Nuclear ground-state properties: new opportunities for nuclear physics and precision tests of fundamental interactions

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Outline

- ISOLDE low energy setups
- EPIC upgrades considered
- Examples of regions of nuclear chart that profit
- Examples of physics:
  - weak interactions
  - nuclear structure
  - nuclear astrophysics
ISOLDE low energy setups

- Decay spectroscopy and atomic physics techniques
- Properties of ground-, isomeric-, and excited-states
EPIC upgrades considered

- Increase in proton energy from 1.4 to 2 GeV
- Increase in proton intensity from 2 to 4 uC
- Parallel (low-energy vs HIE-ISOLDE) operation: longer beamtimes
Examples of regions profiting from EPIC

- 100Sn region
- n-deficient lanthanides
- n-deficient Pb region
- 56Ni region
- 35Ar
- 23Mg
- 10C

Selection, Not exclusive

Yield (ions/µC)

- $10^{13}$ - $10^{12}$
- $10^{12}$ - $10^{11}$
- $10^{11}$ - $10^{10}$
- $10^{10}$ - $10^{9}$
- $10^{9}$ - $10^{8}$
- $10^{8}$ - $10^{7}$
- $10^{7}$ - $10^{6}$
- $10^{6}$ - $10^{5}$
- $10^{5}$ - $10^{4}$
- $10^{4}$ - $10^{3}$
- $10^{3}$ - $10^{2}$
- $10^{2}$ - $10^{1}$
- $10^{1}$ - $10^{0}$
- $10^{0}$ - $10^{-1}$
- $10^{-1}$ - $10^{-2}$

Nucleonica, J. Balloff, J.P. Ramos
Fundamental physics: weak interaction studies
Weak interaction: search for scalar currents

- standard model assumption: only vector current for Fermi transitions
  - limit on scalar current from term in Fermi function: \((1 + b_f \times g_1 / \langle E \rangle)\)
  - from \(0^+ \rightarrow 0^+ \beta\) decay: \(b_f = -0.0028 \pm 0.0026\)

- highest sensitivity for low Q-value (= light nuclei) transitions
  - improve on low-Z nuclei
  - improve BR for \(^{10}\text{C}\)
10C and scalar currents

Technique: decay spectroscopy at LA1

Preliminary result: 
BR = 1.4517(26) %
(systematic errors to be added)

statistical error: ~ 2 %

EPIC:
- 1.4 -> 2 GeV no significant gain
- gain from multi-production site facility
  => longer beam times

today typical beam times in β-decay experiments: 7 days

production of 10C-16O (mass=26)

main contaminants: 13N-13N and 14O-12C
  => need of high-resolution separation to reduce contaminants
  => avoid general limitation due to overall counting rate
**Fundamental physics: \( V_{ud} \)**

- \( V_{ud} \): 1st matrix element of CKM quark mixing matrix;

- Determined from:
  - superallowed beta decays \( I = 0+ \rightarrow 0+ \) and mirror isospin 1/2 decays
  - Neutron lifetime; Pion beta decay

- CKM unitarity:
  \[
  |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \Delta \\
  \Delta \neq 0 \Rightarrow \text{New Physics}
  \]

- \(<2018: |V_{ud}| = 0.97420(21) \Rightarrow \Delta = -0.00061(47)\) from 14 nuclear superallowed 0+-\(\rightarrow\)0+ decays

- 2018: New corrections (PRL 121, 241804 (2018))\(\Rightarrow\)
  \(\Delta = -0.00158(47) \Rightarrow 3.5 \sigma \text{ from SM}\)


Check \(\Delta\) with another method – nuclear mirror decays:

- largest uncertainty: ratio of Fermi to Gamow-Teller decay (\(\rho\))

  - Average from 7 mirror decays: \(|V_{ud}| = 0.9730(14)|\)

- \(\rho\) and \(|V_{ud}|\) precision can be improved using polarised mirror nuclei
**V_{ud} from mirror decay of 35Ar**

- Polarisation of 35Ar and 23Mg at the VITO beamline

**Goal:** measure $\beta$-decay asymmetry parameter $a_\beta$ with 0.5% precision

$\Rightarrow$ determine mixing ratio $\rho$

$\Rightarrow V_{ud}$ precision around $5 \times 10^{-4}$ level

**1st results:** laser polarisation of $^{35}$Ar:

- Gain from EPIC:
  - No gain in beam intensity but
  - Longer beamtime and higher proton intensity $\Rightarrow$ more statistics

W. Gins, PhD thesis KU Leuven [cds.cern.ch/record/2654181?ln=en](cds.cern.ch/record/2654181?ln=en)
Super-allowed decay of 98In

Fundamental studies: super-allowed $\beta$-decay 98In$\rightarrow$ 98Cd

- $V_{ud}$ and CKM unitarity tests
- Experimental precision far from lower-mass cases
- need precise $t_{1/2}$, branching ratio, $\beta$-decay energy (Q-value)

Gain: 1.4 $\rightarrow$ 2 GeV: 2-3x increase in yield with LaC$_2$ target
Target and ion source upgrades needed too

Will this be enough?
Nuclear structure
Nuclear structure with low-energy beams

Spin, lifetime, ex. energy, mass, charge radius, magnetic & quadrupole moment

Nuclear force
- Phenomenology
- Chiral effective field theory

Many-body methods
- Ab-initio
- Shell-model
- DFT

Electro-weak currents
- Effective neutron/proton charges
- Microscopic description of effective operators

Status of ab-initio calculations: 2016

- Ca region
  [Hagen et al, Nature Physics 12, 186 (2016)]

- Ni region

- Sn region?

New developments in EFT + Normalization group + many-body methods:

Adapted from R. Garcia
Nuclear structure and *ab initio* theory

*ab initio* approaches can now address $^{100}$Sn


Doubly magic 100Sn (Z=N=50)

- Heavies Z=N magic nucleus
- Strongest Gamow–Teller strength so far measured in all atomic nuclei
- Test-ground for nuclear theory
- Only rough t1/2 and decay scheme known

Gain: 1.4 -> 2 GeV: 2-3x increase in yield with LaC$_2$ target
Target and ion source upgrades needed too
100Sn region: laser spectroscopy

Questions addressed:
- Robustness of $N = Z = 50$ shell closure
- Evolution of properties with changing $N$
- Ordering of shell-model orbits
- Proton-neutron correlations

Observables:
- Charge radii
- Magnetic moments
- Quadrupole moments
- Spins

SIMULATION 15 SHIFTS

$^{100}{\text{In}}$  
$I = (7+)$

SIMULATION 10 SHIFTS

$^{102}{\text{Sn}}$
Towards a ‘universal’ description of charge radii

- \( N=50 \) shell closure probed with MIRACLS

Fayans energy density functional
- very successful along Ca isotopic chain
- reproduces Cd charge radii (OES and global trend) very well, too
- high quality data constraints DFT \( \Rightarrow \) neutron matter & neutron stars
n-deficient lanthanides: nuclear structure

- neutron-deficient lanthanides:
  - search for cluster emission
  - study of proton emitters

- Gain: 1.4 -> 2 GeV: higher yield

- Feasible cases (p-emitters):
  - $^{147}\text{Tm} (Z=69)$: current yield Ta target 200 ions/uC
  - $^{151}\text{Lu} (Z=71)$: current yield TaTh target 1 ions/uC
Neutron-deficient Pb isotopes

- Strong nuclear structure effects observed by spectroscopy:
  - Deformation seen in radii and somehow masses
  - Especially n-deficient Z = 77 to 84 around mid-shell N = 104

- Similar effects with smaller magnitude observed in Au and Hg isotopes

Ch. Boehm et al. PHYS. REV. 90, 044307, (2014)

V. Manea et al. PHYS. REV. C 95, 054322 (2017)
N-deficient Pb region and masses

- Gain: 1.4 -> 2 GeV: 3-5x yield increase with UC\(_x\) target;
- Extension of studies very close to p-drip line possible
Nuclear astrophysics
Rapid-proton capture

Rp process: stellar nucleosynthesis in proton-rich environments
- High temperature, a lot of 1H
- Suggested sites: accreting binary system: neutron star + partner => tail of X-ray flash

End point:
- due to alpha decay and proton emission
- Sn-Sb-Te cycle
- not yet well established

56Ni region and masses

- \( Q(p, \gamma) = m(Z,A) + m_p - m(Z+1,A+1) \)
- \((\gamma, p)\) reaction rate \( \propto e^{-Q(p,\gamma)} \)
- Strong impact on astrophysical observables: \( ^{58}\text{Zn}, ^{61}\text{Ga}, ^{62}\text{Ge}, ^{65}\text{As}, ^{66}\text{Se} \)

Gain: 1.4 -> 2 GeV: 2x yield increase with ZrO\(_2\) target

H. Schatz et al., The Astrophysical Journal, 884:139 (11pp)
100Sn region

End of rp process due to Sn-Sb-Te cycle:

- $^{98}\text{Cd}, ^{99-101}\text{In} \Rightarrow$ strong impact on composition of X-ray burst ashes

Need:
- $t_{1/2}$
- $\beta$-delayed p branching ratios
- masses

Gain: 1.4 -> 2 GeV: 2-3x increase in yield with LaC$_2$ target
Target and ion source upgrades needed too

From D. Yordanov
Summary

ISOLDE low-energy physics will profit from **EPIC upgrades:**
higher yields, longer beamtimes, and cleaner beam

**Examples:**
- Weak-interaction studies: $^{10}$C, $^{23}$Mg, $^{35}$Ar, ($^{98}$In reachable?)

- Nuclear-structure:
  - Closed shells and tests of nuclear theory: $^{100}$Sn, n-deficient Pb
  - Mid-shell and p-emitters: n-deficient lanthanides

- Nuclear astrophysics:
  - rp process: $^{56}$Ni and $^{100}$Sn regions

Thanks for your attention

Thanks for the input from:
D. Atanasov, B. Blank, R. Garcia, S. Malbrunot, M. Mougeot, A. Vernon
Motivation:

- Nuclear structure: doubly magic 100Sn (Z=N=50)
  - strongest Gamow–Teller strength so far measured in all atomic nuclei
  - Test-ground for nuclear theory
  - Only rough t1/2 and decay scheme known

- Nuclear astrophysics: rapid proton capture
  - end of rp process due to Sn-Sb-Te cycle
  - need t1/2 and β-delayed p branching ratios

- Fundamental studies: super-allowed β-decay 98In-> 98Cd, CKM unitarity tests
  - need precise t1/2, branching ratio, β-decay energy (Q-value)

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100Sn

- RIKEN, 2500 nuclei in total
- GSI, 2012, 260 nuclei in total

Nature 486, 344 (2012)
Laser spectroscopy in a trap

- Trap ⇒ long observation time ⇒ higher sensitivity ⇒ more exotic nuclides accessible

**MR-ToF devices:**
- **F. Wienholtz et al., Nature 498, 346 (2013)**

### Novel approach for collinear laser spectroscopy:
- Ion trap ⇒ long observation time
- 30 keV beam ⇒ high resolution

![Simulation](image)
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**Goal:** measure $\beta$-decay asymmetry parameter $a_\beta$ with 0.5% precision

=>$\rho$ determine mixing ratio

=>$V_{ud}$ precision around $5 \times 10^{-4}$ level

**Our 1st results:** laser polarisation of $^{35}$Ar:

![Graph showing laser detuning vs. asymmetry percentage]

Project together with N. Severijns and G. Neyens, KU Leuven


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