Collinear Laser Spectroscopy for Nuclear Structure Studies at NSCL

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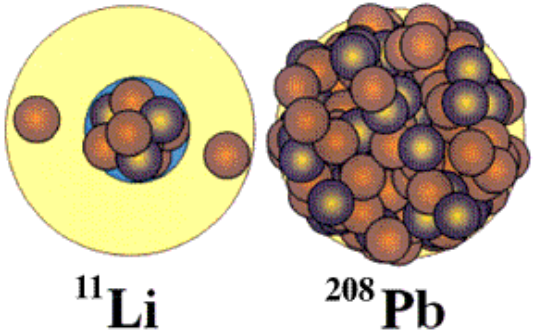
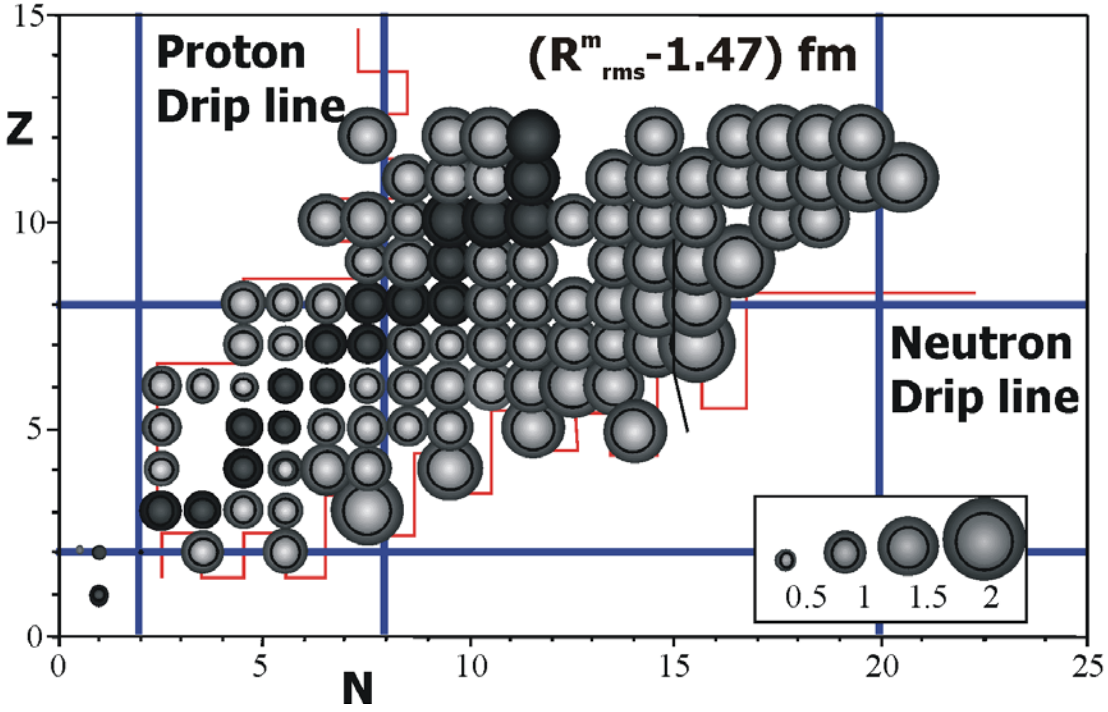
Nuclear Radii Fundamentals

The nuclear radius of ^{11}Li is comparable to that of ^{208}Pb, due to the loosely-bound nature of the valence neutrons (S_{2n} ~ 350 keV)



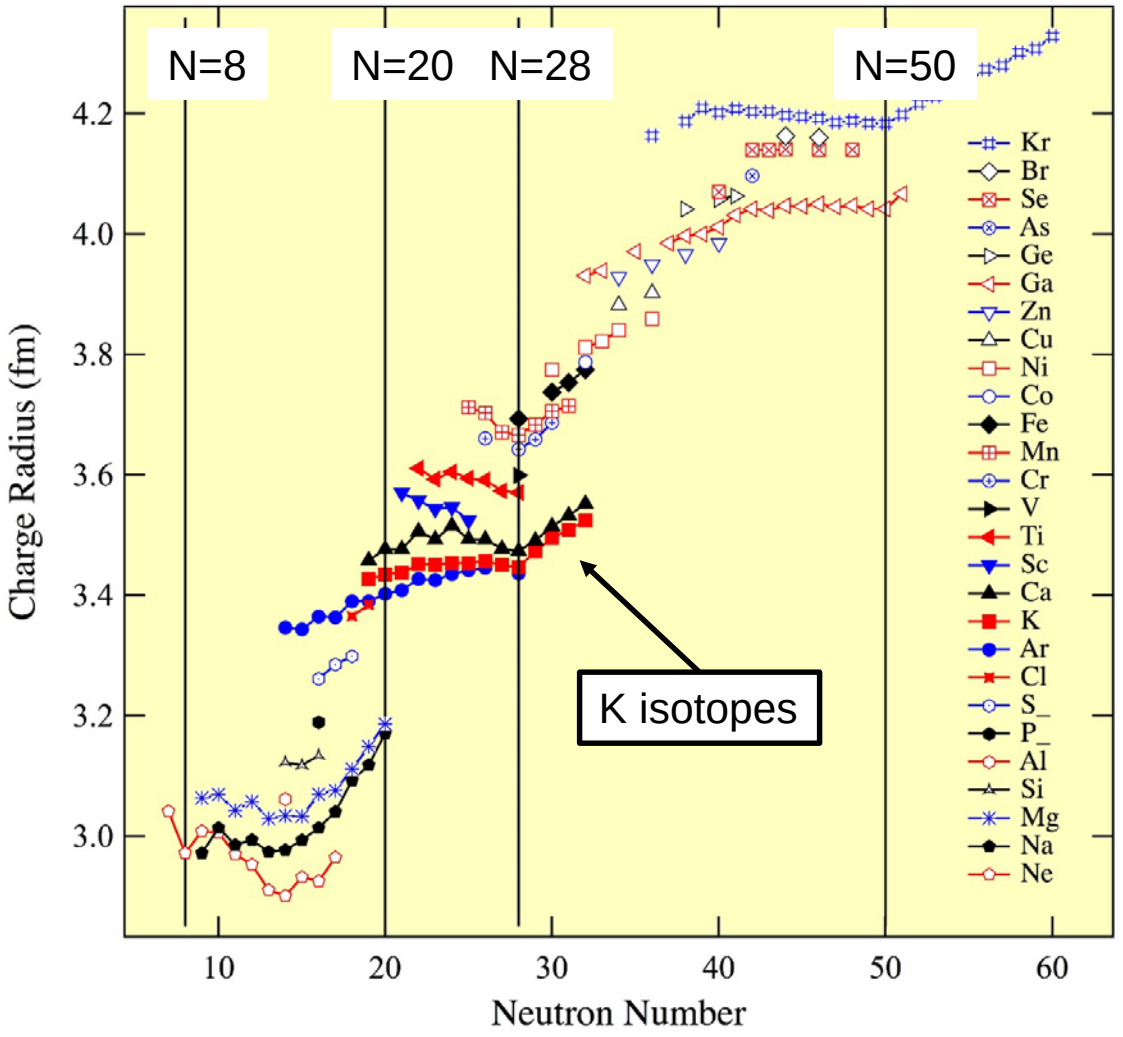


Near the limits of nuclear binding, the nucleus radius deviates dramatically from

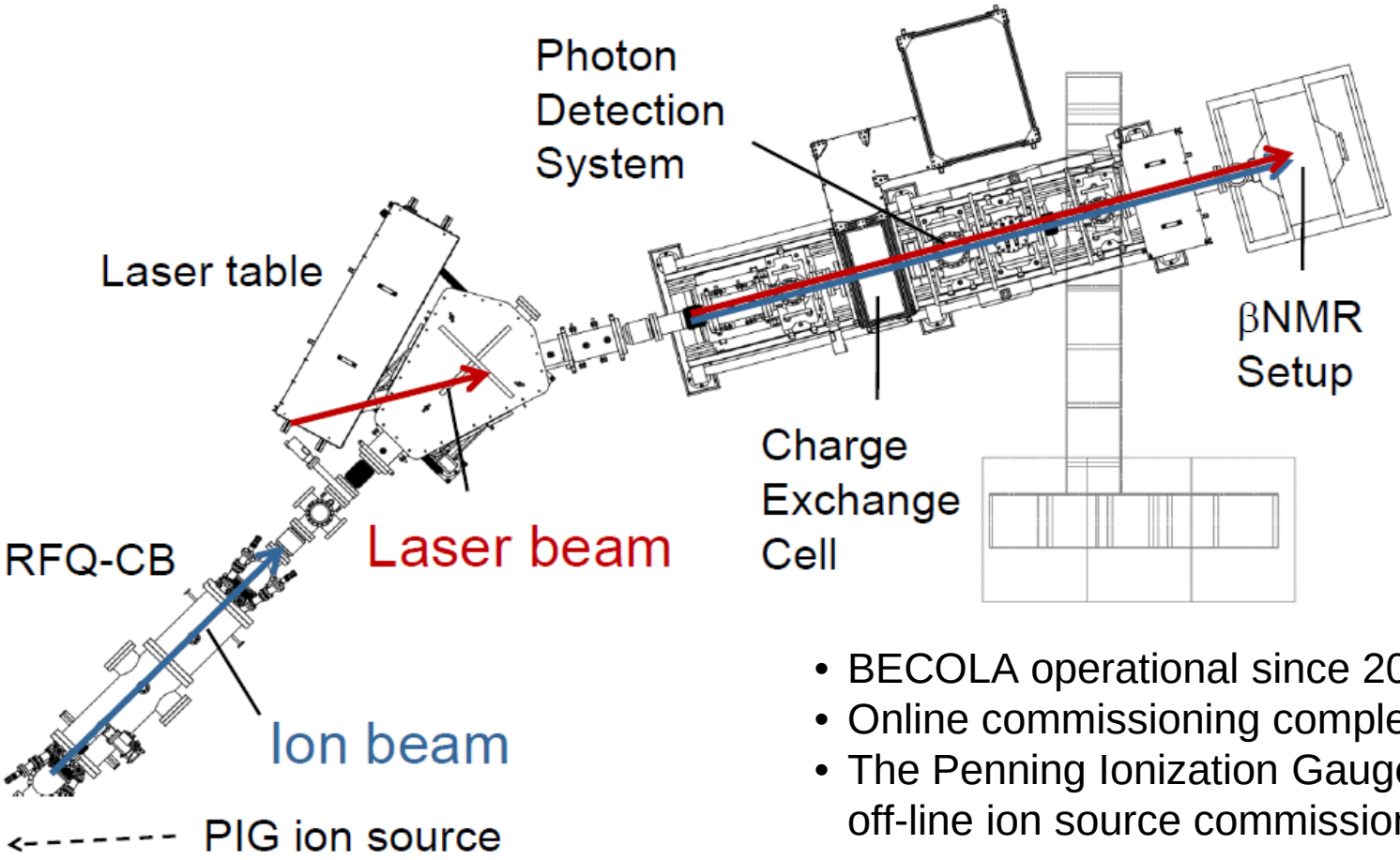
$$R = \text{const } A^{(1/3)}$$

Nuclear Charge Radii and Shell Structure around N=20

- Nuclear charge radii show discontinuity (kink) at known neutron shell closures
- No kink observed at N=20 for elements Ar, K, Ca
- What is physics underlying the trend in charge radii across N=20?
  - Measure hyperfine spectra of beta-unstable, neutron-deficient K isotopes and deduce charge radii



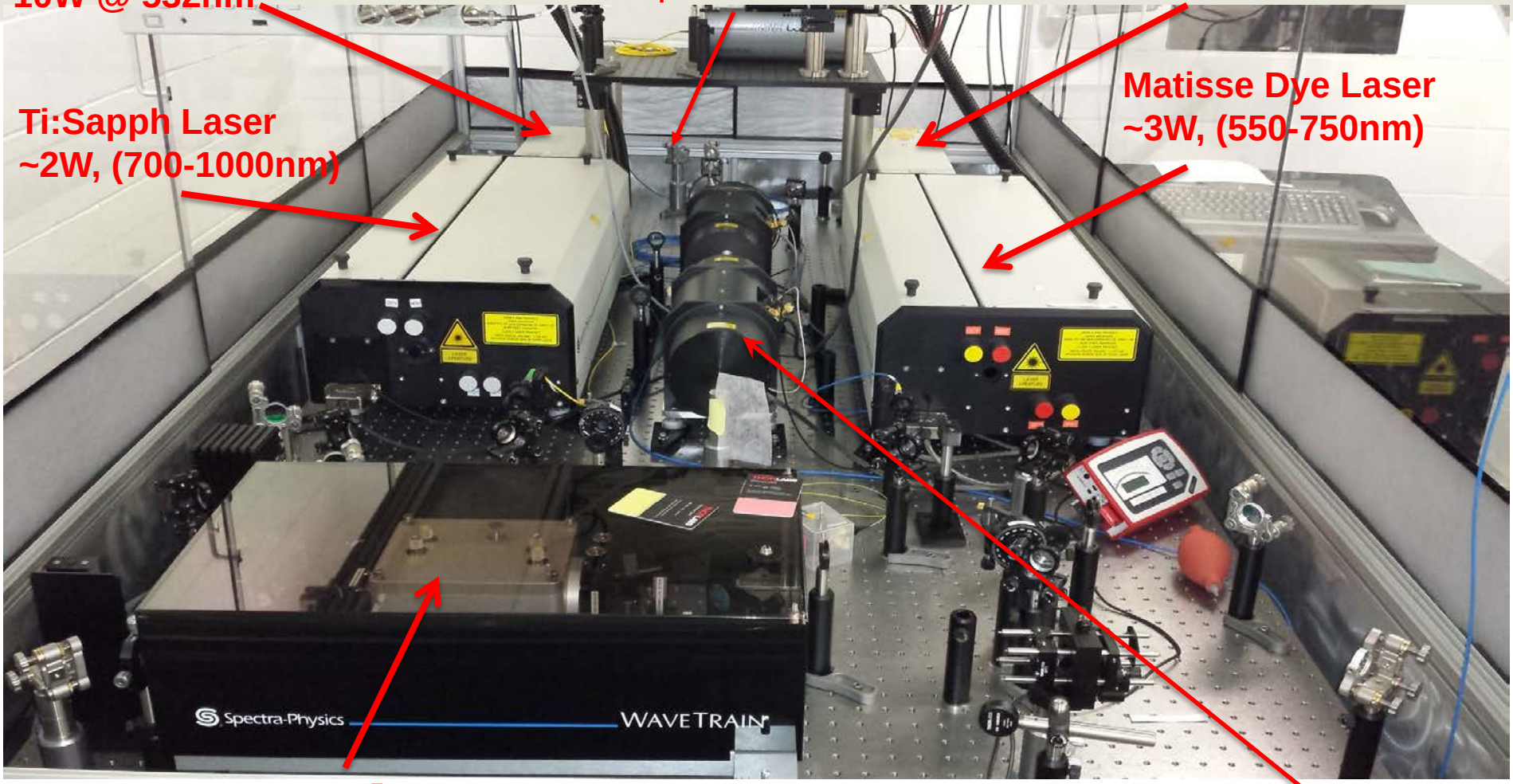
Collinear Laser Spectroscopy with BECOLA



- BECOLA operational since 2013
- Online commissioning completed in 2014
- The Penning Ionization Gauge (PIG) off-line ion source commissioned in 2015

BECOLA: K. Minamisono et al., NIMA 709, 85 (2013); D. Rossi et al., RSI 85, 093503 (2014).
Charge Exchange Cell: A. Klose et al., NIMA 678, 114 (2012); A. Klose et al., PRA 88, 042701 (2013).
PIG ion source: C. A. Ryder et al., SAB 113, 16 (2015).

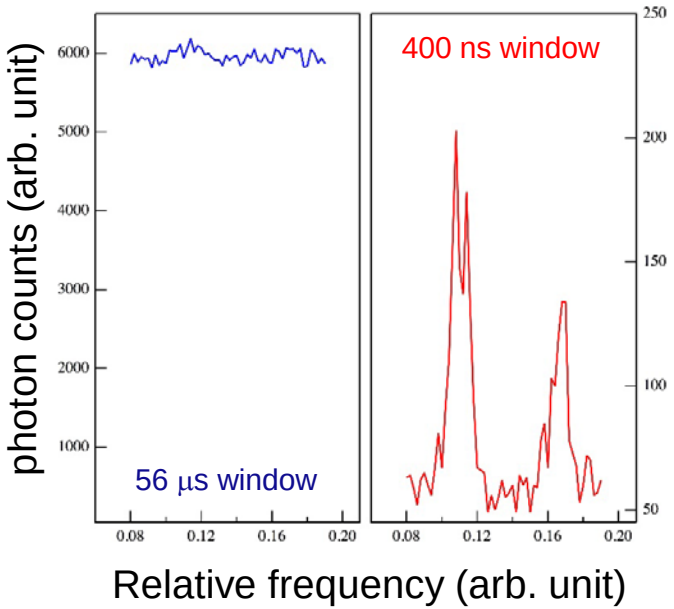
BECOLA Laser Systems

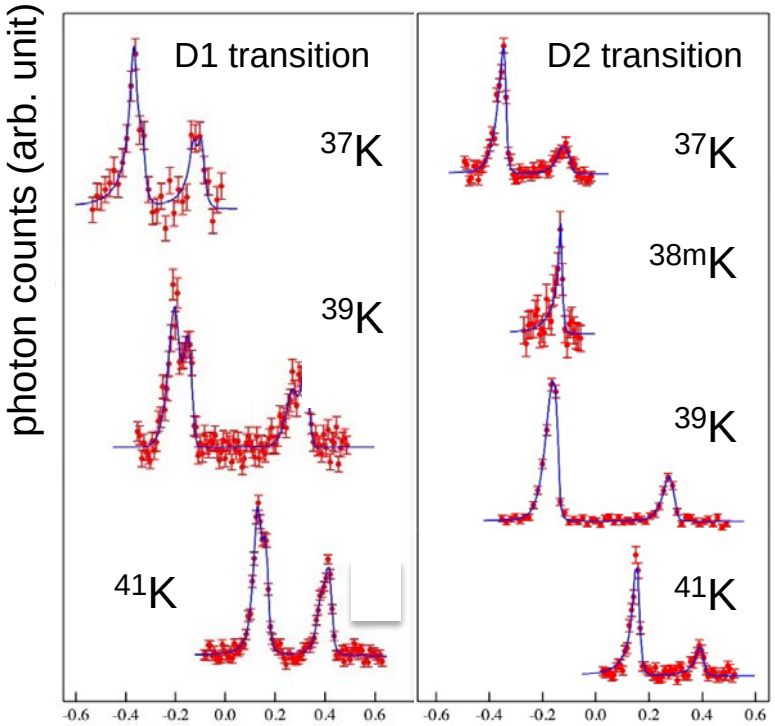


Online Commissioning with ^{37}K

- Successful commissioning with radioactive ^{37}K beam ($T_{1/2}$ = 1.2 s)
  - Measurements of hyperfine structure using resonant photon detection in coincidence with bunched beam

^{39}K I: 4p $^2P_{1/2} \rightarrow$ 4s $^2S_{1/2}$



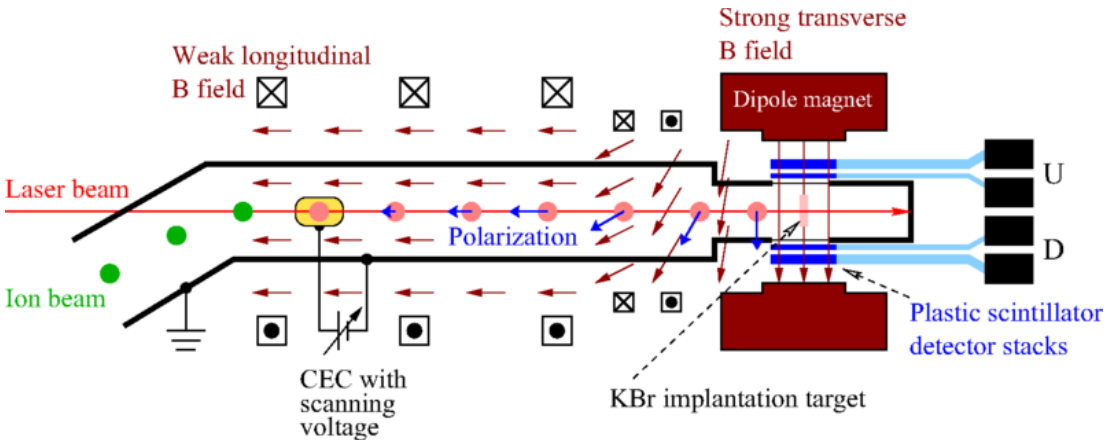


- Background suppression by 50,000
- Measurements possible with beam intensity of ~10^3 atoms/s for “red”-light detection

D. M. Rossi et al., RSI 85, 093503 (2014)
K. Minamisono et al., HI 230, 57 (2014)

Laser Spectroscopy of Radioactive ^{36,37}K

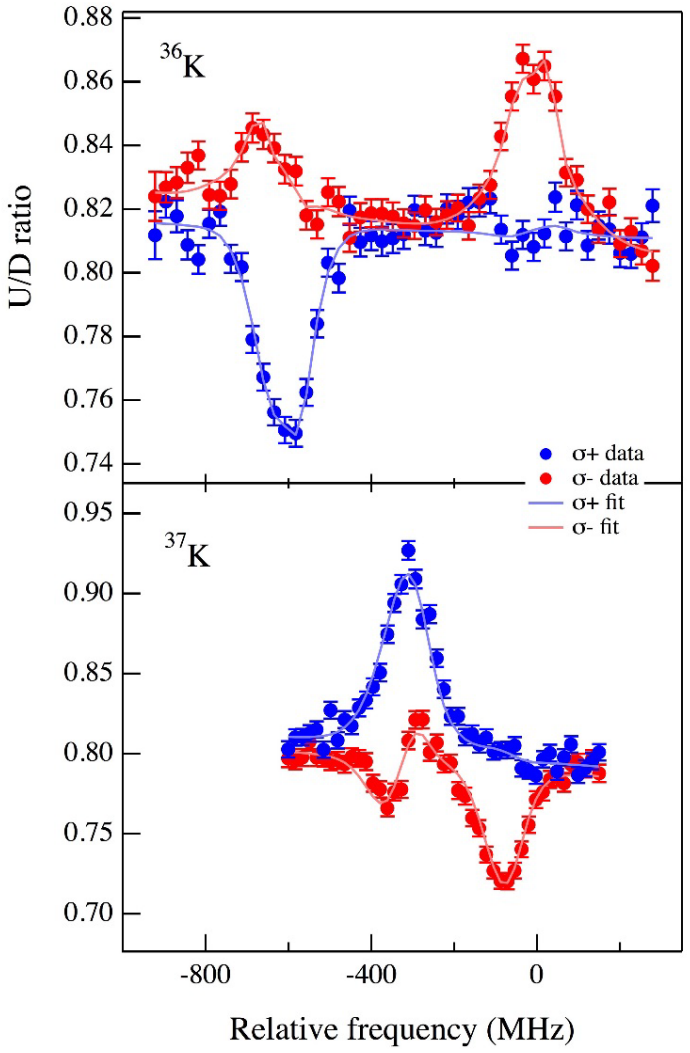
Optically pumped beam implanted in KBr single crystal



$$\text{U/D ratio} = G\frac{1-A_\beta P_I}{1+A_\beta P_I} \qquad \mathrm{P}_I = \frac{\langle m_I \rangle}{I} = \frac{\sum_m m p_m}{I}$$

$$\frac{dN_i}{dt} = \sum_j P_{ij}^{\uparrow\downarrow}(v)\left(M_j - N_i\right) + \sum_j P_{ij}^{\downarrow} M_j$$

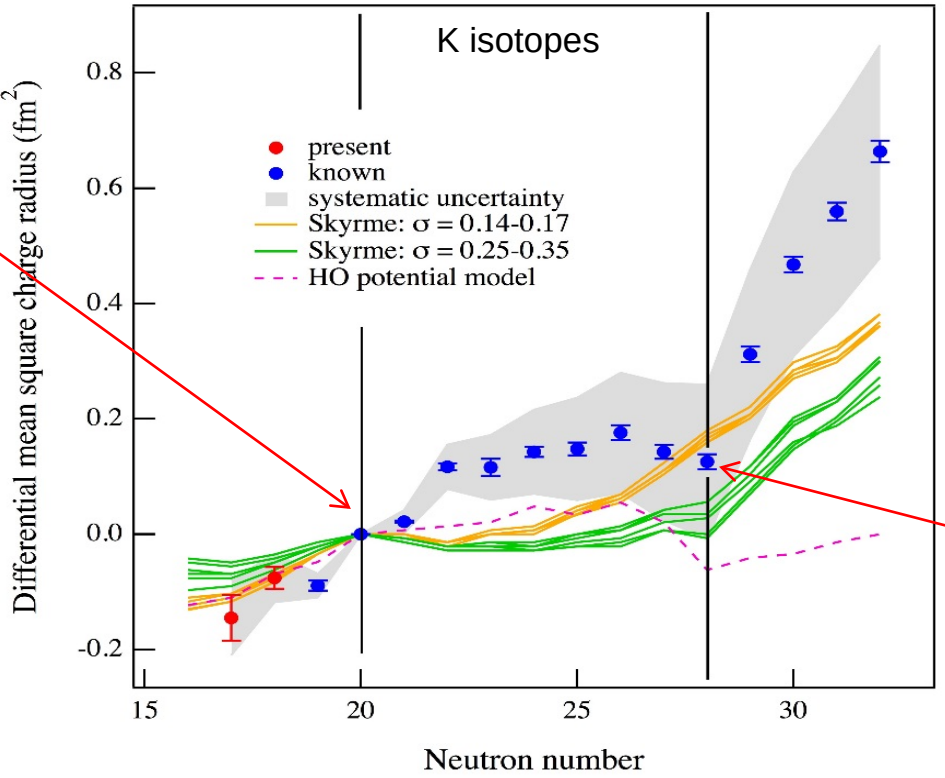
$$\frac{dM_j}{dt} = \sum_i P_{ij}^{\uparrow\downarrow}(v)\left(-M_j + N_i\right) - \sum_i P_{ij}^{\downarrow} M_j$$



Discontinuity Absent at N=20 for K Isotopes

- The characteristic discontinuities in the chain of charge radii, which is well established for nuclei at shell closures, is not apparent at *N* = 20 for the potassium isotopes.

Discontinuity absent at *N* = 20



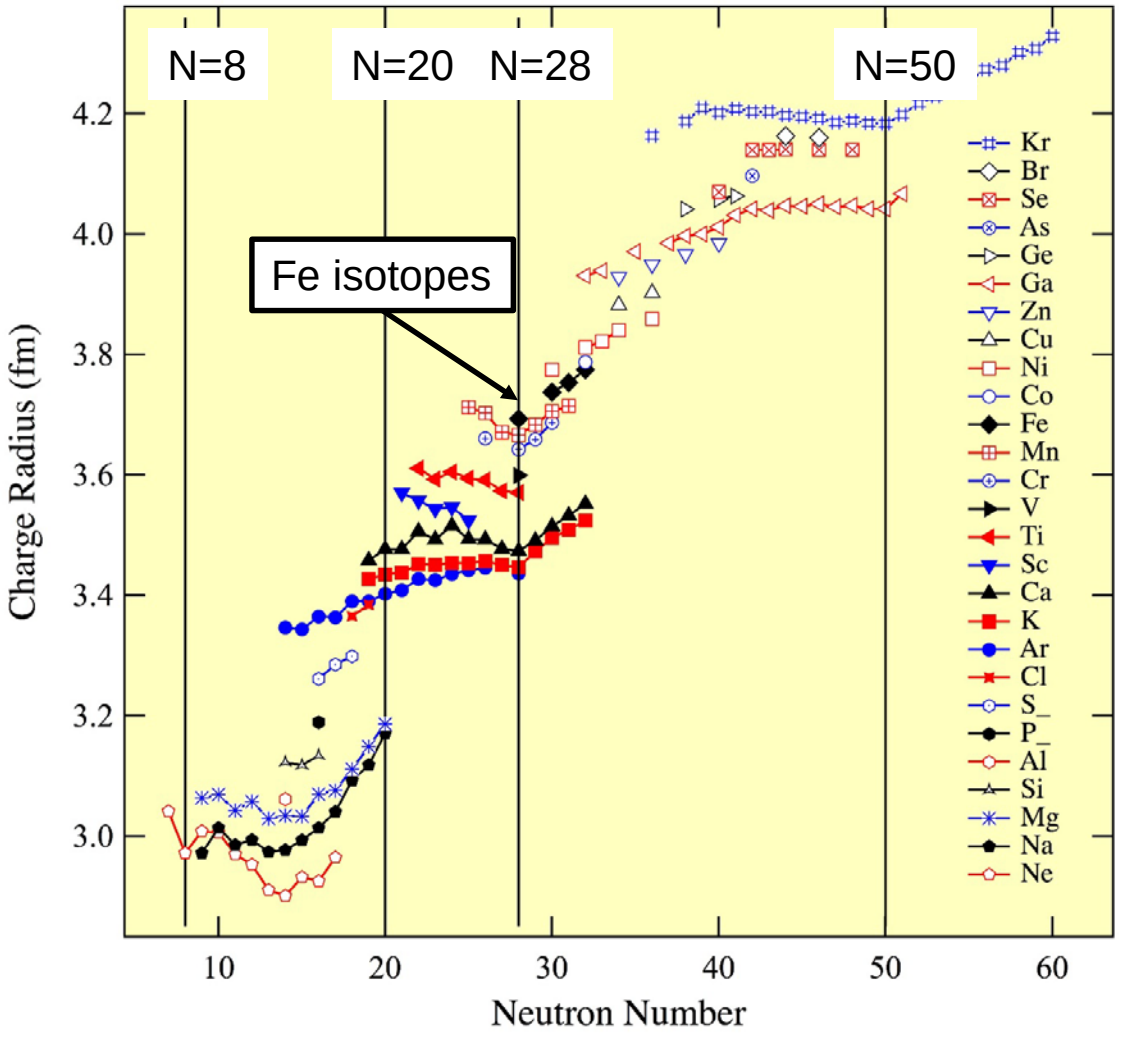
Expected discontinuity at *N* = 28

- Balance of the monopole and quadrupole proton-core polarizations above and below *N* = 20, respectively, causes the anomalous behavior.

D. M. Rossi et al., PRC 92, 014305 (2015)

Nuclear Charge Radii and Shell Structure around N=28

- Nuclear charge radii show discontinuity (kink) at known neutron shell closures
- Well-established kink observed at N=28 for elements Ar (Z=18) to Mn (Z=25)
- What about heavier nuclei, is there a change with transition to systems where N~Z?
  - Measure hyperfine spectra of beta-unstable, neutron-deficient Fe isotopes and deduce charge radii



Laser Spectroscopy of Radioactive ^{52,53}Fe

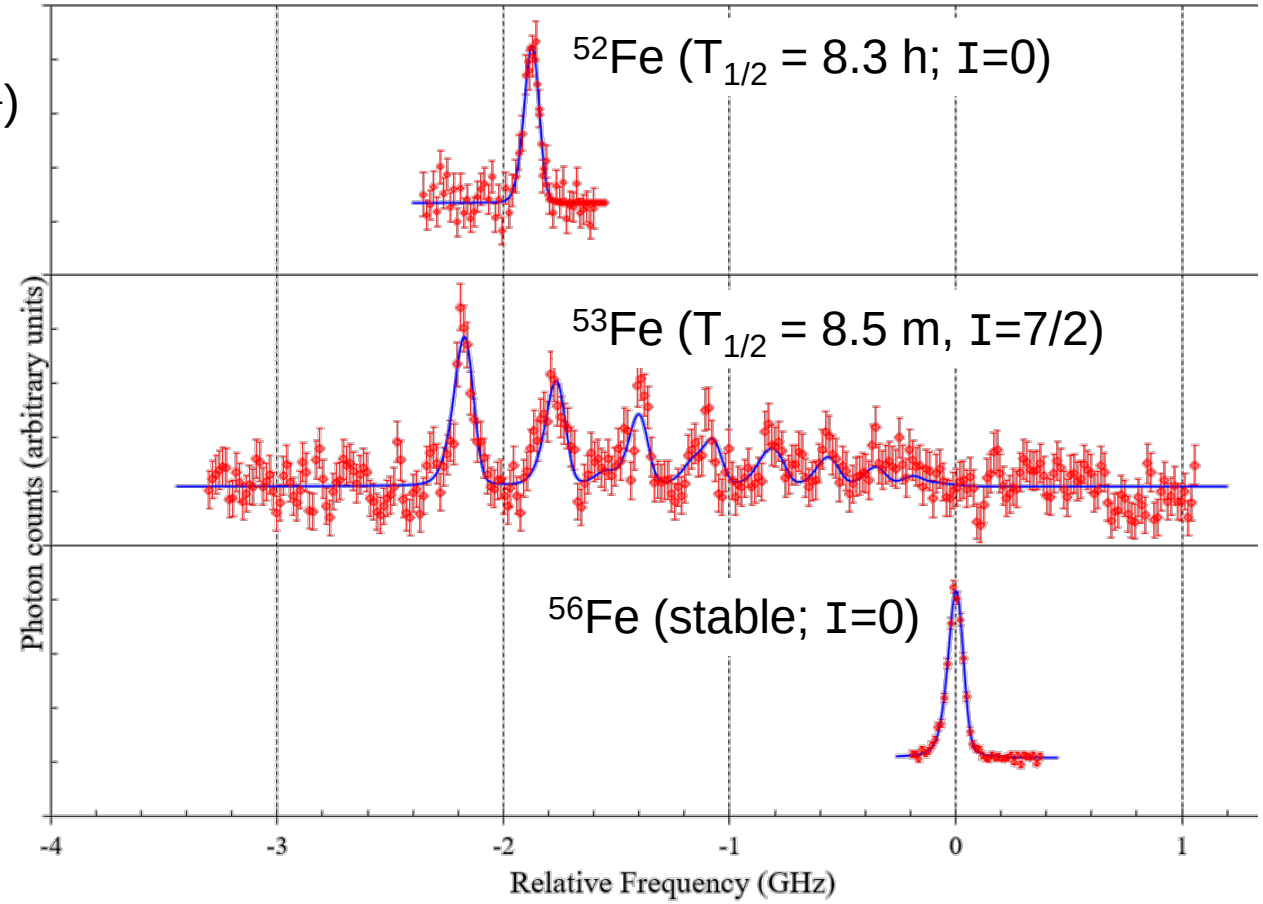
Atomic transition:
$3d^6 4s 4p\ {}^5F_5$ (26874.550 cm^{-1})

↑

$3d^6 4s^2\ {}^5D_4$ (0.000 cm^{-1})

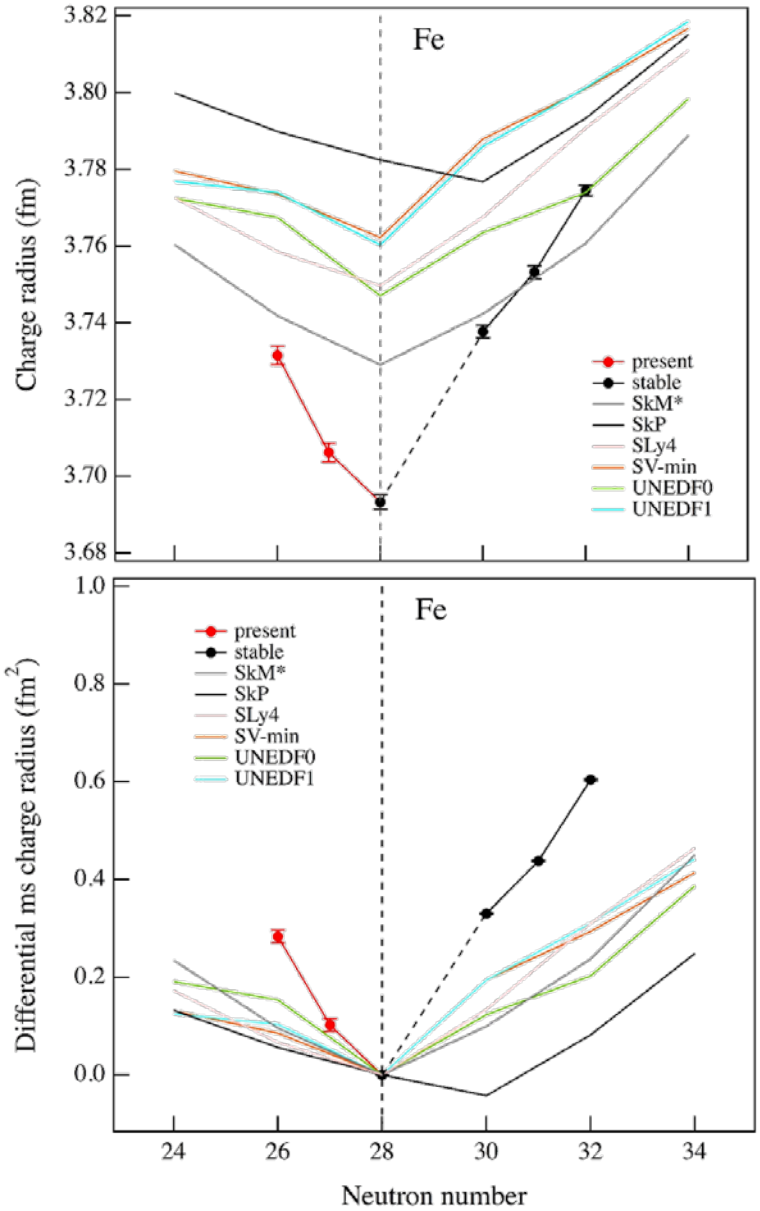
Rate after charge exchange:
^{52}Fe: 500 atoms/s
^{53}Fe: 1,500 atoms/s

Non-resonant charge exchange with Na vapor:
Only a few % population of ground electronic state



C. A. Ryder et al., SAB 113, 16 (2015).

Charge Radii Trend Along Fe Isotopic Chain



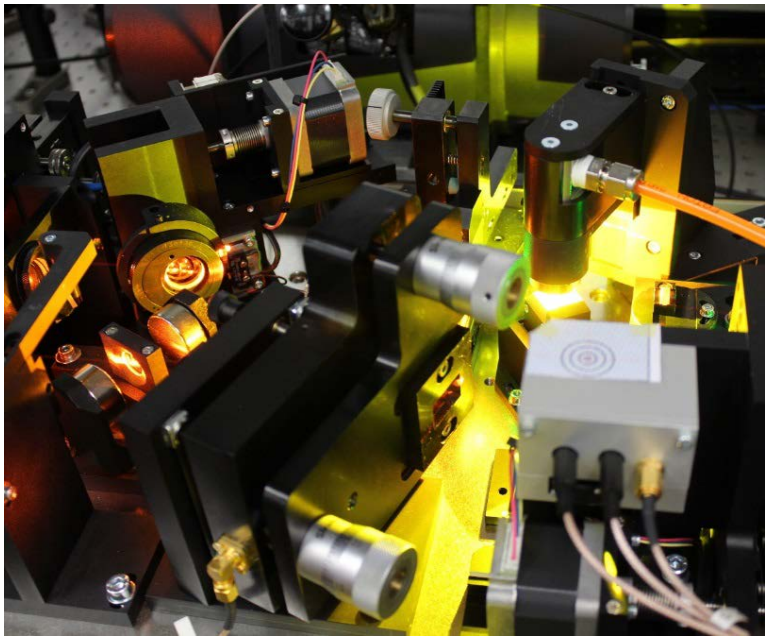
- Charge radii measurements of Fe across the N=28 shell closure
  - Expected “kink” observed at N=28
  - Structure typical of a shell closure
- Nuclear density functional theory (DFT) using the UNEDF1 Skyrme energy density functional (EDF) [blue curve]
  - Reproduces the general trend of the charge radii
  - Overestimate the magnitude of the charge radius
  - No strong odd-even staggering of charge radii along Fe isotopic chain

PRELIMINARY

J. Erler et al., Nature 486, 509 (2012).
http://massexplorer.frib.msu.edu/

Summary

- BECOLA is a CLS facility at NSCL/FRIB
  - electromagnetic moments and charge radii
  - transition metals
  - neutron-deficient isotopes
- Shell structure around N = 20
  - Disappearance of shell signature at N=20
  - Deduced charge radii of neutron-deficient ^{36,37}K
    - » No “kink” at N=20
    - » Balance between monopole and quadrupole
  - Next up, neutron-deficient Ca isotopes
    - » Approved by NSCL PAC 40
- Shell structure around N = 28
  - Strong evidence for shell closure signature at N=28
    - » Neutron-rich Ar (Z=18) to Mn (Z=25)
  - Deduced charge radii of neutron-deficient ^{52,53}Fe
    - » “Kink” persists at N=28 for Fe (Z=26)



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BECOLA Collaborators

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- Atomic factor calculations
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