Collinear Laser Spectroscopy for Nuclear Structure Studies at NSCL

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15 September 2016
The nuclear radius of $^{11}\text{Li}$ is comparable to that of $^{208}\text{Pb}$, due to the loosely-bound nature of the valence neutrons ($S_{2n} \sim 350$ 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

Millennia Pro Pump Laser
10W @ 532nm

Ti:Sapph Laser
~2W, (700-1000nm)

Millennia eV Pump Laser
20W @ 532nm

Matisse Dye Laser
~3W, (550-750nm)

Frequency Doubler ➔ (275-500nm)
~10% of input power (need ~300µW)

Optical fiber

Reference Cavities
Online Commissioning with $^{37}\text{K}$

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

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

- Background suppression by 50,000
- Measurements possible with beam intensity of $\sim 10^3$ 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

\[ \frac{dN_i}{dt} = \sum_j P_{ij}^{\uparrow\downarrow}(\nu)(M_j - N_i) + \sum_j P_{ij}^{\downarrow\uparrow}(M_j) \]

\[ \frac{dM_j}{dt} = \sum_i P_{ij}^{\uparrow\downarrow}(\nu)(-M_j + N_i) - \sum_i P_{ij}^{\downarrow\uparrow}(M_j) \]
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.

- 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)

P. Mantica, INPC 2016, Slide 8
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 $^{52,53}\text{Fe}$

Atomic transition:
$3d^64s4p\,^5F_5\,(26874.550\,\text{cm}^{-1})$

$3d^64s^2\,^5D_4\,(0.000\,\text{cm}^{-1})$

Rate after charge exchange:
$^{52}\text{Fe}$: 500 atoms/s
$^{53}\text{Fe}$: 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 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
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)

Work supported in part by:
NSF PHY-11-02511
DOE NNSA DE-NA00029
BECOLA Collaborators

- **e1101 \((^{36,37}K)/e14006 \((^{52,53}Fe)\)**

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