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A SEARCH FOR MILLICHARGED PARTICLES AT SLAC*

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ABSTRACT

Particles with electric charge $q/e \leq 10^{-3}$ and masses in the range 1–1000 MeV/c^2 are not excluded by present experiments or by astrophysical or cosmological arguments. Such millicharged particles may be a form of shadow matter that couples to ordinary matter by virtue of shadow photon/photon mixing. This paper describes a search for millicharged particles in a dedicated beam-dump experiment at SLAC. A preliminary analysis of part of our data excludes particles of mass $\approx$1 MeV/c^2 with $q/e > 6\times10^{-5}$.

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I. INTRODUCTION

The quantization of electric charge is a fundamental fact of nature that is not understood. It has provoked speculation on the existence of magnetic monopoles, motivated grand unified theories, and stimulated inquiries into how charge conservation might fail. Mechanisms for charge violation may require the existence of particles with electric charges much smaller than the electron charge[1)] Holdum[2)] has discussed a mechanism which might generate apparent millicharge (i.e., $q/e \leq 10^{-3}$), but not violate charge quantization. He imagines the existence of a second electromagnetism-like U(1) gauge group whose shadow photon doesn't directly couple to ordinary matter. Induced couplings give rise to apparent millicharge if shadow photon/photon mixing is mediated by particles which have both ordinary and shadow charge. In this scenario, millicharged particles could comprise (part of) the universal dark matter.

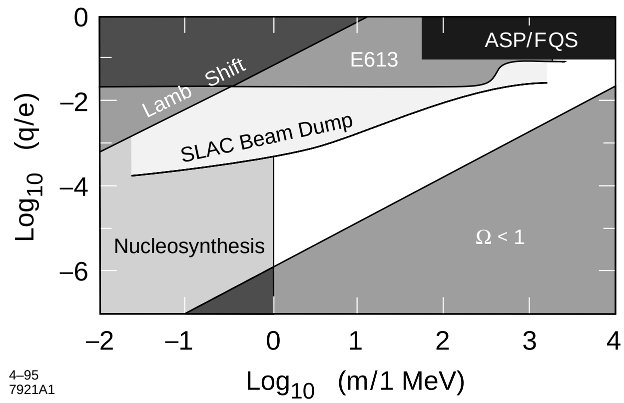

Figure 1. Existing limits on millicharged particles as a function of the charge and mass of the particles, from laboratory experiments and cosmological arguments. See Refs. 3–5 for details

Several theorists[3,4,5)] have considered millicharged particles and investigated constraints on their existence imposed by laboratory experiments, as well as by astrophysical and cosmological arguments. Figure 1 summarizes the regions of the charge/mass plane so excluded. Somewhat stronger bounds exist for models in which millicharge arises from shadow interactions.[6)] There is a relatively large domain in mass and charge where millicharged particles are not yet excluded.

My collaborators[7)] and I have followed the suggestion of Dobroliubov and Ignatiev[3)] to search for electroproduced millicharged particles with a scintillation detector. In the following, we briefly describe the experimental layout, mQ production and detection, and some preliminary results. Our experiment has been running parasitically during SLC operations in 1994 and 1995, and is sensitive to much of the unexplored region shown in Fig. 1.

II. EXPERIMENTAL LAYOUT

Figure 2 shows a schematic view of the experiment. A 29.5 GeV electron beam from the SLAC linac is diverted onto a $6X_0$ tungsten target in order to produce positrons for subsequent acceleration in the SLC. Roughly 3×10^{10} electrons are incident in a few pico-second pulse at 120 Hz. For us, the positron target is a convenient beam dump for millicharged

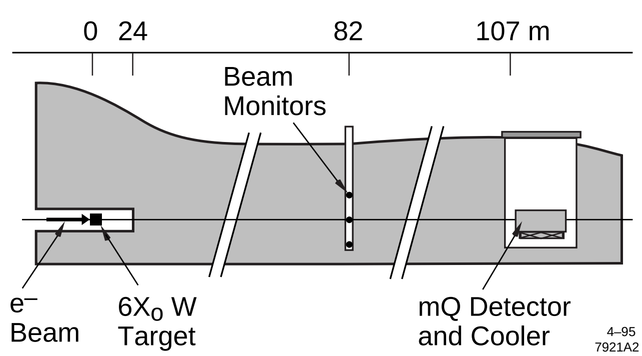

Figure 2. Layout of the mQ search experiment

particle production. Well downstream of the positron target and roughly 6 m underground, we have installed an array of five 20×20 cm^2 scintillation counters, which detect high-energy muons produced in the target. These counters monitor the incident electron flux, fix the arrival time of ß = 1 particles, and determine the beam centroid to check alignment. All remnants of electromagnetic and hadronic showers produced near the target are absorbed in the sandstone between the target and the counters. Further downstream, and well past the range of the most energetic muons, we have excavated a cylindrical pit, 3.6 m in diameter, and situated a scintillation detector directly in line with the incident electron beam.

The detector is a 2×2 array of scintillation counters. The counters are 20×20 cm^2 transverse to the beam and 130 cm long, and are made of Bicron 408 scintillator. Each counter is read out with a 20 cm Thorn EMI 9353 KA phototube. The counter array is cooled to about 0ºC to reduce thermionic noise in the phototubes, and shielded with 10 cm of lead to reduce single photoelectron afterpulses from natural background radiations. Time and pulse height information is recorded.

III. mQ PRODUCTION

Quantum electrodynamics completely characterizes the production of millicharged particles in terms of their charge and mass. The electroproduction cross section (which is proportional to the square of the mQ charge) dominates over photoproduction (which varies as q^4). The appropriate cross sections are given in the literature,[8] and produce a relatively flat momentum spectrum out to the kinematic limit and a very peaked angular distribution characterized by $\Theta \sim M_{mQ}/E$. We have performed a calculation of the mQ production expected from the positron target, including the effects of showering and scattering in the tungsten, and find the number of mQ's produced into our detector solid angle per SLC pulse, to be

$$N_{mQ} \sim 1.3\times 10^7 \; q^2 \left(\frac{1 \text{ MeV}}{M_{mQ}}\right)^2 \qquad (1)$$

Our counter has 40% acceptance for 1 MeV millicharged particles, 25% acceptance at 10 MeV, and 4% acceptance at 100 MeV.

IV. BEAM MONITORING

Muons produced in the positron target are a very useful beam monitor. The transverse profile of the beam is essentially Gaussian as a result of multiple scattering in the material between the target and the counters, and has σ = .65 m. Comparisons of the measured muon beam center and our survey references confirms that our detector is aligned with the expected mQ production direction within about 1 mr.

Figure 3 shows the time distribution of muon hits, relative to a signal synchronized to the pulse passage in the SLC. A sharp peak, with FWHM = 2 ns is seen. We use the muon arrival time to establish the expected mQ arrival time in the detector.

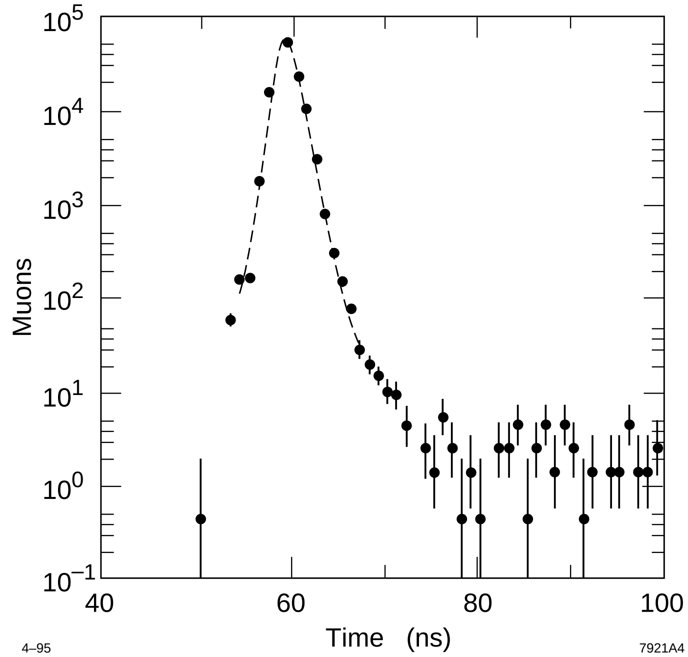

Figure 3. Muon arrival time distribution in the beam monitoring counter.

V. mQ DETECTION

Millicharged particles of masses between 0.1 and 100 MeV lose energy in passing through matter predominantly through excitation and ionization. The cross section for these processes, which is proportional to $\alpha^2/\Delta E$, where ΔE is the energy transferred in the interaction, is nearly 10 million times larger than that for high-energy processes (e.g., pair production), which is proportional to α^4/M_e. The fundamental advantage of searching for a low-energy signal is greatly increased sensitivity.

We assume that energy loss for millicharged particles is described by the Bethe–Block expression for dE/dx[9]

$$-\frac{dE}{dx} = Kq^2 \frac{Z}{A} \frac{1}{\beta^2} \left\{ \frac{1}{2} \ell n \left(\frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} \right) - \beta^2 - \frac{\delta}{2} \right\} . \qquad (2)$$

Here K = 0.3071 MeV $\mathrm{gm}^{-1}\,\mathrm{cm}^2$, I is the mean excitation energy, $T_{\max}$ is the maximum kinetic energy imparted to a delta ray, and $\delta/2$ is the density correction. The energy loss scales with q^2, of course. Since the millicharged particles are relatively light and quite energetic, relativistic effects are important. Density effects should be absent for millicharged interactions since typical impact parameters capable of atomic excitations are small compared to the plasma screening length.

We determine the average light output expected for mQ's by measuring the mean number of photoelectrons detected in the passage of a cosmic ray muon through the detector and scaling this number by the ratio of the energy loss expected from millicharged particles to that from muons. We subtract the delta ray contribution from the millicharged particle energy loss since it presumably contributes to photomultiplier signals above the single photoelectron level we require as the mQ signature.

$$\left\langle n_{pe}^{mQ} \right\rangle = \left\langle n_{pe}^{\mu} \right\rangle \frac{(dE/dx)_{\mathrm{tot}}^{mQ} - (dE/dx)_{\delta}^{mQ}}{(dE/dx)_{\mathrm{tot}}^{\mu}} . \qquad (3)$$

From preliminary light output calibrations, we find (for 1 MeV mQ's):

$$\left\langle n_{pe}^{mQ} \right\rangle \; = \; 2.9 \times 10^5 \;\; q^2 \;\; N_{mQ} \;\; . \qquad (4)$$

Equations (1) and (4) show that a signal is expected in the counter with every SLC pulse for q/e < 7×10^{-4}. For smaller charges, $\left\langle n_{pe}^{mQ} \right\rangle$ drops below 1 per pulse. We assume that the signal for a millicharged particle of q/e < 7×10^{-4} is a single photoelectron, coming at a well defined arrival time. The short SLC bunch length and high current capability per bunch make SLAC an ideal place for this search.

VI. RESULTS

The pulse height spectrum from each of the four counters shows a clean single photoelectron peak. It also shows that the noise spectrum in the counter is dominated by single photoelectrons. We reduced noise in the counter by lowering the high voltage and using electronic amplification, shielding the counter from backgrounds, modifying the base to limit the current from very large light pulses, cooling the entire counter, and gating the counter off after large pulses. We achieved noise rates per counter of 4 kHz, considerably above the tube-only rates of ~100 Hz.

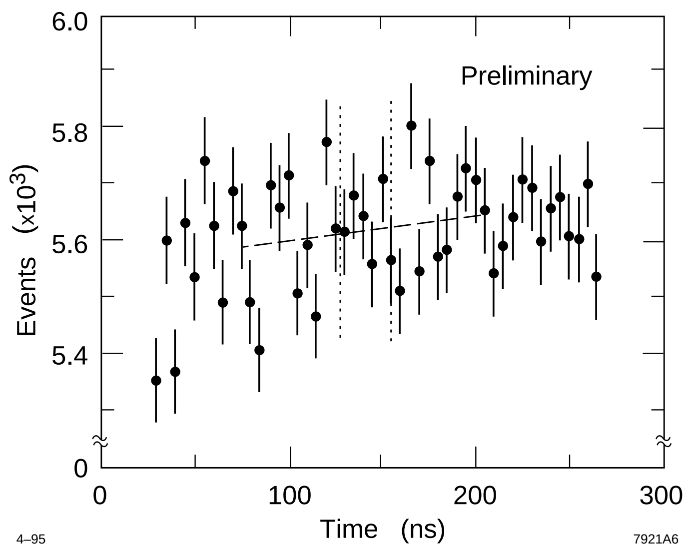

Figure 4. Timing distribution for pulses with single photoelectron pulse height. The dashed lines mark the expected arrival time window for single photo-electrons from millicharged particles.

The timing calibration for the mQ detector is derived from the observed muon time, a time-of-flight correction, a measured correction for cable length and tube transit time differences between the muon counters and the mQ detector, and a delay coming from the fact that a single photon signal arrives on average about 15 ns later than the timing signal from a mip (which is 40 thousand times larger). Eighty-seven per cent of the single photoelectron signal arrives in a 25 ns bin, which we use as the arrival time for the experiment.

The arrival times for pulses of single photo-electron pulse height are shown in Fig. 4, with markers indicating the calculated arrival time of the mQ signal. There is no sign of an excess of events in the appropriate timing window, or elsewhere in the plot. Using 50 ns wide sidebands above and below the signal region as a measure of the background, we find a net signal of 108±188 events, consistent with zero. Very conservatively, we can conclude that q/e < 6×10^{-5} for millicharged particles of 1 MeV mass. A detailed analysis is in progress.

VII. CONCLUSIONS

A dedicated experiment to search for millicharged particles below a mass of about 100 MeV has taken data parasitically during the 1994/1995 SLC run period at SLAC. This search has roughly 1 million times the experimental sensitivity of earlier experiments, which translates into a factor 30 more sensitivity to charge. A preliminary analysis shows no indication of millicharged particles with $q/e < 6\times10^{-5}$. Our search, which utilizes a low-energy signature, is also sensitive to other exotic particles that could be produced in the positron target and interact weakly in the detector.

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