Physics Opportunities with Muon Beams from Low to High Energies

BDX and Beyond Workshop
Jefferson Lab
Newport News, USA

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Topics

- Nuclear physics studies with muons, lepton-mass effects and QED corrections;
- Tests of fundamental symmetries
- Support of major projects elsewhere: Muon Collider
- Applied problems: muon radiography, nondestructive evaluation, isotope production

Studying Nuclear Structure with Electrons and Muons

Provided lepton-photon coupling is universal, key differences are in higher-order QED corrections

- An accelerated charge always radiates, but the magnitude of the effect depends on kinematics
- For large $Q^2 \gg m_l^2$ the QED correction is enhanced by a large logarithm, $\log(Q^2/m_l^2) \approx 15$ for $1\mathrm{GeV}^2$ momentum transfers by electrons vs 4.6 for muon; rad corrections due to brem for muons are smaller by $\approx$ 3x.
- For small $Q^2 \ll m_l^2$ QED correction is suppressed by a factor Q^2/m_e^2
- For intermediate Q^2 m_l^2, neither enhancement nor suppression, rad correction of the order α/π

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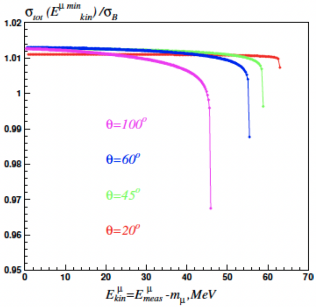
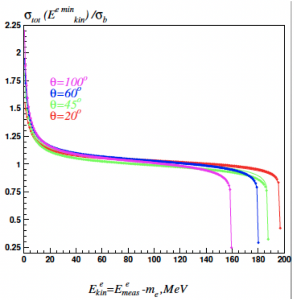
Computational Approaches to QED Rad Corrections

- Ilyichev (Minsk) and AA: EPJA 58, 156 (2022) MASSRAD (semi-analytic), updated ELRADGEN Monte Carlo, (Afanasev et al., Czech. J. Phys. 53 (2003) B449; Akushevich et al., Comput. Phys. Commun. 183 (2012) 1448) to include (a) mass effects and (b) two-photon effects (c) hard brem included
- Dedicated MS generators for MAMI (Bernauer), OLYMPUS (Gramolin), McMule (Signer) PRAD, MUSE,...





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Spin-0 Meson Exchange for Elastic ep-scattering

Koshchii, Afanasev, Contribution of σ meson exchange to elastic lepton-proton scattering PRD 94, 116007 (2016); Naik, Afanasev, Contribution of π^0 exchange in elastic muon-proton scattering, PRC 110, 035202 (2024).

- Spin-0 mesons (strongly interacting particles) can contribute to electromagnetic lepton-hadron scattering via 2-photon coupling
- Scalar mesons (σ, f) contribute to cross sections and asymmetries; Pseudo-scalar mesons (π^0, η) contribute to spin asymmetries only
- Effect is suppressed by m_l/E_{beam} and a higher order (1/137) of QED: 0.5% for muons and ≈200 times smaller for electrons

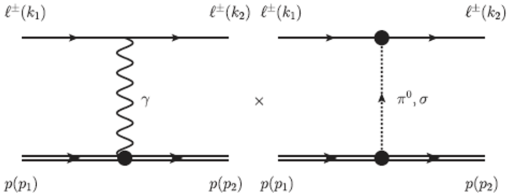

FIG. 1. Interference term between the single photon exchange and the single meson exchange diagrams in the t channel.

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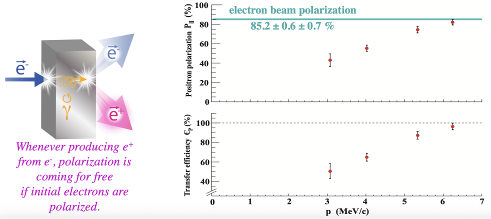
Advantage of Pair Production Mechanism

For production of muons via pion decay, muon polarization is connected to pion charge: positive muons are produced with negative helicity, and negative muons with positive helicity

Not possible to separate charge asymmetries and helicity asymmetries

- For the pair-production mechanism, highest-energy muon carries close to 100% of initial electron polarization, c.f. PEPPO demonstration (PEPPo Collaboration) D. Abbott et al. , Phys. Rev. Lett. 116 (2016) 214801
- As a result, charge-asymmetric correlations can be separated from helicity asymmetries, *e.g.* 2- vs 3-photon exchange, Coulomb distortion, CP-violation



Isospin-Breaking Nuclear Forces

Nuclear physics with neutron beams

What is the difference between pp-, pn- and nn-scattering?

- After removing Coulomb effects, we can study charge-symmetry breaking effects
- Outstanding problem: mass difference between mirror nuclei

ANNUAL REVIEW OF NUCLEAR AND PARTICLE SCIENCE Volume 56, 2006

Review Article | Subscribed

Charge Symmetry Breaking and QCD

Gerald A. Miller[1], Allena K. Opper[2] and Edward J. Stephenson[3]
View Affiliations

Vol. 56:253-292 (Volume publication date November 2006) | https://doi.org/10.1146/annurev.nucl.56.080805.140446

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R&D in Support of Muon Collider

Also talk by Dikstys Stratakis from Thursday

Problem: To achieve luminosities for the physics program, the beam should be cooled in 6D phase space

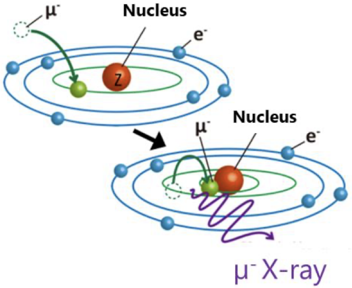
Ionization cooling is most efficient; JLab contributed to development of the technical solution (Y. Derbenev, R.P. Johnson, Six-dimensional muon beam cooling using a homogeneous absorber: Concepts, beam dynamics, cooling decrements, and equilibrium emittances in a helical dipole channel, Phys. Rev. ST Accel. Beams 8, 041002 (2005)

- Use of the pair production mechanism allows to generate muons with lower emittance and higher energies compared to pion decay
- More studies for beam collection and cooling of pair-produced muons may help the muon collider program

Applied Topic: Spectroscopy of Muonic Atoms

See also presentation by Takayuki Yamazaki

- Atomic radii are 1/200 times smaller for muonic atoms; characteristic emission spectra get x200 energy boost: 10eV$\to$keV, optical $\to$ X-ray
- Advantage: can probe large objects
- Example: spectroscopy of high-Z nuclei (U, Pu); chemical compounds with high density and Nitrogen+Oxygen content
- Applications for nuclear forensics, nonproliferation and stockpile stewardship: National Nuclear Security Administration; Department of Defense



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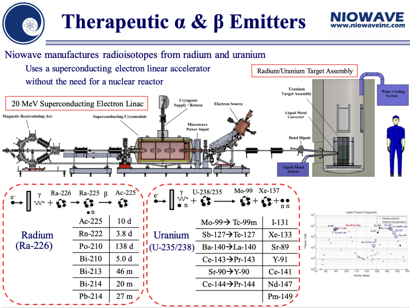
Applied Topic: Isotope Program

Production of radioactive isotopes for a variety of applications: medical isotopes, radioisotope batteries (alpha- and betavoltaic devices).

- V. N. Starovoitova, T. L. Grimm, A. K. Grimm, F. Y. Odeh, W. A. Peters (Niowave, Inc.), A. Afanasev, N. Guardala (George Washington Univ.), J. Carroll, M. Litz (U.S. Army Research Lab.), T. Adams (Naval Surface Warfare Center), S. Maximenko (U.S. Naval Research Lab.), Production of Alpha and Beta Radioisotopes for Nuclear Batteries Using a Superconducting Electron Linac, ANS Transactions, Volume 118 — Number 1 — June 2018 — Pages 333-335.



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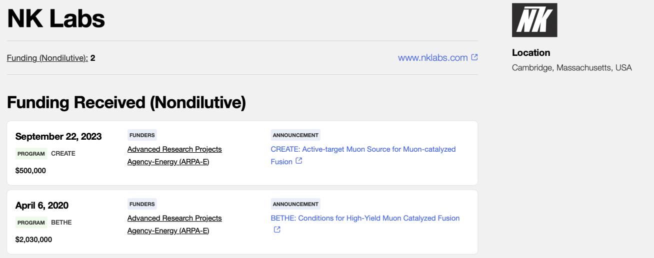
Applied Topic: Muon-Catalyzed Fusion

Muonic atoms have x200 smaller sizes - may facilitate nuclear fusion reactions

- Predicted by F.C. Frank (1947) and Andrei Sakharov (1948); discovered experimentally by L.W. Alvarez in Berkley Lab (1957)
- Considerable experimental effort in Dubna, LANL, PSI, RAL, RIKEN, TRIUMF during 1970-80s
- Interest declined in 1990s - not a viable source of energy, unless "...an energetically cheaper way to produce muons can be found" Jackson, J.D. (1957). "Catalysis of Nuclear Reactions between hydrogen isotopes by μ-Mesons". Physical Review. 106 (2): 330.
- Currently funded by ARPAe: NK Labs



NK Labs

Funding (Nondilutive): **2** www.nklabs.com

Location
Cambridge, Massachusetts, USA

Funding Received (Nondilutive)

September 22, 2023
PROGRAM CREATE
$500,000
FUNDERS: Advanced Research Projects Agency-Energy (ARPA-E)
ANNOUNCEMENT: CREATE: Active-target Muon Source for Muon-catalyzed Fusion

April 6, 2020
PROGRAM BETHE
$2,030,000
FUNDERS: Advanced Research Projects Agency-Energy (ARPA-E)
ANNOUNCEMENT: BETHE: Conditions for High-Yield Muon Catalyzed Fusion

Summary

Availability of secondary beams at BDX facility offer new opportunities for fundamental and applied physics

- Nuclear physics studies with muons, lepton-mass effects and QED corrections;
- Tests of fundamental symmetries: isospin-breaking nuclear forces
- Support of major projects elsewhere: JLab muon source as a testbed for the Muon Collider R&D on muon generation and beam cooling
- Applied problems