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Jefferson Labs secondary beams for nuclear physics

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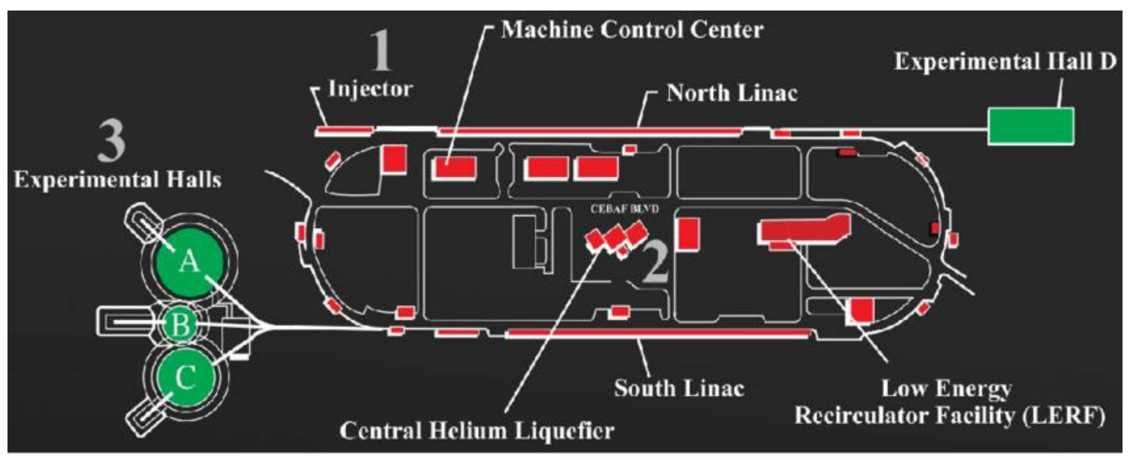
Intense secondary beams of muons, neutrinos, and (hypothetical) dark scalar particles result from the interaction of the Continuous Electron Beam Accelerator Facility (CEBAF) 10 GeV high-current electron beam O(100 uA) and the Hall-A beam dump. While most radiation (gamma, electron/positron) is contained in the thick absorber, deep-penetrating particles (muons, neutrinos, and light-dark matter particles) propagate over a long distance, generating high-intensity secondary beams that can be used for several studies. High-intensity muon beams have applications in many research fields spanning from fundamental particle physics to materials science or inspection and imaging (e.g. elastic muon-proton scattering offers an alternative method to measure the proton charge radius). Decay at rest neutrinos are suitable for studying coherent elastic neutrino-nucleus scattering (CEvNS). Experiments designed to observe CEvNS events provide a unique opportunity to precisely measure the weak mixing angle as well as other nuclear properties (e.g. the neutron skin of heavy nuclei). Similarly, light-dark matter searches could take advantage of the large electron charge dumped on the Beam-Dump competing with leading experiments planned at CERN Lab.

Jefferson Lab accelerator facility

The Jefferson Lab (JLab) is a US Department of Energy laboratory in Newport News, Virginia. JLab hosts CEBAF, a continuous wave electron accelerator, made by two 1-GeV LINACs. Four experimental halls can receive, simultaneously, a primary 11 GeV e-beam (Hall-A,-B,and-C) and up to 12 GeV e-beam (Hall-D). With a current of 75 uA the corresponding a yearly accumulated charge is about 10^{22} EOT

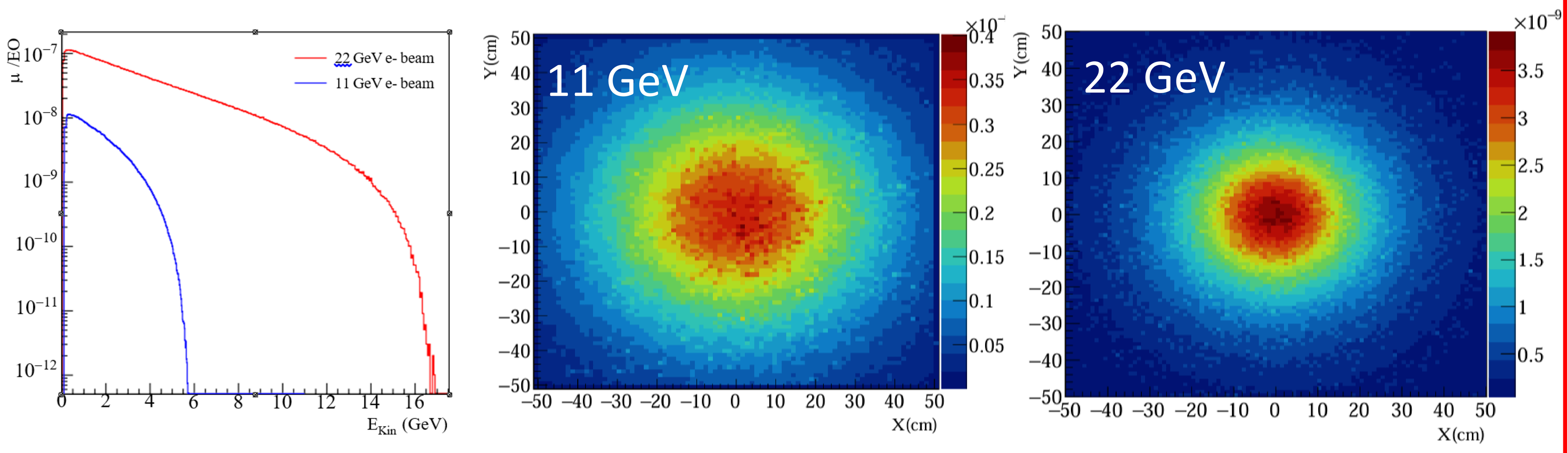
The physics program includes the study of the hadron spectrum, nucleon structure, nuclear interaction, and BSM searches.



Taking advantage of progress in accelerator technologies, it will be possible to extend the energy reach of the CEBAF accelerator up to 22 GeV [1].

Secondary Muon Beam

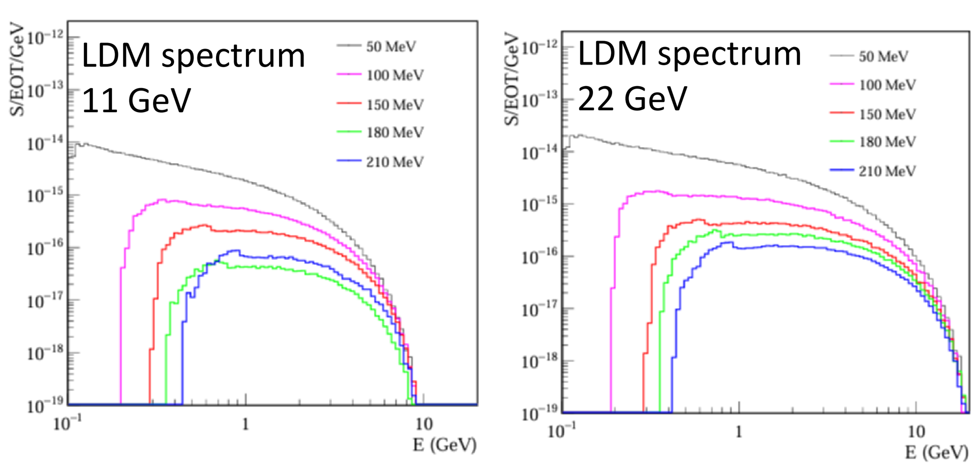
A high-intensity multi-GeV electron beam hitting a thick target is likewise a copious source of muons. In this case, muons are produced via two classes of processes: Decay by Photo-production of π's and K's and direct $\mu^+\mu^-$ pair production.



As can be see on Figures, 22 GeV e-Beam produce a Bremsstrahlung-like spectrum (left), similar to the 11 GeV case, but it covers an extended energy range (up to ~16 GeV) with an almost ×8 yield. The spatial distribution (center-right) results in being more forward-peaked [4].

Secondary Dark Matter Beam

Particle nature of dark matter remains one of the biggest endeavors in fundamental science. In past the efforts are focused on the search of weakly interacting massive particle candidates (WIMPs). The lack of experimental evidences has motivated the interest toward sub-GeV LDM [1,41–43]. In the proposals to detect LDM one minimal model that could explain the $(g-2)_\mu$ anomaly hypothesize a new *leptophilic* scalar dark matter state (*dark scalar* or *S*) that couples only to muons. Medium-energy electron beam dump experiments, providing an intense source of secondary muons that can penetrate deeply into the dump and surrounding materials, losing energy mainly through ionization and may radiate a *S* particle.



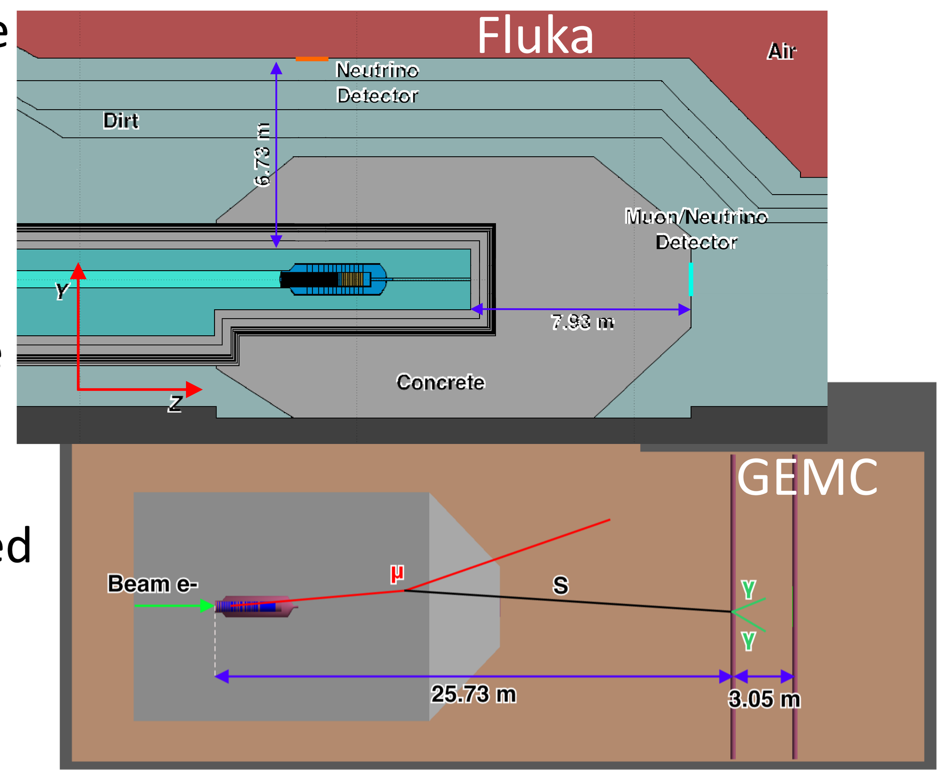
$$\Gamma_{\gamma\gamma} = \frac{\alpha^2 m_S^3}{128\pi^3}\left|\frac{g_\mu}{m_\mu}\frac{4m_\mu^2}{m_S^2}\left[1+\left(1-\frac{4m_\mu^2}{m_S^2}\right)\arcsin^2\left(\frac{4m_\mu^2}{m_S^2}\right)^{-1/2}\right]\right|^2$$

For the mass range ($m_S < 2m_\mu$), *S* could only decay into two photons with a decay width, $\Gamma_{\gamma\gamma}$, which depends on the μ–S coupling constant, g_μ, and the ratio of muon to *S* masses, m_μ/m_S [10]. Simulations were performed assuming a fixed coupling constant g_μ = 3.87 10−4 and m_S in the range 25 MeV–210 MeV.

Simulation Framework

The interaction of the 11 GeV (22 GeV) primary electron beam with Hall's Beam Dump and subsequent transportation of the secondary particles was studied by Monte Carlo simulations using FLUKA [2] and GEANT4 [3] toolkits.

FLUKA version 4-3.1 was used to simulate the production and the propagation of muons and neutrinos through concrete and dirt to reach a hypothetical downstream detector. Light Dark Matter (LDM) produced by the interaction of the secondary muon beam was computed using GEANT4 via the GEMC interface. In this case, muon beam parameter obtained with FUKA and converted in the LUND format (particle ID, vertex and momentum), and fed to GEMC.

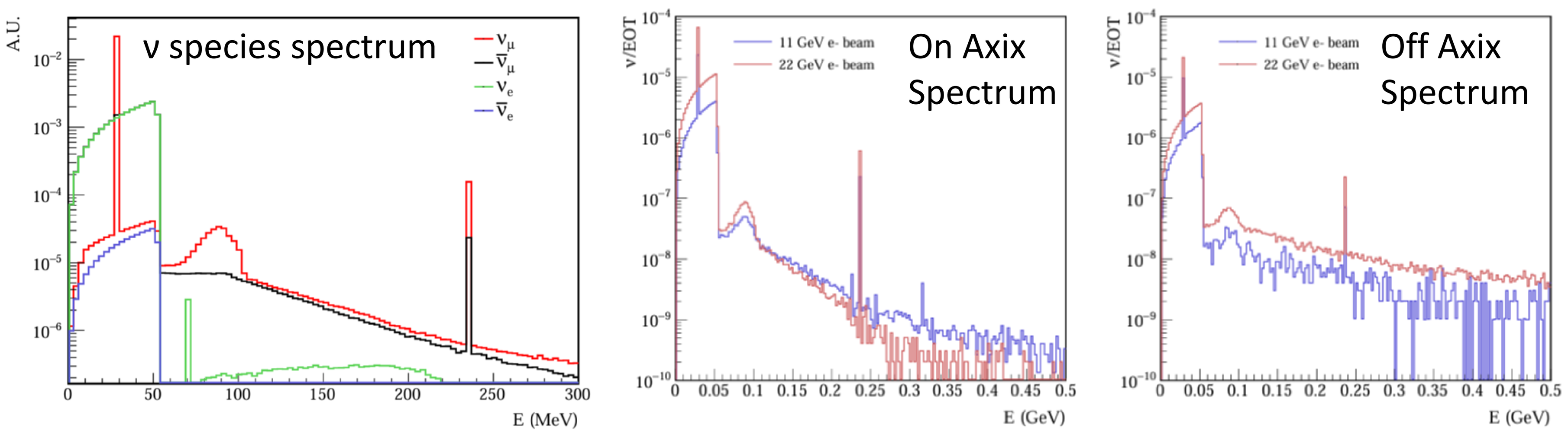


Secondary neutrino Beam

In accelerators, high-energy protons or electrons hit a target to generate short-lived hadrons (mainly $\pi^\pm$ and $K\pm$) that successively either decay in flight (DIF) or decay at rest (DAR) into neutrinos. DAR neutrinos, mainly produced by spallation neutron sources [6], show an isotropic spatial distribution with an energy spectrum depending on the decay:

$\pi^+ \dashrightarrow \mu^+ + \nu_\mu$	E_ν ~ 29.8 MeV, almost monochromatic;
$\mu^+ \dashrightarrow \bar{\nu}_\mu + \nu_e + e^+$	E_ν in the range 0–52.8 MeV;
$K+ \dashrightarrow \mu^+ + \nu_\mu$	E_ν ~ 236 MeV, almost monochromatic.

Due to these process, accelerator neutrino beam contain 4 (anti)neutrino (left) species in contrast with electron only produce in nuclear reactor[5].



DAR neutrinos are suitable for studying coherent elastic neutrino-nucleus scattering (CEvNS). This process, predicted a long time ago, has been only recently observed [7] and is a leading candidate for the study of non-standard (BSM) neutrino interactions [8].

Conclusion

The existing high-intensity electron beam facilities may provide low-cost, opportunistic, high-intensity secondary particle beams that will broaden their scientific programs. We studied in detail the characteristics of muon, neutrino, and hypothetical light dark matter beams obtained by the interaction of the CEBAF 11 GeV primary electron beam with the Jefferson Lab experimental Hall-A beam dump. High statistic simulations were performed with the FLUKA and GEANT4 toolkit. Results showed that the CEBAF energy upgrade will be extremely beneficial for the secondary muon beam, extending the energy range up to 16 GeV and the muon flux by almost an order of magnitude. For the secondary neutrino beam, the DAR yield is expected to double, and, for the dark matter beam, the dark scalar particle yield would increase by up to an order of magnitude.

Reference

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[2] *Nucl. Data Sheets* **2014**, *120*, 211–214.
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[4] *arXiv* **2023,** arXiv:2311.08440v3
[5] *Phys. Rev. D* **2022**, *106*, 032003
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