Searching for New Physics at the TRIUMF ARIEL Electron-Linac

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Abstract

The DarkLight experiment S2134 at the ARIEL electron-linac at the TRIUMF laboratory is being carried out by an international collaboration and has opened up the possibility to realize a new, unique North American program in high intensity, low-energy electron scattering. The S2134 experiment is under construction with first data taking anticipated in 2024. Meanwhile, a workshop to explore additional scientific opportunities using ARIEL was held at TRIUMF in May 2022. In this whitepaper, we describe the DarkLight experiment and present a number of opportunities to explore new physics beyond the Standard Model that originated in discussion at the workshop. These have also been considered in the Snowmass 2021 process [1, 2].

I. INTRODUCTION

The Advanced Rare Isotope Laboratory (ARIEL), now under construction [3], will extend TRIUMF's existing isotope program, enabling world-class research on the nature of atomic nuclei, the origin of the heavy chemical elements, and contributing more broadly to nuclear medicine, materials science, and nuclear and particle physics research. ARIEL is driven jointly by the TRIUMF cyclotron and by a newly constructed superconducting electron accelerator (e-linac) which will enable isotope production via photo-production and photo-fission. Designed to provide a continuous, 10 mA beam with energies up to 30 MeV (300 kW), and with several upgrade paths available (see T. Planches's contribution in [4]), this e-linac can also enable new physics programs independently of the ISAC facility, both in its current form and through those upgrades.

In March 2021, the DarkLight collaboration submitted a new research proposal S2134 to *Search for New Physics in* e^+e^- *Final States with an Invariant Mass of 10-20 MeV Using the Ariel Electron Accelerator* to the TRIUMF laboratory, Vancouver, Canada [5]. Proposal S2134 was reviewed by the TRIUMF Particle Physics Experiment Evaluation Committee at its meeting in April 22, 2021 and approved for 1300 hours with high priority. S2134 is being carried out [6] by a collaboration from the U.S., Canada and Germany, and will be constructed and installed in 2023 with data taking is anticipated to commence in 2024.

In May 2022, a workshop to explore new scientific opportunities at the TRIUMF ARIEL electron-linac was held at TRIUMF, Vancouver, Canada [4]. It identified opportunities across hadronic structure, nuclear astrophysics, nuclear structure and applications. However, here we restrict to the scientific opportunities to search for new physics beyond the Standard Model. Beyond the DarkLight@ARIEL experiment discussed in sections 2-4: in section 5 possible QED tests are discussed; in section 6, possible searches for dark matter and BSM physics are presented.

II. SCIENTIFIC MOTIVATION FOR THE DARKLIGHT@ARIEL EXPERIMENT

Recently, there has been a focus in both experimental and theoretical physics communities on a mediator of a new fifth force with mass lower than 1 GeV/c^2. In addition to cosmological motivations, observed anomalies in measurements involving the muon and nuclear transitions hint at this possibility. For example, the observed 4.2σ deviation between the measured and expected anomalous magnetic moment of the muon [7] can be explained by a fifth force mediator with mass in the range 10 to 100 MeV [8]. The search for a dark photon has been extensively covered through the study of π^0-decay and much of the parameter space of coupling and mass that corresponds to these anomalies is excluded at 2σ [9]. However, it is not required that a potential dark sector coupling must be directly proportional to the electric charges, so a more general fifth force can not yet be ruled out.

It is possible to adjust the quark couplings of a fifth force to satisfy existing constraints and still allow such a force acting via lepton coupling to be experimentally detected. In addition to the muon g-2, other recently-reported experimental signatures motivate focused searches for a fifth force carrier at low energies. A group studying the decays of excited states of ^{8}Be and ^{4}He to their ground state have found a 6.8σ anomaly in the opening angle and invariant mass distribution of e^+e^- pairs produced in these transitions [10–12] (The ATOMKI anomalies). While these discrepancies may be the result of experimental effects or unidentified nuclear transitions, they are also consistent with the production of a new boson with a mass around 17 MeV/c^2 (the X17 particle).

New bosons that couple atomic electrons with neutrons in the nucleus are also implicated in atomic physics experiments. The effect of this new interaction on energy levels and transition frequencies could be detected through precision isotope shift measurements. In particular, the scaled isotope shifts of two different transitions should exhibit a linear relationship (the so-called *King plot*). A deviation from linearity may arise to a small degree from Standard Model effects, but can be evidence of a new force mediator. Such deviations

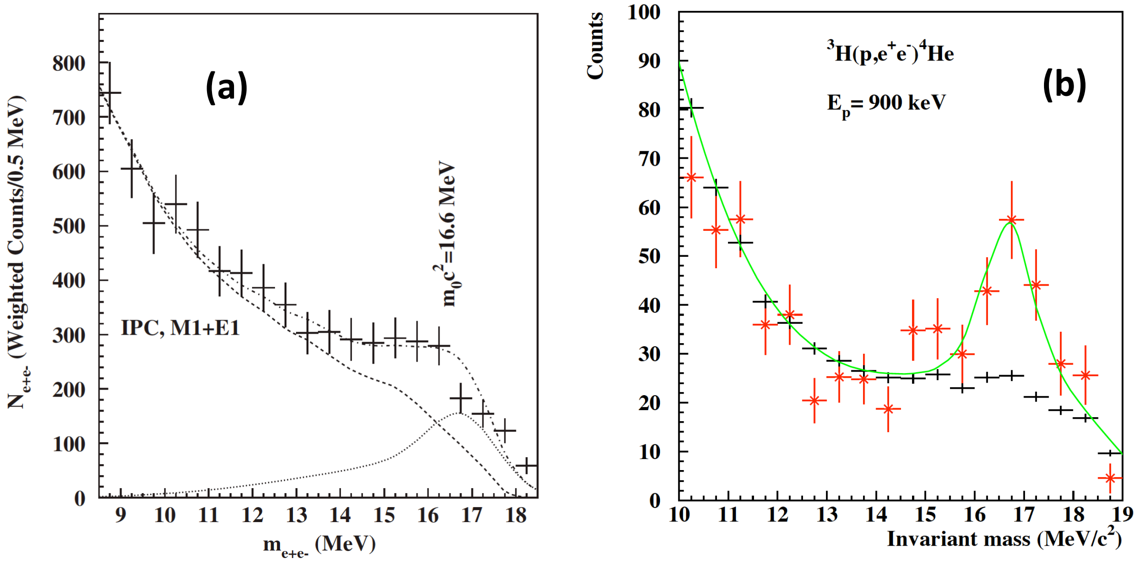

FIG. 1. (a): Anomaly in ^{8}Be [10]. (b): Anomaly in ^{4}He [12].

at the 3σ level have been reported [13] in the isotope shifts for five Yb^+ isotopes on two narrow optical quadrupole transitions $^2S_{1/2} \rightarrow {}^2D_{3/2} \rightarrow {}^2D_{5/2}$.

Motivated by these developments, we have designed the DarkLight experiment to use the future 50 MeV electron beam from the e-linac driver at the Advanced Rare IsotopE Laboratory (ARIEL) to search for evidence of the reported ATOMKI anomaly in e^+e^- final-states.

A. Beyond the Standard Model Interpretations

It has been shown that different couplings to quark and lepton flavors could reconcile the ATOMKI anomalies; different u and d couplings that produce protophobic or nearly protophobic interactions would satisfy current limits [14]. In light of that observation, the X17 anomaly has been interpreted in various more specific theoretical models as a new particle, a Z', axion, or other light pseudoscalar [15–18]. There are also several proposed explanations for the X17 particle within the standard model framework arising from higher order effects [19–21].

III. DARKLIGHT EXPERIMENT DESIGN AT ARIEL

The beam energy at the ARIEL e-linac is relatively low, currently 31 MeV, but will be upgraded to 50 MeV. The advantage of the low beam energy is the smaller boost given to the produced e^+e^- pairs from the decay of the X17 boson, which in turn corresponds to a large opening angle between them. The proposed experiment takes advantage of these larger angles. DarkLight will run with a two spectrometer setup, optimized for the 17 MeV/c^2 invariant mass region. The spectrometers will be placed asymmetrically around the fixed foil target located in the beam line. The proposed experiment will measure the process e^- Ta $\rightarrow e^-$ Ta $X \rightarrow e^-$ Ta (e^+e^-) as a resonant excess of e^+e^- pairs on top of the QED background at the invariant mass of the X17.

A. The Electron Accelerator

TRIUMF's existing superconducting electron linac can currently produce an electron beam of up to 31 MeV in energy and peak intensities up to 3 mA. As a driver of ARIEL the e-linac is designed to deliver electrons to a photo-converter target station for the production of neutron-rich rare isotope beams via photo-fission. For testing and production running at 31 MeV, the experiment will be placed in front of the existing 10 kW beam dump (position A in Fig. 2). The linac will be operated in a continuous wave mode, with a bunch frequency of 650 MHz, and an average beam current of up to 300 µA. As this configuration involves minimal modifications to the beam line, data taking could commence in 2023.

The TRIUMF e-Linac is planning an upgrade to the overall beam energy deliverable to ARIEL. The approach to reach 50 MeV involves the installation of a second superconducting cavity and cryomodule. The cavity could be installed early/mid 2024, and production data taking for DarkLight at 50 MeV can commence late 2024.

After this upgrade, a new 50 kW beam dump will be installed, and the experiment will move to Position B in Fig. 2. In order to facilitate simultaneous data taking with DarkLight and the rare isotope laboratory, a septum magnet and RF deflector will be added. The increased beam energy available will allow DarkLight to perform a comprehensive search of the parameter space of the X17.

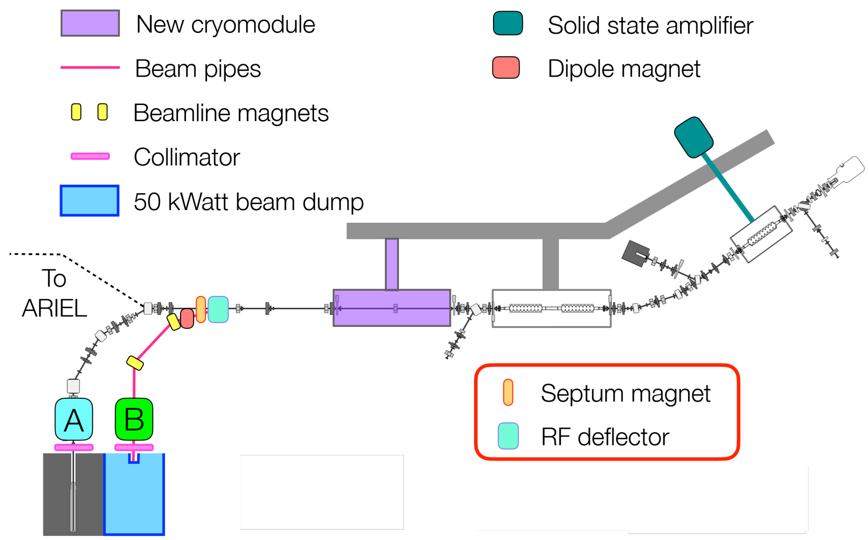

FIG. 2. Floorplan of the ARIEL linac. For the first measurements at 31 MeV, the experiment will be placed in the area marked A. For 50 MeV beam, it will be moved to position B. The septum magnet and RF deflector enables concurrent beam delivery to ARIEL and DarkLight.

B. Target

The experiment design assumes several beam energies, ranging from 30 MeV to 50 MeV, with a current of 150 µA. It will impinge on a 1 µm tantalum foil. This produces an instantaneous luminosity of $\mathcal{L} = 5.2\,\mathrm{nb}^{-1}\,\mathrm{s}^{-1}$, and will cause a beam spread of approximately $0.5°$ downstream of the target.

The beam will heat up the foil with about 0.4 W, which can be dissipated via radiation for typical beam spot sizes. Also under consideration is a spinning foil disc target, linked to the accelerator Fast Shutdown, to protect against accidental melting.

C. Spectrometers

The experiment will measure final state e^+e^- pairs using two dipole spectrometers, with very similar magnetic characteristics, to be built by MIT/Bates. The magnetic design and pole shapes of the spectrometer have been completed. Currently the mechanical design of the supports and coils are being finalized. Both spectrometers will be designed to nearly the same specifications, presented in Table I.

The two spectrometers share a common design but will be operated at different currents

TABLE I. Design parameters for the spectrometers.

In-plane acceptance	$\pm 2^\circ$
Out-of-plane acceptance	$\pm 5^\circ$
Momentum acceptance	$\pm 20\,\%$
Minimum central angle	16°
Maximum central momentum	28 MeV
Dipole field	0.32 T
Nominal bend radius	30 cm
Pole gap	4 cm

to produce the desired magnetic fields. They are conventional iron-core magnets with simple, planar coils. The magnet design and pole face rotations were optimized for a 0.5 m distance from target to spectrometer entrance and for post-magnet trajectories suitable for tracking with 40 cm long GEMs. The final engineering of the magnet will include detailed design optimization to increase magnetic performance, minimize size, and maximize clearance to the exit beamline. The magnets in its present configuration weigh about 950 kg each. The magnets will have full fiducialization to allow for laser tracking alignment and a six-strut mechanical support system to allow for 200 µm alignment (similar to other MIT-Bates designs). The focal plane of each spectrometer will be instrumented with triple-GEM detector planes followed by trigger scintillators. A 3D CAD rendering of the experiment and spectrometers is shown in Fig. 3.

GEM detectors: Each spectrometer will be instrumented with an identical tracking detector system consisting of triple-GEM elements with an active area of 25x40 cm^2, which have been built by Hampton University. These modules have two-dimensional APV front-end readout cards with 400 μm pitch between strips. The APVs are read out into Multi-Purpose Digitzer front-end cards. They were constructed using the so-called NS2 scheme [22]. A similar system of these GEMs+APVs+MPDs has recently been mass-produced for the Super-Bigbite Spectrometer (SBS) construction at Jefferson Lab. The existing GEMs can be tested and commissioned with cosmics within 9-12 months.

Trigger Hodoscopes: The standard GEM readout requires a trigger signal. This will

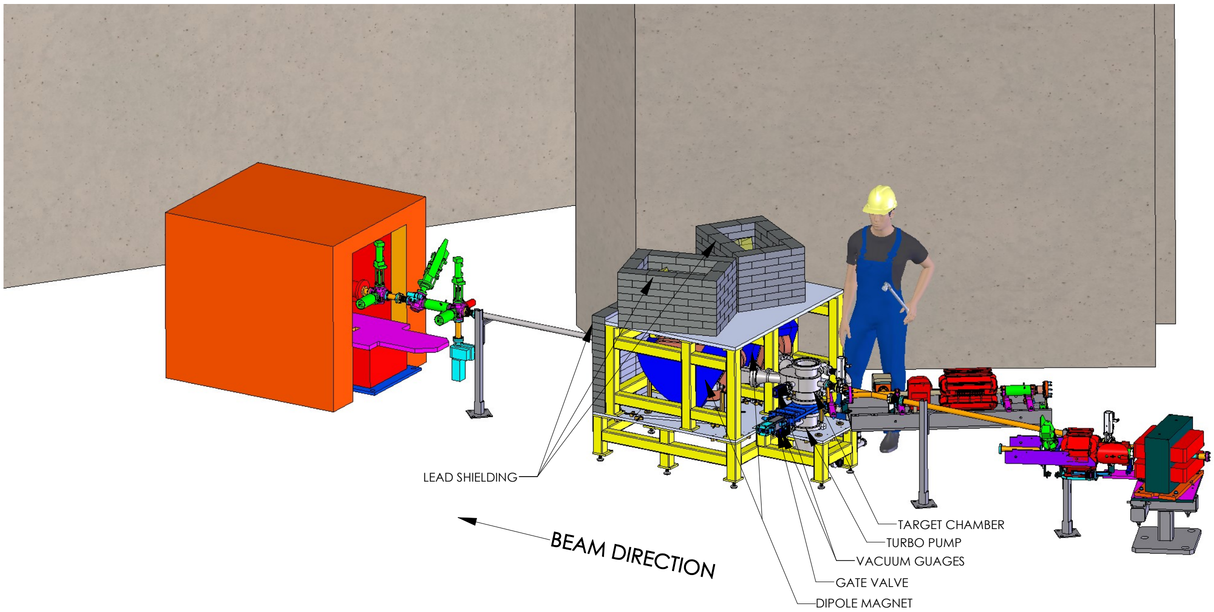

FIG. 3. 3D CAD rendering of the conceptual design, with part of the shielding. Additional shielding around the target is anticipated. The exit beam line will be conical (6 cm radius at 3 m distance) to allow for the increased beam width from the target interaction.

be generated from the coincidence of two fast trigger detectors in the spectrometers. To reduce accidental coincidences in the trigger logic, it is important to resolve the beam bunch clock of 650 MHz in the analysis. This high-resolution timing information must be provided by the trigger detector. When performing offline analysis, the timing can be corrected by the particle path length reconstructed from the tracking detector information. However, to reduce readout dead-time and data volume, it is important to be close to the ideal timing during data-taking. The main time dispersion is generated by the momentum-dependent dispersion inside the spectrometers. We therefore propose a trigger detector made from scintillator paddles, divided along the dispersive direction into 10 segments, each end read out by SiPMs.

The scintillator paddles will be made from a standard plastic scintillator material and have a size of about 150x30x2 mm^3.

IV. PROJECTED REACH OF DARKLIGHT@ARIEL

The shape of the background is dominated by the overall acceptance, so the irreducible background and random coincidences are similar. To estimate the total background, we can scale the irreducible background up according to the predicted rates. The reach is calculated by integrating the background over the expected signal width ($\pm 1.7\sigma$), and calculating the fifth force coupling (ϵ^2) such that the signal would be bigger than a 2σ fluctuation of the background.

If ϵ^2 is small enough the signal may not be visually detectable on top of the background. Given the excellent statistical precision of the experimental background it will still be possible to detect fluctuations corresponding to a signal in the analysis.

Since random coincidences dominate the background, the pure random background will be very accurately measured by the experiment itself by mixing electron and positron spectrometer data from different events. This mixing destroys all correlations between the spectrometers, generating a pure sample of the random coincidences. Since, in principle, every combination of uncorrelated events can be used, the available statistics for the background measurement grows quadratically with the recorded number of events.

It is worth noting that at the kinematics and beam conditions of the experiment, the random coincidence background dominates, and scales with $\mathcal{L}^2$. The figure of merit (FOM) is given by the number of signal events divided by the square root of the background. This means in a regime where the random background dominates the FOM is independent of the instantaneous luminosity. The reach of the experiment depends only on the measurement time.

Figure 4 shows the achievable reach for the four settings assuming 1000 hours beam-time each. The precise optimization of the experimental reach is still in progress.

V. QED TESTS

A. Threshold Positron Production

In both pair and triplet production a positron and electron are produced spontaneously as a photon interacts with a strong electric field from either a nucleus (pair production) or

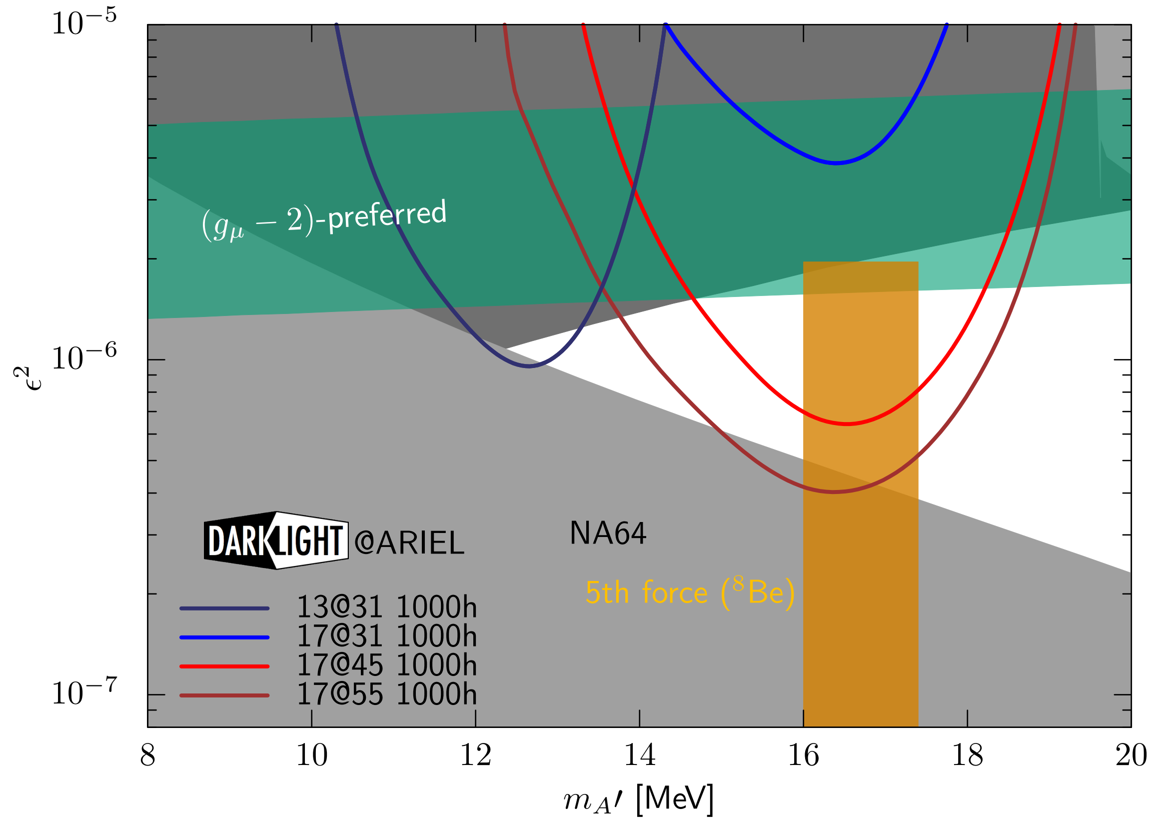

FIG. 4. The projected reaches on a linear plot for three separate data taking runs: 13@31 (dark blue) – a 1000 h run at 31 MeV optimized for $m_{A'}$ = 13 MeV; 17@31 (light blue) – a 1000 h run at 31 MeV optimized for $m_{A'}$ = 17 MeV; 17@45 (light red) – a 1000 h run at 45 MeV optimized for $m_{A'}$ = 17 MeV; 17@55 (dark red) – a 1000 h run at 55 MeV optimized for $m_{A'}$ = 17 MeV. Light gray areas are excluded by other experiments sensitive to a lepton coupling. The dark gray area is excluded by electron g-2 only.

an electron (triplet production) as shown in Fig. 5.

The threshold electron beam energy for these effects to take place is

$$(h\nu)_{\text{min}} = 2m_0c^2\left(1 + \frac{m_0}{M}\right) \ , \tag{1}$$

where m_0 and M are the incident electron and target masses, respectively and

$$M \ \equiv \ M_{\text{nucleus}} >> m_0 \text{ (pair production)} \tag{2}$$

$$M \ = \ m_0 \text{ (triplet production)} \ . \tag{3}$$

The mean kinetic energy given to each of the two particles is half of the available kinetic energy T_{avail} (actually the positron gets a bit more energy because of the push from the

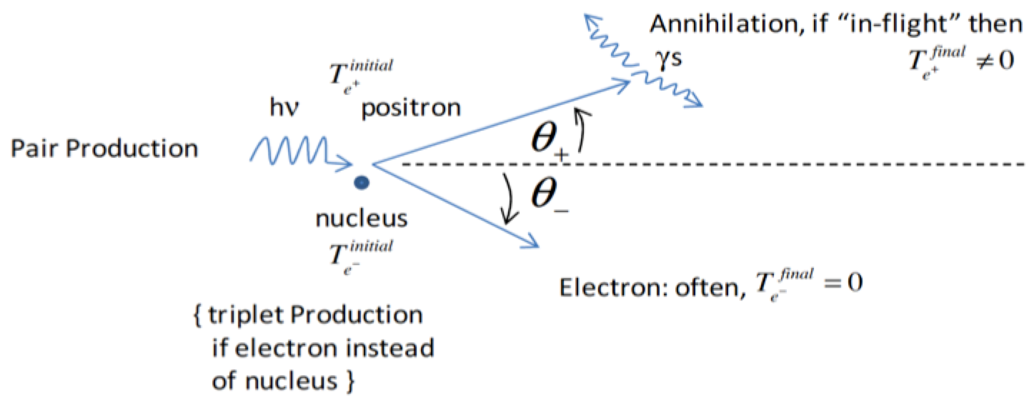

FIG. 5. Pair and triplet e^+e^- production from an atom.

positively charged nucleus). The mean angle given to each of the two particles with respect to the incident electron directions is

$$\overline{\theta}_\pm = \frac{2m_0c^2}{T_{avail}} \ . \tag{4}$$

The $1/T$ dependence is similar to bremsstrahlung: higher energy particles get more forward directed.

Bethe and Heitler [23] derived the cross section per atom for **pair production** as

$$\frac{d\kappa_a^{pair}}{d\overline{T}_\pm} = \sigma_0 \frac{Z^2}{T_{avail}} P \ , \tag{5}$$

where P is a function shown in Fig. 6, Z is the nuclear charge and $\sigma_0 \equiv \frac{r_0^2}{137} = 4.8 \times 10^{-28}\text{cm}^2/\text{atom}$.

In the case of **triplet production**, the electric field is now from an electron, a very light particle, which becomes indistinguishable from the created particle. The mean kinetic energy given to each of the three particles is now one-third of the available kinetic energy. The threshold is now $4m_0c^2$. The triplet production cross section is related to the pair production cross section as

$$\kappa_a^{triplet} = \kappa_a^{pair} \cdot \frac{1}{CZ} \ , \tag{6}$$

where $C \approx 1$ and has no Z dependence.

Measurements have been reported [26–29] with sporadic sightings of triplet events. The first definitive observation of triplet production was in 1972 [25] using a streamer chamber

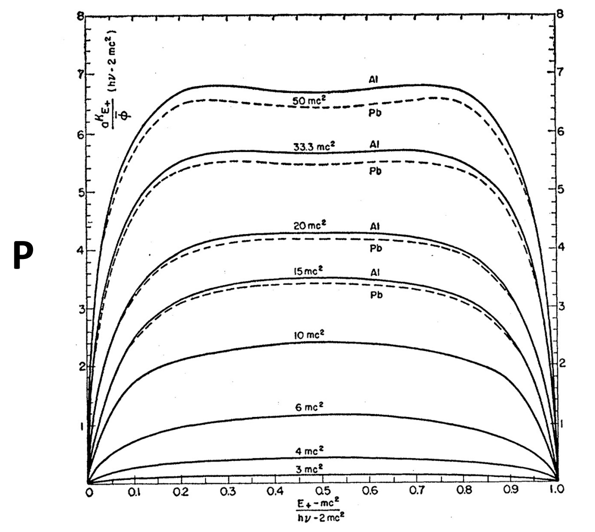

FIG. 6. P vs. kinetic energy fraction given to the positron from [24]. Notice the symmetry: energy not given to the positron is given to the electron and vice-versa.

(Fig. 7). At ARIEL, such an experiment could be mounted as well. With 2 μA of 2.5 MeV electron beam on a 5 micron thick carbon foil (luminosity = 3×10^{33} cm^{-2} s^{-1}) the rate of positrons produced via the triplet mechanism is estimated (using [25]) at about 2 Hz into a spectrometer of solid angle 1 msr. This should allow much more precise measurements of positrons at threshold than previously possible. Clearly, low electron beam energies of order 1-3 MeV are required.

B. Radiative Møller Scattering

Møller (electron-electron) scattering is a background in electron scattering experiments, and is a purely QED process at low energies. It is theoretically straightforward to calculate, and has been so for decades. However, a modern retrospective has revealed gaps in previous treatments, particularly the omission of the electron mass in the calculation of the radiative diagrams shown in Fig. 8. Corrections due to these diagrams are typically included as a multiplicative factor to the Born cross section:

$$\frac{d\sigma}{d\Omega}|_{\rm soft} = (1+\delta)\frac{d\sigma}{d\Omega}|_{\rm Born} \ , \tag{7}$$

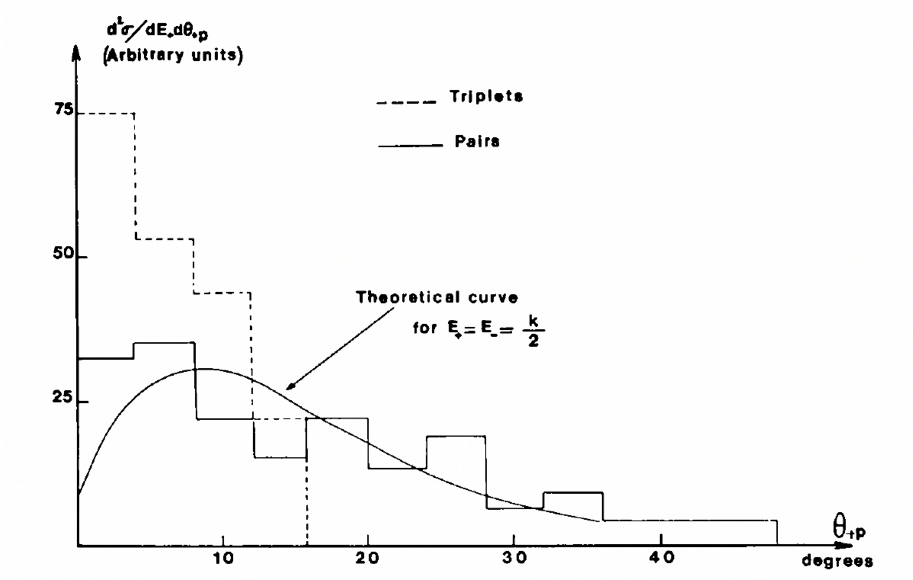

FIG. 7. Positron angular distribution relative to the projected emission angle from [25]. Experimental histograms are given for triplet and pair production. The theoretical curve is plotted for pair production.

with $\delta = \delta(\Delta E, \Omega)$. This traditional method requires defining a cut-off ΔE, the maximum amount of energy a photon can carry away for which the event passes acceptance cuts. For an experiment having spectrometers with small, well-defined energy and angular acceptances, this formulation of the radiative corrections can be applied straightforwardly.

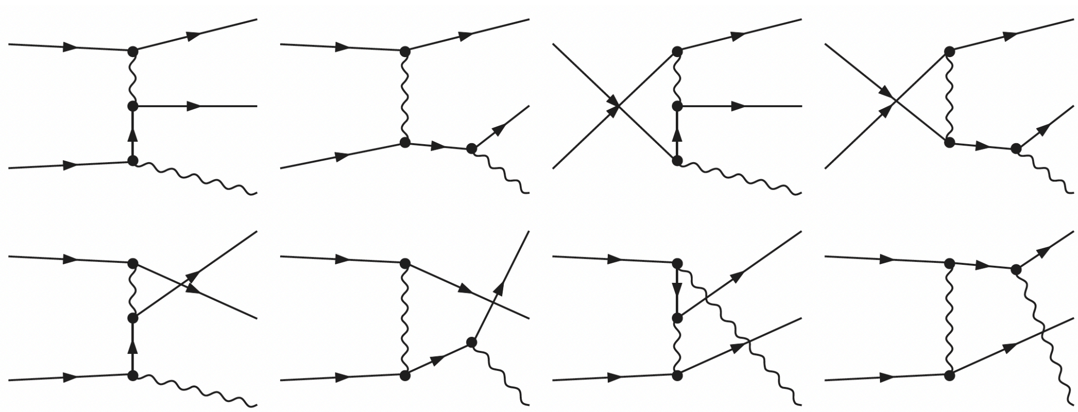

FIG. 8. Feynman diagrams for radiative Møller scattering.

Radiative corrections for hard-photon bremsstrahlung emission in both Møller and Bhabha scattering have been performed [30] in a consistent approach without ultrarelativistic approximations and permit a complete analysis at next-to-leading-order.

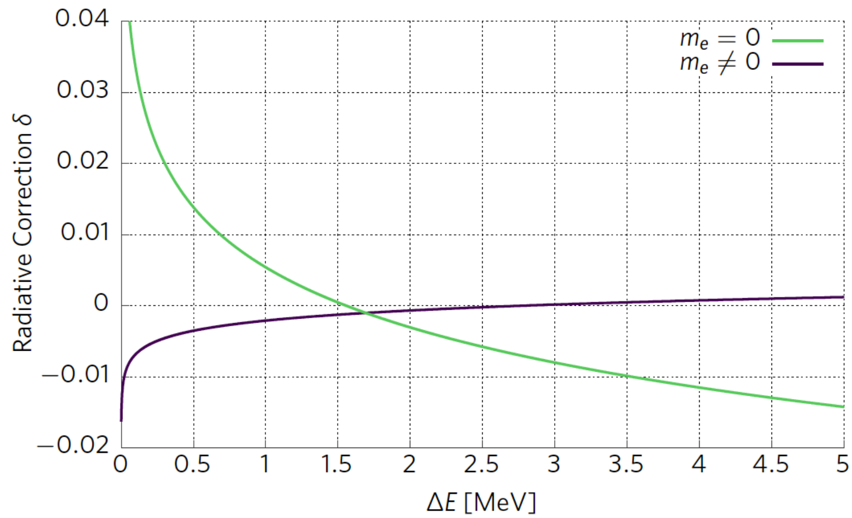

FIG. 9. Comparison of the Møller radiative correction term δ for a 100 MeV electron beam at 5° in the CM frame for different electron masses from [30].

Measurement of radiative Møller scattering as a function of energy between 10 and 100 MeV is highly desirable to validate the correction procedure. This has been carried out at 2.5 MeV (where radiative effects are negligible) using a focusing spectrometer [31] by the DarkLight collaboration. The desired measurements can be straightforwardly carried out using the ARIEL electron linac with the apparatus proposed for the DarkLight experiment.

VI. SEARCHES FOR DARK MATTER AND BSM PHYSICS

A dark sector search is already being undertaken at the ARIEL e-linac by the DarkLight collaboration, so it is natural to explore related searches that might be done with the same accelerator. The physics scope for the ARIEL e-linac is limited by its maximum energy of 50 MeV, and it is important to note that the low-energy dark sector landscape in both visible and invisible final states is well populated by a range of existing experiments. Finding a new area where an experiment at TRIUMF can make a strong contribution depends on either identifying an uncovered niche outside of the benchmark simplified models typically used by the field, as DarkLight did with protophobic bosons [32], or by taking advantage of the ARIEL e-linac's unique strength: the high intensity of its beam. The clearest opportunities presented are, e.g. rare processes at low mass which are too time-consuming to probe with lower intensity beams, or for which the low energy allows for some particular access to challenging kinematics or limits SM backgrounds. In what follows we offer concrete examples that illustrate the possibilities.

A. Delbrück Scattering to Search for Dark Photons of sub-MeV in Mass

A dark photon, the boson A' associated with a U(1) gauge symmetry of a dark sector [33], can mix with the SM photon with strength ε, with $\varepsilon \ll 1$, to produce millicharged couplings, namely, $\mathcal{L}_{\rm mix} = \varepsilon A'_\mu J^\mu_{\rm EM}$, with the electromagnetically charged fermions of the SM. The nature of this "portal" interaction between the dark and visible sectors allows an enormous range of dark photon masses and mixing parameters to appear, and we must look to experiment to constrain the possibilities. Studies in e^-e^+ collisions [34, 35] have been very effective in limiting the parameter space for dark photons in excess of $2m_e$ in mass, and there are a broad sweep of astrophysical and cosmological constraints as well [36, 37]. However, if the dark photon mass $m_{A'}$ satisfies $m_{A'} \lesssim 2m_e$, then its mixing with the photon guarantees that the decay $A' \to 3\gamma$ can occur, though the dark photon in this case can be quite long-lived, because the decay is a one-loop process with a rate that scales as $\varepsilon^2\alpha^4$.

Nevertheless, there may be discoverable phase space yet to explore [38]. This conclusion largely stems from a proper assessment of the decay rate: Earlier work computed the decay rate in the Euler-Heisenberg limit [39], which assumes that $m_{A'} \ll m_e$, but the exact one-loop calculation yields a result some 10-100 times larger if $850\,\text{keV} \lesssim m_{A'} \lesssim 1\,\text{MeV}$, shortening the dark photon lifetime and altering the excluded phase space significantly [38]. Referring to Fig. 4 of [38], we note that $850\,\text{keV} \lesssim m_{A'} \lesssim 1\,\text{MeV}$ and $10^{-5} \lesssim \varepsilon' \lesssim 10^{-4}$ represents an interesting window of opportunity [38], with constraints coming from big-bang nucleosynthesis, which would appear to demand $\tau_{A'} < 1\,\text{sec}$, and from the anomalous magnetic moment of the electron, $(g-2)_e$ [40, 41]. A constraint also comes from nonobservation of $A' + e \to e + \gamma$ in the LSND experiment, presuming the production of A' from $\pi^0 \to A'\gamma$ decay [42]. The authors of [42] thus contend this region is excluded, but the LSND constraint can be evaded through a non-minimal dark vector model, such as the protophobic gauge boson. We note, too, the experimental controversy in the precise value of the fine-structure constant α from atom interferometry [43, 44], noting [45] for context, with resolutions that

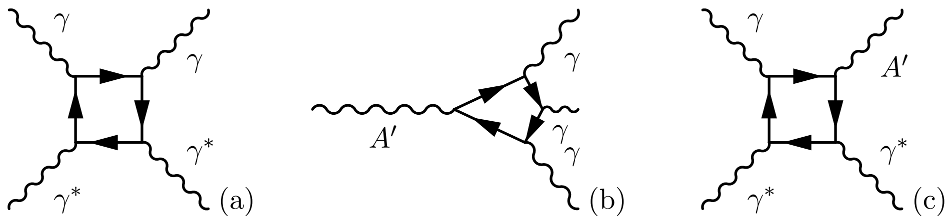

FIG. 10. Representative Feynman diagrams to illustrate (a) Delbrück scattering, which is light scattering in the Coulomb field of an atom or nucleus, as indicated by the appearance of γ^*, (b) $A' \to 3\gamma$ decay, and (c) Delbrück scattering modified to probe a sub-MeV dark photon, with the appearance of missing momentum giving the experimental signature. Note that crossed diagrams exist but have not been shown. The solid lines denote any of the electrically charged fermions of the SM, with the electron/positron giving the dominant contribution.

would alter the $(g-2)_e$ constraint of [41] somewhat.

Delbrück scattering, in which a photon is deflected in a strong Coulomb field due to vacuum polarization, would be sensitive to the A' in this region without assumption concerning the production mechanism.

Pertinent diagrams are illustrated in Fig. 10. We note that at ARIEL energies, Delbrück scattering has been clearly identified [46]. The suggested new-physics search would require the ability to assess the existence of missing momentum or energy.

B. $|\Delta B| = 2$ Processes in Nuclei

Experimental limits on processes that would change baryon number by one unit, i.e., $|\Delta B| = 1$, are among the most stringent known to science [47, 48]. Experimental studies on processes that would change baryon number by two or more units, however, have been much more limited [49], although their physical origin can be altogether different [50–52]. There is clear reason to search for such effects: The existence of $|\Delta(B-L)| = 2$ violation is necessary to make a massive neutrino its own antiparticle [53], and observable B and/or $B-L$ violation in the quark sector would help to identify its dynamical mechanism.

The ARIEL accelerator facility's intense electron beam would be well suited to the search for $|\Delta B| = 2$ through low-energy channels. Of particular note are the processes $e^- p \to e^+ \bar{p}$ or $e^- p \to \bar{n}\bar{\nu}$ [52], with the $B-L$-violating channel $e^- n \to e^- \bar{n}$ also open to study [54] —

here the use of a deuteron target could prove advantageous [52, 54]. The estimated event rates for the B violating, but $B - L$ conserving, processes we have noted are no more than $\mathcal{O}(10)$ events per year [55, 56]. Thus the low energy of the existing electron linac at ARIEL is a key advantage, rather than a limitation, both in controlling backgrounds and in detecting the produced anti-nucleons. At ARIEL, backgrounds are controlled by the extremely low energy of the electron scattering process; in particular, the accelerator operates at energies far below pion production threshold. Moreover, the produced anti-nucleon would be at sufficiently low energy that the annihilation should be prompt and thus occur within the target, typically yielding a five-pion final state, as determined in R&D studies of searches for $n - \bar{n}$ oscillations [57, 58]. In the ARIEL environment, the supposed five-pion final state signal should be quite striking. Their total charge, in a proton target, should signal the electric charge of the anti-nucleon and hence the precise process. This search could potentially run parasitically at ARIEL.

C. Beam-Dump Experiments to Search for Dark Matter

The high intensity of the ARIEL e-linac makes it an interesting potential location to consider a beam dump dark matter experiment as well. The sensitivity relative to DarkMESA, LDMX, and other light DM searches should be examined using an appropriate benchmark model and the usefulness of such an experiment determined in light of the fact that it would necessarily begin much later than already-approved experiments.

Dark matter searches at beam dumps are relatively model-independent. A high-current beam is directed to a target where dark sector particles may be created. Enough shielding to stop essentially all Standard Model particles is placed behind or incorporated into the target, and a detector behind the shielding searches for dark matter particles exiting the dump. The detector is sensitive to dark matter particles via their scattering in the target material. Examples of such experiments, interpretations, and proposals include BDX [59], DarkMESA (see L. Doria's contribution in [4]), E137 [60], the SHiP Scattering Neutrino Detector [61], COHERENT [62], and MiniBooNE (in its dedicated dark matter configuration [63]). A schematic of a beam dump DM experimental setup, including a simplified detector of moderate scale, is shown in Fig. 11.

Beam-dump experiments probe the same types of final states as missing-momentum or

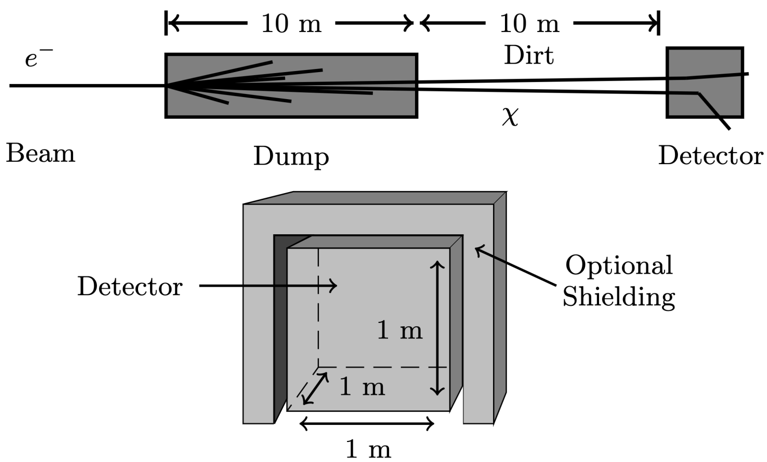

FIG. 11. Schematic of a beam dump experiment searching for light dark matter, from [64].

missing-energy based experiments (LDMX, NA64). They share with them the advantage that these approaches, unlike visible final state searches, are relatively agnostic to the lifetime of the mediator particle(s) and to the decay chain producing the dark matter and can therefore constrain a wide range of models [65]. Scattering-based beam dump experiments are, however, disadvantaged relative to missing-momentum experiments in that they depend on an additional interaction and therefore gain a $\sim \alpha_D \epsilon^2$ suppression factor [66]. The difference could be made up with sufficient beam intensity, since missing momentum experiments must run at low current, and the ARIEL e-linac's uniquely high power makes it worth investigating as a potential site.

A viable location for a beam dump experiment does exist at the ARIEL e-linac. A small room behind the ARIEL targets could host a detector, allowing this new experiment to take data parasitically to ARIEL and without disrupting the operation of DarkLight or another future experiment in its position. One potential experimental challenge is the low momentum transfer from scattering DM particles in the detector at the mass and momentum ranges accessible at ARIEL. This is not insurmountable but would require thoughtful detector design.

The current and proposed future exclusion landscape for light dark matter in the context of invisible dark photon decays is shown in Fig. 12. The dominant sensitivity in the sub-10 MeV mass range is projected to come from LDMX. For reference, the landscape for visible dark photon decays is shown in Fig. 13.

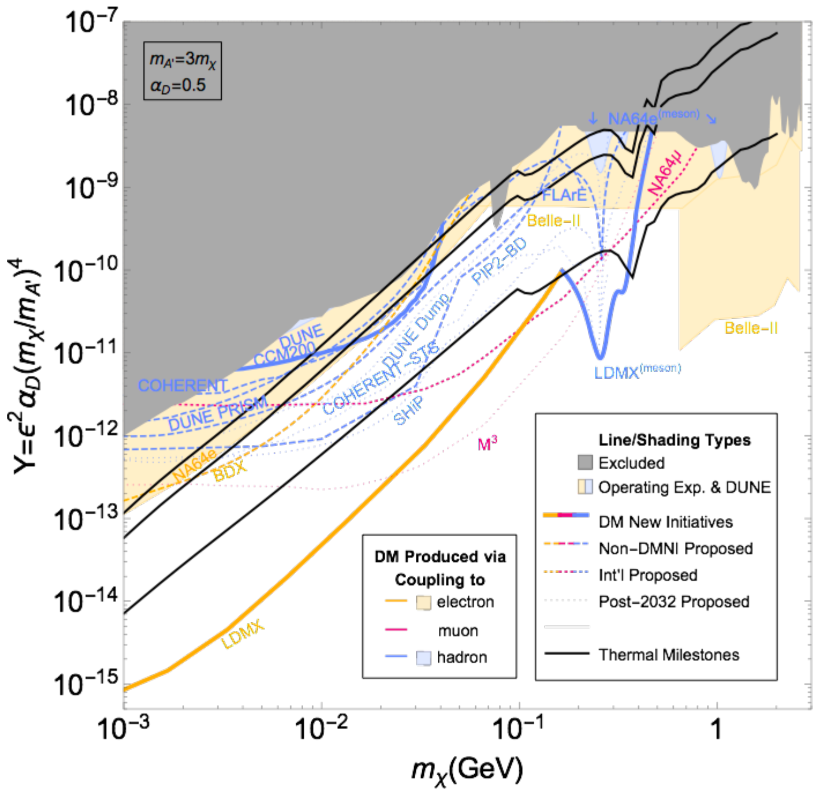

FIG. 12. Constraints on light dark matter in the context of invisible decays of dark photons from current, future, and proposed experiments [67].

It could also be considered whether there is any scope for a missing-energy or missing-momentum search at the ARIEL e-linac. The practical advantages of a classic beam dump experiment at TRIUMF would be negated, since such an experiment could not operate parasitically behind the ARIEL targets, but it would offer the opportunity for significantly higher sensitivity. This approach would require a solution to the experimental challenges of missing momentum reconstruction in the presence of extremely high electron multiplicity in the beam bunches.

We conclude this section by noting another way in which dark-sector searches at the ARIEL facility could be complementary to accelerator-based DM experiments planned elsewhere. At the proposed LDMX experiment [65, 66, 69], e.g., invisible decays of a dark photon A' can be probed through its missing-momentum signature. That is, as shown in Fig. 14, an A' produced through bremsstrahlung in electron-nucleus scattering can decay invisibly via $A' \to \chi\chi$, and this possibility can be probed through the measurement of the momentum of the final-state electron. This may be a unique possibility to probe χ because

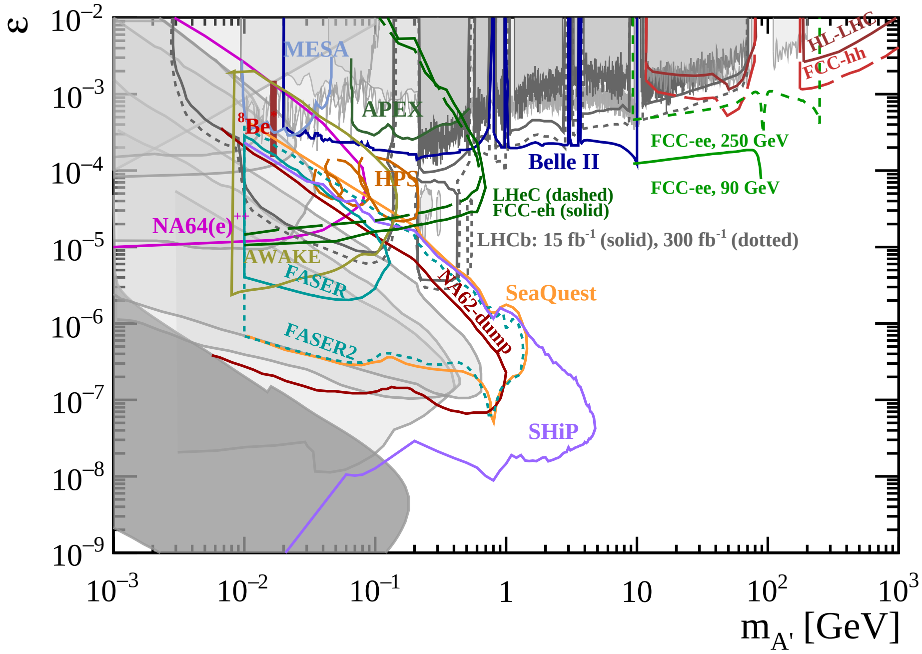

FIG. 13. Constraints on dark photons detectable through visible decays in the context of current, future, and proposed experiments. Grayed regions represent existing limits, in the assumption of flavor-independent couplings. Colored lines represent future projected exclusions [68].

χ carries no SM charges. However, in place of the usual dark photon, the gauge boson mediator could couple to baryon number instead [48, 70–72]. The gauge boson in such a model couples to neutrons and photons, and it can couple to electrically charged particles, through kinetic mixing with the SM photon. In this case the dark gauge boson can still be produced via bremsstrahlung, but it could decay to a $\chi\bar{\chi}$ pair, in which χ carries baryon number $B = 1/3$. Figure 14 also illustrates this possibility upon the replacement of $\chi\chi$ with $\chi\bar{\chi}$.

Although this model would generate a missing momentum signature, χ and $\bar{\chi}$ could also interact with neutrons and protons in the far detector. One possibility with a striking, observable signature concerns *destabilization* of the nucleus: Here the incoming DM particle χ stimulates the decay of a nucleus in the far detector via the neutron-decay process $\bar{\chi}n \to \chi\chi$. We note that $n \to 3\chi$ has also been considered in the context of the neutron lifetime anomaly [73], noting [74], and the decay rate need not be exceedingly small [48]. The breakup of the nucleus, with roughly a GeV of energy loss, could be documented through gamma detectors placed at the far detector. The latter could be sufficiently removed from the electron beam environment to make such a photon fingerprinting process possible. The viability of such an approach has been studied in work by KamLAND [75], and references therein.

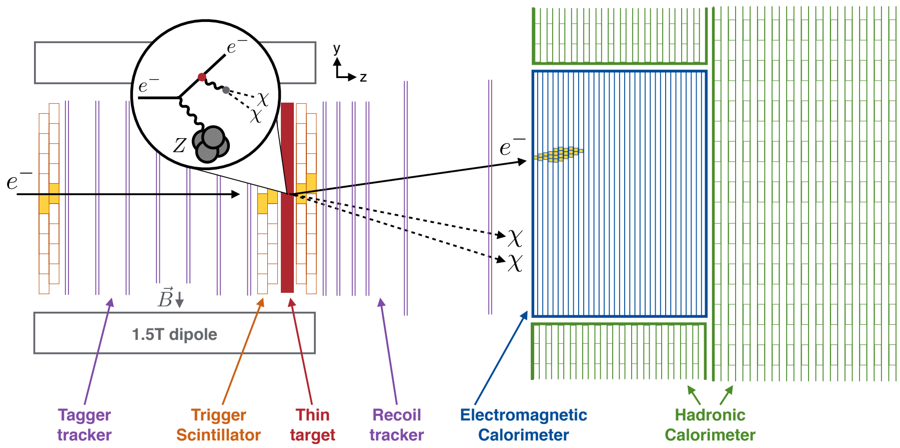

FIG. 14. Illustration of the production of dark matter particles χ through dark photon decay, apropos to the LDMX detector, from [69]. Replacing $\chi\chi$ with $\chi\bar{\chi}$ illustrates the possibility of a dark gauge boson coupled to baryon number, as discussed in the text.

D. Search for X17 in e^+e^- Decay of Giant Dipole Resonance

It has been suggested that the X17 may also be able to be produced in the decay of giant nuclear resonances. Both Isoscalar Giant Monopole Resonances (ISGMR) and Isovector Giant Dipole Resonances (IVGDR) can be readily excited in an electron beam fixed target experiment, and the typical energy scale of these resonances (ISGMR) follows Eq. 8. For atomic numbers above about 20, these can be readily reached with a 30-50 MeV beam.

$$E_c = 80A^{-1/3}\text{MeV} \tag{8}$$

Final states may carry angular distributions associated with the excited multipole but should be randomly oriented in the detector frame, producing a signature that is independent of the angle with respect to the electron beam, distinguishing those decay particles from the forward-peaking prompt events.

Unfortunately, electron scattering has a large contribution from the radiative tail, which increases the background associated with identifying a resonance, and identifying the particles from that resonance's decay, substantially. At the collision energies of the current or upgraded ARIEL accelerator, techniques to separate prompt and resonant final states spatially or temporally would need to have exquisite resolutions that are not currently feasible. The lifetime of the resonance is extremely short (typically 10^{-21} to 10^{-19} s), and its recoil energy essentially zero. At higher beam energies these constraints are relaxed, but these are beyond the upgrades currently discussed for ARIEL.

We note that different excitation techniques, in particular tagged photons, may make giant resonances a more fruitful area both for exotic particle searches and other studies of resonance structures, but would require the development of a photon-tagging station on the beamline.

VII. SUMMARY

As described above, the DarkLight experiment is designed to seek the protophobic new force suggested by low energy anomalies, e.g. muon $(g-2)$ and the ATOMKI data on nuclei. The experiment represents a natural evolution of a fixed-target experiment to reach the low mass expected if those anomalies truly represent a new particle. By using a high quality, low energy beam, the experiment simplifies the final states to only e^+e^- pairs, with no hadronic backgrounds detected. The experiment can operate at the instantaneous luminosity saturation point, where quadratic backgrounds dominate, and the FOM depends only on measurement time. The initial 1000 hour experimental run will seek a $13\,\mathrm{MeV}/c^2$ resonance and explore a small region of g-2 favored parameter space beginning in 2024, limited by the beam energy currently available at ARIEL. The apparatus will require only minor adjustment of the angles and magnet currents to accommodate the higher energies from the proposed ARIEL upgrades, which will enable searching in the $17\,\mathrm{MeV}/c^2$ range directly. Beyond the DarkLight experiment itself, development of the unique ARIEL electron beam capabilities and pursuit of higher beam energies can be exploited in novel experiments that are modest in scale and provide great opportunities to educate and train young physicists.

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