Nuclear Physics at the ISOLDE-facility at CERN

Lecture 3: Nuclear Physics research and Applied research at ISOLDE

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on behalf of the CERN ISOLDE team www.cern.ch/isolde
Outline

Aimed at both physics and non-physics students

- Lecture 1: Introduction to nuclear physics
- Lecture 2: CERN-ISOLDE facility
- This lecture: Nuclear Physics and Applications at ISOLDE
  - What observables do we measure for nuclear structure research at ISOLDE?
  - Which experimental techniques are used?
  - Recent results with each method
  - A few selected applied research topics

Literature: Focus on Exotic Beams at ISOLDE: A Laboratory Portrait
Journal of Physics G44 (June 2017)
> 23 papers on the ISOLDE facilities and physics at ISOLDE
Small quiz

Who are the two most important VIP’s in this photo?

King Philip of Belgium
Prof. Francois Englert (noble price winner 2013 – Higgs-boson)

21 May 2014
Where protons are used at CERN

In 2016

1.3 \times 10^{20} protons in total in PSB

- PSB: PS Booster
- ISOLDE: Isotopes Separator On Line Device
- PS: Proton Synchrotron
- EA: East Experimental Area
- AD: Antiproton Decelarator
- SPS: Super Proton Synchrotron
- n_TOF: Neutron Time-of-Flight facility
- LHC: Large Hadron Collider
- NA: North Experimental Area
- ... Other uses, including accelerator studies (machine development)

**Quantity of protons used in 2016 by each accelerator and experimental facility, shown as a percentage of the number of protons sent by the PS Booster**

1.34 \times 10^{20} protons were accelerated in the accelerator complex in 2016. This might sound like a huge number, but in reality it corresponds to a minuscule quantity of matter, roughly equivalent to the number of protons in a grain of sand. In fact, protons are so small that this amount is enough to supply all the experiments. The LHC uses only a tiny portion of these protons, less than 0.1%, as shown in the diagram.
The ISOLDE users community

- > 800 scientists from 209 institutes from 41 countries
- ~ 50 experiments/year
- > 20 PhD’s per year
- > 80 publications/year of which many high-impact (PRL, PLB, Nature, …)

5 main users countries: Germany, France, UK, Belgium, Switzerland
Nuclear Physics experiments

- About 75% of all beam time!
  - 40% for low-energy experiments
  - 35% for experiments with post-accelerated RIB (still in upgrade phase)
- About 15% is for Bio and medical physics related research
- About 20% is for Solid State Physics research
Experiments to probe nuclear structure

Nuclear Reaction

Gamma spectroscopy (excitation schemes)

Few-nucleon transfer
5-10 MeV/u (probe quantum orbits)

A⁻¹X (d,p)

Coulomb excitation
3-4 MeV/u (probe collectivity)

Radioactive decay
(α, β, γ, n, p, fission)

T₁/₂, angular correlations

Mass spectroscopy

Energy

A

T₁/₂

Iπ

Laser spectroscopy
(spin, moments, radius)
LOW ENERGY NUCLEAR PHYSICS
EXPERIMENTS

Laser Spectroscopy (Collinear and in the RILIS ion source)

Mass Measurements (Penning Trap)

Decay Spectroscopy (ISOLDE Decay Station)
Laser spectroscopy

Determine nuclear ground state properties (and long-lived isomers)

Spin \( I \)

Magnetic dipole moment \( \mu \)
(probe wave function)

Electric Quadrupole moment \( Q_s \)
(shape)

Charge radius \( \delta \langle r^2 \rangle \)
(size)

Measure the atomic hyperfine splitting

and isotope shifts

\[
\text{Counts}
\]

\[
\text{Relative frequency [MHz]}
\]

\[
\text{Counts}
\]

\[
\text{Frequency relative to } ^{55}\text{Mn centroid [MHz]}
\]
Collinear laser spectroscopy

- Ion beam: $E_{\text{kin}} \sim 60$ keV
- Laser beam: fixed frequency
- Electrostatic deflection
- Electrostatic lenses for retardation
- Charge exchange cell (Na) (neutralize the ion beam)
- Resonant laser excitation of the atoms & observation of fluorescent photons

Since late 70’ies

Accelerated beam
→ Small relative velocity spread
→ Reduction of Doppler Broadening
→ Small line widths – resolve all hyperfine peaks
Collinear laser spectroscopy on Ca isotopes

10^7 ions/s

2013: New magic numbers suggested from masses and energies

2016

Unexpectedly large charge radii of neutron-rich calcium isotopes


Masses of exotic calcium isotopes pin down nuclear forces


Affiliations | Contributions | Corresponding author

Evidence for a new nuclear ‘magic number’ from the level structure of ^{54}\text{Ca}

Collinear Resonance Ionization Spectroscopy (CRIS)

- ultra-low background (1 event /10 min)
- high efficiency (~1-5 %)
- high resolution (~20-60 MHz)
- current sensitivity 10-20 ions/s

Most recent result @ ISOLDE
HFS of 63-78Cu
(R.P. de Groote et al., submitted to PRL)
In-source laser spectroscopy

Use selective **Resonance Ionization Laser Ion Source (RILIS)** to do spectroscopy

- More sensitive (<1 ions/s needed)
- Less resolution (few GHz !)
- Isotope shifts (no quadrupole moments)

![Diagram of laser spectroscopy](image)

**Detect ions**
- Non-resonant ionization
- Excitation auto-ionizing

**Ion counts**

Scan this step

Scan laser frequency step 1
Charge radii around lead

Isotope shifts measured with RILIS setup

Most exotic Po: < 1/s

- Onset of deformation
- Shape staggering
- Shape coexistence

STUDY INTERPLAY BETWEEN COLLECTIVE AND SINGLE PARTICLE BEHAVIOR
Studies with ion traps

- Penning trap = cross of magnetic and electric field
- Ion manipulation with radiofrequencies
- Possibility of purifying the ion ensembles
free cyclotron frequency is inversely proportional to the mass of the ions!

Free cyclotron frequency is inversely proportional to the mass of the ions!

\[ \omega_c = \frac{qB}{m} \]
Penning-trap mass spectrometry

**ISOLTRAP setup**

From cyclotron frequency to mass

\[ \nu_c = \frac{1}{2\pi} \frac{q}{m} B \]

Relative mass uncertainty around 10^{-8}

**determination of cyclotron frequency**

\( R = 10^7 \)

**removal of contaminant ions**

\( R = 10^5 \)

**Bunching of the continuous beam**

- alkali ion source
- RFQ cooler and buncher
- ISOLDE 60 keV ion beam
- HV platform

**Beta- and gamma decay studies**

- TOF detector
- 50 ms - 10 s, 100%
- preparation Penning trap
- laser ablation ion source
- 10-100 ms, >50%

**MR-TOF MS**

- MR-TOF detector or BN beam gate
- ND:YAG 532nm

50 ms - 1 s, 100%

**From cyclotron frequency to mass**

**Relative mass uncertainty**

around 10^{-8}

**10 ms, 1-10%**
Mass filters (mass differences) to “filter out” specific effects, e.g.

- Differences in binding energies (one- or two-neutron/proton separation energies)

Two-neutron separation energy

\[ S_{2n} = B(N - 2, Z) - B(N, Z), \]

Closed shells visible as a sudden drop after the magic number (N=20 and 28)
Mass of zinc-82

After several attempts at ISOLTRAP and elsewhere

- Combined ISOLDE technical know-how:
  - neutron-converter and quartz transfer line (contaminant suppression)
  - laser ionisation (beam enhancement)

Neutron-star composition:
- Test of neutron-star models
- $^{82}\text{Zn}$ is not in the crust

Mean-field models:

Different detectors are sensitive to observe:
- Alpha particles or Fission Fragments
- Beta particles
- Gamma rays
- Protons or neutrons
Decay spectroscopy: the Windmill (KU Leuven design)

- Very thin C foils to implant a heavy radioisotope
  - 40 keV $^{180}$Tl stops in a few nm of C

- Lighter Fission Fragments (FF) or alpha particles are emitted from the isotope, and can leave the very thin C foil
  - Detection using Si-detectors

- Gamma rays detected with HPGe detectors
Nuclear shell effects are important in fission, but:

- Unexpectedly $^{180}\text{Hg}$ does not fission in two semi-magic $^{90}\text{Zr}$ ($Z=40, N=50$)
- Fission theories do not predict the results correctly
HIGH ENERGY NUCLEAR PHYSICS EXPERIMENTS with accelerated RIB’s

Coulomb excitation (3-4 MeV/u max)

Transfer reaction (5-10 MeV/u)
RIB from ISOLDE-CERN: the HIE-ISOLDE post-accelerator

2016: max 5 MeV/u (2 superconducting cavities)
2017 (this week): first beams at 7 MeV/u (3 cavities)
2018: max energy reached (10 MeV/u) (4 cavities)
Coulomb excitation

Miniball Ge detector

Double sided silicon strip detector

Target $^{196}\text{Pt}$

$2 \text{ mg/cm}^2$

$^{74}\text{Zn}$

$^{196}\text{Pt}$

$E_p$

$\theta_p$
Coulomb excitation

Excitation of an accelerated (radioactive) nucleus by the electromagnetic field of the target (made of stable nuclei)

Observables: Transition energies and intensities
=> Determine new excited levels and study deformations

Conflicting data for

- $^{74}\text{Zn}$
  - 4.0 MeV/u (~ 5 hours)
  - 2.8 MeV/u (~ 16 hours)
Octupole deformation from Coulex

- Octupole shape – very rare nuclear shape
  - Test ground for nuclear models
  - Important in searches for permanent electric-dipole moments (EDM) – beyond Standard Model Physics

Nucleon-transfer reactions

**Typical reaction:** transfer of a neutron

Accelerated RIB (5-10 MeV/u) → Similar configurations → Large overlap of wave functions → Large probability of transfer reaction

**Observables:**
- energy of protons and emitted RIB
- γ-rays
- angular distributions of protons (+ γ-rays)

**Information:**
- (single-particle) level energies
- spin/parity of levels

**Miniball + T-REX setup** (Si detector barrel)
- gamma detectors and particle identification
- study single-particle properties of nuclei
- Similar configurations = large overlap of wave functions = Large probability of transfer reaction
Applications

- Use known radiation from not totally exotic radioisotopes

Profit from radionuclides:
- Pure samples of radioisotopes (offline studies)
- High detection efficiency for radiation (online studies)

Techniques:
- Emission Channeling
- PAC (Perturbed Angular Correlations)
- Diffusion
- Photoluminescence
Material science

- Emission channeling
  - Position of implanted ions

Crystal lattice

- Implantation of radioactive ions
- β- or ε-decay

2-dimensional detector

Emission channelling pattern

Experiment vs Simulation $S_{Ga}$ sites

- [0001]
- [1102]
- [1101]
- [2113]
Heavy-ion toxicity

Studied with Perturbed Angular Correlation method

Over 1/3 of all proteins require metal ions to function:

- **Magnesium**
  - Catalysis in cellular energy transformations
  - Photosynthesis - component of chlorophyll

- **Copper**
  - Alzheimer’s disease
  - Wilson’s disease
  - Graph showing body response vs. copper dosage:
    - Deficiency
    - Optimal
    - Toxicity
    - Survival
    - Lethality
    - ~ 300 mg

- **Prion disease**
  - Brain section showing spongiform pathology characteristic of Creutzfeldt-Jakob
  - Parkinson’s disease

But they are difficult to study:

“Magnesium in biological chemistry is a Cinderella element: We know its hidden power and personality only indirectly since we are unable to label and follow it in a sensitive manner.”
Metals in biology and beta-NMR

- **New approach – beta-Nuclear Magnetic Resonance**
  - Beta-decay of polarized nuclei is anisotropic
  - Resonances observed as change in decay asymmetry
  - **Up to 10^{10}** more sensitive than conventional NMR

- **Proof-of-principle experiment**
  - Magnesium-31 beam
  - Polarization with lasers
  - 1st beta-NMR in a liquid

- **Outlook:**
  - First biological studies on Mg and Cu

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Soon be continued within MK’EU ERC Starting Grant
new PET isotopes

- PET (positron emission tomography) – uses β+ emitting nuclei and their annihilation inside the body in diagnosis and therapy
- Produced at ISOLDE and later investigated together with the creators of the PET technique at the Geneva Hospital
Production of medical isotopes for trials (not commercial use) via ISOLDE “dump” protons

-> little ISOLDE + chemical preparation

Use protons (~90%) normally lost into the Beam Dump
New medical isotopes

Collection at ISOLDE
Radiochemical purification and labeling
Injection into mouse
PET/SPECT imaging and tumor treatment

- Theranostics = therapy and diagnostics together
  - Production of isotopes at ISOLDE
  - Chemical selection and mice treatment in PSI

- Soon at ISOLDE-Medicis

A visit to ISOLDE?

CONTACT Kara Lynch by end of this week latest
kara.marie.lynch@cern.ch

THE FIRST 24 PERSONS THAT SIGN UP
WILL GET A GUIDED TOUR

Already registered:
Maisam Pyarali
Etienne Fayen
Lauren Weiss
Summary

Research topics with radionuclides:
- Nuclear and atomic physics
- Astrophysics
- Fundamental studies
- Applications

Studied properties:
- mass, radius, spin, moments, half-life, decay pattern, transition probabilities

Examples of ISOLDE experimental techniques
- Laser spectroscopy
- Ion traps
- Decay spectroscopy
- Coulomb excitation
- Nucleon-transfer reactions

Applications
- Material science
- Life sciences: bio- and medical

VISIT: Kara Lynch
kara.marie.lynch@cern.ch
Only first 24 applicants!
Nuclear moments and spins near exotic (doubly magic?) $^{78}\text{Ni}$

Theoretical models predict $^{78}\text{Ni}$ is doubly magic

Closest we can get: $^{78}\text{Cu} = ^{78}\text{Ni} - p - n$

20 ions/s produced at ISOLDE

⇒ To measure shape: need CRIS!

Quadrupole moments

⇒ TEST MODERN THEORIES

R.P. de Groote et al., submitted to Phys Rev Lett.
Studies of radioactive nuclides

Properties/observables (for ground states and isomers – long-lived excited states)

- mass
- Spin, parity
- radius
- e-m moments
- half-life
- Decay pattern
- Transition probability

Techniques/ devices
- Laser spectroscopy
- Beta-detected NMR
- Ion traps
- Decay spectroscopy
- Coulomb excitation
- Nucleon-transfer reactions

To obtain the full picture: need to study several properties and use several techniques
Halo: nucleus built from a core and at least one neutron/proton with spatial distribution much larger than that of the core

- Interaction of the core and halo nucleons not well understood

Combination of techniques: Charge radii of Hg & Au

Several techniques combined:
- RILIS lasers to probe the hyperfine structure of Hg & Au isotopes

Detection:
- Alpha spectroscopy with Windmill
- Selective ion counting in MR-ToF

Bonn et al., PLB38 (1972) 308
Ulm et al., Z Physik A 325 (1986) 247
EDM searches in radionuclides


odd-A Rn:

$^{219,221}$Rn inferior to $^{223,225}$Ra

Next step: $^{223,225}$Rn
HIE-ISOLDE (CERN)

odd-A Ra:

$^{225}$Ra

Next step: $^{225}$Ra directly
TSR@HIE-ISOLDE
Fundamental studies with traps

determine beta-neutrino ($\beta\nu$) correlation in $\beta$ decay of $^{35}\text{Ar}$ with $(\Delta a/a)_{\text{stat}} \leq 0.5\%$

$=>$ test the Standard Model

\[ H_\beta = H_S + H_V + H_T + H_A + H_P \]

Angular distribution of $\beta$ radiation

\[ W(\theta) \approx 1 + a \frac{V}{c} \cos \theta \]

Simulated ion recoil for different $a$

\[ a \approx 1 - \frac{|C_S|^2 + |C'_S|^2}{|C_V|^2} \]

Current experimental limits: (from nuclear & neutron $\beta$ decay)
\[ \frac{C_S}{C_V} < 7\%, \frac{C_T}{C_A} < 9\% \]
WITCH

Weak Interaction Trap for Charged particles
Transfer reactions on beryllium-11

11Be:
- Halo nucleus
- Cluster structures in neighbours
- N=8 broken in 12Be
CRIS

Collinear Resonant Ionisation Spectroscopy
High sensitivity, lower resolution -> perfect for heavy ions

5. Ions deflected on to decay spectroscopy station

6. Alpha-gamma coincidences used to identify the decay of $^{204g,m}\text{Fr}$ to $^{200}\text{At}$

1. Bunched ion beam of $\sim 1\mu$s temporal width

2. Doppler tuning voltage applied to ion bunch

3. Ion bunch neutralized by alkali vapour charge exchange cell

4. Bunch is ionized when on resonance with laser

Open projects:
IS471: Collinear resonant ionization laser spectroscopy of rare francium isotopes
IS531: Collinear resonant ionization spectroscopy for neutron rich copper isotopes
RILIS

Resonant Ionization Laser Ion Source

- Dye lasers with 2nd harmonic generation and UV pumping option
- Dye laser 3rd harmonic generator
- Narrow band dye laser for high resolution spectroscopy or isomer selectivity
- Nd:YAG laser for dye pumping or non-resonant ionization
- Nd:YAG pump laser for the Ti:Sa lasers
- 3 Ti:Sa lasers
- Harmonic generation unit for Ti:Sa system
COLLAPS – Ne charge radii

Laser spectroscopy

Intrinsic density distributions of dominant proton FMD configurations

Geithner et al, PRL 101, 252502 ('08)
Marinova et al, PRC ('12)
HIE-ISOLDE

- SC-linac between 1.2 and 10 MeV/u
- 32 SC QWR (20 @ $\beta_0=10.3\%$ and 12@ $\beta_0=6.3\%$)
- Energy fully variable; energy spread and bunch length are tunable. Average synchronous phase $f_s = -20$ deg
- $2.5<A/q<4.5$ limited by the room temperature cavity
- 16.02 m length (without matching section)
- No ad-hoc longitudinal matching section (incorporated in the lattice)
- New beam transfer line to the experimental stations
First high-statistics run in Nov 2011: under analysis

M. Tandecki et al., NIM A629 (2011) 396
S. Van Gorp et al., NIM A638 (2011) 192

-> energy spectrum of recoiling ions with a retardation spectrometer
Use a Penning trap to create a small, cold ion bunch

June 2011 data

\[ a = -1 \]

\[ a = 1 \]

fit: \( a = 1.12(33) \)
EDM

Static Electric Dipole Moment implies CP-violation

Schiff Theorem: neutral atomic system of point particles in electric field readjusts itself to give zero E field at all charges.

BUT: finite size and shape of nucleus breaks the symmetry
EDM

related to $Q_3$

$P,T$-violating n-n interaction

Schiff moment:

$S = -2 \frac{J}{J + 1} \frac{< \hat{S}_z >}{< \hat{V}_{PT} >} \Delta E$

energy splitting of parity doublet

Schiff moment enhanced by $\sim 3$ orders of magnitude in pear-shaped nuclei

$225^{\text{Ra}}$

$219,221^{\text{Rn}}$ inferior to $223,225^{\text{Ra}}$

$224^{\text{Ra}}$

J Dobaczewski (Trento, 2010)

V Spevak, N Auerbach, and VV Flambaum
PR C 56 (1997) 1357
EDM searches

odd-A Rn [TRIUMF]
odd-A Ra [Argonne]
odd-A Ra [Groningen]

odd-A Rn:

$^{219,221}\text{Rn inferior to }^{223,225}\text{Ra}$

Next step: $^{223,225}\text{Rn}$
HIE-ISOLDE (CERN)

odd-A Ra:

$^{225}\text{Ra}$

Next step: $^{225}\text{Ra}$ directly
TSR@HIE-ISOLDE
### In units of $e\cdot cm$, selected EDM limits are:

<table>
<thead>
<tr>
<th>Particle</th>
<th>EDM limit</th>
<th>System</th>
<th>SM Prediction</th>
<th>New Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td>$1.9 \times 10^{-27}$</td>
<td>$^{205}$Ti atom</td>
<td>$10^{-38}$</td>
<td>$10^{-27}$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$1.1 \times 10^{-19}$</td>
<td>rest frame $\vec{E}$</td>
<td>$10^{-35}$</td>
<td>$10^{-22}$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$3.1 \times 10^{-16}$</td>
<td>$e^{+}e^{-} \rightarrow \tau^{+}\tau^{-}\gamma$</td>
<td>$10^{-34}$</td>
<td>$10^{-20}$</td>
</tr>
<tr>
<td>$p$</td>
<td>$6.5 \times 10^{-23}$</td>
<td>TIF molecule</td>
<td>$10^{-31}$</td>
<td>$10^{-26}$</td>
</tr>
<tr>
<td>$n$</td>
<td>$2.9 \times 10^{-26}$</td>
<td>UCN</td>
<td>$10^{-31}$</td>
<td>$10^{-26}$</td>
</tr>
<tr>
<td>$^{199}$Hg</td>
<td>$2.1 \times 10^{-28}$</td>
<td>atom cell</td>
<td>$10^{-33}$</td>
<td>$10^{-28}$</td>
</tr>
</tbody>
</table>

### A non-exhaustive list:

<table>
<thead>
<tr>
<th>Leptonic EDMs</th>
<th>Hadronic EDMs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System</strong></td>
<td><strong>Group</strong></td>
</tr>
<tr>
<td>Cs (trapped)</td>
<td>Penn St.</td>
</tr>
<tr>
<td>Cs (trapped)</td>
<td>Texas</td>
</tr>
<tr>
<td>Cs (fountain)</td>
<td>LBNL</td>
</tr>
<tr>
<td>YbF (beam)</td>
<td>Imperial</td>
</tr>
<tr>
<td>PbO (cell)</td>
<td>Yale</td>
</tr>
<tr>
<td>HBr$^+$ (trapped)</td>
<td>JILA</td>
</tr>
<tr>
<td>PbF (trapped)</td>
<td>Oklahoma</td>
</tr>
<tr>
<td>GdIG (solid)</td>
<td>Amherst</td>
</tr>
<tr>
<td>GGGG (solid)</td>
<td>Yale/Indiana</td>
</tr>
<tr>
<td>muon (ring)</td>
<td>J-PARC</td>
</tr>
</tbody>
</table>
Matter-antimatter

Sakharov conditions require CP symmetry violation

This violation is observed in electro-weak interaction, but probably cannot account for matter-antimatter imbalance

No evidence for CP violation in strong interaction

\[ |d(n)| < 3.1 \times 10^{-26} \text{ e cm} \quad (Baker et al \textit{PRL} 97 (2006) 131801) \]

\[ |d(^{199}\text{Hg})| < 3.1 \times 10^{-29} \text{ e cm} \quad (Griffith et al \textit{PRL} 102 (2009) 101601) \]

\[ |d(\text{ThO})| < 8.7 \times 10^{-29} \text{ e cm} \quad (Baron et al \textit{arXiv:1310.7534v2 (2013)}) \]

In many cases provides best test of extensions of the Standard Model that violate CP symmetry.

\[ \text{Accounted for by cancellations?} \]

– \textit{study of minimal supersymmetric SM (J Ellis)}

\textit{CP violation in the lepton sector is not known, could also account for matter-antimatter difference}
Fundamental EDM

Interactions
Atomic, nuclear properties

Observable Dipole Moment
30Mg: E0 transition

E0 decay of 30Mg electron spectrometer

Identification of 0+ state at 1789 keV; small mixing amplitude with spherical ground state => deformed state

30Mg: spherical 0+ground-state, deformed 1st 0+ state (2 neutrons across N=20) => shape coexistence

Laser spectroscopy and nuclear physics

- **Spin** (orbital+intrinsic angular momentum), **parity** ($I^π$)
- Nuclear **$g$-factor** and **magnetic dipole moment** ($g_I$ and $μ_I$)
- Electric quadrupole moment ($Q$)
- **Charge radius** ($⟨r^2⟩$)

**Give information on:**
- Configuration of neutrons and protons in the nucleus
- Size and form of the nucleus

### $I^π$

#### $1/2^+$
- $0d_{3/2}$
- $1s_{1/2}$
- $0d_{5/2}$

#### $3/2^+$
- $0d_{3/2}$
- $1s_{1/2}$
- $0d_{5/2}$

### $g_I$ and $μ_I$

- $|I^p=2^+|$
- $\mu = +0.54$
- $|0d_{3/2}|$
- $|1s_{1/2}|$
- $|0d_{5/2}|$

- $|I^p=2^+|$
- $\mu = +1.83$
- $|0d_{3/2}|$
- $|1s_{1/2}|$
- $|0d_{5/2}|$

### $Q$

- $Q=0$
  - Spherical
- $Q>0$
  - Prolate
- $Q<0$
  - Oblate

### $⟨r^2⟩$

- Volume
- Deformation
- Pairing
## Laser spectroscopy

**Atomic hyperfine structure**
(interaction of nuclear and atomic spins)

\[
\Delta E_{HFS} = \frac{A}{2} K + \frac{3}{4} B \frac{K(K + 1) - I(I + 1)J(J + 1)}{2(2I - 1)(2J - 1)I \cdot J}
\]

where \( K = F(F + 1) - I(I + 1) - J(J + 1) \)

\[
A = \frac{\mu_1 H_e(0)}{I \cdot J} \quad \quad B = eQV_{zz}(0)
\]

**Isotope shifts** in atomic transitions
(change in mass and size of different isotopes of the same chemical element)

\[
\delta v^{A,A'} = (K_{NMS} + K_{SMS}) \times \frac{A' - A}{A' A} + F \times \delta \langle r^2 \rangle^{A,A'}
\]

**Nuclear Magnetic Resonance – NMR**
(Zeeman splitting of nuclear levels)

\[
\Delta E_{mag} = g_I \cdot \mu_N \cdot B + \frac{1}{2} Q \cdot V_{zz}
\]

---

**Isotope shift**

\( B = 0 \) \( B \neq 0 \)
Beta-detected NMR

Beta particles (e-,e+) can be used as a detection tool, instead of rf absorption (beams down to 1000 ions/s can be studied)

Measured asymmetry:

\[ A = \frac{N(0^\circ) - N(180^\circ)}{N(0^\circ) + N(180^\circ)} \]

Nuclear Magnetic Resonance – NMR (Zeeman splitting of nuclear levels)

\[ \Delta E_{mag} = g_1 \cdot \mu_N \cdot B + \frac{1}{2} Q \cdot V_{zz} \]

Results:
Magnetic and electric moments of nuclei (position of last nucleons, shapes)
Nuclear shell model

- Created in analogy to the atomic shell model (electrons orbiting a nucleus)
- Based on the observation of higher stability of certain nuclei
  - filled shell of neutrons or protons results in greater stability
  - neutron and proton numbers corresponding to a closed shell are called ‘magic’
- Assumption: independent nuclei move in a self-created potential → solve Schrodinger Equation to derive quantum levels

Quantum levels for Harmonic Oscillator potential

Quantum levels when adding spin-orbit and l² term
Mean field is derived iteratively by solving the HF equations and by assuming a potential for the nucleon-nucleon interaction.

- No inert core
- Very good at describing deformations
- Can predict properties of very exotic nuclei
- Not so good at closed shells
Pear shape: beyond Standard Model

- Results: Enhanced electric-octupole transitions
  - direct measure of octupole correlations

- Pear shape shown experimentally in radium-224

- Best candidates for EDM searches identified: radium-223, 225

- Enhanced atomic EDM moment
  - Schiff moment enhanced by ~ 3 orders of magnitude in pear-shaped nuclei
  - In radium atoms, additional enhancement due to near-degeneracy of atomic states

- Outlook - HIE-ISOLDE:
  - Coulomb excitation on odd-mass radium and radon isotopes
  - Searches for permanent EDM in trapped radium isotopes
  => Looking for physics beyond the Standard Model