DEVELOPMENT OF A VERY LOW ENERGY μ^+ BEAM AT PSI

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At PSI we are investigating the technique of decelerating an existing very intense secondary beam of surface μ^+ (~ 4 MeV) to an energy of ~ 10 eV using appropriate moderators. These μ^+ can then be used as a source of a tertiary beam of low energy muons with tunable kinetic energy between ~ 10 eV and ~ 10 keV.

With a 1000 Å layer of solid Argon deposited on an Al substrate we obtain a moderation efficiency (with respect to the number of incoming surface μ^+) of the order of 10^{-4} .

Results of our investigations and the present status of the project are presented together with future plans and possibilities.

1. Introduction

Presently, the straightforward way to obtain low energy positive muons is to tune a conventional surface μ^+ beam to momenta lower than 29 MeV/c (subsurface μ^+ beam) [1]. Due to the $p^{3.5}$ momentum dependence of the intensity this method provides reasonable beams only down to several hundreds of keV of kinetic energy [2]. This energy is still too high for experiments where the relevant parameter is either the velocity of atomic electrons, as in atomic and molecular physics, or where the penetration depth of the μ^+ in matter must be well below 1 μm (as for instance in the use of polarized μ^+ as magnetic microprobe of surfaces or thin films).

The availability of a tunable beam of polarized muons in the energy range between some 10 eV and some tens of keV would therefore open new dimensions in fundamental as well as in applied muon physics [3].

At PSI we are further developing the technique of moderating an existing secondary beam of surface μ^+ in appropriate solid moderators to a few eV of energy, and studying the possibility of using these μ^+ as the source of a very slow tertiary beam delivering (possibly polarized) μ^+ in the desired energy range with a useful rate.

This choice has been triggered by two developments. First of all it has recently been shown that, in analogy to positrons (where the moderation technique is routinely used [4]), μ^+ can be moderated to an energy of a few eV [5,6,7]. With a solid Ar layer deposited on a metallic foil, Harshman *et al.* reported that $\sim 10^{-5}$ of the incoming μ^+ beam are emitted with an energy of the order of 10 eV and with an energy width of the same order of magnitude. The second important development is the PSI upgrade program. At the end of this program the cyclotron ring will provide a proton current of 1 to 1.5 mA. A new large acceptance beam line, ($\pi E5$), has been designed and built and is expected to deliver a flux of $\sim 10^8$ surface μ^+ per second (at 1mA proton current) [8].

The technique chosen clearly has the potential to produce at least $\sim 10^3$ very slow μ^+ per second at PSI

2. Experimental Setup and Results

To study and optimize the emission of very slow muons from various solids and to develop the moderation technique, the apparatus shown in Fig. 1 has been built. It can also serve as the basis for a facility providing a tertiary beam of very slow muons. The central component is an Ultra High Vacuum (UHV) chamber designed for a basis vacuum pressure of $\sim 10^{-10}$ mbar. To date the most promising moderator appears to be a rare gas solid [9], as is the case for positrons. A solid layer of a rare gas can be deposited on a substrate (presently a very pure Al foil), which can be cooled down to ~ 10 K by an UHV compatible helium cryostat. The UHV environment is needed to reduce the influence of target contamination on the moderation process and to ensure reproducible results during a measurement. For the same reasons, UHV conditions are the standard environment used for surface and thin film studies, which represent a potentially very large field of application for the ultra-slow μ^+ beam. A dedicated UHV chamber for such applications can be flanged to our apparatus without problems.

Fig. 1. UHV apparatus with cryostat used for the moderation studies.

Yields and energy spectra of the eV μ^+ are measured with a time-of-flight (TOF) system. The incident polarized surface μ^+ traverse a thin ($100\ \mu\text{m}$) scintillator starting the TOF measurement. In the moderator, a fraction of the muons are slowed down to energies of several eV and emitted into the vacuum. The cold metal substrate is electrically insulated and it is held at a voltage of typically 8 kV to accelerate and extract the very slow muons from the production region. The acceleration takes place in a two stage system formed by the substrate and two accelerating grids. With two electrostatic einzel lenses and an electrostatic mirror the slow muons are focussed on a microchannel plate detector (MCP2 in Fig. 1) providing the stop signal of the TOF measurement. The muons can be unambiguously identified using the signal of the MCP2 detector in coincidence with delayed signal from one of four pairs of scintillator paddles which surround MCP2 and detect the decay positrons. The electrostatic mirror formed by two grids at a voltage difference of typically 13 kV separates the slow muons from the dominant fraction of energetic muons, which continue straight ahead and are detected by another microchannel plate (MCP1 in

Fig. 1) giving the stop signal for another TOF measurement. This TOF serves mainly for beam tuning and beam monitoring purposes.

In 1992 we carried out first measurements by using a surface μ^+ beam in the $\pi E1$ area at PSI. Figure 2a shows a TOF spectrum of moderated μ^+ obtained with the Al substrate alone. A broad bump is observed corresponding to energies ranging up to ~ 10 keV. The shape is essentially determined by the response function of the low energy transport system. Figure 2b shows the TOF spectrum measured with a thin Ar layer deposited on the Al substrate, normalized to the same number of incident muons as in Fig. 2a. The Ar spectrum has a much narrower and stronger component corresponding to very slow μ^+ emitted from the Ar layer. A preliminary analysis indicates that the initial average energy of the muons is of the order of 20 eV with a comparable width. From a detailed simulation of the whole experiment, which is underway, and a comparison with experimental data obtained at various settings of the acceleration system we expect to obtain the full energy spectrum of the low energy μ^+ . The difference between Fig. 2a and Fig. 2b is striking and the comparison points out the special role played by the rare gas solid in the production of very slow μ^+ . A similar behavior, though less pronounced, is observed with solid layers of Kr and Xe.

The particularly high efficiency of rare gas solids in moderating muons down to $\sim$ eV energies seems correlated to the large ionization energy of these elements. A plausible explanation is the following: Energy loss channels, such as target atom ionization, muonium formation and muonium electron loss, have positive threshold energies in the lightest noble gases. When the μ^+ reaches kinetic energies of the order of these threshold levels, the corresponding energy loss mechanisms are strongly suppressed or even energetically impossible [10]. The ~ 10 eV μ^+ emission is therefore a consequence of an open energy window in the moderation process, which noticeably increases the escape depth of these muons (hot or epithermal μ^+ emission). Argon experimentally gives the largest moderation efficiency (defined as the ratio of the number of emitted slow muons to the number of incoming surface μ^+).

We investigated the dependence of the slow μ^+ yield on some parameters characterizing the rare gas layer [11]. By optimizing quantities such as the temperature of the Al substrate, the Ar layer thickness, the deposition rate when growing the layer and μ^+ stopping density at the down-stream moderator surface, an efficiency of $\sim 10^{-4}$ has been obtained, measured

Fig. 2. TOF spectrum between scintillator and MCP2 (see Fig. 1) showing the very slow μ^+ . The moderator is at 8 kV potential. a) Only Al substrate as moderator. b) Thin layer of solid Ar evaporated on the Al substrate. a) and b) are normalized to the same number of incoming surface muons.

immediately after depositing a fresh layer. At a vacuum of $3 \cdot 10^{-9}$ mbar, this value decreases to $\sim 50\%$ after 2-3 hours and to 30% after 8 hours. This yield is an order of magnitude larger than the value reported in [6,7]. By measuring the moderation efficiency as a function of the layer thickness the escape depth of the very slow μ^+ in Ar and Kr has been found to be ~ 900 Å and ~ 600 Å respectively.

Installing a moderator setup at the $\pi E5$ beam line the presently achieved moderation efficiency should translate into a source flux of more

than 10^4 very slow μ^+ per second (at 1 mA proton current). This result proves the realistic potential of the relatively simple moderation technique as a basis of a tertiary low energy μ^+ beam.

3. Future Plans and Characteristics of a Tertiary Beam

The optimization of the moderation efficiency is not completed and will be further pursued. The efficiency may be further improved if the role played by various mechanisms in the moderation process are theoretically better understood. Other moderator candidates such as Ne or non-cryogenic wide band gap insulators will also be tested.

Before the slow μ^+ can be routinely used for various experiments and a tertiary μ^+ beam will be available some other steps and technical developments are necessary. A measurement of the polarization of the very slow μ^+ is in preparation. This parameter is very important for applications in solid state and surface physics. From a theoretical point of view it is expected that the 100% polarization of the surface μ^+ is conserved in the moderation process which is extremely rapid (of the order of 10 ps).

Let us assume for a moment that the very slow μ^+ are polarized, and that we want to do a time differential μSR experiment on a thin film with good statistics. Since the PSI ring accelerator is (for μ^+) a DC machine, we cannot use the entrance scintillator (counting at a rate of more than 10^8 μ^+ per second (at 1 mA)) as a start signal for a Δt measurement. This problem would not be present at a pulsed machine with a narrow time structure, and also if an integral surface μSR is planned.

To obtain a clean start signal it is foreseen to insert a thin foil detector between the electrostatic mirror and the second einzel lens (see Fig. 1) The slow μ^+ traversing the thin foil (typically a $2\mu g/cm^2$ carbon foil) eject one or more secondary electrons with large probability. These electrons are directed by a small grid system to a microchannel plate located at 90° with respect to the foil, where they are detected and can be used as a start signal for a time differential μSR experiment.

Of course, the thin foil has some effect on the characteristics of the low energy μ^+ beam. In a foil μ^+ can be neutralized forming muonium. This process, which represents an intensity loss, can be minimized by accelerating the μ^+ before the foil to 20 keV or more. At 20 keV less than 10% of the μ^+ are neutralized [12]. On the other hand, muonium formation in a thin foil could be used to provide a (partially polarized) muonium beam with adjustable energy. The foil also introduces some

energy and angular straggling. The mean energy loss for a 20 keV μ^+ in a $2 \mu\text{g}/\text{cm}^2$ C foil is ~ 2 keV [13] and the energy straggling is ~ 400 eV. The energy spread introduced by the foil can be reduced by using a pulsed electrode triggered by the secondary electron signal described above. By choosing an appropriate pulse shape a sizeable reduction of the energy spread can be achieved.

As for conventional μSR , appropriate models and analytical tools to interpret the results should be developed. A quantity which must be known for a correct interpretation of the results is, for instance, the relation between μ^+ energy and range straggling in the probe to be investigated. Some information (at least at several keV energy) can be obtained by scaling the corresponding data for protons at the same velocity. At smaller energies the scaling is more questionable. Also, the effect of processes like backscattering from the probe at very low energies must be taken into account.

In conclusion, though the moderation technique for μ^+ has not yet been fully exploited and work remains to be done to provide several thousand very low energetic μ^+ per second, the results obtained so far instill confidence that a first case experiment to demonstrate the potential offered by low energy μ^+ is within reachable distance.

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