Two-proton radioactivity

Lecture 1

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ON NEUTRON-DEFICIENT ISOTOPES OF LIGHT NUCLEI
AND THE PHENOMENA OF PROTON AND TWO-PROTON RADIOACTIVITY

V I GOLDSKY
P. N. Lebedev Physical Institute, USSR Academy of Sciences, Moscow
Received 14 March 1960

Abstract: Application of isobaric invariance principle to light nuclei leads to a very simple
relation between the Z th proton binding energy $E_p$ in nucleus 1 ($Z_1^A$) and the Z th neutron
binding energy $E_n$ in the mirror nucleus 2 ($Z_2^{2A}$). With an accuracy of the order of a few
per cent their difference $E_{n2} - E_{p1} = \Delta E_{np}$ is independent of $N$ for a given $Z$ and is given by

$$\Delta E_{np} \approx E_n(2Z)^2 - E_p(2Z)^2 \approx \frac{Z - 1}{(2Z - 1)^3},$$

which is more correct than the usual expression $1/2 \left( \frac{Z - 1}{Z + N - 1} \right)$. By exploiting
this fact one can predict the existence and properties of almost ninety new neutron-deficient
isotopes of light nuclei (up to $Z = 34$) and establish the limits of stability of the isotopes with
respect to decay with proton emission. Among the specific properties of neutron-deficient
isotopes, proton and two-proton radioactivity effects which may occur are of special interest.
Some nuclei are indicated in which these effects may be observed. The main features of a
very curious phenomenon of two-proton radioactivity are discussed.

Vitaly Iosifovich Goldansky
18.06.1923 (Witebsk) – 14.01.2001 (Moscow)

Nuclear Physics 19 (1960) 482
Outline

- Basic introduction
- The story of $^{45}$Fe
  - mass predictions
  - production method
  - discovery of 2p decay
- Quest for p-p correlations
  - OTPC detector
  - images of $^{45}$Fe decay
- Introduction to theory
  - Jacobi coordinates
  - Simplified models
- Momentum correlations
- Decays of $^6$Be, $^{19}$Mg, $^{48}$Ni and $^{54}$Zn
- Predictions of heavier emitters
  and the full 2p landscape
- Summary
What is radioactive?

- What is plotted on the chart? Present practice: all systems we know something about.
- Should they plot only those which exist? But what does exist?

**Radioactivity**
- Slow enough to form neutral atoms
- Characteristic time measured directly
- Independent of formation mechanism

\[ T_{1/2} \geq 10^{-14} \text{ s} \]

**Reactions/Resonances**
- Fast on atomic scale
- Characteristic width measured directly
- Influenced by reaction mechanism

\[ \Gamma \geq 1 \text{ meV} \]
Mass parabola

$Q \cong 19 \text{ MeV}$

$Q \cong 14 \text{ MeV}$

$Q \cong 12 \text{ MeV}$

$Q \cong 7 \text{ MeV}$

$Q \cong 2 \text{ MeV}$
When the decay energy is large, many exotic decay channels open.

Blank and Borge, Progress in Part. Nucl. Phys. 60 (2008) 403
Beyond the proton drip-line

Competition between two decay modes

- **The $\beta^+$ decay**
  
  Probability of transition:
  \[ \lambda \sim Q^5 \]
  
  Decay energy may be large, but the weak interaction is really weak
  \[ T_{1/2} > 1 \text{ ms} \]

- **The emission of particles**
  
  There is a potential barrier which hampers emission of an unbound proton ($\alpha$, 2p, $^{14}$C,..)

  \[
  \lambda \sim \exp \left\{ -\frac{2}{\hbar} \int_{r_{in}}^{r_{out}} \sqrt{2\mu [V(r) - Q_p]} \cdot dr \right\}
  \]

- To find where the drip-line actually is and to predict which decay will happen, precise estimates of atomic masses are required!
- To study particle radioactivity fast techniques are needed!

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Why particle radioactivity?

- Charged particles ($p$, $\alpha$, $2p$,...) are much easier to detect than $\gamma$ or electrons
- They provide information about very exotic nuclear systems, beyond drip-line
- Allow to determine masses
- Provide a tool to investigate quantum tunneling process
- Test nuclear structure models (single particle levels)
- Probe details of nuclear wave function
- Help to understand decay dynamics
- Yield information about proton pairing
- ...

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Two protons can be unbound!

- It is possible that pair of protons is unbound while each of individual proton is bound!

\[
S_p > \Gamma_1 + \Gamma_2
\]

Goldansky, Nucl. Phys. 19 (1960) 482
Goldansky, Nucl. Phys. 27 (1961) 648
Goldansky, Nuovo Cimento 25, Suppl. 2 (1962) 123
Early considerations

Baz, Goldansky, Goldberg, Zeldovich,
„Light and medium nuclei at the limits of stability, Moscow 1972

Рис. 48. Различные варианты испускания ядрами пар протонов
Two-proton emission

Energy conditions for different modes of the 2p emission

- a) $^{18}$Ne$^*$
- b) $^{14}$O$^*$, $^{17}$Ne$^*$
- c) $^{19}$Mg, $^{45}$Fe, $^{48}$Ni, $^{54}$Zn, ...
- d,e) $^6$Be, $^{12}$O(?)

→ True 2p decay is an essentially three-body phenomenon

Pfutzner, Karny, Grigorenko, Riisager, Rev. Mod. Phys. 84 (2012) 567

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Global mass models are not precise enough to determine the decay mode. However, there is a trick based on the Isobaric Multiplet Mass Equation (IMME):

\[ BE(A, T, T_z) = a(A, T) + b(A, T)T_z + c(A, T)T_z^2 \]

\[ T_z = (N - Z)/2 \]

\[ BE(T_z = -T) = BE(T_z = T) - 2bT \]

To get the mass (binding energy) of the neutron-deficient nuclide, we need the measured mass of its neutron-rich analogue and the value of the coefficient \( b \) from the theory (shell-model, systematics...)

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First 2p candidates

Predicted 1p and 2p separation energies

- Brown, PRC 43 (91) R1513
- Ormand, PRC 55 (97) 2407
- Cole, PRC 54 (96) 1240
- Brown et al., PRC 65 (02) 045802

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Production methods

- To produce short-lived and very proton-rich radioactive nuclei, in-flight techniques proved advantageous.

- **Fusion-evaporation**
  - reactions between heavy-ions
  - *GSI, Argonne, Oak Ridge, Jyväskylä,*...
  - *recoil separators*

- **Fragmentation**
  - of relativistic heavy-ions
  - *GSI, NSCL, GANIL, RIKEN,*...
  - *fragment separators*

**Low energy: ≈ Coulomb barrier**
- large beam intensity
- thin target
- identification by decays

**High energy: ≈ above Fermi energy**
- lower beam intensity
- thick target
- identification in-flight
- single ion sensitivity

*p and α radioactivity,*
(also superheavy elements)

2p radioactivity
Example: FRS at GSI Darmstadt
FRS – ion optics and particle ID

- **Standard, achromatic mode**

- Beam different emission angles
- Target
- ions of different $A/q$
- Energy loss $\Delta E$
- Time-of-flight $(s = 36 \text{ m})$
- Energy loss $\Delta E \rightarrow Z$
- Time-of-flight $\rightarrow \nu$
- Positions + B field $\rightarrow B\rho$

- Full in-flight identification of each ion

- Geissel et al., NIM B70 (1992) 286
A long way to discovery

by Bordeaux-GANIL-GSI-Warsaw collaboration

- **GSI 1992**: first experiment, determination of x-sections, $^{50}\text{Ni}$
- **GSI 1996**: first observation of $^{45}\text{Fe}$ (3 ions!), $^{49}\text{Ni}$ and $^{42}\text{Cr}$
- **GANIL 1999**: discovery of $^{48}\text{Ni}$, 53 ions of $^{45}\text{Fe}$
- **GANIL VII 2000**: next attempt of $^{45}\text{Fe}$ spectroscopy: 22 ions of $^{45}\text{Fe}$
- **GSI VII 2001**: new approach to $^{45}\text{Fe}$ studies: focus on $\mu$s lifetimes
Example of identification

- First observation of three new nuclides: $^{42}\text{Cr}$, $^{45}\text{Fe}$ and $^{49}\text{Ni}$

FRS, GSI, 1996
Decay of $^{45}$Fe studied at GSI

Target
4 g/cm$^2$ Be

$^{58}$Ni, 650 A MeV
4x10$^8$ ions/s

Degrader 1
3.2 g/cm$^2$ Al

Degrader 2
3.6 g/cm$^2$ Al

Two TOFs allowed redundant in-flight identification by the $Bp$ – TOF – $\Delta E$ method

Dead-time free recording of all events following the implantation due to digital electronics (XIA) ➔ great sensitivity!

FRS @ GSI July 2001

Nal barrel:
$\varnothing_{<} = 8$ cm,
$\varnothing_{>} = 40$ cm,
$L = 30$ cm

Si telescope
7 x 300 mm $\varnothing = 60$ mm

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FRS Messhütte, 27 July, 2001

On-line joke?

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Results from the GSI experiment

M. P. et al., EPJ A 14 (2002) 279
M. P. et al., NIM A 493 (2002) 155

Events correlated with the stopped ions: implantation and decay in the same detector

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Emission of 2p is the dominant (80%) decay mode of $^{45}\text{Fe}$:

- $E_{2p} = 1.1(1)$ MeV
- $T_{1/2} = 3.2^{+2.6}_{-1.0}$ ms

Counts vs. Energy [keV]

- 6 × $^{45}\text{Fe}$
- $^{44}\text{V}$
- 664 other ions
Results from the GANIL experiment

- **LISE @ GANIL July 2000**

$^{58}\text{Ni} \text{ at } 75 \text{ MeV/A on nickel target}

High primary beam intensity: 3-5 µA

Results from the GANIL experiment

- 22 ions of $^{45}\text{Fe}$ implanted
  - 12 counts in a narrow peak
  - no $\beta$ and no $\gamma$ in coincidence
  - no $\beta\gamma$ pile-up

$E_{2p} = 1.14(5) \text{ MeV}$

$T_{1/2} = 4.7^{+3.4}_{-1.4} \text{ ms}$
The decay energy and the lifetime are enough to establish the 2p decay.

Brown and Barker, PRC 67 (2003) 041304(R)
Other $2p$ candidates

GANIL: fragmentation of $^{58}\text{Ni}$ beam @ 75 MeV/u
8 $^{54}\text{Zn}$ ions implanted in a Si strip detector
B. Blank et al., PRL 94 (05) 232501

$^{54}\text{Zn} @ \text{GANIL}$

$^{54}_{30}\text{Zn}$

$T_{1/2} \approx 3 \text{ ms}$

GANIL: fragmentation of $^{58}\text{Ni}$ beam @ 75 MeV/u
4 $^{48}\text{Ni}$ ions implanted in a Si strip detector
C. Dossat et al., PRC 72 (05) 054315

$^{48}\text{Ni} @ \text{GANIL}$

$2p$ decay event candidate

Total decay energy and half-life can be precisely measured after implantation into a thick Si detector. Then, however, information on individual proton’s momenta is lost!
The experimental challenge of $2p$ decay

- To explore fully the physics of the process, the correlations between proton’s momenta must be determined!
- The three-body model by Grigorenko and Zhukov is the only one which predicts these correlations.

- The goal: detect both protons separately, measure their energies, and determine their angular distribution

L. Grigorenko: simulation for 200 events

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Solution: a TPC detector

A „classical” Time Projection Chamber (TPC) constructed at CEN Bordeaux.

It has fully electronic readout. The position on the $x$-$y$ plane is detected by two orthogonal sets of 768 strips readout by ASIC-type electronics.

Expensive and difficult to handle. Problems with information on $z$ coordinate

J. Giovinazzo et al., PRL 99 (2007) 102501

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Novel idea: optical readout

- **OTPC: Optical Time Projection Chamber**

Gas mixture: He + Ar + N$_2$ ($\approx$1%)

$V_{\text{drift}} \approx 1 \text{ cm/µs}$

M. Ćwiok et al., IEEE TNS, 52 (2005) 2895
K. Miernik et al., NIM A581 (2007) 194

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OTPC data acquisition

CCD 2/3”
- 1000 × 1000 pix.
- 12-bits
- image ampl. (×2000)

HI identification & selection

HI

OTPC

HV

PM

Camera

Frame Grabber

PXI

Digitizer

100 MHz

TOF

ΔE

Trigger logic

trigger

LabView

PC

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OTPC
Principle of operation

CCD image

tracks of the ion and emitted particle(s)

or only emitted particle(s)

PMT signal sampled

time sequence of events

HI implantation

decay time

decay details

decay
Event reconstruction

\[ L = \sqrt{115^2 + (5 \cdot 10)^2} = 125 \text{ mm} \]

\[ \Leftrightarrow E_\alpha = 7.8 \text{ MeV} \]

\[ 214\text{Po} \alpha \text{ decay} \]

238U \rightarrow 214\text{Bi (19.9 mn)} \rightarrow 210\text{Tl (1.3 mn)} \rightarrow 210\text{Pb (22.3 y)}

\[ L_{PM} = v_d t \]

\[ \Delta t = 5 \mu s \]
Acculinna @ FLNR, Dubna

Low-energy fragment separator, full identification of selected ions by TOF-ΔE method

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Testing with decays of implanted ions

Acculina separator, JINR, Dubna, 2006

$^{20}\text{Ne} (50 \text{ MeV/u}) + \text{Be} \rightarrow \ldots$

$\beta p$ emission from $^{13}\text{O}$

$^{13}\text{O} \xrightarrow{\beta} ^{13}\text{N}^* \rightarrow ^{12}\text{C} + p$

K. Miernik et al., NIM A581 (2007) 194

$\beta\text{3\alpha}$ decay of $^{12}\text{N}$

$^{12}\text{O} \xrightarrow{\beta} ^{12}\text{C}^* \rightarrow 3\alpha$

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$\beta\text{2\alpha}$ decay of $^{8}\text{Li}$

$^{8}\text{Li} \xrightarrow{\beta} ^{8}\text{Be}^* \rightarrow 2\alpha$

$^{8}\text{Li}$

$^{12}\text{N}$

$^{13}\text{O}$

$p$
Experiment at NSCL/MSU

February 2007

Gas mixture:
- 66% He + 32% Ar + 1% N₂ + 1% CH₄
- range of 550 keV proton ≈ 2.3 cm
- range spread of ⁴⁵Fe ion ≈ 50 cm
Active volume: 20×20×42 cm³

Reaction: ⁵⁸Ni at 161 MeV/u + natNi → ⁴⁵Fe

Separation and in-flight identification (ΔE + TOF)
in A1900 with two-wedge system
A1900 separator

Reaction: $^{58}\text{Ni} \text{ at } 161 \text{ MeV/u} + ^{\text{nat}}\text{Ni} \rightarrow ^{45}\text{Fe}$

Ion identification in-flight: $\Delta E + \text{TOF}$
Ion identification

All ions coming to OTPC (A1900 identification)

$^{45}$Fe: 2/h
$^{43}$Cr: 8/min.

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2p events from $^{45}$Fe
β delayed protons from $^{45}$Fe

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Decays of $^{45}$Fe and $^{43}$Cr

- $\beta^+\to 4^3\text{Cr}+2p$
- $Q_{\text{EC}} = 18.7$ MeV
- $T_{1/2} = 7$ ms

- $\beta^+\to 4^{4}\text{Mn}+p$
- $0.08\%$

- $\beta^+\to 4^{2}\text{Ti}+p$
- $\approx 70\%$

- $\beta^+\to 4^{4}\text{Ca}+3p$
- $\approx 30\%$

- $\beta^+\to 4^{1}\text{Sc}+2p$

- $\beta^+\to 4^{3}\text{V}$

- $\beta^+\to 4^{4}\text{Cr}+p$

- $\beta^+\to 4^{40}\text{Ti}+4p$

- $\beta^+\to 4^{41}\text{Sc}+4p$

- $\beta^+\to 4^{42}\text{Ti}+3p$

- $\beta^+\to 4^{43}\text{V}+2p$

- $\beta^+\to 4^{44}\text{Mn}+p$

References:
- M. Pomorski et al., Phys. Rev. 83 (2011) 014306
- M. Pfützner, Euroschool on Exotic Beams, Dubna 2013, Lecture 1/2
3D reconstruction

- Full $p$-$p$ correlation pattern could be established

\[ \vartheta_1 = (104 \pm 2)^\circ, \quad \vartheta_1 = (70 \pm 3)^\circ \]
\[ \Delta\varphi = (142 \pm 3)^\circ \Rightarrow \theta_{pp} = (143 \pm 5)^\circ \]

K. Miernik et al., PRL 99 (07) 192501
More information on the OTPC and more decay images can be found at http://www.fuw.edu.pl/~pfutzner/Research/OTPC/OTPC.html
Radioactive decays

"Classical" era

\(\alpha, \beta\) – Rutherford, 1899
\(\beta^+\) – Curie & Joliot, 1934
EC – Alvarez, 1937
SF – Flerov & Petrzhak, 1940

Modern times

\(p\) – Hofmann / Klepper, 1982
\(^{14}\text{C}\) – Rose & Jones, 1984
\(2p\) – M.P. / Giovinazzo 2002
\(n, 2n\) – ?