Identifying dark matter is one of the most pressing open problems in fundamental physics. Although a rich experimental program continues to probe dark matter (DM) interactions for masses in the 10 GeV—TeV range, sensitivity to DM at lower masses remains remarkably poor. There are well-motivated scenarios of sub-GeV DM, especially those that include new gauge forces (“dark forces”) that kinetically mix with the photon—these models can account for the observed relic density consistently with all available data, and have been the focus of intense discussion in the literature [1].

In this note, we show that the electron beam dump millicharge search at SLAC (mQ) was sensitive to sub-GeV DM interacting through dark photons. In a simple model, we compute the total detection yield for MeV-scale DM components that would have been produced in the mQ target. We use these yields and the original mQ analysis to establish constraints on such DM. The new constraints cover part of the parameter space that can reconcile the apparent \( (g - 2) \), anomaly. Simple adjustments to the original SLAC search for millicharges may extend sensitivity to cover a sizeable portion of the remaining \( (g - 2) \) anomaly-motivated region. The mQ sensitivity is therefore complementary to on-going searches for visible decays of dark photons. Compared to existing direct detection searches, mQ sensitivity to electron-dark matter scattering cross sections is more than an order of magnitude better for a significant range of masses and couplings in simple models.

Previous literature has considered numerous constraints on sub-GeV DM derived from the CMB, supernovae, B-factory searches, rare Kaon decay measurements, and precision \((g - 2)\) and \((g - 2)\) measurements [2]. For comparison to the mQ sensitivity, we include the constraints relevant for the low \(m_{A'}\) range. A companion paper [2] discusses the viability of using the simple benchmark Lagrangian above to model fixed-target physics, where \(\chi\) can be all of or a sub-dominant part of the DM consistent with all available data.

In the mQ experiment, 1.35 Coulombs \((8.4 \times 10^{18} e^-)\) of 29.5 GeV electrons were deposited on a tungsten production target. Approximately 90 m of sandstone separated the target from the detector (Bicron-408 plastic scintillator), which was sensitive to signals as small as a single scintillation photon and subtended a solid angle of \(2 \times 2 \text{ mrad}^2\). SM particles essentially ranged out in the sandstone, while any penetrating particles like mQ’s were able to reach the detector and trigger a small scintillation signal [5]. Collected data consisted entirely of timing and height of PMT pulses. No significant signal was found over a rather large \((\sim 146\text{K})\) but well-measured instrumental background [7].

As illustrated in Figure 1, this setup would have produced significant numbers of \(A'\)’s in the target via a bremsstrahlung-like process. We examine the case of prompt invisible decay \(A' \rightarrow \chi \bar{V} \); the \(\chi\)’s would have traversed the sandstone given their large mean free path. The secondary beam of \(\chi\)’s could have deposited energy in the mQ detector via \(Z^2\)-enhanced elastic scattering off carbon nuclei (and sub-dominantly though quasi-elastic \(\chi\)-nucleon scattering, which we neglect).
Our analysis assumes $2m_{\chi} < m_{A'}$ (on-shell $A'$), but we expect this approach to have sensitivity even for $2m_{\chi} > m_{A'}$ where $\chi$’s are produced via an off-shell $A'$ (see [4]). We used the procedure in [4], based on a variation on the Weizsacker-Williams method, for computing $A'$ production. We also simulated all reactions using MadGraph and MadEvent 4 [8]. We assigned to the $e^+e^-A'$ vertex the coupling $e_{EM}e$, and to the $N_tN_\gamma\gamma$ vertex $e_{EM} Z t \eta$ (for target nucleus $N_t$ of atomic number $Z$, with $\eta$ the square root of the form-factor in [4].)

The typical emission angle for the $A'$ relative to the beam is parametrically smaller than the opening angle of $A'$ decay products, and is collinear to a good approximation. Neglecting $\gamma$,

$$\frac{d\sigma_{A' prod}}{dx} \approx \frac{8Z^2 \alpha^3 e^2}{3m_{A'}^2} x \times \log \left( \frac{3 + x^2}{1 - x} \right),$$  \hspace{1cm} (1)$$

where $Z$ is the atomic number of the target nucleus, $x \equiv E_{A'}/E_0$ with $E_0$ the lab-frame energy of the beam electron, and $\log$ is an $O(10)$ factor dependent upon kinematics, atomic screening, and nuclear size effects [4].

Since the angular size of the mQ detector was $\theta_d \approx 2$ mrad, angular acceptance limits overall sensitivity. Produced $A'$’s typically carry most of the beam energy, with $x_{\text{median}} \sim 1 - \min \left( \frac{m_{A'}}{m_{A'}}, \frac{m_{A'}}{E_0} \right) [4]$. In the $A' \to \chi \chi$ decay, the angle $\theta_{\chi}$ of the $\chi$’s relative to the beamline scales as $\frac{m_{A'}}{E_0}$. The angular distribution of $\chi$ is shown in Figure 2 for reference.

For the coherent scattering illustrated in Figure 1 we assigned the $N_tN_\gamma A'$ vertex the coupling $e_{EM} Z d \eta e$ (for detector nucleus $N_d$ carbon.) With $T$ the lab-frame kinetic energy of the recoiling nucleus of mass $M \ll T$, the coherent scattering cross-section (neglecting $\eta$) is approximately

$$\frac{d\sigma_{\chi N \text{scatt}}}{dT} \approx -\frac{8\pi \alpha^2 e^2 Z^2 M}{(m_{A'}^2 + 2MT)^2}.$$  \hspace{1cm} (2)$$

The recoil distributions in full simulation for representative $m_{A'}$ are shown in Figure 3. The nuclear recoil energy is typically $O(0.025 - 1.0)$ MeV. Based on neutron scattering experiments with plastic scintillator, a proton recoiling with kinetic energy 1 MeV should produce $\sim 59$ PEs, and 0.1 MeV $\sim 2.3$ PEs. The quenching factor for a C nucleus is about half that for a proton [9]. Therefore a 1 MeV recoiling C should produce $\sim 30$ PEs, and 0.1 MeV $\sim 1$ PE. Figure 3 shows that with a $\sim 0.1$ MeV threshold for producing a PE, about 20% of the $\chi$-C threshold would produce at least a single PE at $m_{A'} = 0.03$ GeV, and 90% at $m_{A'} = 0.25$ GeV.

In finding the total number of $\chi$ produced in the target, we can neglect $\chi$ production in lower energy showers initiated by
the beam electron because the angular acceptance of mQ is small. To account for the more important effect of the energy loss of the beam $e^-$ as it traverses the target, we use an “effective” radiation length of $T_{\text{eff}} = 1$. This can be justified as follows. For the small angular size of mQ, the angular acceptance scales as $E^2$ (for low $A'$ masses), where $E$ is the beam electron energy. Thus, the $E^2$-weighted average of the beam energy distribution integrated over the thickness of the target (6 radiation lengths) and energy yields an effective thickness (in units of radiation length). Using the beam energy distribution $I(E, E_0)$ in [4], we obtain $T_{\text{eff}} = \int ds \int dE(E/E_0)^2 I(E, E_0, s) = \frac{2}{3} \ln 2 \approx 1$. To a good approximation, the differential production yield for fixed $\chi$ energy $E_{\chi}$ is

$$\frac{dN_{\chi}}{dE_{\chi}} \approx 2T_{\text{eff}} \frac{N_e N_0 X_0}{A} \frac{d\sigma_{\chi \text{prod}}}{dE_{\chi}} \quad (3)$$

where $N_e$ is the total number of beam $e^-$ incident on target, $N_0$ is Avogadro’s number, $X_0$ is the unit radiation length of target material, and $A$ is the target atomic mass. The differential production cross section at fixed $\chi$ energy, $d\sigma_{\chi \text{prod}}/dE_{\chi}$, was computed with full simulation. To find the number of expected $\chi-N_Q$ scattering events in the mQ detector, $N_{\text{evts}}$, we include angular acceptance cuts with full simulation, which reduces $N_{\chi}$ to $N_{\chi \text{ acc}}$. The final yield is then

$$N_{\text{evts}} = \int dE_{\chi} \frac{dN_{\chi \text{ acc}}}{dE_{\chi}} \sigma_{\chi \text{ scatt}}(E_{\chi}) t_{\text{Det}} \rho_{\text{Det}}, \quad (4)$$

where $t_{\text{Det}}$ is the detector thickness, and $\rho_{\text{Det}}$ is the number density of C nuclei in the detector.

An order-of-magnitude estimate can be obtained by $N_{\chi \text{ acc}} \approx 2N_e P_{\text{prod}} P_{\text{scatt}} F$, where the probability per beam $e^-$ to produce a $\chi$ pair is

$$P_{\text{prod}} \approx 1.2 \times 10^{-11} \left(\frac{\epsilon^2}{10^{-6}}\right) \left(\frac{0.05 \text{ GeV}}{m_{A'}}\right)^2,$$

the probability of $\chi$-$C$ coherent nuclear scattering is

$$P_{\text{scatt}} \approx 2.5 \times 10^{-8} \left(\frac{\epsilon^2}{10^{-6}}\right) \left(\frac{0.05 \text{ GeV}}{m_{A'}}\right) \frac{\alpha_D}{\alpha_{EM}},$$

and $F \sim (\theta_d E_0/m_{A'})^2$ is the fraction of $\chi$’s that pass angular acceptance cuts. Table I gives the simulated cross-sections and production totals, along with the corresponding analytical estimates, for one example set of parameter values – the agreement is quite good.

Using five “benchmark” points with $m_\chi = 0.01 \text{ GeV}$, in the $m_{A'} = 0.03 – 0.25 \text{ GeV}$ range, we evaluated the limits in the $(m_{A'}, \epsilon)$ parameter space by comparing total yields to single PE mQ background measurements. The mQ data analysis estimated $\sim 94\%$ of the 146061 background events involved only a single PE [7]. For $m_{A'} > 100 \text{ MeV}$, scattering events should produce much more than one PE, so it should be possible to use a PMT pulse-height cut to help separate $\chi$ signal from background. It is reasonable to expect such a cut to improve S/B by at least an order of magnitude in the higher $m_{A'}$ range because the vast majority of the background is single PE noise. Figure 4 shows the $2\sigma$ constraints that would be obtained for $m_\chi = 10 \text{ MeV}$ with no background reduction, and with $100\times$ the reported S/B. Note, Figure 4 assumes every scattering event in the detector produces at least one photoelectron and is observed. Losses from failure to produce any PEs could reduce sensitivity by a factor of $\sim 2$ in the lowest ($\sim 30 \text{ MeV}$) part of the $m_{A'}$ range.

Given significant background reduction, mQ would be able to cover a sizeable swath of unexplored parameter space, including part of the $(g - 2)_\mu$ anomaly-motivated region for $m_{A'} \sim 0.03 – 0.160 \text{ GeV}$. It should be noted that there is currently a MiniBooNE proposal for future running specifically to cover this range [10]. Likewise, LSND could likely impose constraints at the level of $\epsilon \sim 10^{-4} – 10^{-3}$ for $m_{A'} < O(100 \text{ MeV})$, $m_\chi \ll \frac{m_{A'}}{2}$ though no analysis is yet publicly available.

Our analysis results can be interpreted as constraints on electron-$\chi$ scattering cross sections $\sigma_\epsilon$, which can also be probed by direct detection. Recent results from XENON10 established limits on $\sigma_\epsilon$ as a function of DM mass in the $1 – 1000 \text{ MeV}$ range [11]. Using “benchmark” points shown in Figure 5, we employed mQ constraints on $(m_{A'}, \epsilon)$ to establish constraints on $\sigma_\epsilon$ via $\sigma_\epsilon = \frac{16\pi G F M_D m_{A'}^3}{m_{A'}^2}$. If $\chi$ accounts for all the DM, mQ sets limits more stringent than XENON10 for $m_\chi < 20 \text{ MeV}$, $\chi$ could instead be a sub-dominant DM component, in which case XENON10 constraints are weakened.

It is convenient to consider mQ because the data already exists – but this experiment was not optimized for light DM searches. Characteristics that would make future $e^-$ beam-dumps even more effective for this purpose include optimal sensitivity to quasi-elastic $\chi$-nucleon processes, broader angular acceptance, greater luminosity, and an effective background-rejection scheme [2]. The main backgrounds are typically intrinsic detector noise, cosmic rays, $\gamma$’s from ambient radioactivity, and fast neutrons (produced from the target). Neutral-current $\nu$ interactions are negligible [7]. As an exercise, each benchmark point in Figure 4 was

| Quantity | Simulated Value | Analytic Estimate |
|----------|-----------------|------------------|
| $\sigma_{\chi \text{prod}} \quad [\text{pb}]$ | 37722 | 38000 |
| No. $\chi$ produced | $1.39 \times 10^{10}$ | $1.42 \times 10^{10}$ |
| $F$ | 0.52 | 0.60 |
| $\sigma_{\chi \text{scatt,rel}} \quad [\text{pb}]$ | 3950 | 4200 |
| No. scattering evts | 189 | 239 |
re-calculated for a luminosity of $10^{22}$ electrons, with no angular acceptance cuts. This luminosity could be reasonably achieved at a facility such as Jefferson Laboratory or a future Linear Collider. Sensitivity to 500 signal events for example (realistic for $>>1$ PE yield signals), would cover an impressive swath of parameter space (dotted line in Figure 4).

In conclusion, we find the SLAC mQ search is indeed relevant for exploring the parameter space of models where a dark photon of mass $\sim 30-300$ MeV decays to lighter, long-lived $\chi$'s. This includes a parameter region in which dark photon models can alleviate the current $(g-2)_\mu$ discrepancy, and adjustments to the original SLAC analysis are expected to strengthen the constraints – or make a discovery – in this region. In a broader context, our analysis provides a proof-of-concept for the use of $e^{-}$ beam-dumps to search for DM particles with masses of tens to hundreds of MeV, a regime that poses great difficulty for direct detection and collider experiments. In simple models, we find that mQ constrains the DM-electron scattering cross-section $\sigma_{e}\lesssim 10^{-38}-10^{-37}$ cm$^2$ for $m_\chi \sim 10-40$ MeV – up to an order of magnitude stronger than the leading direct-detection limits where applicable.

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FIG. 4. For each benchmark $m_{A'}$ with $m_{\chi} = 0.010$ GeV, the $\epsilon$ that would correspond to a $2\sigma$ result in SLAC mQ. Note the dependence on $\alpha_D$, and the improvement that would come from achieving $100\times$ the reported mQ S/B. These results change fairly little with $m_\chi$. Overlaid on existing $A' \rightarrow inv$ constraints; $(g-2)_{\mu}$ is a $2\sigma$ power constrained limit [2]. Yellow band: $(g-2)_{\mu}$ anomaly-favoured [12]. Note, LSND would be expected to provide additional constraints, at the level of $\epsilon^2 \sim 10^{-6}-10^{-8}$ for $m_{A'} \lesssim 0.05$ GeV.

FIG. 5. For benchmark $m_{\chi}$ with $m_{A'} = 0.10$ GeV and $m_{A'} = 0.05$ GeV ($\alpha_D = \alpha_D^{10}$), the constraints on scattering cross-section of DM off $e^{-}$ corresponding to a $2\sigma$ result in mQ, assuming the reported mQ signal-to-background. Overlaid on the XENON10 direct detection results [11]; direct comparison valid only assuming $\chi$ accounts for all the DM in the universe.