.

(o) - Engelhard Industries, Inc. - Chemical Div. - Newark - N. J.

In view of studying the transfer rate of muons from hydrogen to xenon, measurements of the time distribution of the NaI pulses corresponding to 3. 8 MeV gamma rays were performed for two values of the xenon concentration in the protonium-xenon mixture (see table I), the hydrogen beeing at the pressure of 26 abs. atm. ($T = 300^oK$). The neutrons due to the nuclear capture of $\mu^-$ in the iron of the vessel gave an appreciable contribution to the counting rate of the NaI counter, specially for earliest times after the muon arrival (up to about 200 nsec). In order to take account of this background, the measurements done with the $H_2$-Xe mixture were often alternated with measurements done filling the vessel with pure $H_2$ only.

TABLE I

| $H_2$ Pressure | $c_{Xe} \cdot 10^4$ | $\tau$ (nsec) | $(\chi/\bar{\chi})^2$ | $\lambda_{Xe} \cdot 10^{-11}$ | Amount of injected xenon at p=1 abs. atm. and T=20°C ($cm^3$) |
|---|---|---|---|---|---|
| (25.8 ± .2) | (1.00 ± .04) | 490±53 | 1. 5 | (4.64 ± .70) | 14. 3 |
| 26.0 ± .2 | (0.51 ± .02) | 715±64 | 0. 85 | (5.18 ± .58) | 7. 3 |

Summary of the experimental conditions and results of the $\lambda_{Xe}$ experiment.

In fig. 5a is shown the time distribution obtained for the case of $c_{Xe} = 0.51 \cdot 10^{-4}$ after having subtracted the background contribution measured when the target was filled with pure hydrogen, and normalized to the same number of incoming muons as in the $H_2$ - Xe mixture measurements.

In fig. 5b the corresponding time distribution for the case of $c_{Xe} = 1.00 \cdot 10^{-4}$ is shown.

By performing a best fit analysis of the spectra shown in fig. 5 by the expression (5), we got for $\tau$ the values summarized in table I.

The 2 values of $\lambda_{Xe}$ obtained from the two different measurements agree rather well with each other; hence we can extract the unique value:

$$\lambda_{Xe} = (4.96 \pm .46) \times 10^{11}$$

To study the ratio $\lambda_Y/\lambda_{Xe}$, where Y stands for neon, argon, kripton, we followed the procedure explained in § 2 (see formula 9); i. e. we have measured the relative decrease of the total yield of the 3. 8 MeV mesic gamma rays obtained when another element Y is added to a $H_2$ - Xe mixture.

The measurements were performed putting into the target a $H_2$-Xe mixture with $c_{Xe} = 1,2 \cdot 10^{-3}$ (the hydrogen pressure was of 26 atm). In table II experimental conditions and the results of the measurements are summarized.

TABLE II

| $C_{Xe} = (1.20 \pm .05) \times 10^{-3}$ | | | $P_{H2} = (26.0 \pm .2)$ abs. atm. | | |
|---|---|---|---|---|---|
| Added Element Y | $Z_Y$ | $C_Y$ | $\frac{N_{Xe} - N_{Xe}^{Y}}{N_{Xe}}$ | $\frac{\lambda_Y}{\lambda_{Xe}}$ | $\lambda_Y \cdot 10^{-11}\ sec^{-1}$ (for $\lambda_{Xe} = 4.96 \times 10^{11}\ sec^{-1}$) |
| Neon | 10 | $(5.8 \pm 5) \times 10^{-3}$ | $.360 \pm .045$ | $.115 \pm .025$ | $.58 \pm .14$ |
| Argon | 18 | $(3.37 \pm .11) \times 10^{-3}$ | $.500 \pm .030$ | $.36 \pm .05$ | $1.74 \pm .30$ |
| Kripton | 36 | $(1.75 \pm .12) \times 10^{-3}$ | $.500 \pm .035$ | $.69 \pm .11$ | $3.42 \pm .63$ |

Summary of the experimental conditions and results of the measurement of $\lambda_Y/\lambda_{Xe}$.

## 5. DISCUSSION AND CONCLUSIONS. -

The final results of our measurements are plotted in fig. 6 together with data recently published on the same subject by S. G. Basiladze et al. [7].

Our measurements confirm the general thrend of $\lambda_Y$ to increase with the atomic number $Z_Y$ of the nucleus to which the muon is transferred; they agree moreover with the results obtained by Basiladze et al. on the same elements.

Calculations to predict the value of the transfer rates $\lambda_Y$, have been performed by Gershtein[11]. He shows that a mechanism of crossing of molecular terms can account for the huge transferring of $\mu^-$ from $\mu p$ systems to nuclei Y with atomic number $Z_Y > 1$; in particular he predicts that if $Z_Y$ obeys the limit:

$$E_{\mu p} \ll \frac{8}{Z_Y^2} \qquad (10)$$

where $E_{\mu p}$ is the kinetic energy of the mesoatom, than $\lambda_Y$ is approximately proportional to $Z_Y$. This qualitative feature is certainly experimentally confirmed as shown in fig. 6; in fact it seems to be valid well beyond the limit established by the condition (10).

More detailed calculations, also performed by Gershtein, have given for carbon and oxigen the values:

$$\lambda_c = 3.38 \times 10^{10}\ sec^{-1}$$
$$\lambda_o = 6.75 \times 10^{10}\ sec^{-1}$$

These calculated values seem to lie in the neighborhood of a straight line drawn through the measured values of $\lambda_Y$ (see fig. 6).

For what is concerning our interest in the knowledge of $\lambda_{Xe}$ and

$\lambda_Y$ in view of studying the $\mu^-$ nuclear capture reaction in hydrogen gas, we confirmed that:

a) - $\lambda_{Xe}$ is so high that injection in hydrogen gas (say at 10 Atm) of a small quantity of Xenon (not enough to alter the stopping power of the hydrogen) can remove all the muons from the $\mu p$ systems; after about 1 $\mu$sec; therefore, practically no more nuclear capture reactions due to those muons stopped in hydrogen can take place.

b) - Assume that air is the most abundant impurity present in the gaseous hydrogen, in which the nuclear capture rate of $\mu^-$ has to be studied (the other elements being filtered out). Under this hypothesis the contamination of the hydrogen must be less tha 0.2 ppm for a gas pressure of 10 Atm. and a temperature of 300$^o$K.

Most of the calculations have been performed using the computer at Centro Nazionale Universitario di Calcolo Elettronico (Pisa). The efforts of Mr. G. Sicher and Mr. B. Smith are greatly appreciated. We would like to thank Prof. G. Puppi and Prof. P. Bassi for their encouragements and support.

REFERENCES. -


(1) - A. S. Wightman, Phys. Rev. 77, 521 (1950).

(2) - Y. B. Zel'dovich and S. S. Gorshtein, Usp. Fiz. Nauk. 71, 581 (1960); Sov. Phys. Uspekhi 3, 593 (1961).

(3) - G. Conforto, C. Rubbia, E. Zavattini and S. Focardi, Nuovo Cimento 33, 1001 (1964).

(4) - E. J. Bleser, L. M. Lederman, J. L. Rosen, J. E. Rothberg and E. Zavattini, Phys. Rev. Letters 8, 128 (1962); E. J. Bleser, E. W. Anderson, L. M. Lederman, S. L. Meyer, J. L. Rosen, J. E. Rothberg and I. T. Wang; Phys. Rev. 132, 2679 (1963).

(5) - V. P. Dzhelopov, P. F. Ermolov, V. I. Moskalev, V. V. Fil'chnkov and M. Friml, Proceedings of the International Conference on High Energy Physics, Dubna, 1964, pag. 878.

(6) - M. Schiff, Nuovo Cimento 22, 66 (1961).

(7) - S. C. Basiladze, P. F. Ermolov and K. O. Oganesyan, JETP 49, 1042 (1965); Sov. Phys. JETP 22, 725 (1966).

(8) - O. A. Zaimidoroga, M. M. Kulyukin, R. M. Sulyaev, A. I. Filippov, V. M. Tsupko-Sitnikov and Yu. A. Shcherbakov, JETP 44, 1852 (1963), Sov; Phys. JETP 17, 1246 (1963).

(9) - V. P. Dzhelepov, F. F. Ermolov, E. A. Kushnirenko, V. I. Moskalev and S. S. Gershtein, JETP 42, 439 (1962); Sov. Phys. JETP 15, 306 (1962); V. P. Dzhelepov, P. F. Ermolov, V. I. Moskalev, V. V. Fil'chenkov and M. Friml, JETP 47, 1243 (1964); Sov. Phys. JETP 20, 841 (1965).

(10) - K. W. Ford and J. G. Wills, Nuclear Phys. 35, 295 (1962); P. Brix, R. Engfdr, U. Hegel, D. Quitmann, G. Backenstoss, K. Goebel and B. Stadler, Phys. Letters 1, 56 (1962).

(11) - S. S. Gershtein, JETP 43, 706 (1962); Sov. Phys. JETP 16, 501 (1963).

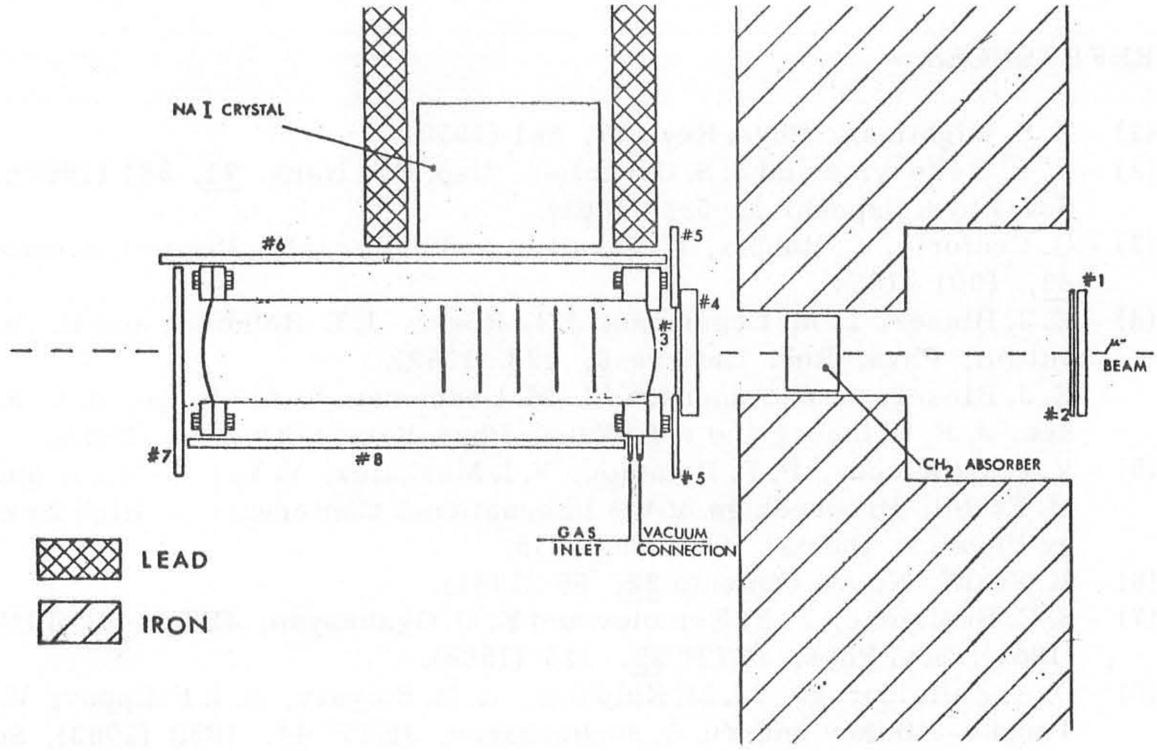


Fig. 1 - Experimental layout - target and counters.

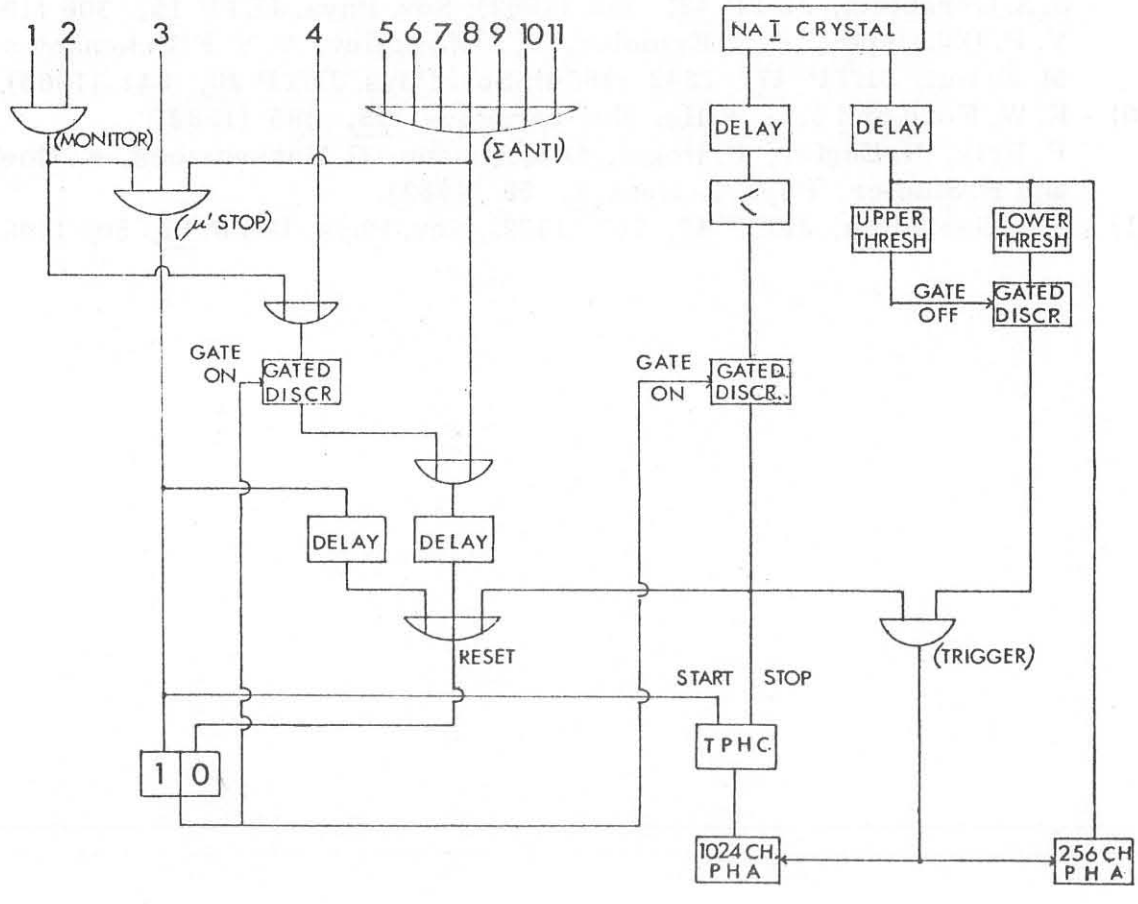


FIG. 2 - Block diagram of the electronics.

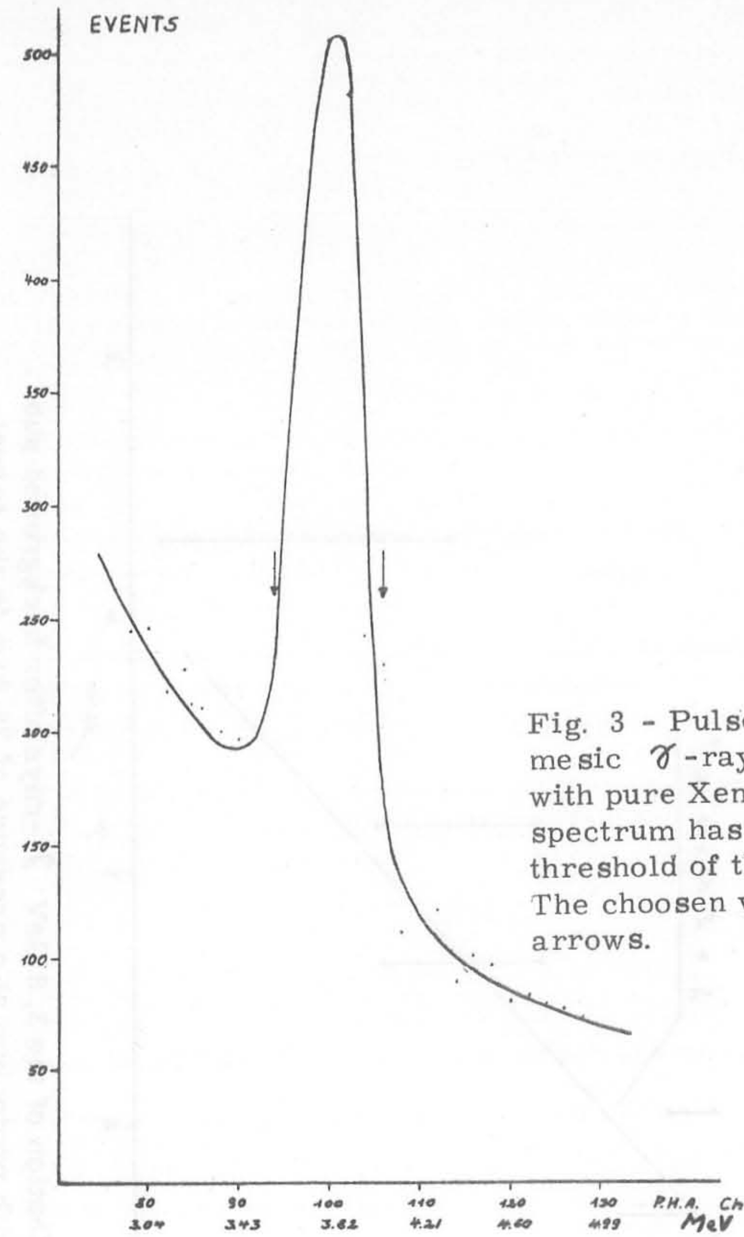


Fig. 3 - Pulse-amplitude spectrum of the mesic $\gamma$-rays obtained filling the target with pure Xenon at 2. 2 Atm pressure. The spectrum has been measured to fix the threshold of the window slow disciminator. The choosen values are indicated by the arrows.

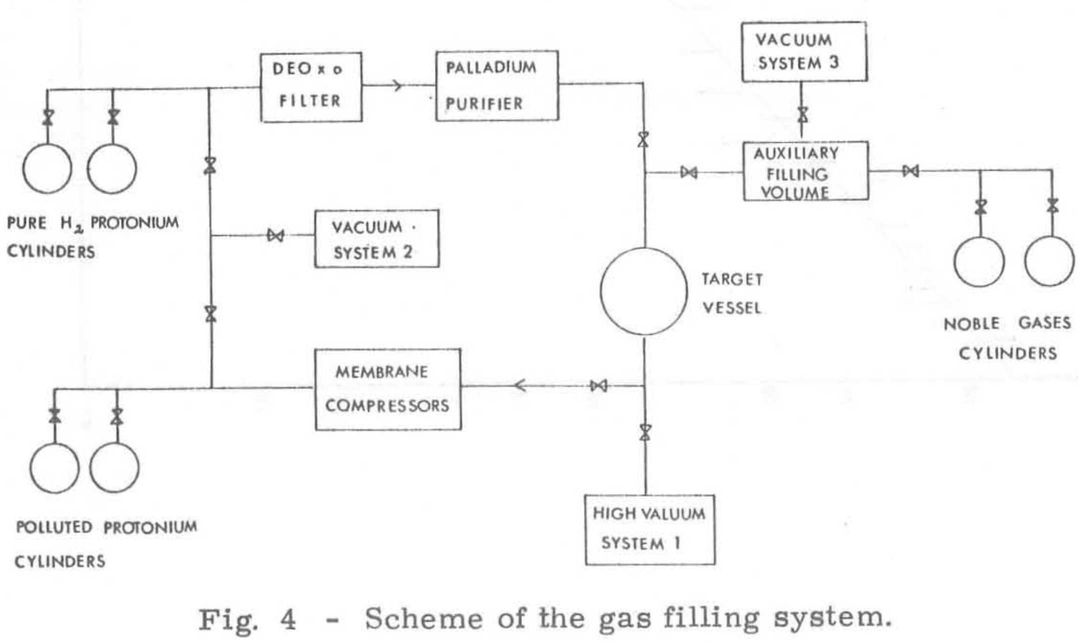


Fig. 4 - Scheme of the gas filling system.

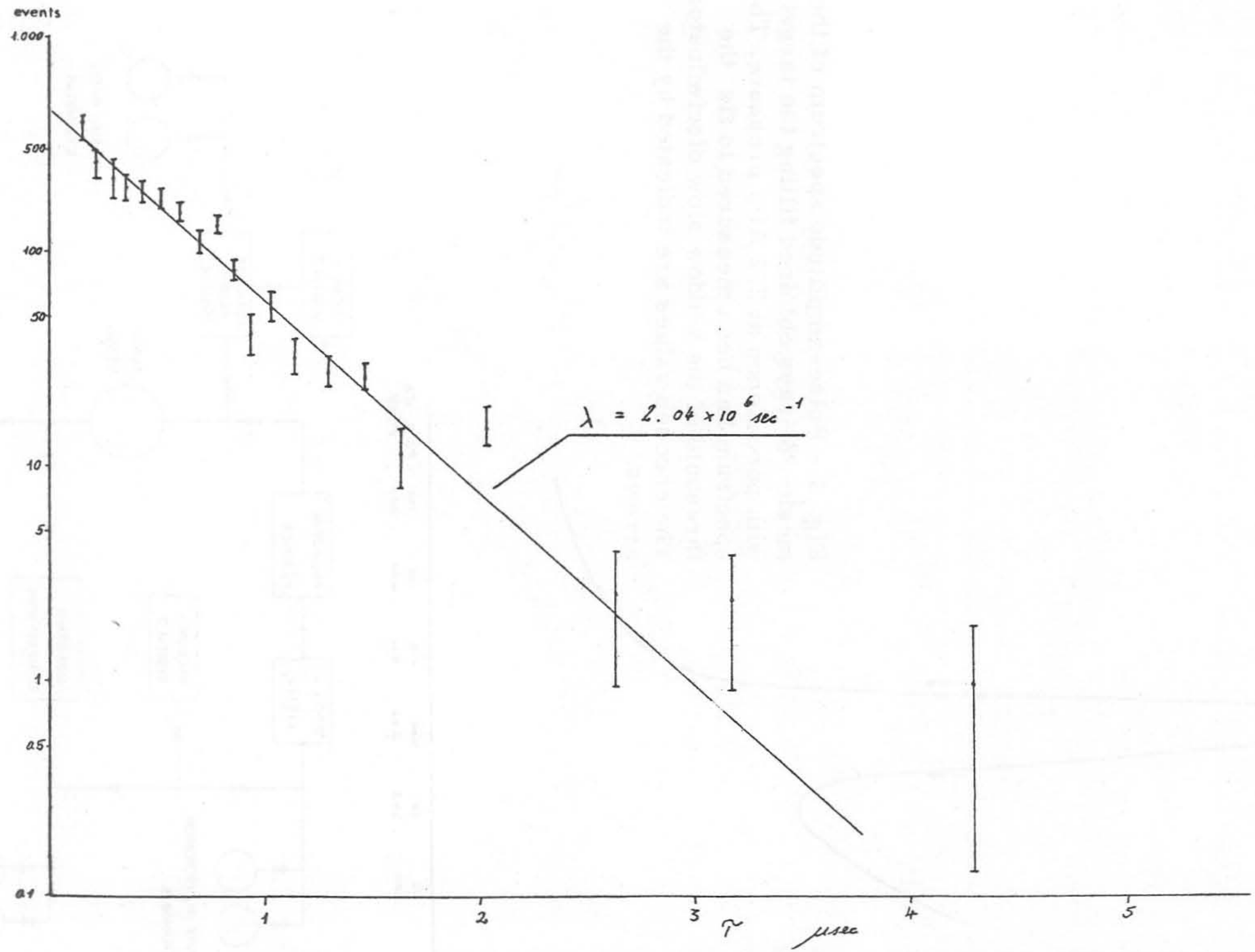


Fig. 5a - Time distribution of the 3.8 GeV γ-rays after background subtraction, measured with protonium at a pressure of 26 Atm in the target $c_{Xe}$ = 0.51 x $10^{-4}$.

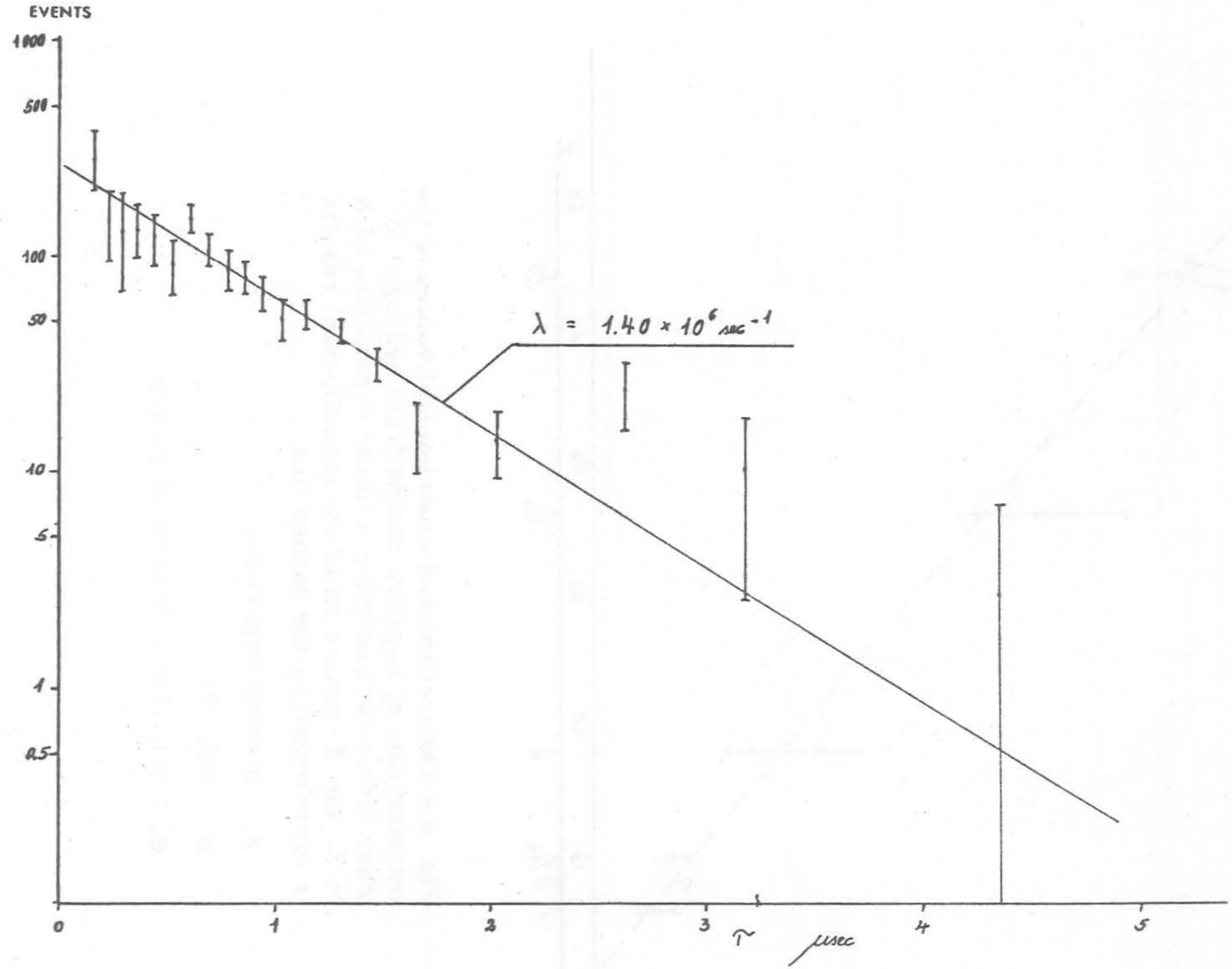


Fig. 5b - Time distribution of the 3.8 MeV $\gamma$-rays after background subtraction, measured with protonium at a pressure of 26 Atm in the target $c_{Xe} = 1.00 \times 10^{-4}$.

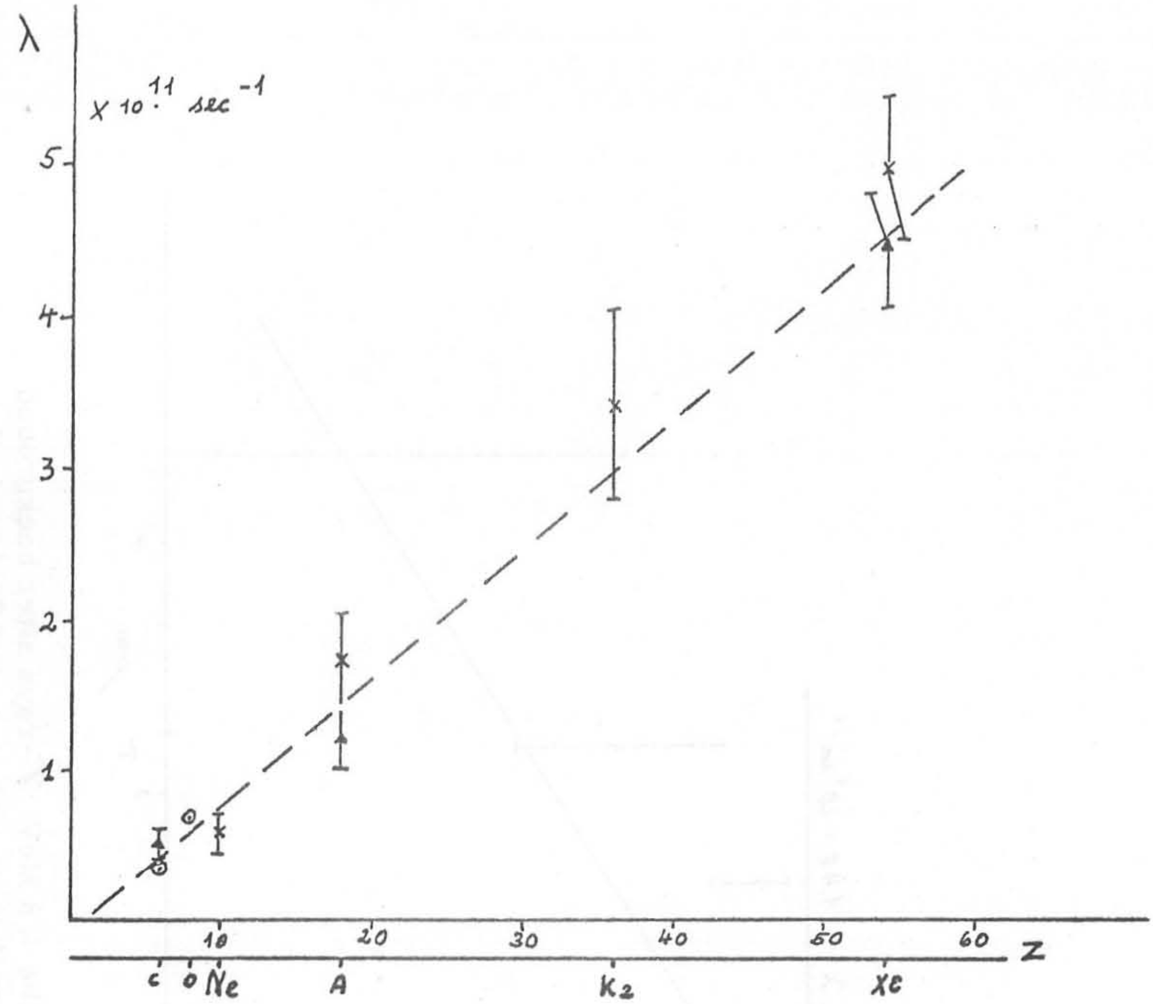


Fig. 6 - Theoretical and experimental values of the transfer rate of negative muons from hydrogen to other elements; assuming a linear dependence of λ on Z, the χ -square fit of the experimental results is represented by the dashed line.

× present experiment

△ ref. (7)

⊙ ref. (11) - theoretical values.