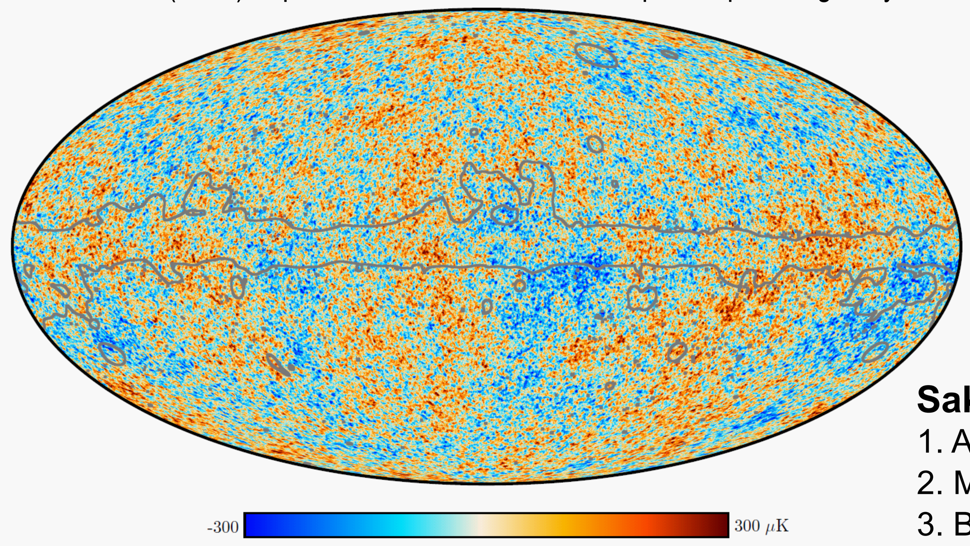
MICHIGAN STATE UNIVERSITY

The FRIB-EDM³ Instrument: A Tool For Creating Molecules Using Octupole Deformed Nuclei For Tests Of Fundamental Symmetries

Aiden Boyer (boyera@frib.msu.edu), Nicholas Nusgart, Meyhar Dudeja, Jaideep Singh
Facility for Rare Isotope Beams (FRIB), Michigan State University, 640 S Shaw Ln, East Lansing, MI 48824 USA
FACILITY FOR RARE ISOTOPE BEAMS

Introduction

Planck (2018) https://www.cosmos.esa.int/web/planck/picture-gallery



$$\eta = \frac{\text{matter} - \text{antimatter}}{\text{relic photons}} \propto \sin(\delta)$$

$\eta_{\text{exp}} \approx 10^{-9}$
PDG2024

$\eta_{\text{CKM}} \approx 10^{-26}$
Huet & Sather PRD 51:379 (1995)

Sakharov Conditions
1. A baryon number violating interaction exists
2. Must be a departure from thermal equilibrium
3. Both C- & CP-symmetry violation required

A. D. Sakharov JETP Letters, 5:1 (1967)

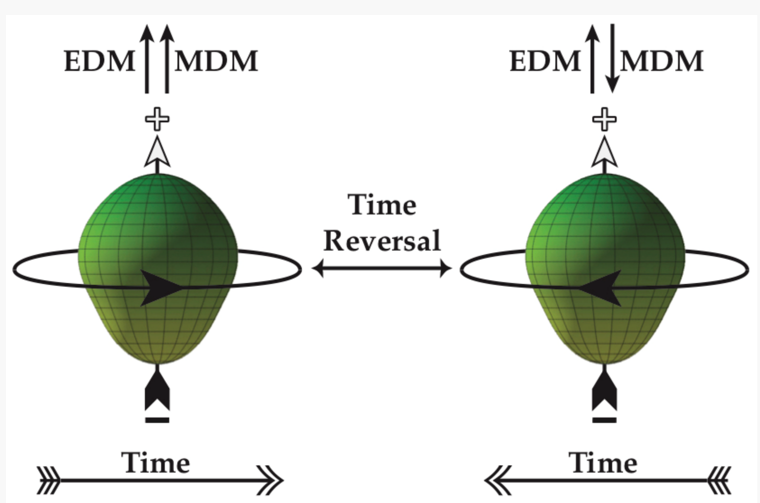
Electric Dipole Moments (EDMs) measure a separation of charge: $\vec{d} = \int \vec{r}\rho_Q d^3r = d\frac{\langle \vec{J}\rangle}{J}$

J	Total angular momentum
B	Magnetic field
E	Electric field
d	Electric dipole moment
μ	Magnetic dipole moment
ρ_Q	Charge Distribution

Dipole moments can couple to electromagnetic fields:

$$\mathcal{H} = -(\vec{\mu}\cdot\vec{B} + \vec{d}\cdot\vec{E}) = -\frac{(\mu\vec{J}\cdot\vec{B} + d\vec{J}\cdot\vec{E})}{J}$$

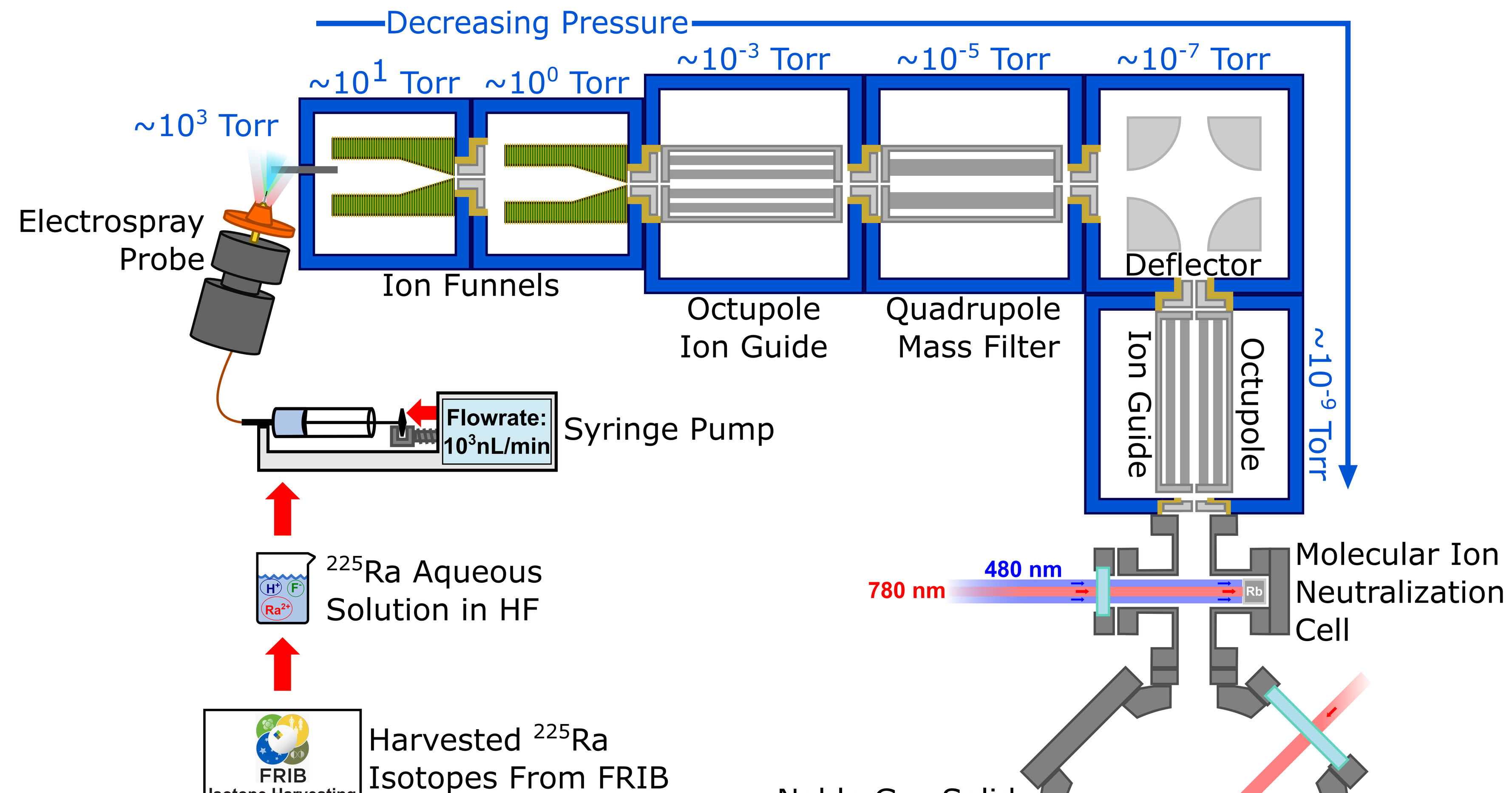
Quantity	P (Parity)	T (Time-reversal)
$\vec{J}$	Even (+)	Odd (-)
$\vec{B}$	Even (+)	Odd (-)
$\vec{E}$	Odd (-)	Even (+)
$\vec{J}\cdot\vec{B}$	Even (+)	Even (+)
$\vec{J}\cdot\vec{E}$	Odd (-)	Odd (-)

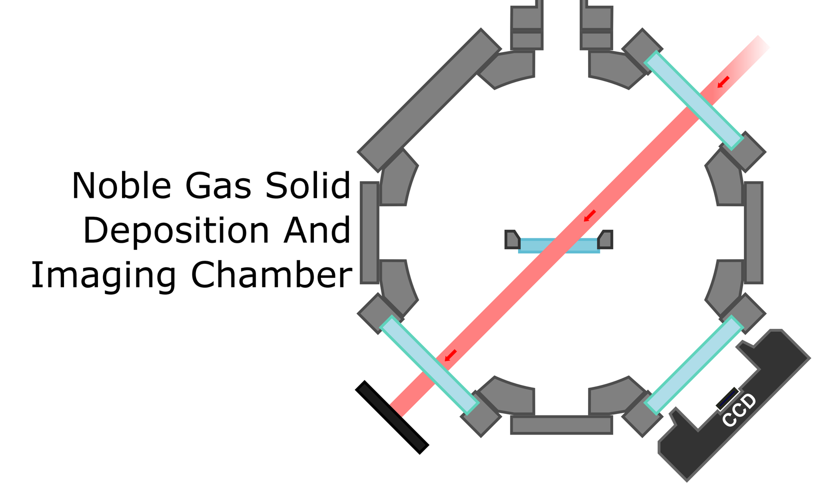


CPT Theorem:
T-Violation = CP-Violation

FRIB-EDM³

We are collaborating with York University and the Univesity of Toronto to adapt their technique for measuring electron EDMs in solids for NSM measurements in solids



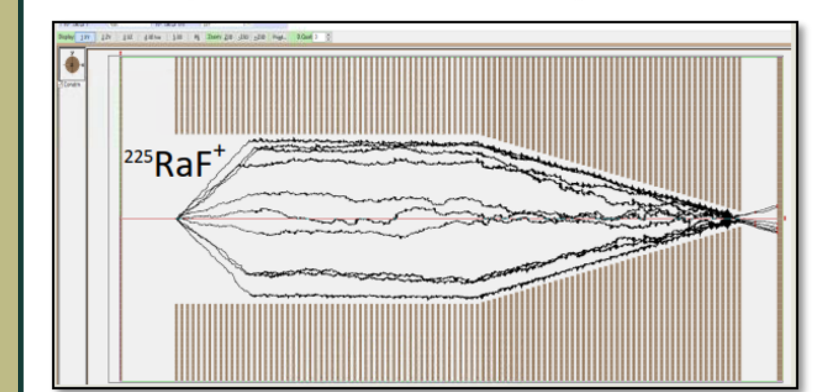


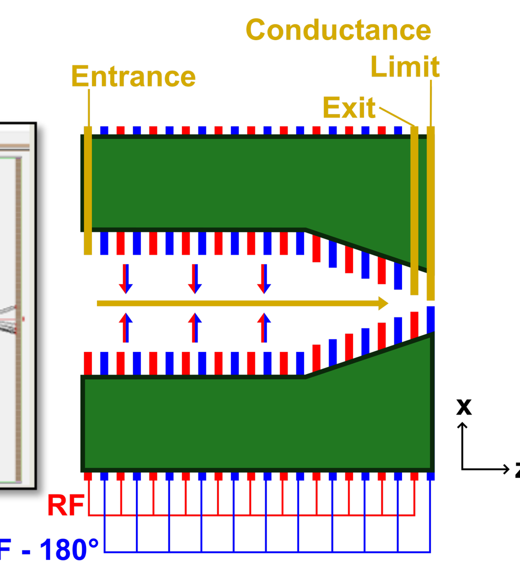
We want a technique that:
- Can form an isotopically pure beam of neutral molecules
- Is UHV compatible
- Has a high formation efficiency

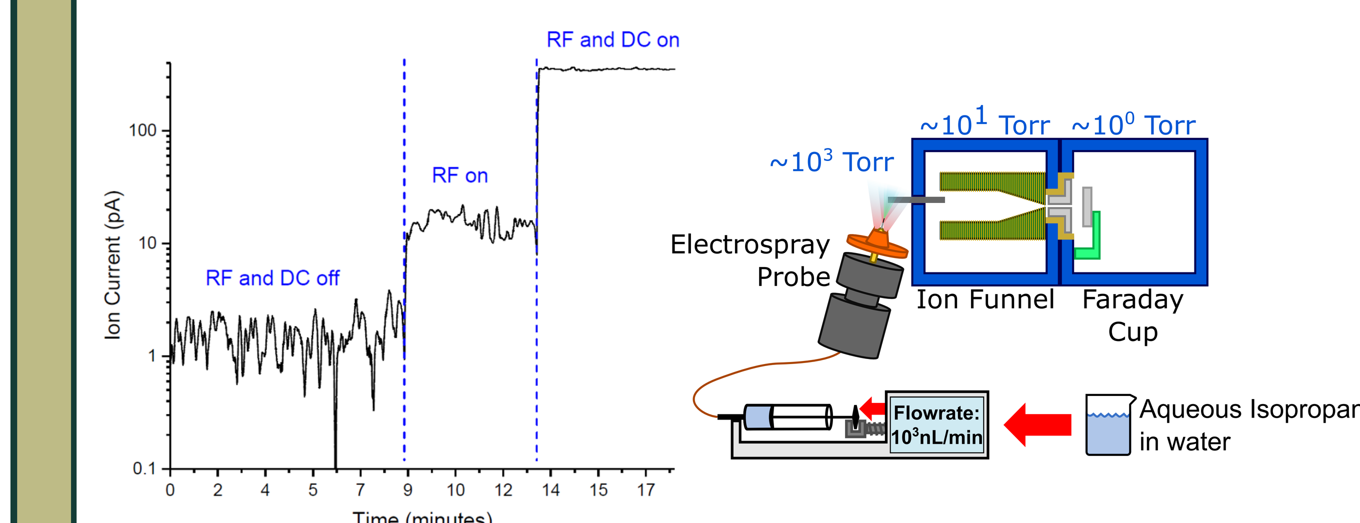
See also: Vutha et al. PRA 98 (2018), J. T. Singh Hyp. Int. 240 (2019), Ramachandran & Vutha, PRA 108 (2023), Vutha et. al NJP 25 (2023)

Collimating An Ion Beam

Ion funnels collect ions and separate them from the gas load

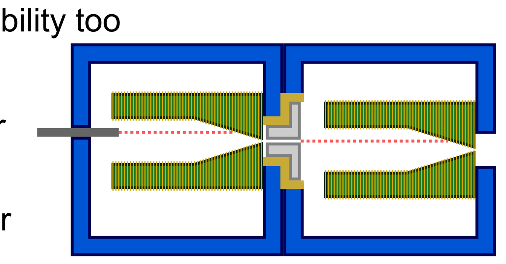




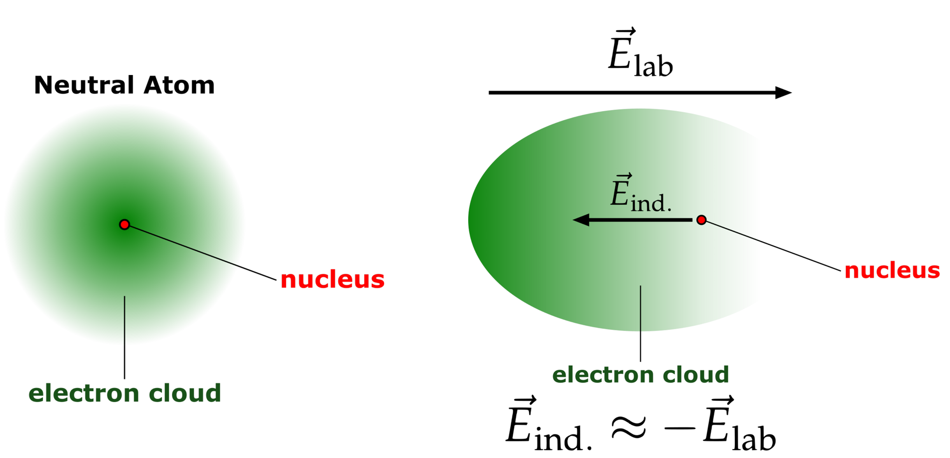


Stable ion beams are possible but difficult:
- Stability depends on ambient conditions (humidity, temperature, pressure, gas type)
- Stability dependent on position and alignment of electrospray probe
- More ion current for higher flow rate, but more instability too

Downstream filtering planned:
- Isotope selection by m/z with quadrupole mass filter
- Gas load disruption with funnel offsets
- Separation of ions from neutrals with electric bender



Octupole Deformation And Molecules



$\vec{E}_{\text{ind.}} \approx -\vec{E}_{\text{lab}}$

Nuclei in diamagnetic atoms react to counter an applied lab field. What's left over is a nuclear Schiff moment:

$$S_z = \frac{\langle er^2 z\rangle}{10} - \frac{\langle r^2\rangle\langle ez\rangle}{6}$$

Nuclear Schiff moments in the lab frame:

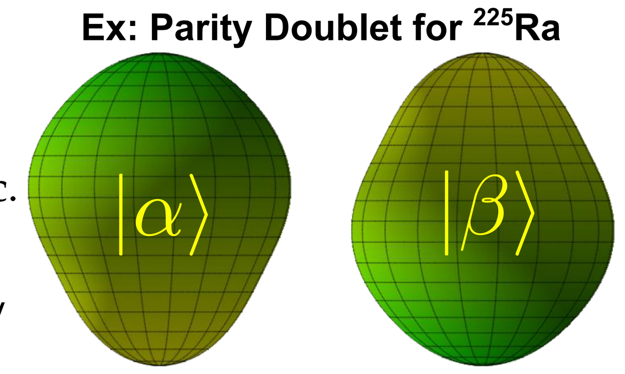
$$S \equiv \langle\Psi_0|S_z|\Psi_0\rangle = \sum_{k\neq 0}\frac{\langle\Psi_0|S_z|\Psi_k\rangle\langle\Psi_k|V_{\text{PT}}|\Psi_0\rangle}{E_0 - E_k} + \text{c.c.}$$

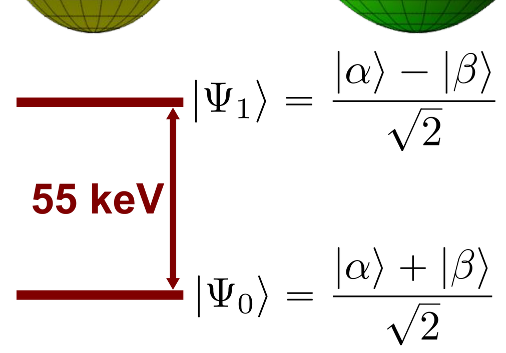
In the lab frame, octupole deformed nuclei amplify our ability to see **symmetry violating physics** because of their:

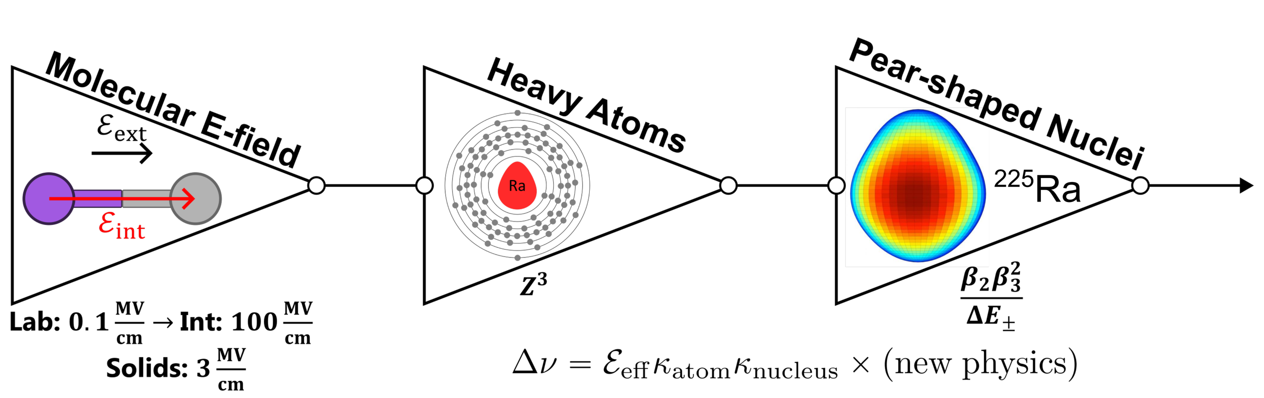
1. Nearly degenerate parity doublets
Haxton & Henley PRL 51:1937 (1983)

2. Large intrinsic Schiff moment
Auerbach, Flambaum, & Spevak PRL 76:4316 (1996)

Ex: Parity Doublet for ²²⁵Ra







Enhancement
Up to 10⁷ expected in 1st generation

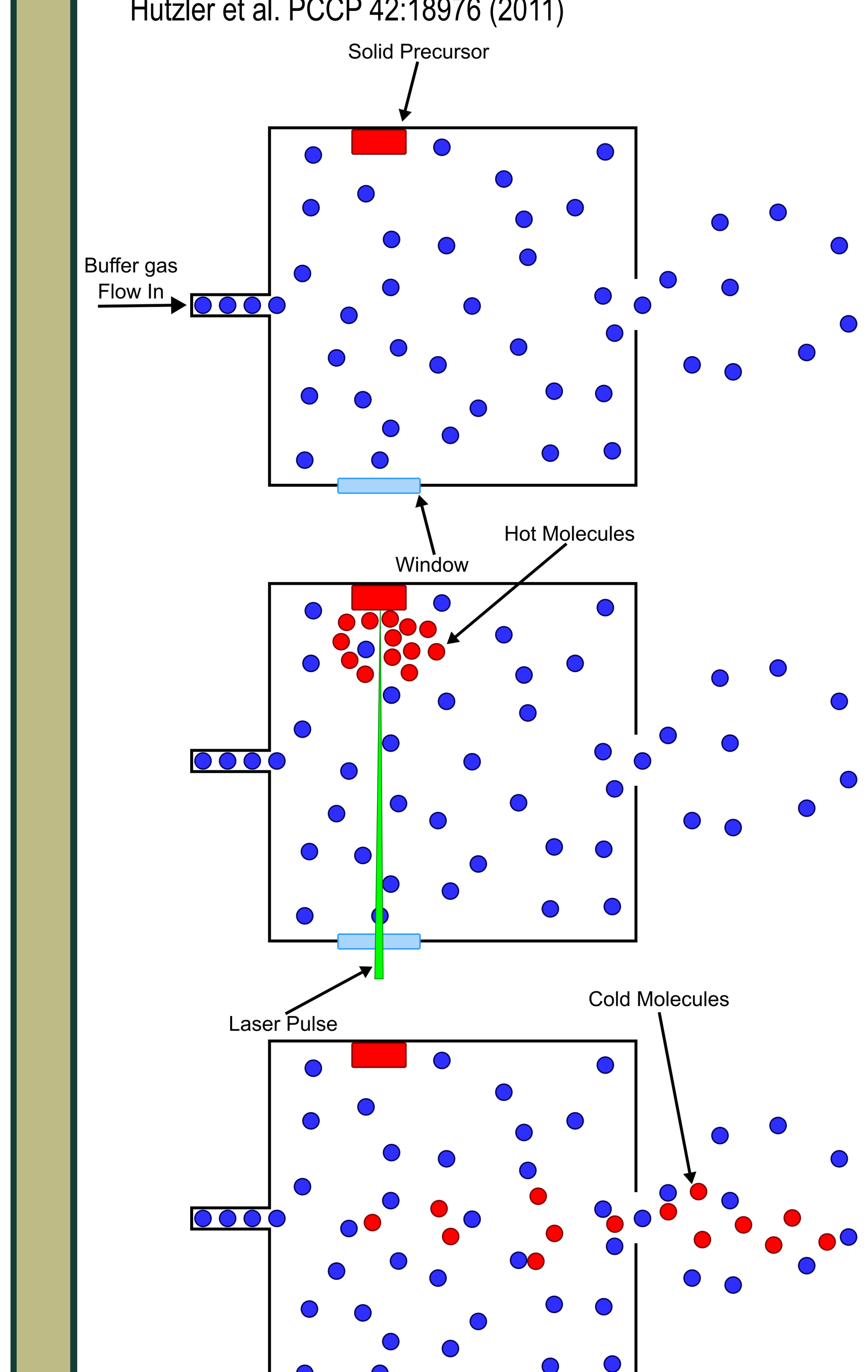
$$\Delta\nu = \mathcal{E}_{\text{eff}}\kappa_{\text{atom}}\kappa_{\text{nucleus}} \times (\text{new physics})$$

Cern (2020) https://cds.cern.ch/images/CERN-HOMEWEB-PHO-2020-012-1

Molecule Formation

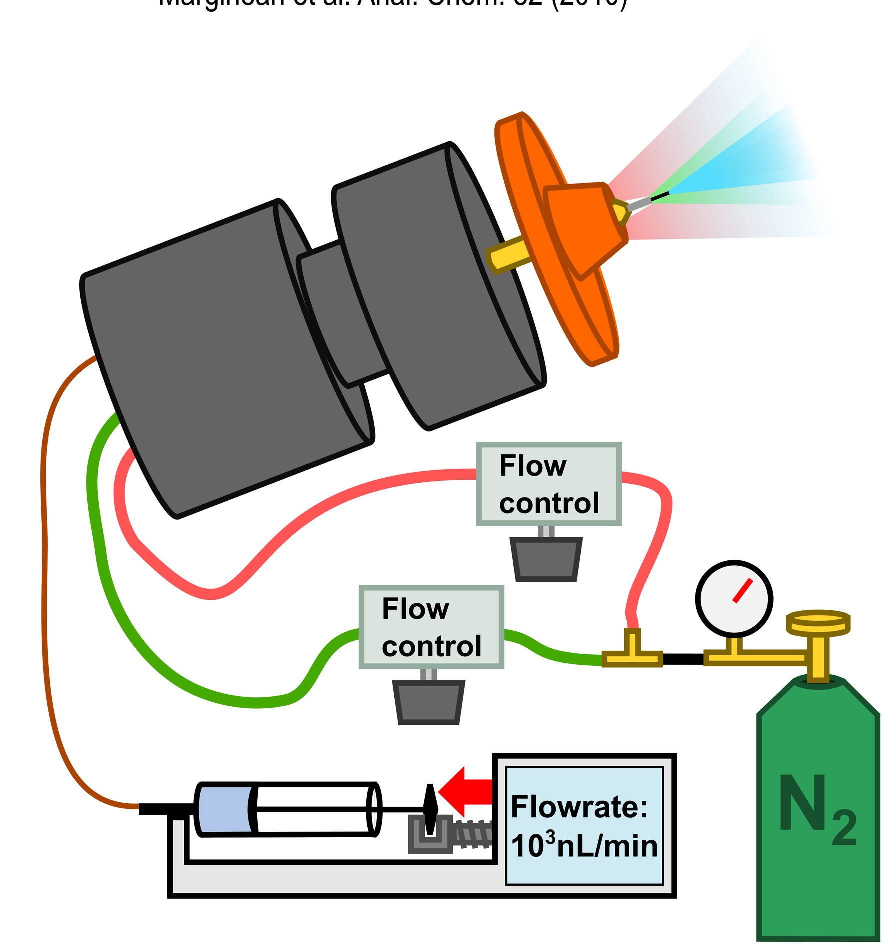
State-of-the-art: Cryogenic Buffer Gas Beam
- Creates molecular ions from solid precursor
- Molecule production efficiencies vary (20% for ThO)
- Precursor formation and ablation efficiencies unknown but estimated ~1% (3% for ThO)

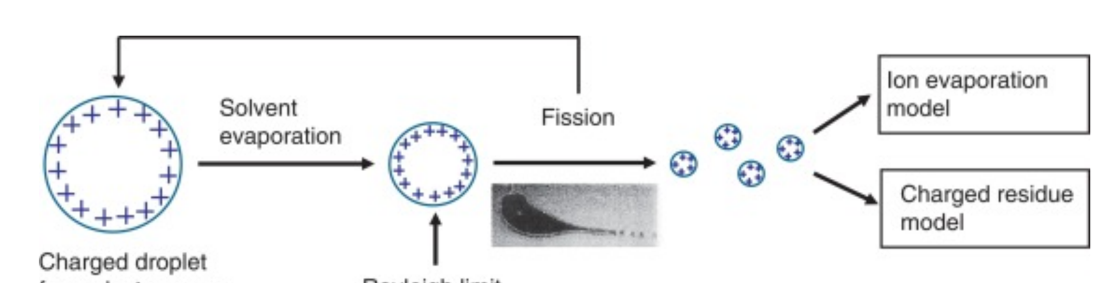
Hutzler et al. PCCP 42:18976 (2011)



Our Approach: Electrospray Ionization
- Creates molecular ions from aqueous precursor
- Ideal for small radioactive samples (~10² μL)
- Ion utilization efficiencies as high as 50%

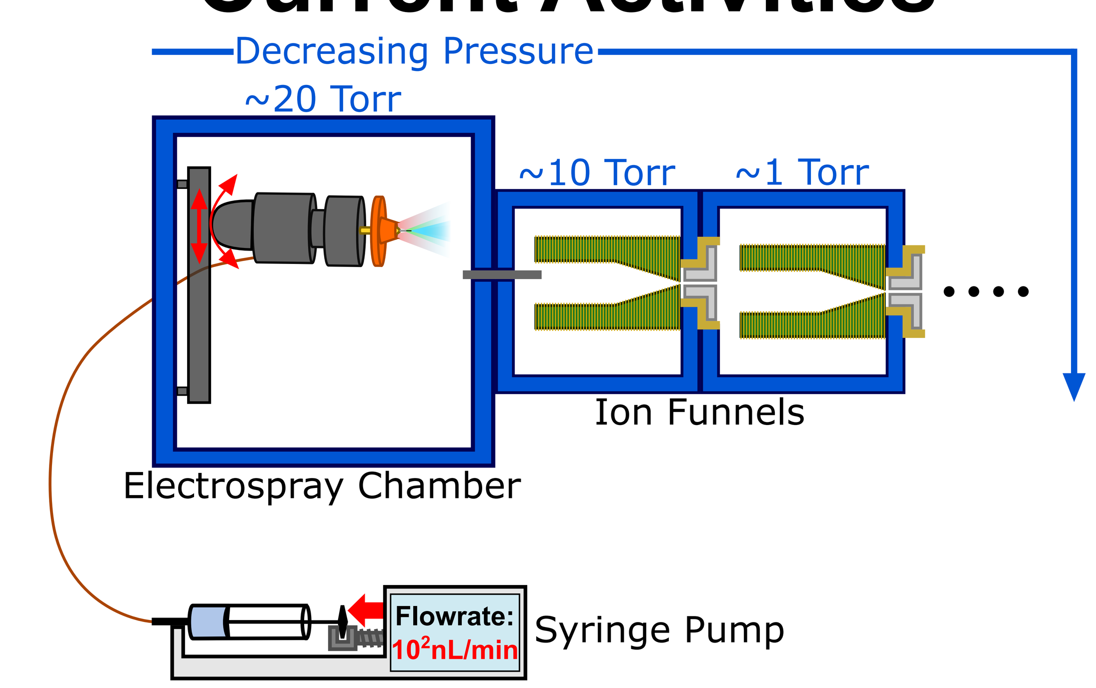
Marginean et al. Anal. Chem. 82 (2010)





Tang et al. Encyclopedia of Spectroscopy and Spectrometry 476 (2017)

Current Activities



We are designing new electrospray ion source that will allow for:
- Improved ion transmission via low pressure differential
- Increased spray stability with lower flow rates
- Precise positioning and alignment of spray probe

We are also designing a vacuum chamber to house our quadrupole mass filter

Acknowledgements

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633. This work is supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics under Award Number DE-SC0022299. This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Award Number DE-SC0019015.