Nuclear Physics at CERN

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Lecture 1: From tiny acorns...

- Introduction
- How to produce radioactive isotopes
- The ISOLDE facility at CERN
- Topical examples:
  - Mass measurements
  - Beta-delayed fission
  - Laser spectroscopy
It was as if you fired a 15-inch shell at a sheet of tissue paper and it came back to hit you...
I. The Scattering of $\alpha$ and $\beta$ Particles by Matter and the Structure of the Atom. By Professor E. Rutherford, F.R.S., University of Manchester.

§ 1. It is well known that the $\alpha$ and $\beta$ particles suffer deflexions from their rectilinear paths by encounters with atoms of matter. This scattering is far more marked for the $\beta$ than for the $\alpha$ particle on account of the much smaller momentum and energy of the former particle. There seems to be no doubt that such swiftly moving particles pass through the atoms in their path, and that the deflexions observed are due to the strong electric field traversed within the atomic system. It has generally been
deflexion must in most cases be exceedingly small. A simple calculation shows that the atom must be a seat of an intense electric field in order to produce such a large deflexion at a single encounter.

The theory of Sir J. J. Thomson is based on the assumption that the scattering due to a single atomic encounter is small, and the particular structure assumed for the atom does not admit of a very large deflexion of an $\alpha$ particle in traversing a single atom, unless it be supposed that the diameter of the sphere of positive electricity is minute compared with the diameter of the sphere of influence of the atom.
- 1 cm³ of Iron = 7.9 g
  
  \[7.9g \cdot N_A / 56 = 86 \times 10^{21} \text{ atoms}\]
  
  99,999,999,999,999% of matter is empty

- 1 cm³ of Fe nuclei = 300 Tons
Nuclei consist of protons (red) and neutrons (blue), which are each made up of three elementary quarks held together by gluons.
Why are we still studying the nucleus 100 years on?

- Ensemble of protons and neutrons
- “Mesoscopic system”
- Emergent phenomenon
- Nuclear force attractive at long range, repulsive at short range
Physics at the Femtometer scale

- Coupling to continuum
- 2p radioactivity
- Lattice Effective Field Theory
- N-π pairing
- Equation of state
- Fission dynamics
- Limits of existence
- New magic numbers
- Exotic Shapes
- Neutron halos
- Clusters
- Shape Coexistence
**Observables:**
- Ground-state properties: mass, radius, $J$, $\mu$, $Q$ moments, half-lives and decay modes, transition probabilities
- Half-lives and decay modes
- Transitions and decay modes

**Main models:**
- Shell model (magic numbers)
- Mean-field models (deformations)
- Ab-initio approaches (light nuclei)

**How are complex nuclei built from their basic constituents?**
- How do complex nuclei exhibit collective behavior?

**How do regular and simple patterns emerge in the structure of complex nuclei?**
- How to explain collective properties from individual nucleon behavior?
Low Energy QCD

Realistic Nuclear Interactions

Many Body methods

Variational Methods
Non-core SM: Coupled Cluster Method
Stochastic formulation
Variational MC
Green Function MC

NN + 3N interaction

Low Energy QCD

3-body forces

Illinois potential
Modifications of the shell structure in nuclei far from stability

Modifications of mean field and residual interactions by e.g. diffuse surface

Evolution of shell structure towards $^{78}\text{Ni}$ and $^{132}\text{Sn}$
Nucleosynthesis in the Universe

- Protons and neutrons formed $10^{-6}$ s - 1s after Big Bang (13.7 x $10^9$ years ago)
- H, D, He, Li, Be, B formed 3-20 min after Big Bang
- Other nuclei born later in heavy stars and supernovae

He-burning + Nuclei Fusion to Fe
How to reach unstable isotopes?
Evolution of the *Table of Isotopes*

**Publication Year**
- 1940
- 1944
- 1948
- 1953
- 1958

- Naturally Abundant
Evolution of the *Table of Isotopes*
“Splitting the atom…”
Radioactive ion production

**Isotope Separation On-Line (ISOL)**
- thick target, high yield, high quality beam

**In-Flight separation (IF)**
- thin target, chemistry independent, fast

**GANIL, GSI, MSU, RIBF FAIR**

**REX-ISOLDE, SPIRAL-1, HRIBF, ISAC HIE-ISOLDE, SPIRAL-2, SPES**
Production

HEAVY ION ACCELERATOR

Thin target

Degrader

Magnetic Separator

ΔE ∝ \frac{Z^2}{m}

First and Second Selection

Thin target

First Selection

Neutron Number N

Proton Number Z

Proton Number Z

First and Second Selection

78\text{Ni}

Selection

Observation

Detector Electronics

DAQ
**Projectile Fragmentation**

Nucleon-nucleon collisions, abrasion, ablation

$\vec{v}_f \approx \vec{v}_\rho$

**Projectile Fission**

Electromagnetic excitation, fission in flight

$\vec{v} \approx \vec{v}_1 + \vec{v}_2$
• **Primary nuclear reaction:**
  - fragmentation: high energy protons or heavy ions
  - fission: proton, neutron and photon induced
  - spallation: high energy protons
  - fusion: heavy- and light ion induced

⇒ targets and beams available to produce many isotopes (not all!)
ISOL: Isotope Separation On-Line

- Target - ion source
- Primary beam
- Analysing magnet
- Radioactive ion beams
Radioactive beam production: SPIRAL
How does CERN contribute?
Added Value of ISOLDE:
• Cover several Physics Domains
• Possibility of high-precision nuclear experiments
• Complementary to particle physics,
• A place for many potential new users
• Easier for small countries

Common Interest with Other CERN Experiments
• Detector and Instrumentation
• Computing techniques
• N-ToF, Antiprotons….
Radioactive beam is provided by ISOL technique:

- 1.4-GeV protons hit thick target material
- Low-energy beam
- Singly-charged ions
- Isotopically pure beam
- Mixture of isobars

Physics @ ISOLDE

**Nuclear Physics**
- Nuclear Decay Spectroscopy and Reactions
  - Structure of Nuclei
  - Exotic Decay Modes

**Atomic Physics**
- Laser Spectroscopy and Direct Mass Measurements
  - Radii, Moments, Nuclear Binding Energies

**Nuclear Astrophysics**
- Dedicated Nuclear Decay/Reaction Studies
  - Element Synthesis, Solar Processes

**Applied Physics**
- Implanted Radioactive Probes, Tailored Isotopes for Diagnosis and Therapy
  - Condensed Matter Physics and Life Sciences

**Fundamental Physics**
- Direct Mass Measurements, Dedicated Decay Studies - W1
  - CKM unitarity tests, $\beta$-$\nu$ correlations,

**f (N, Z)**
ISOLDE DE facility

- Decay spectroscopy, Fast Timing
- Coulomb excitation
- Transfer reactions
- Laser spectroscopy
- Beta-NMR
- Penning traps: mass
- Travelling setups: NICOLE, MINIBALL and T-REX
- Post-accelerated beams
- Mass-sep. HRS
- ISCOOL
- RILIS
- PS-Booster 1.4 GeV protons
- Target stations HRS & GPS
- 3x10^{13} ppp
- Collection points For Applications
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Mass measurements
The ISOLTRAP Experiment

R. N. Wolf et al., NIM A 686, 82 (2012)
Detection Principle

- Charged particle stored by superposition of strong homogeneous magnetic field in z direction and weak, electrostatic potential for axial confinement
  - Frequency measurement
  - Long storage times
  - Single-ion sensitivity
  - High precision

Frequency measurement: eigenmotion in the trap can be used to determine mass

\[ \nu_c = \nu_+ + \nu_- \quad \Rightarrow \quad \nu_c = \frac{1}{2\pi} \frac{q}{m} B \]

MR-TOF Measurements

Implementation of multi-reflection time-of-flight mass separator (MR-TOF MS) opened a wide range of possibilities

- Support Penning-trap mass spectrometry on fast time scales
- MR-TOF plus detector as a stand-alone system

Versatile tool allows for:

- Higher contamination yield – $10^6$:1
- Lower production yield – 10/s
- Lower half-lives – tens of ms
- High repetition rate – 20Hz

R. N. Wolf et al., NIM A 686, 82 (2012)
Outer crust of neutron stars is a possible birthplace of the heavy elements.

To determine the composition, the principle of minimisation of the Gibbs free energy is used. For a given pressure, this will depend mainly on the binding energy of the nucleus!

Nuclear structure remains crucial: nuclei cluster around $N=50$ and $N=82$.

Depth profile of a neutron star by using experimental masses and mass models as input for equation of state.

Mass Measurement of $^{82}$Zn

Before only AME extrapolation with 400keV uncertainty

Mass excess $\text{ME}(^{82}\text{Zn}) = m - \text{Au} = -42.314(3) \text{ MeV/c}^2$

$\Rightarrow$ Uncertainty $\delta m/m = 4 \cdot 10^{-8}$

Most exotic nuclei measured for neutron-star crustal composition

G. Audi and M. Wang, private communication (2011)
R. N. Wolf et al., PRL 110, 041101 (2013)
Sequence of nuclei in the outer crust of neutron stars has been determined using BRUSLIB models HFB19-21 as well as calculations from Dobaczewski and colleagues.

In all models, the prior predicted nucleus is ruled out from the experimental $^{82}\text{Zn}$ value!

R. N. Wolf et al., PRL 110, 041101 (2013)
S. Kreim, M. Hempel et al., in preparation
Beta-delayed fission
Symmetric vs Asymmetric Fission

Macroscopic only
(like a liquid drop)

Microscopic effects added
(nuclear shells and pairing)

Figure 2. Macroscopic (a) and macro-microscopic (b) potential energy surface for the $^{238}$U nucleus in the coordinates $(R, \eta)$. The potential energy is obtained for $\delta = 0$ and $\epsilon = 0.35$. The macroscopic part is normalized to zero for the spherical shape of the compound nucleus.
Beta-Delayed Fission

\[ ^{180}\text{Tl}(Z=81,N=99) \]

- Low-energy fission! (E*\textasciitilde3-12 MeV, limited by Q_{EC})
- Relatively low angular momentum of the state
- 12 cases known previously (neutron-deficient Uranium region)

\[ ^{180}\text{Hg}(Z=80,N=100) \]

- \( \beta^+ \)/EC
- \( Q_{EC} = 10.44 \text{ MeV} \)
- \( B_f \sim 10 \text{ MeV} \)

\[ \beta_{DF} \text{ branch} \]

\[ P_{\beta_{DF}} = \frac{N_{\beta_{DF}}}{N_\beta} \]

\( P_{\beta_{DF}} \) depends strongly on:
- \( Q_{EC} \) of the parent: the higher \( Q_{EC} \), the larger the \( P_{\beta_{DF}} \)
- \( B_f \) of the daughter: the lower \( B_f \), the larger the \( P_{\beta_{DF}} \)
- Actually, \( Q_{EC} - B_f \) and \( \beta \)-strength \( S_\beta \) are the most important parameters
Detection system for $\beta$DF studies at ISOLDE

A. Andreyev et al. PRL 105 (2010)
ASYMMETRIC energy split! Thus asymmetric mass split: $M_H = 100(4)$ and $M_L = 80(4)$

The most probable fission fragments are $^{100}\text{Ru} (N=56, Z=44)$ and $^{80}\text{Kr} (N=44, Z=36)$
New Type of Asymmetric Fission in Proton-Rich Nuclei

via $\beta_{DF}$ of $^{180}$Tl

Calculations according to 5D fission model (P. Möller et al., Nature 409, 785 (2001))
Laser spectroscopy
ISOLDE - CERN

- 1.4 GeV protons from PSB
- GPS target
- COLLAPS laser line
- radioactively active laboratory
- HRS target
- HRS
- ISCOOL
- HIE - ISOLDE extension
- GPS
- control room
- ISOLTRAP
Atomic structure of astatine

- Most abundant isotope $^{218}\text{At}$, ($t_{1/2} = 1.5$ s)
- I. Asimov: 1st mile of earth’s crust: 70mg (~3.5 atoms/kg)
- Artificial production: $^{209}\text{Bi}(\alpha,2n)^{210}\text{At}$, Corson et al. (1940)
- First optical spectroscopy of $^{210}\text{At}$, 70 ng sample, (2x10$^{14}$ atoms), McLaughlin (1964)
- Ionization potential (IP) unknown – last in the list of naturally occurring elements

**Theoretical predictions of IP(At)**

<table>
<thead>
<tr>
<th>Theoretical Predictions</th>
<th>IP (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finkelnburg 1950</td>
<td>9.5 ± 0.2 eV</td>
</tr>
<tr>
<td>Varshni 1953</td>
<td>10.4 eV</td>
</tr>
<tr>
<td>Finkelnburg 1955</td>
<td>9.2 ± 0.4 eV</td>
</tr>
<tr>
<td>Kiser 1960</td>
<td>9.5 eV</td>
</tr>
<tr>
<td>Dong 2010</td>
<td>9.35 eV (75412 cm$^{-1}$)</td>
</tr>
</tbody>
</table>

**Energy Levels of neutral Astatine (from NIST)**

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Term</th>
<th>$J$</th>
<th>Level (cm$^{-1}$)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$6p^5$</td>
<td>$^2p^0$</td>
<td>3/2</td>
<td>0.0</td>
<td>M64a</td>
</tr>
<tr>
<td>$6p^4(3p)7s$</td>
<td>$^4p$</td>
<td>5/2</td>
<td>44549.3</td>
<td>M64a</td>
</tr>
<tr>
<td>$^3p^2$</td>
<td>$^3p^2$</td>
<td>3/2</td>
<td>46233.6</td>
<td>M64a</td>
</tr>
</tbody>
</table>

Prior to this work: This is all that was known about the atomic structure of astatine!
Step 1:
Ionization scheme development → study of the atomic structure

Step 2:
Measure the ionization potential

Step 3:
Use the best scheme for nuclear structure studies by atomic spectroscopy

Step 4:
The use of RILIS ionized At beams for other experiments at ISOLDE
Decay studies/Mass measurements
• Many new atomic levels were found
• An efficient three-step ionization scheme was determined
• RILIS ionized At beams are now available and have already been studied at ISOLDE
Measurement of the first ionization potential of astatine by laser ionization spectroscopy


S. Rothe et al 2013, Nature Communications published 15th May! DOI:10.1038/ncomms2819
Hyperfine Structure of atomic transition

Analysis yields $A$ and $B$ hyperfine factors

$$A = \frac{\mu I B_e(0)}{IJ} \quad B = eQ_s \left\langle \frac{\partial^2 V_e}{\partial z^2} \right\rangle$$

Nuclear spin $I$

Magnetic moment $\mu$

Quadrupole moment $Q_s$

+  

Nuclear size differences from isotope shifts

For measurements on radioactive nuclei, need:

• High sensitivity

• Doppler-free resolution

M.D. Seliverstov et al., PLB 719 (2013) 362.
Bunches are delivered from the ISOLDE HRS ISCOOL at 30 to 50 keV;
Ions are (Doppler-tuned and) neutralised in a K charge exchange cell operated at $10^{-6}$ mbar;
Non-neutralised ions are deflected away while the atoms drift through the interaction region, maintained at $< 10^{-9}$ mbar;
Lasers are sent through the interaction region;
Re-ionised isotopes are deflected towards an MCP or an $\alpha$-decay station.
Fall 2012 campaign

- Resonant step using the RILIS Ti:Sa laser system (1 GHz linewidth)
  ⇒ only $\delta \langle r^2 \rangle$ and $\mu$

- Easy down to 100 ions per second
  ⇒ only $\frac{9}{2}^+$ state observed in neutron-deficient isotopes