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Muon Physics with the Proposed Pulsed Lepton Source at LAMPF

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1 Introduction

The Pulsed Lepton Source (PLS) project opens some exciting possibilities for muon and neutrino physics. The PLS would use the 0.25 μ s proton pulses from the upgraded Proton Storage Ring (PSR) at LAMPF to create short, intense bursts of muons and neutrinos. The neutrino beam would be used for a few fundamentally important weak interaction physics experiments. The muon beams would find a wide variety of applications in both fundamental and "applied" muon physics areas. After a brief discussion of the physical layouts of the PSR and the proposed PLS in Sec. 2 and muon area in Sec. 3, we note some of the muon physics experiments and areas that could advantageously be addressed at the PLS in Secs. 4 and 5, and conclude in Sec. 6.

2 The Proton Storage Ring and the Pulsed Lepton Source

The PSR now delivers quarter- μ s bursts of protons, with 20 Hz repetition rate and an average current approaching 100 μ A, to the neutron production target of LANSCE (Manuel Lujan Jr. Neutron Scattering Center), for what are mainly materials science studies. The PSR is shown in Fig. 1. The ring is filled using 800 MeV H^+ beam

from the LAMPF accelerator, over many turns and $\sim 500 \mu\text{s}$, and then is extracted in a single turn (30 A peak current!) to give the time-compression to $0.25 \mu\text{s}$. With some upgrading to the PSR (probably including conversion to single-step injection from the two-step process shown in the figure), the repetition rate would be increased to 60 Hz, thus keeping the maximum charge in the ring (3×10^{13} protons) fixed and increasing the average current to 300 μA . The additional 200 μA at 40 Hz would then be transported to the PLS area as shown in Fig. 2.

The PLS facility consists of separate muon and neutrino areas and production targets, as shown in Figs. 2 and 3. The downstream target is thick, and includes a "horn" for focussing pions and sufficient space to allow them to produce a "decay-in-flight" neutrino beam. The muon area is shown in detail in Fig. 3.

3 The Muon Area

The muon area has been designed to make ample beam time available for both fundamental and materials science (μSR) studies. Low-momentum surface μ^+ /cloud μ^- channels are located on opposite sides of the thin muon production target as shown in Figs. 3 and 4. The proton beam and muon production target are located several meters below the level of the muon hall, and the double-bend channels (modeled on the PSI πE3 channel) raise the beams to a convenient level, this arrangement avoids having a massive ridge of shielding blocks bisecting the muon hall.

An important feature of the muon area is the "time-sharing" feature, indicated in Fig. 3. Parallel plate deflectors, analogous to the "Uppset" device used at RAL, move the beam from straight ahead to left and right (or vice-versa) across a magnetic septum when alternate plates are grounded, enabling each $0.25 \mu\text{s}$ pulse to be divided among several experiment stations as sketched in the Inset of Fig. 3. This not only allows several experiments to run

simultaneously on a single channel, but shortens the pulse for each, thus improving the time resolution. Eight simultaneous experiments are allowed in the scheme as shown in the figure, but this number could be increased when demand warrants

4 Fundamental muon physics

Among the advantages of pulsed muons for fundamental physics experiments are a precise zero in time, freedom from short-lived backgrounds, line-width narrowing, and higher efficiency using coincidence with laser pulses. Experiments testing quantum electrodynamics are extremely important, since the history of physics leads us to believe that the theory of QED, as beautiful as it is, *must* break down eventually, just *where* this occurs is the crucial question

Muonium (μ^+e^-) experiments test QED in the absence of hadrons, a crucial simplification. Muonium hyperfine transitions, corresponding to those shown in the "Breit-Rabi diagram" at the top of Fig. 5, have RF absorption profiles (bottom of Fig. 5) that are narrowed when the e^+ observation period is delayed with respect to the formation of the Mu atoms, these narrower lines will allow a more precise determination of the line centers [1]. This "old muonium" technique is simple and efficient to implement at a pulsed muon source. The two HF transitions determine two quantities: the hyperfine interval Δ_{HF} and the magnetic moment ratio μ_μ/μ_p , these quantities are related by QED, so the measurement is a QED test. Furthermore, higher precision for the μ_μ/μ_p ratio is needed for the BNL $g_\mu-2$ experiment.

Another important Mu experiment is the observation of the $1S \rightarrow 2S$ Doppler-free two-photon transition, the pulsed laser beam makes a pulsed μ^+ beam essential. This experiment will measure the QED corrections, dominated by the radiative corrections, to the $1S$ and $2S$ levels. The first detection of this transition was

accomplished at KEK four years ago; a sketch of the layout and the transition spectrum are shown in Fig. 6. [2]

Lamb shift experiments in light muonic atoms, specifically μ^-p and μ^-He , are very challenging, and the pulsed high-powered lasers require pulsed μ^- beams. Observation of a single transition provides a very precise determination of the r.m.s. nuclear radius, if more than one transition with the same nucleus are observed, a precise measurement of the vacuum polarization contribution results.

In addition to probing QED, pulsed muons can give important weak interaction information. More precise measurements of the muon lifetime should be possible with this high intensity pulsed source, thus fixing the weak decay constant G_μ with greater precision. New opportunities in muon capture by nuclei will also be possible. One example is μ^- capture in liquid hydrogen, where information on the ortho to para transition in the $pp\mu$ molecule comes from observing the time-dependence of the appearance of neutrons (Fig. 7); the uncertainty in this rate is an important contributor to the error in the induced pseudoscalar coupling constant g_p [3]. Furthermore, it may be possible to harness the technique for laser-polarizing the μ^- after its arrival in the ground state, recently demonstrated at LAMPF for He [4], for measuring g_p and symmetry tests, etc.

5. Materials science with muons

Muon spin rotation, resonance, relaxation (μ^+SR) has grown to be a powerful tool for materials science, with application to an expanding range of problems in physics and chemistry [5]. The μ^+ can be implanted in any material, where it precesses in local interstitial magnetic and hyperfine fields, information on the polarization at the instant of decay is transmitted by the asymmetric e^+ emission, as illustrated in the cartoon of Fig. 8. There are many varieties of μ^+SR : LF (transverse field) μ^+SR , LF (longitudinal field) μ^+SR , μ^+CR (level-crossing resonance

spectroscopy), RF μ SR, etc. All can benefit from pulsed beam. Instead of being restricted to a single μ^+ in a $\approx 20\mu\text{s}$ interval, as is necessary for any TD(time-differential) μ SR at a cw source, there can be *many* within a interval Δt ; hence very much higher data rates are possible. (Obviously, the time resolution is limited to Δt). Fig 9 shows the famous "wiggles" of TF μ SR.

We mention just a few applications of μ SR. As a magnetic probe, the μ^+ has been used to detect magnetic ordering of many materials (see Fig 10 for a nice example of this), and, for high temperature superconductors, to probe the magnetic field distribution from the vortex lattice and therefore to determine the London penetration depth. As a light isotope of hydrogen, the μ^+ has been used to study localization and diffusion in metals, insulators, etc., in semiconductors to investigate the behavior of isolated H defects and passivation by hydrogen; and in radical chemistry to probe the structure, dynamics and reaction rates involved in the formation and decay of radicals.

μ SR has the largest muon user community, but in the U.S. has been severely hampered by a lack of facilities and beam time. Through the time sharing of the μ^+ beams, the PLS could change this situation very dramatically.

6. Conclusions

In our brief discussion, we have noted a number of topics for which the proposed muon area of the PLS would contribute to fundamental muon science and to applications - which of course are fundamental studies in materials science, chemistry, etc. The list of topics is far from complete and is meant merely to give a flavor of the possibilities. The most important aspect of the PLS would be the drastically increased μ^+ beam availability arising from the time-sharing scheme outlined in Sec. 5. Not only could the facility

accommodate more experimental teams, but they each could remain set up for longer periods, significantly increasing their productivity

Acknowledgment

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- 6 D.W. Cooke et al., *Phys. Rev.* B41 (1990) 4801.

Figure captions

- 1 Plan of the Proton Storage Ring.
- 2 Layout of the LAMPF accelerator, the PSR and LANSCE, and the proposed PLS facility. The inset shows the proton pulse shape (1 μ s full horizontal scale).
- 3 Layout of the Muon Area. The inset shows one possible way of time-sharing the surface μ^+ pulse among the five experiment stations of the TF μ SR Area.
- 4 Elevation showing the muon channels.
- 5 Top: Breit-Rabi diagram for muonium
Bottom: Experimental RF resonance profiles for the two transitions. (From P. Egan [1].)
- 6 The KEK Mu 1S $\rightarrow$ 2S experiment (from S. Chu et al. [2]) The ionization as a function of photon energy is shown at the bottom
- 7 The time dependence of neutron appearance from μ^- capture in liquid hydrogen, showing the effect of the ortho to para transition of pp μ (from G. Bardin et al. [3]).
- 8 Illustrating how muons give information about local fields in μ SR (from S.F.J. Cox [5]).
- 9 Precession signal in TF μ SR [5]
- 10 Lower plot: Phase diagram showing superconducting and (two) antiferromagnetic phases in the doped YBCO compound shown
Upper plots: The oscillating signal in the absence of any external magnetic field is a sensitive indicator of magnetic ordering. (From D.W. Cooke et al. [6])

PULSED LEPTON SOURCE

Fundamental Physics and LFμSR Area

UT-MSL/KEK

(a) muon implantation

(b) muon spin rotation

(c) muon decay

μ SR

(from S.F.J. Cox)