Generation of very slow polarized muons by moderation

E. Morenzoni^a, M. Birke^{a,d}, H. Glückler^a, A. Hofer^{a,c}, J. Litterst^d, M. Meyberg^a,
C. Niedermayer^c, Th. Prokscha^{b,a}, G. Schatz^c and Th. Wutzke^a

^a Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

^b Physik Institut, Universität Heidelberg, Philosophenweg 12, D-69120 Heidelberg, Germany

^c Fakultät für Physik, Universität Konstanz, D-78434 Konstanz, Germany

^d Institut für Metallphysik und Nukleare Festkörperphysik, Technische Universität Braunschweig,
D-38106 Braunschweig, Germany

At the Paul Scherrer Institute very slow, nearly 100% polarized, positive muons with an energy of ~ 10 eV are produced by moderating a secondary beam of surface muons in a thin film of an appropriate condensed gases. These epithermal muons can be used as a source of a tertiary beam of tunable energy between ~ 10 eV and ~ 20 keV. Such a beam allows the μ SR technique to be extended to the study of thin films and surfaces.

In order to be able to perform time differential μ SR experiments we have developed an ultra-thin detector that registers the passage of keV muons and permits to trigger the experiment. The results achieved so far demonstrate that first investigations of thin film samples can be performed with the present set-up.

1. Introduction

During the last few decades the use of polarized muons (μ^+) as spin probes of solids, liquids and gases has continuously developed and the μ SR method has matured and diversified into a large variety of techniques. The state of the art of a method such as μ SR which relies on accelerator and beam lines is dependent on the quality and characteristics of the available muon beams. Until now, available beams for μ SR studies have delivered polarized muons with energies in the MeV range, resulting in a deep penetration and penetration straggling of the muons into the sample material under investigation. This presently limits the applications of the μ SR technique to the study of the bulk characteristics of matter. To achieve variable implantation depths between typically fractions of a nm and a few hundred nm, polarized muons with variable energy between ~ 10 eV and a few tens of keV are needed. With the availability of such particles thin films, solid–solid and vacuum–solid interfaces would become

accessible to μSR studies thus offering a new investigative tool to the growing field of thin film and surface physics.

At the Paul Scherrer Institute (PSI) we are investigating the method of moderating a fraction of an existing intense secondary beam of surface μ^+ from an initial energy of ~ 4 MeV to ~ 10 eV using appropriate insulators [1,2]. The moderated particles can then be used as a source of a tertiary beam of low energy μ^+ with tunable kinetic energy in the desired range. Another scheme for the production of thermal muons is being pursued at the University of Tokyo [3].

In this paper, after summarizing the main characteristics of the moderated muons, we present the status of the development of a tertiary muon. Particular emphasis is given in section 3 to the description of the properties of a detector of very slow muons, which is an important component of the tertiary beam and is essential for the use of very slow polarized muons in μSR studies.

2. Characteristics of moderated muons

The set-up and the experimental methods used to study the physics of the moderation process and to determine the muon characteristics are described in detail in [2,4]. A schematic drawing is shown in fig. 1. Briefly, in the moderator (consisting of a thin Al substrate cooled by the He cryostat down to ~ 15 K and covered with a few 100 nm thick layer of a condensed van der Waals gas) a fraction of the impinging ~ 4 MeV μ^+ are slowed down to epithermal energies. The cold metal substrate is electrically insulated and can be set to a voltage as high as 20 kV. This allows to accelerate and extract the very slow μ^+ from the production region and to select the energy of the tertiary beam. These μ^+ are deflected by an electrostatic mirror through 90 degrees with respect to the incoming beam and are focussed by two electrostatic “einzeln” lenses at a position where a microchannel plate detector (MCP 2) is located. Alternatively, a holder for thin film samples can be mounted in place of the MCP. The e^+ emitted by the decay of the stopped μ^+ at MCP 2 are observed by four pairs of plastic scintillators. In the following we summarize the most important characteristics of the moderated μ^+ . Their energy distribution shows a maximum at 6 eV with a FWHM of 15 eV and a tail extending to higher energies, up to ~ 100 eV. This indicates that they are emitted from the moderator before thermalization (hot muon emission). In wide band gap insulators such as solid Ne, Ar and N_2 the processes, which are responsible for the slowing down of the μ^+ (ionization, muonium formation, muonium break-up), have positive threshold energies (band gap energy 21, 14 and 14 eV [5]). Once the μ^+ has reached a kinetic energy of the order of these threshold levels, the corresponding efficient energy loss mechanisms are strongly suppressed or even energetically impossible. Therefore the energy loss rate becomes low since the only remaining energy loss mechanism is via relatively inefficient elastic collisions. This results in an increase of the escape depth for epithermal μ^+ (which has been measured

then cooled down again show an increased moderation efficiency of about 50 percent indicating an annealing effect. Surface cleanness is essential. This can be shown by considering the time constant of the moderation efficiency decay under different UHV conditions. With a pressure in the order of 10^{-10} mbar the efficiency can be kept nearly constant over several days, an important factor for the operation of a future slow muon facility. A very important property of the slow muons is their polarization. In a first experiment [2] we measured the polarization by stopping moderated μ^+ in MCP 2 and using it as an active target. With this method the following values were obtained: with an Ar moderator ($87 \pm 3\%$), with Kr ($80 \pm 20\%$) and with N_2 ($76 \pm 14\%$). A new alternative measurement of the polarization is reported in section 3.

3. An ultra-thin detector for slow muons

For a μ SR time differential measurement, a unique signal starting the clock must be provided. The PSI cyclotron delivers practically continuous muon beams. Therefore, due to the low moderation efficiency, the start scintillator detecting the incoming μ^+ (see fig. 1) cannot be used to provide an efficient timing start signal, unless an unacceptable reduction of the intensity of the incoming muon beam is taken into account. To solve this problem we have developed a detector (trigger detector) that registers the moderated muons accelerated to typically 10–20 keV. It consists of a very thin carbon foil (thickness $\sim 3.3 \mu\text{g}/\text{cm}^2$) combined with a MCP located perpendicularly to the foil (fig. 2). It is based on the detection of electrons which, ejected by the μ^+ traversing the foil, are directed by a small grid system to the MCP where they are detected. The detector is placed between the electrostatic mirror and the second electrostatic lens. Figure 3 shows an example of time-of-flight spectra obtained with this detector. The left side shows the time-of-flight in the first section of the tertiary beam. The start is given by an energetic particle traversing the scintillator and the stop by a particle producing a signal in the trigger detector.

The most intense peak corresponds to the epithermal muons accelerated to 15 keV. Figure 3(b) shows an expanded view of the time-of-flight of the second section of the very slow μ^+ beam. The start is given by a trigger detector signal and the stop by a signal of the MCP 2 detector. The broad structure indicated as fast μ^+ corresponds to muons with an intrinsic energy of several keV which are mainly degraded in the Al substrate and do not become epithermal in the frozen gas layer of the moderator. They appear also in fig. 3(a) as a shoulder to the left of the epithermal μ^+ peak. By selecting in the first time-of-flight the epithermal muons (hatched peak in fig. 3(a)) only two peaks remain in the second time-of-flight (hatched area in fig. 3(b)). The most intense component corresponds to the very slow μ^+ . The other component is produced by those slow μ^+ which capture an electron in the foil and continue as muonium. Note that this spectrum has been obtained with the “*einzel*” lens switched off and with an additional drift section inserted. It directly reproduces the fraction of muonium produced at the trigger foil. By using the electrostatic lens to focus the very

Fig. 2. Ultra-thin detector for keV μ^+ .

Fig. 3. (a) Time-of-flight between start scintillator and trigger detector (first section of the very slow μ^+ beam). (b) Expanded region of the time-of-flight between trigger detector and MCP 2 (second section of the very slow μ^+ beam), showing the muon and muonium peaks. The time zero is offset by 250 ns. The hatched area corresponds to events contained in the epithermal μ^+ peak in the first time-of-flight (hatched area in fig. 3(a)).

slow μ^+ onto MCP 2 (or onto the sample), we can increase their fraction by a factor ~ 4 .

In the trigger detector the amount of material interacting with the muons is minimal: the foil thickness corresponds to only ~ 70 atomic layers. Nevertheless the optics of the very slow μ^+ in the second section is determined by the interactions of the muons with these atoms. We have investigated in detail the various effects resulting from these interactions. In the foil the μ^+ is scattered and loses energy. Due to the

Table 1
Parameters of the trigger detector (for 16 keV μ^+).

Energy loss	2.04 ± 0.15 keV
Energy straggling ^a	0.43 ± 0.05 keV
Muonium fraction	$11 \pm 3\%$
Efficiency ^b	$67 \pm 4\%$
Angular spread ^a	0.035 r

^arms

^bIncluding losses due to muonium formation

Fig. 4. Asymmetry signal from the decay of 16 keV muons stopped in an Ag foil and precessing in a 5 mT transverse magnetic field.

statistical fluctuation in the number of collisions, the slowing-down is accompanied by a spreading of the energy (energy straggling). Moreover, the muon can be neutralized, as shown in fig. 3(b). Table 1 gives an overview of the most relevant results. With the development of the thin foil detector first μ SR spectra in transverse and zero fields have been obtained [4]. Figure 4 shows the μ SR signal of 16 keV muons stopped in an Ag sample. This experiment allows an independent determination of the polarization P of the very slow muons, previously measured by another method [2] and discussed in section 2. A preliminary analysis indicates a value of P larger than $\sim 90\%$.

4. Conclusions

In conclusion it has been shown that the moderation of a surface μ^+ beam by condensed van der Waals moderators produces highly polarized epithermal muons. This and the successful test of a trigger detector are essential steps toward the extension of μ SR techniques to thin films and surface studies. First μ SR measurements with very slow μ^+ have been performed.

Before they can be routinely used for various experiments and a general purpose tertiary μ^+ beam is available, further developments are necessary. For instance, to make efficient use of the muons down to very low energies, an acceleration–deceleration section must be inserted between moderator and sample. Parallel to this the search for moderators with high efficiency remains an important task for the development of slow μ^+ physics.

References

- [1] D.R. Harshman, J.B. Warren, J.L. Beveridge, K.R. Kendall, R.F. Kiefl, C.J. Oram, A.P. Mills, W.S. Crane, A.S. Rupaal and J.H. Turner, Phys. Rev. Lett. 56 (1986) 2850.
- [2] E. Morenzoni, F. Kottmann, D. Maden, B. Matthias, M. Meyberg, Th. Prokscha, Th. Wutzke and U. Zimmermann, Phys. Rev. Lett. 72 (1994) 2793.
- [3] Y. Miyake, K. Shimomura, A.P. Mills and K. Nagamine, these Proceedings.
- [4] E. Morenzoni, M. Birke, A. Hofer, F. Kottmann, J. Litterst, B. Matthias, M. Meyberg, C. Niedermayer, Th. Prokscha, G. Schatz and Th. Wutzke, Hyp. Int. 97/98 (1996) 395.
- [5] M.L. Klein and J.A. Venables (eds.), *Rare Gas Solids*, Vol. 1 (Academic Press, New York, 1976).