Low-Energy Nuclear Structure Lecture 2: Ground States and Excitation Spectra

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The (Second) Plan

- Other ground-state properties
  - Magnetic dipole moments and electric quadrupole moments
- Trends in excitation spectra
  - Collective vs. single-particle
  - Vibration, rotation, …
- Nuclear decay – measurements and more
  - Gamma-decay
  - Beta-decay
  - Alpha-decay

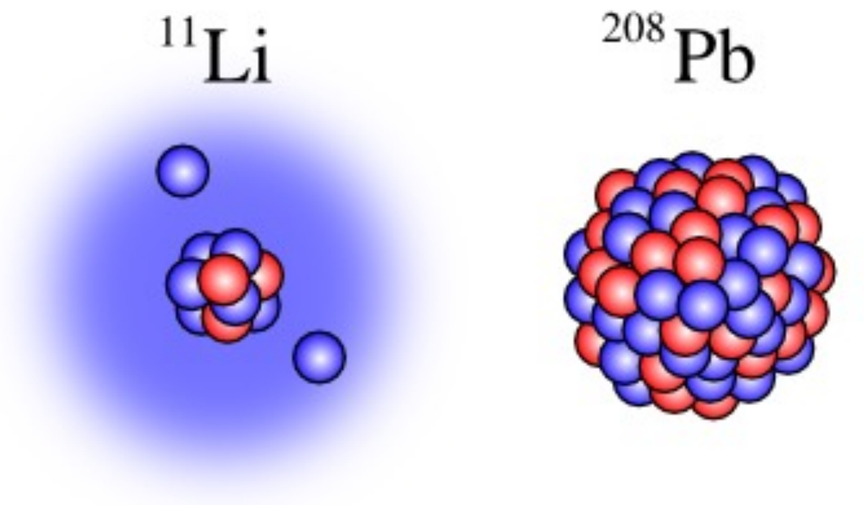
Other Ground State Properties

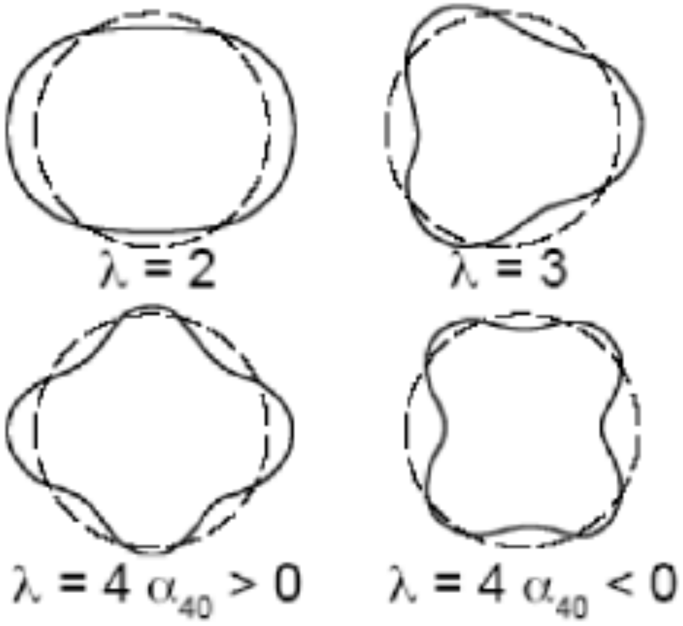
Other Ground State Properties

Radii and moments

Nuclear radii and nuclear shapes

A fundamental property of the ground state is the shape and size of the nucleus – the nuclear radius provides insight into nuclear extent (matter and charge).





The nuclear shape can deviate from spherical, but usually maintains symmetry with quadrupole deformation.

Nuclear radii definitions

$$\langle r_c^2 \rangle = \frac{\int_0^R \rho(r) r^2 \, dr}{\int_0^R \rho(r) \, dr}$$

$$\langle r_m^2 \rangle^{1/2}$$

$$\langle r_n^2 \rangle^{1/2}$$

Consider RMS radii (matter and neutron)

Nuclear quadrupole deformation

$$R = R_0 \left[1 + \sum_{\mu=-2}^{2} a_{2\mu} Y_{2\mu}(\theta, \phi) \right]$$

REVIEWS OF MODERN PHYSICS VOLUME 30, NUMBER 2 APRIL, 1958

International Congress on Nuclear Sizes and Density Distributions

Held at Stanford University, December 17–19, 1957

REVIEWS OF MODERN PHYSICS VOLUME 30, NUMBER 2 APRIL, 1958

Nuclear Radii as Determined by Scattering of Neutrons

S. Fernbach

University of California Radiation Laboratory, Livermore, California

REVIEWS OF MODERN PHYSICS VOLUME 30, NUMBER 2 APRIL, 1958

Nuclear Density Distributions from Proton Scattering

A. E. Glassgold

Department of Physics, University of California, Berkeley, California

REVIEWS OF MODERN PHYSICS VOLUME 30, NUMBER 2 APRI

Electron Scattering and Nuclear Charge Distributions

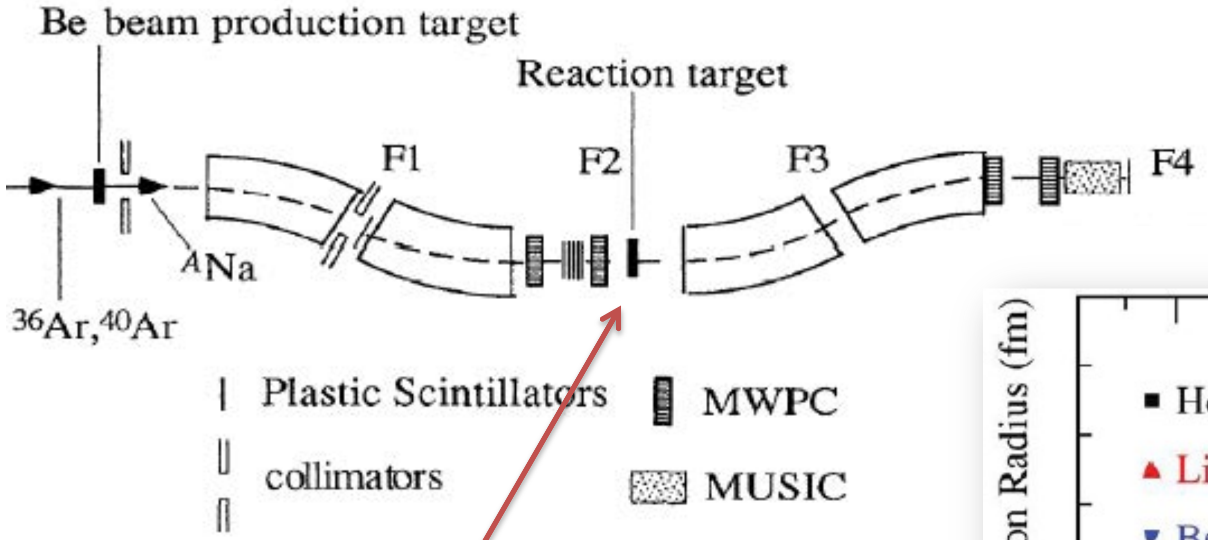
D. G. Ravenhall

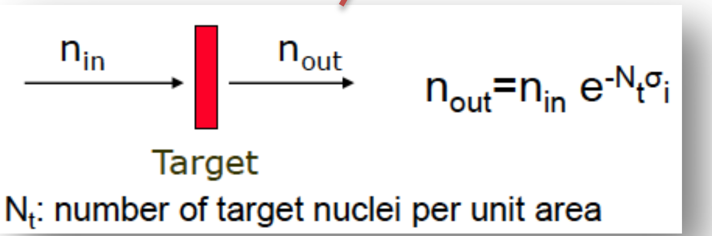
Department of Physics, University of Illinois

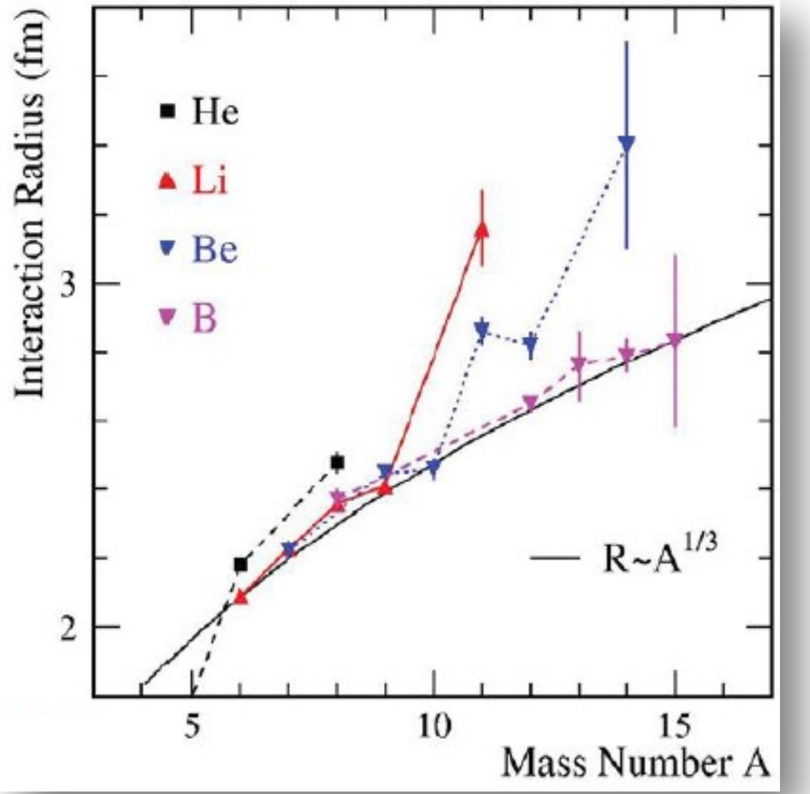
Near stability we know:

$$R = r_0 A^{1/3}$$

Matter radii: total interaction cross-sections



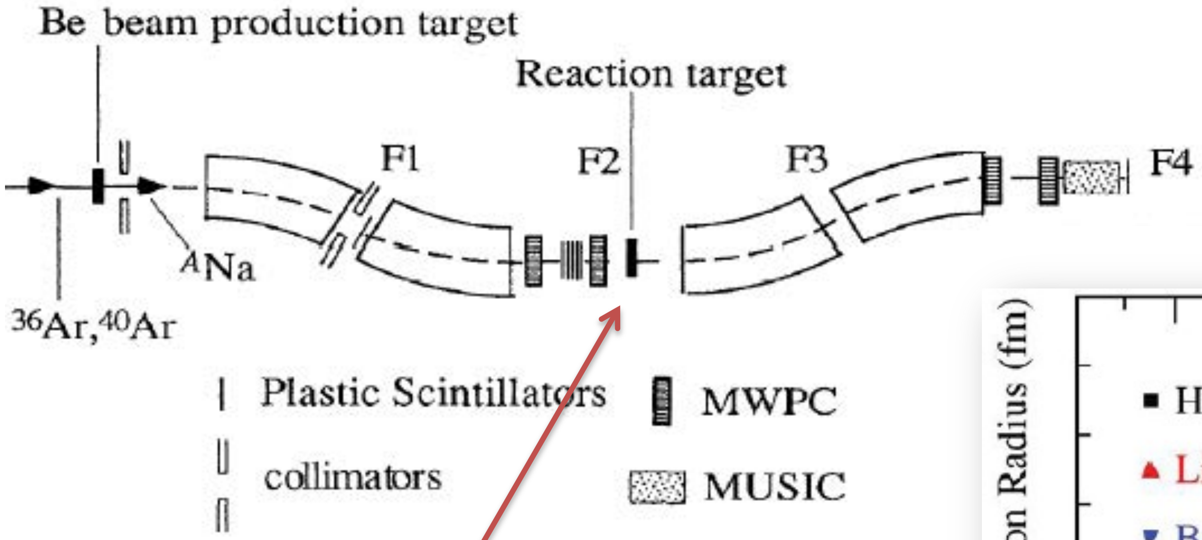


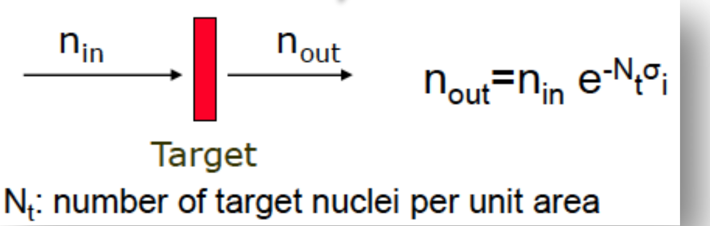


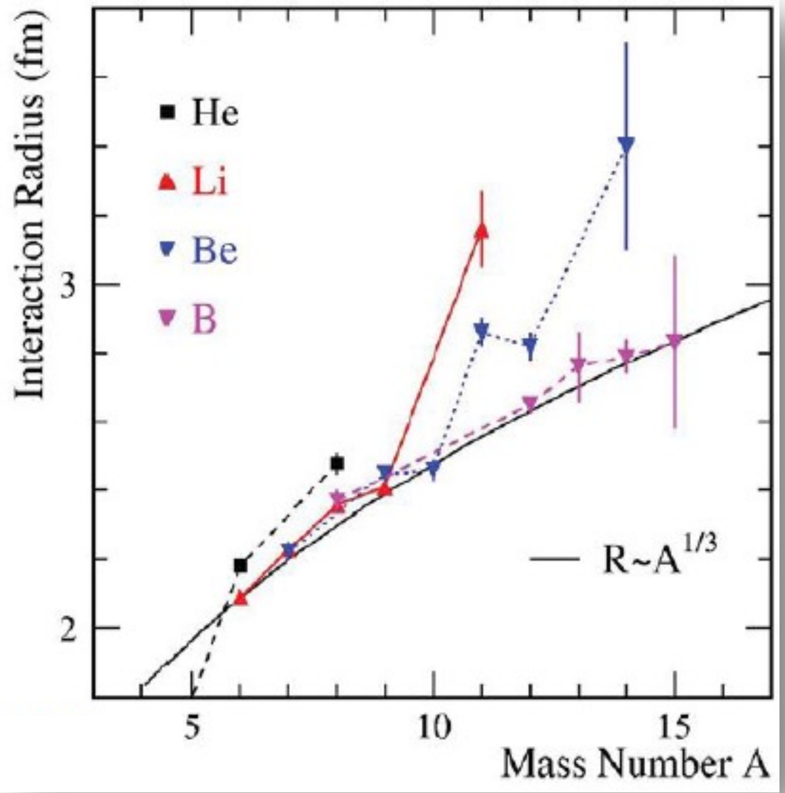
Theoretical model: $\sigma_i = \pi[R_i(p) + R_i(t)]^2$

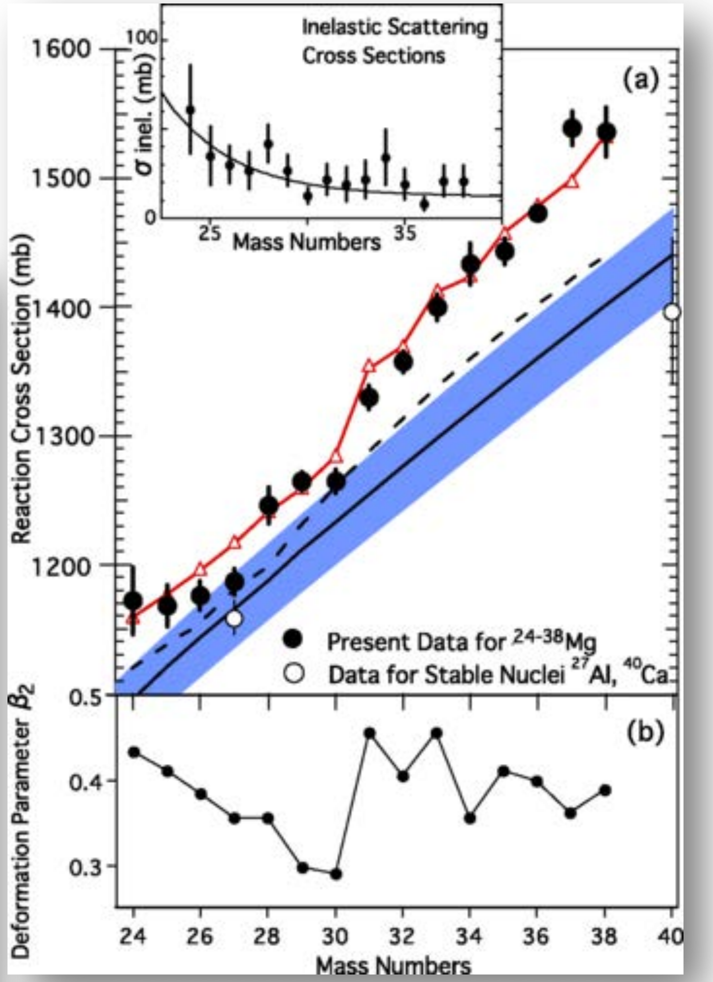
I. Tanihata, J. Phys. G 22, 157 (1996).

Matter radii: total interaction cross-sections









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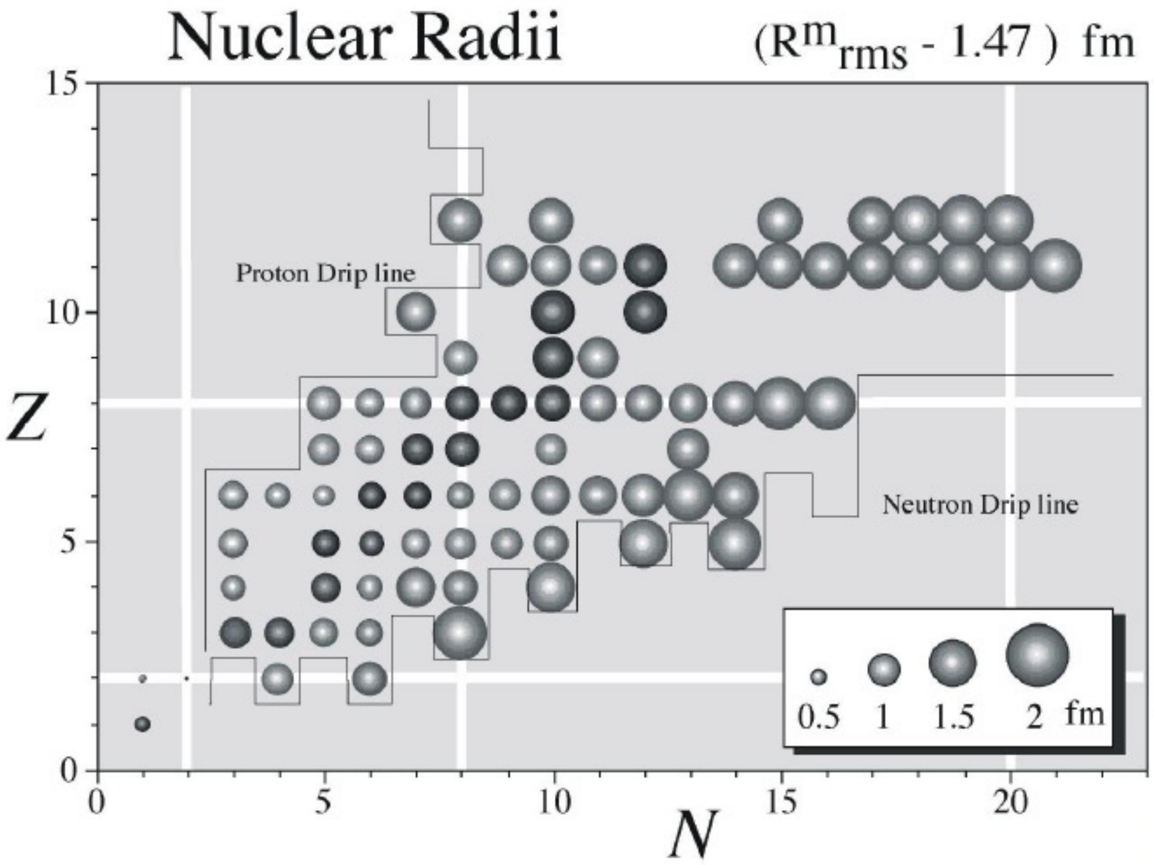
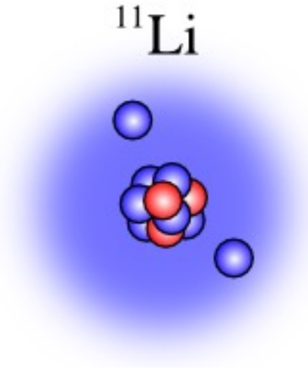
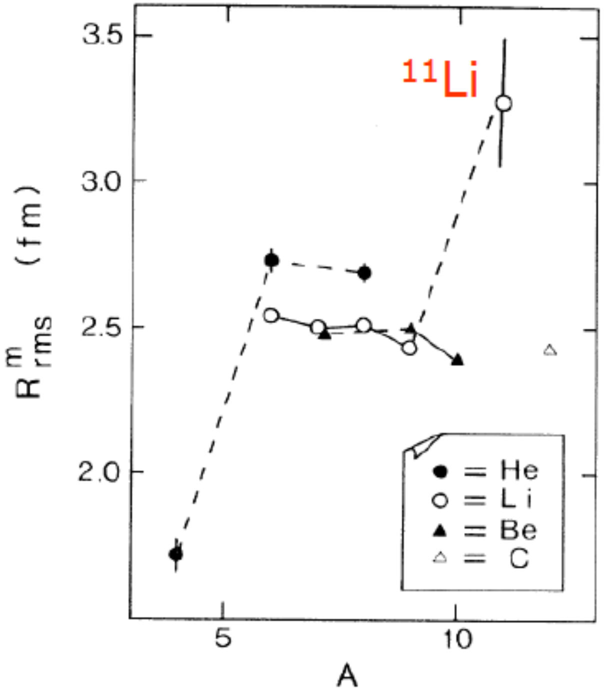
I. Tanihata, J. Phys. G 22, 157 (1996).

M. Takechi *et al.*, Phys. Rev. C **90**, 061305 (2014).

Skins and halos



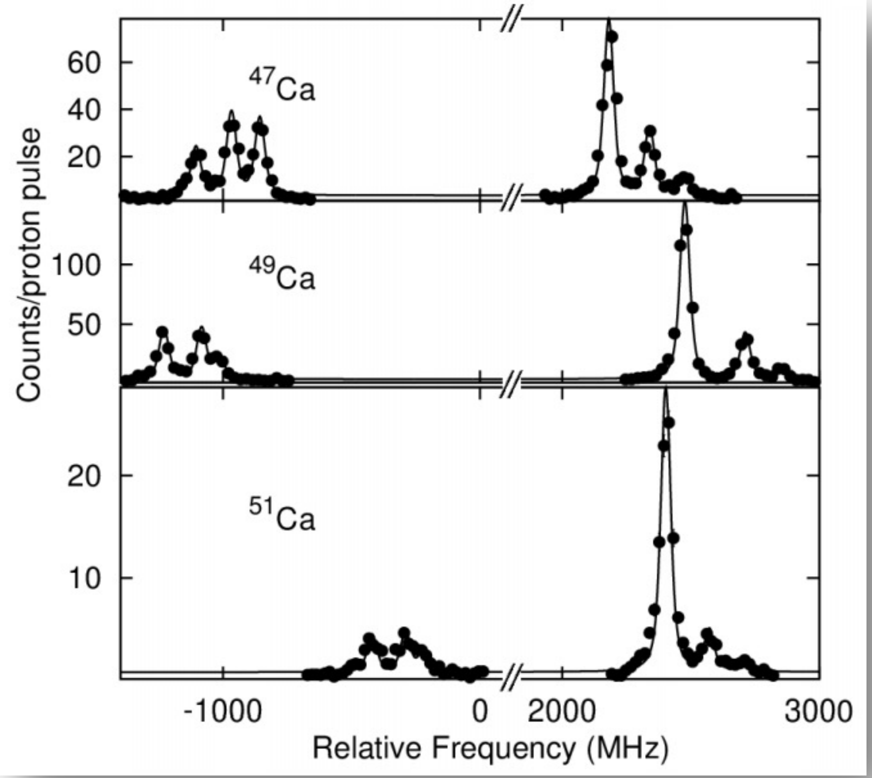


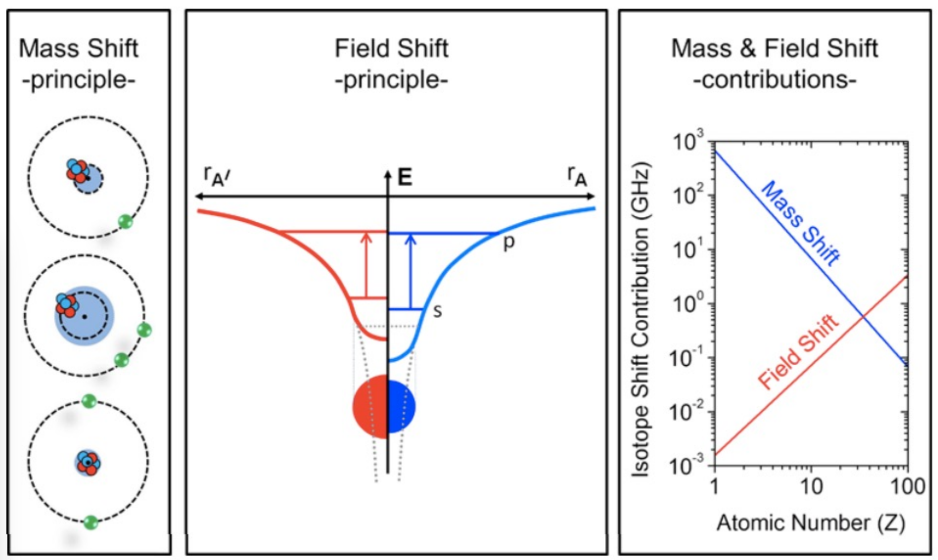


I. Tanihata, Phys. Rev. Lett. 55, 2676 (1985).

Laser spectroscopy for radii --> isotope shifts

$$\delta\nu_{\mathrm{IS}}^{AA'} = \delta\nu_{\mathrm{MS}}^{AA'} + F\,\delta\langle r_c^2\rangle^{AA'}$$

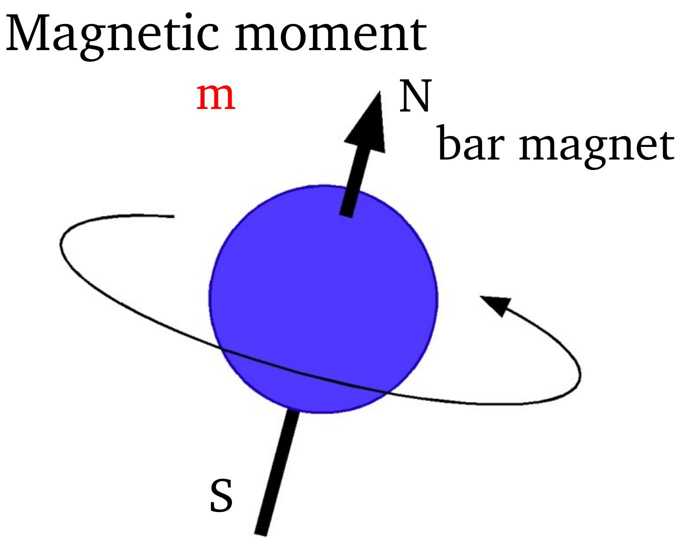


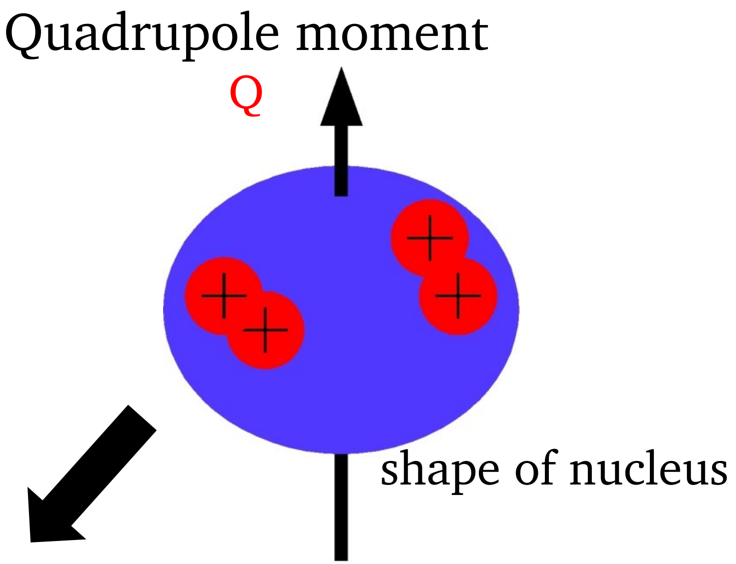


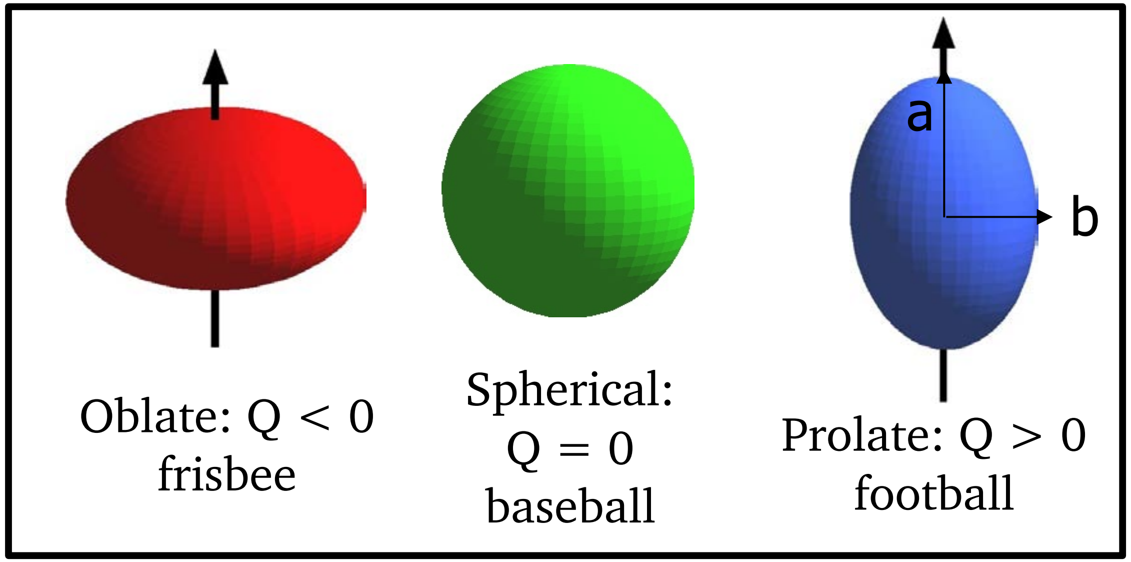
The finite size and mass of the atomic nucleus has a distinct influence on the optical spectrum, which can be probed with high precision using laser spectroscopy.

R.F. Garcia Ruiz et al., Phys. Rev. C **91**, 041304(R), 2015.
http://www.euroschoolonexoticbeams.be/site/files/nlp/LNP879_Chapter6.pdf

Ground state nuclear moments





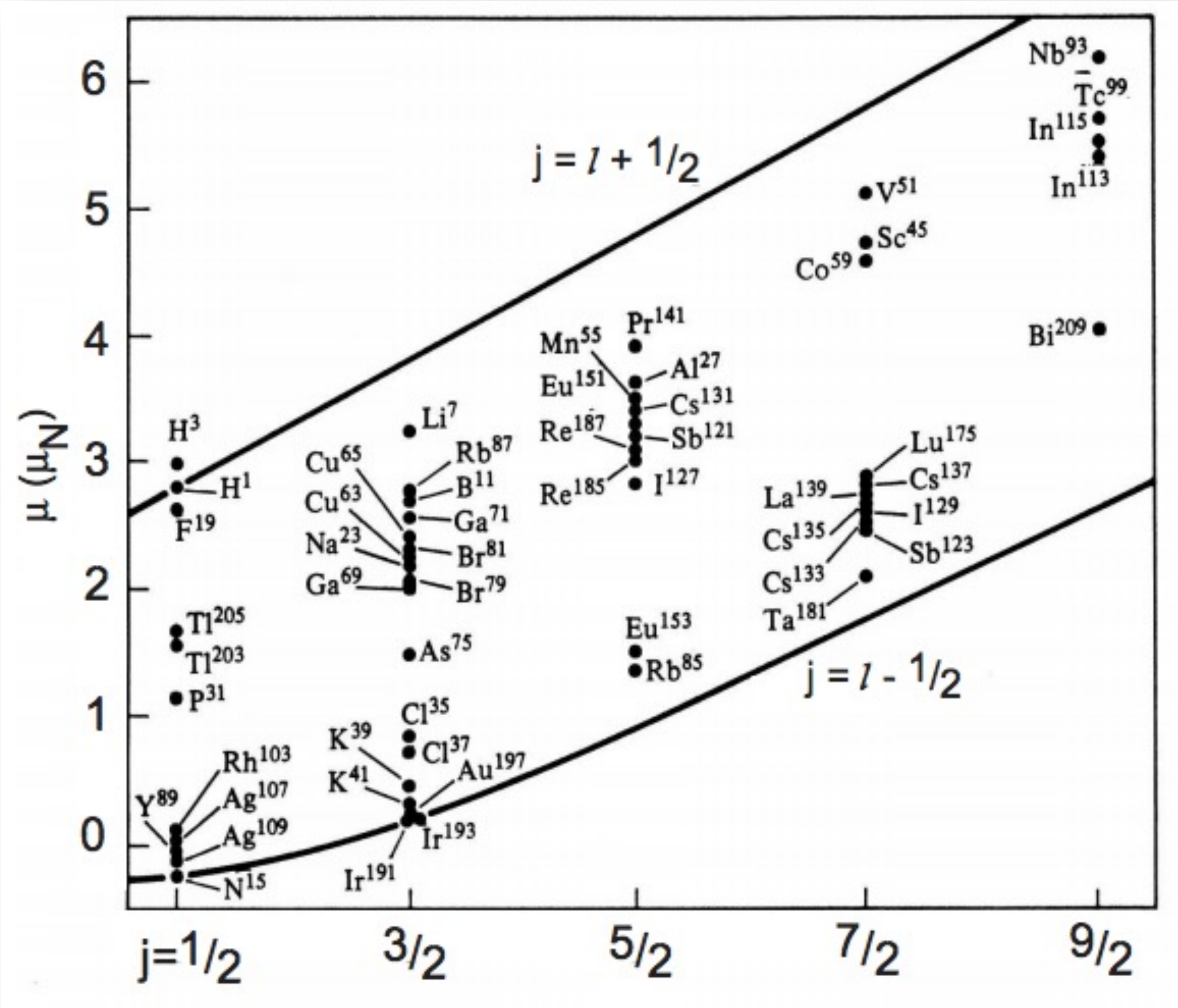


Magnetic moments

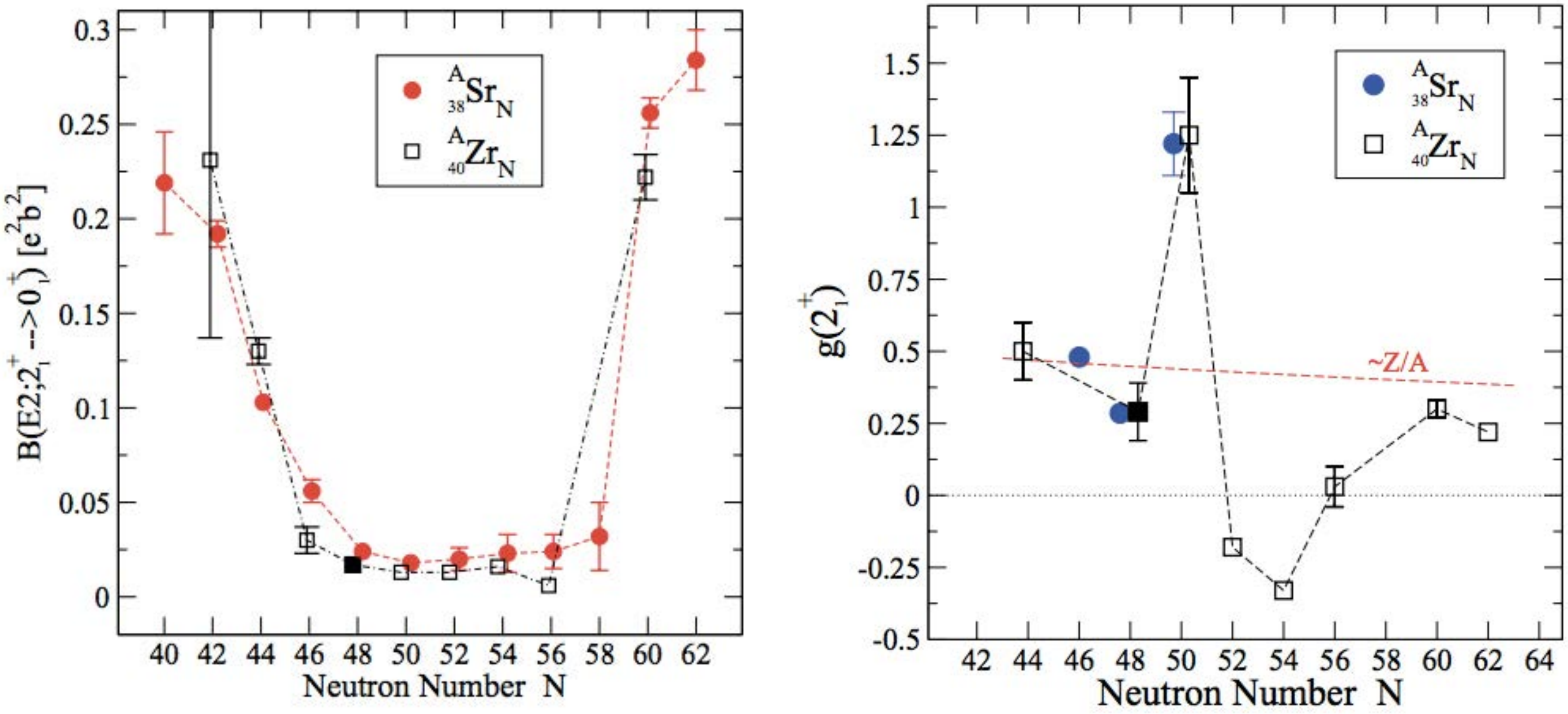
$$\mu = \int \psi^*_{J,M}(\vec{\mu})_z \psi_{J,M}$$

$$\vec{\mu} = \sum_{k=1}^{A} g_L^{(k)} \vec{L}^{(k)} + \sum_{k=1}^{A} g_S^{(k)} \vec{S}^{(k)}$$

$$\mu_{s.p.} = j\left[g_l \pm \frac{g_s - g_l}{2l+1}\right] \text{ for } j = l \pm \frac{1}{2}$$



Physics in magnetic moments



- g-factors are sensitive to proton/neutron contributions to nuclear states – where collective properties may vary smoothly, proton and neutron contributions can vary substantially

G. J. Kumbartzki et al., Phys. Rev. C 85, 044322 (2012).

Hyperfine structure

Hyperfine structure refers to the splitting of a single electronic level for nuclei with I > 0

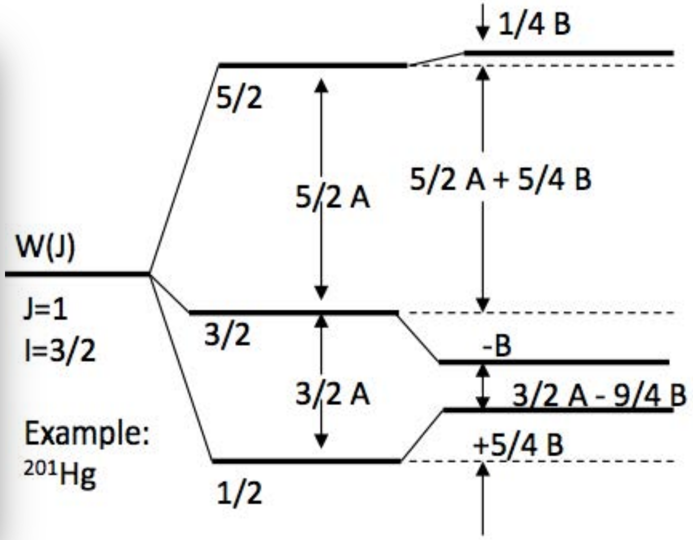
$$\Delta E_{mag} = |g_I| \cdot \mu_N \cdot B + \frac{1}{2} Q \cdot V_{zz}$$

Derived properties of nuclei:

- **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** ($\langle r^2 \rangle$)

Give information on:

- Configuration of neutrons and protons in nucleus
- Size and form of nucleus

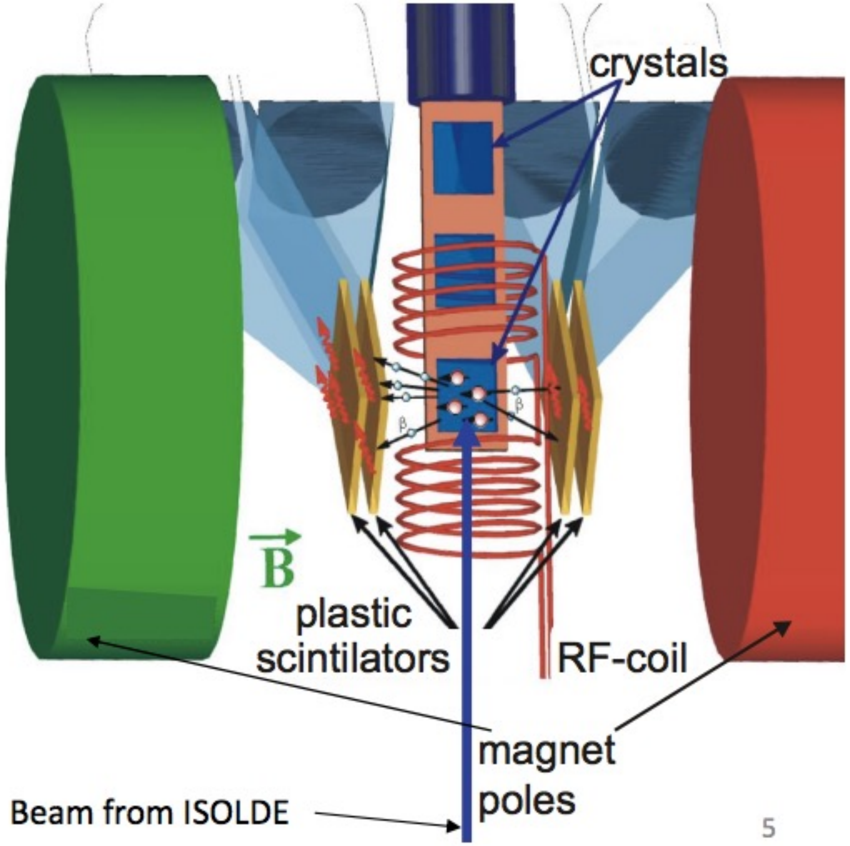


β-NMR/NQR technique

Beta-Nuclear Magnetic Resonance:
Use decay (β-/β+) as a detection tool; asymmetric emission for spin-polarized nuclei

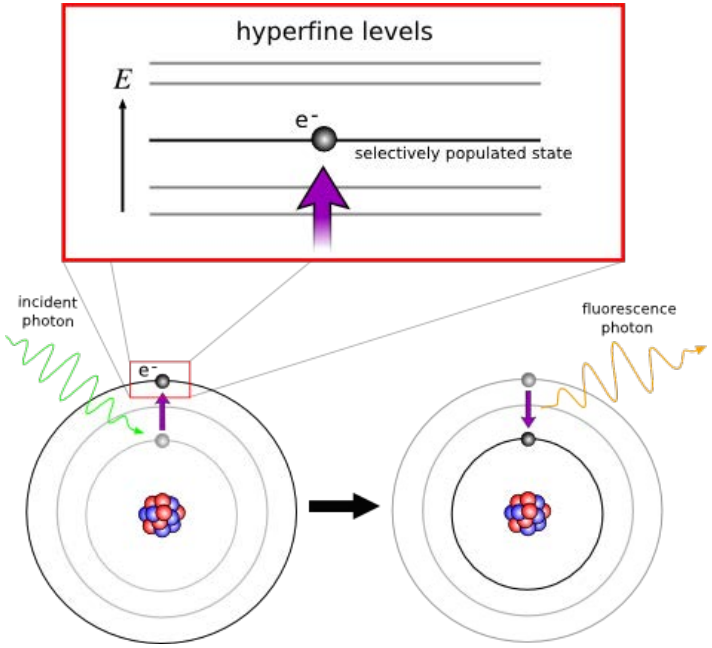
Measured decay asymmetry:

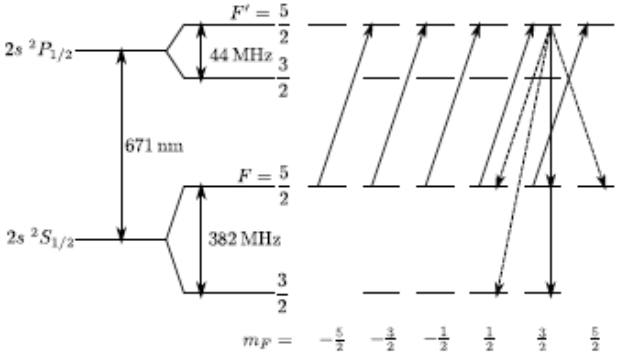
$$A = \frac{N(0°) - N(180°)}{N(0°) + N(180°)}$$

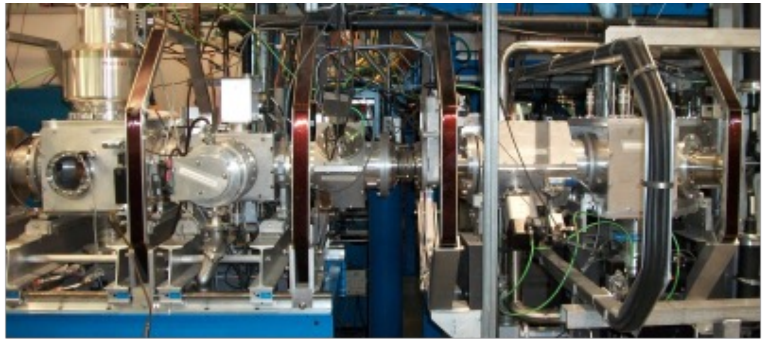


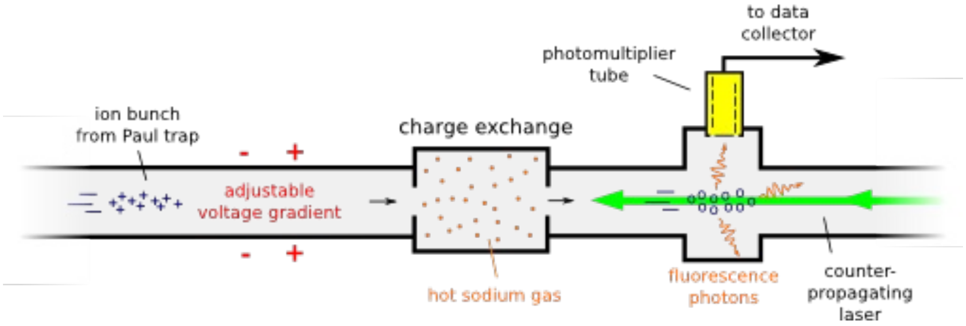
Laser polarization

One method to achieve nuclear polarization is using lasers to create atomic polarization, which then couples to the nucleus.





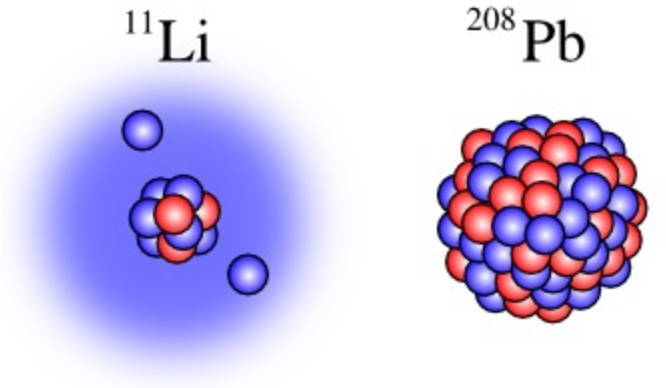


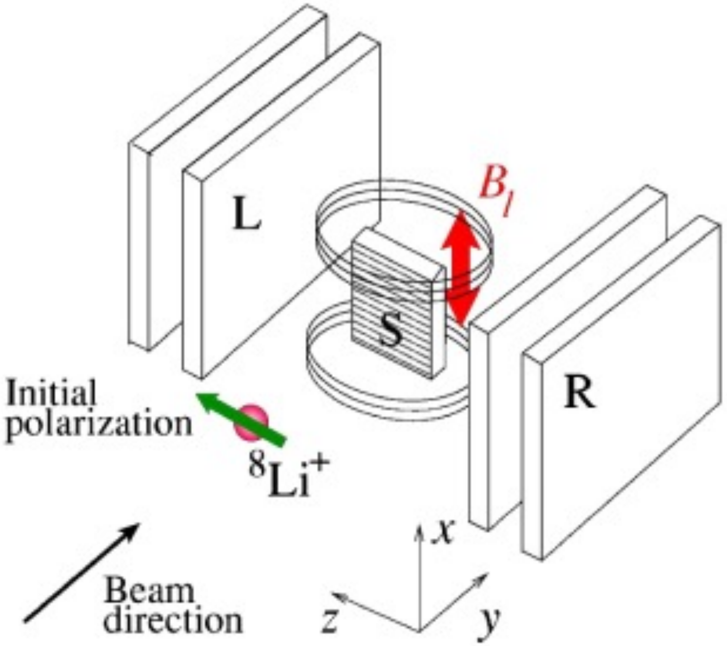


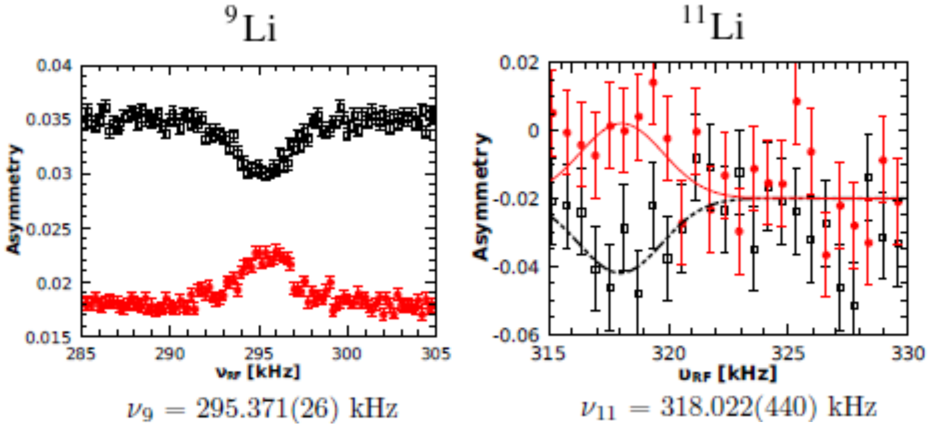
Facilities around the world (i.e. TRIUMF) have or are commissioning laser systems to expand their experimental capabilities.

β-NQR of ^{11}Li at TRIUMF

^{11}Li is a neutron-halo nucleus – the matter radius of ^{11}Li is on the order of that of ^{208}Pb – a measure of the quadrupole moment will provide more insight into the structure





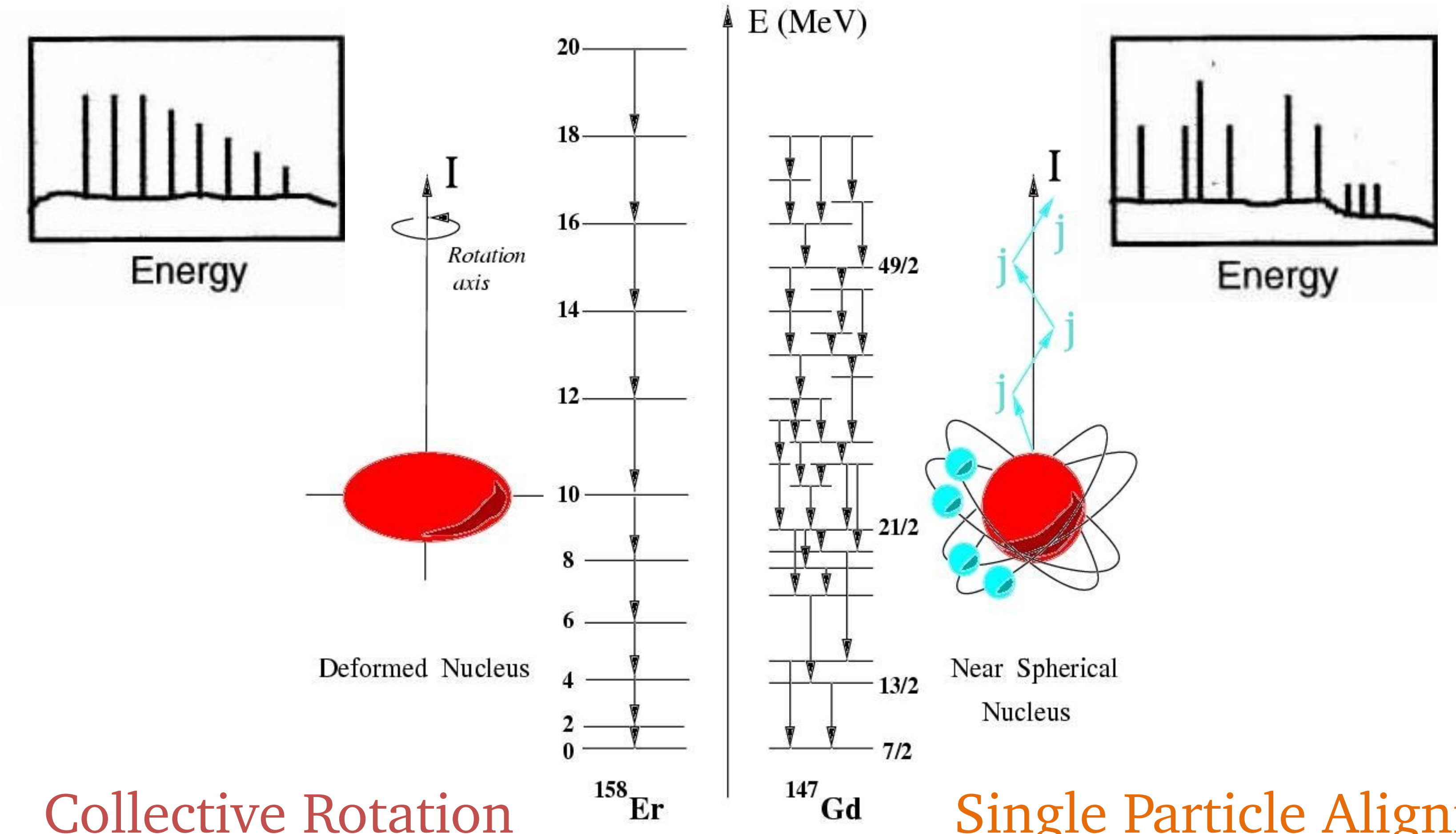


www.triumf.ca/laser-spectroscopy/β-nqr-lithium-isotopes

Excitation Spectra

Level schemes – collective vs. single particle

Level Schemes Contain Structural Information



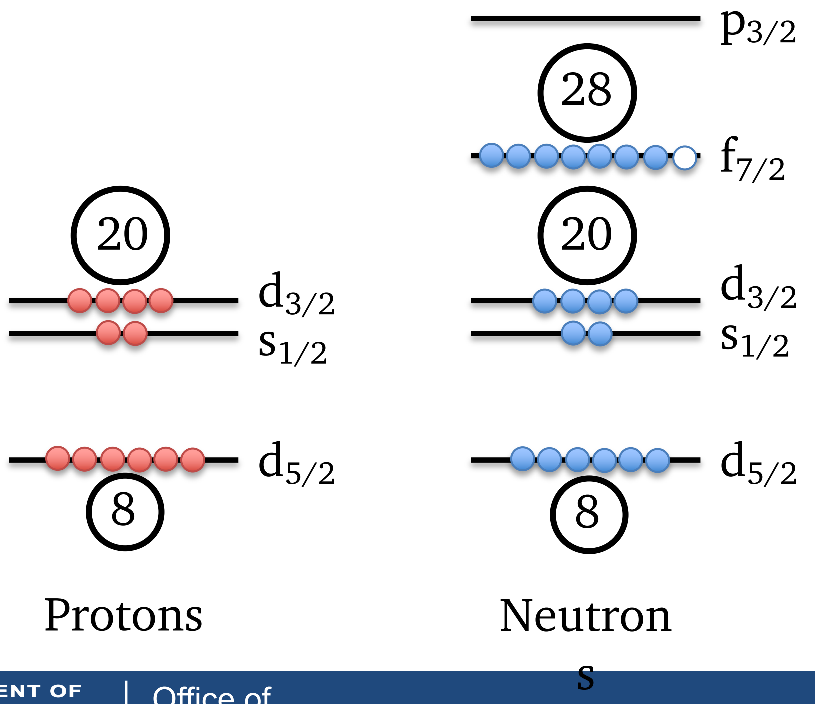
Collective Rotation

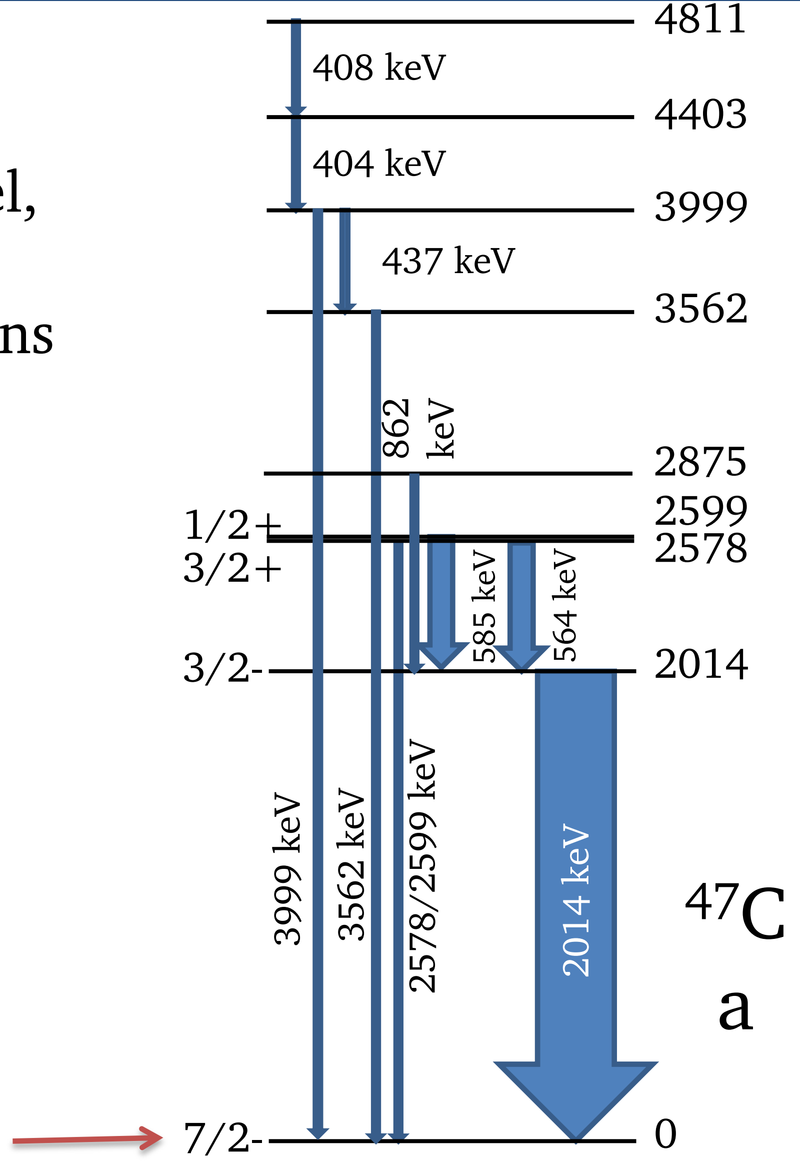
Single Particle Alignment

Nuclear excitations

Single particle excitations

- Within a independent particle model, a subset of nuclear excitations correspond to different configurations of protons and neutrons





Nuclear excitations

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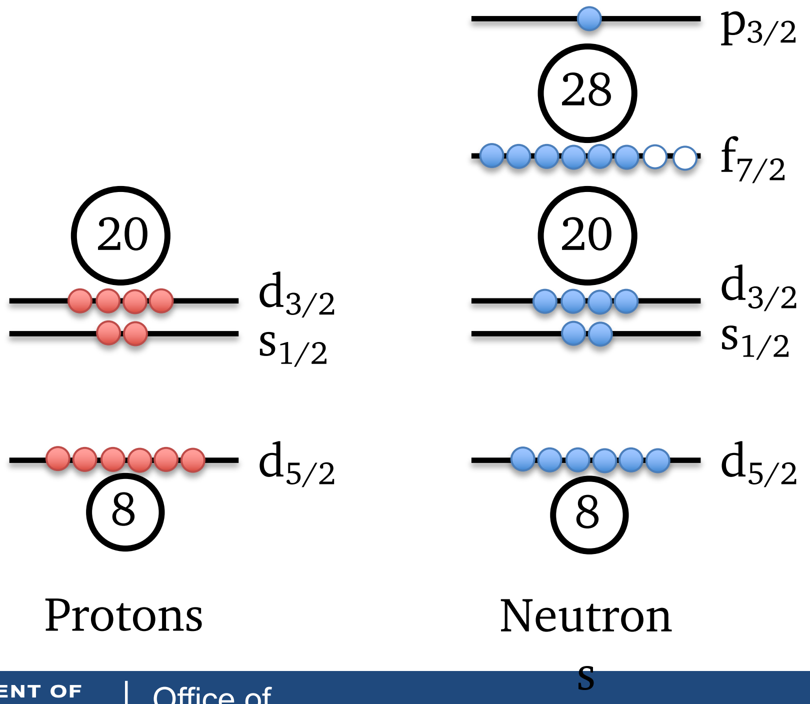

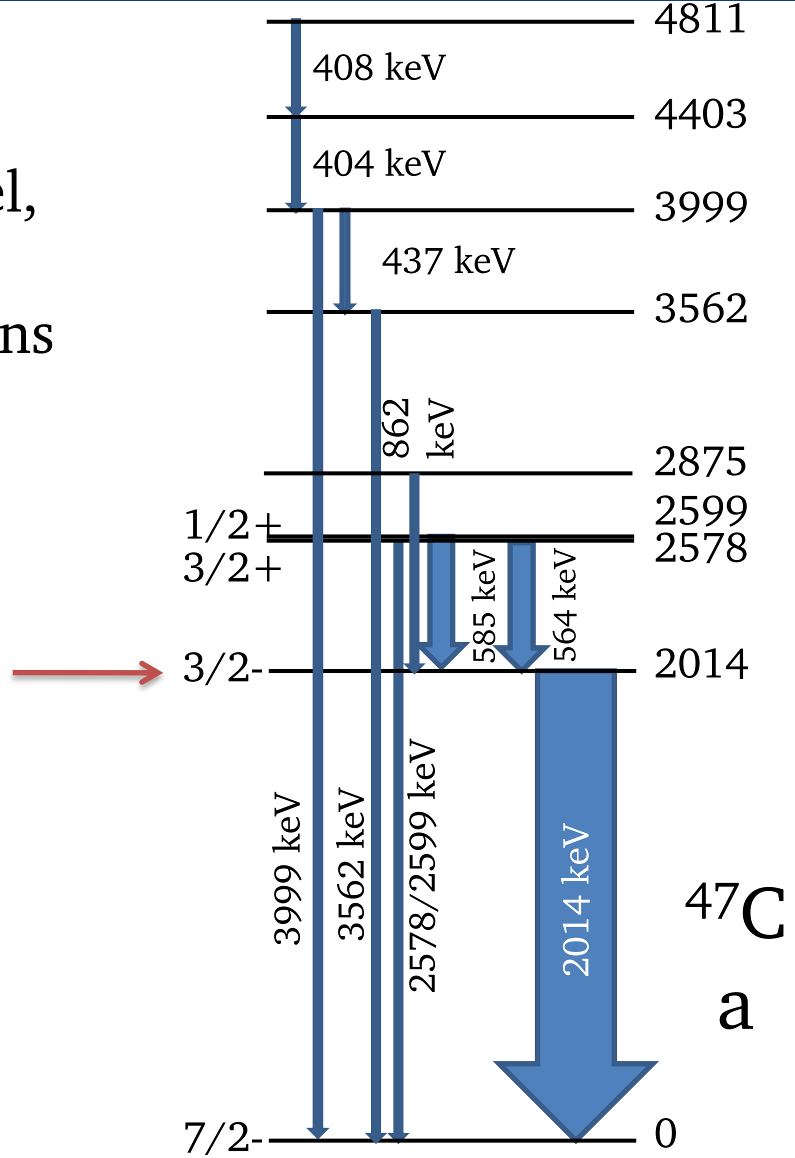

Nuclear excitations

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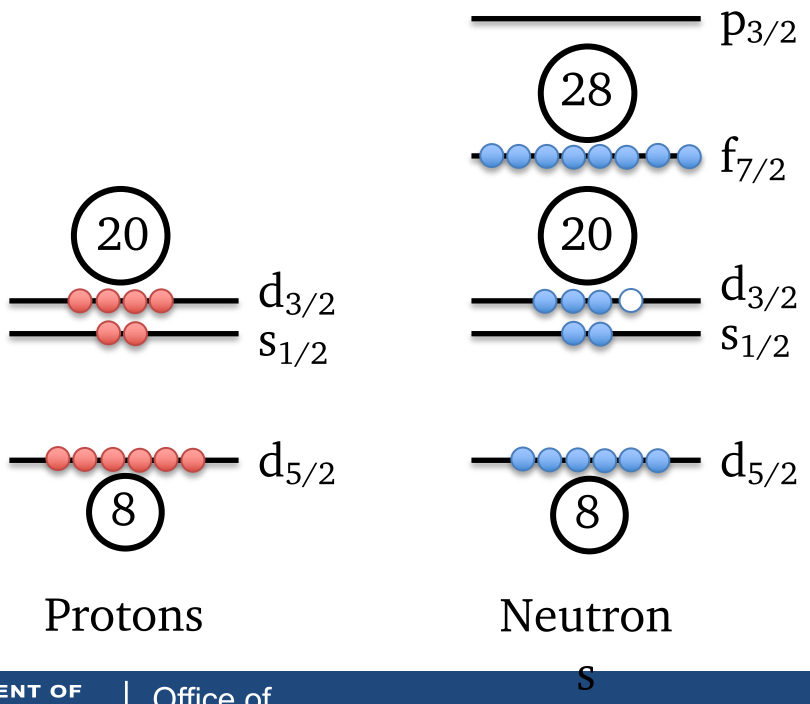

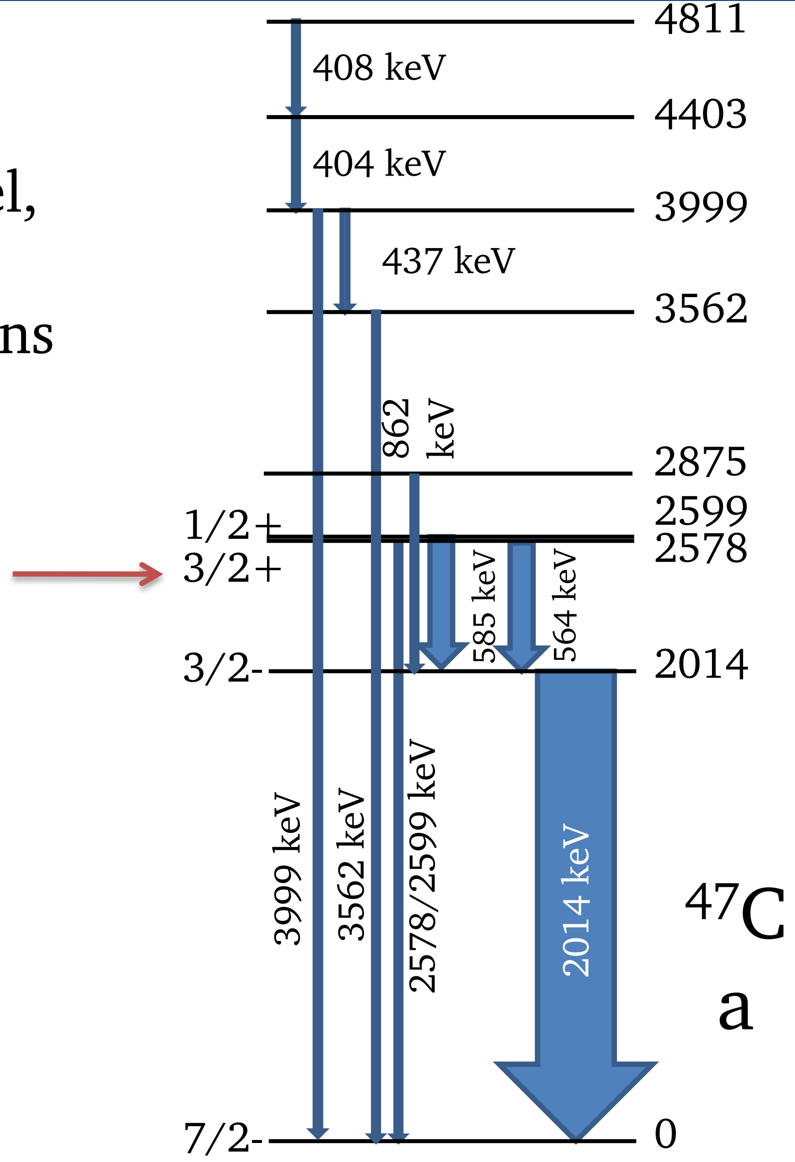

Nuclear excitations

Single particle excitations

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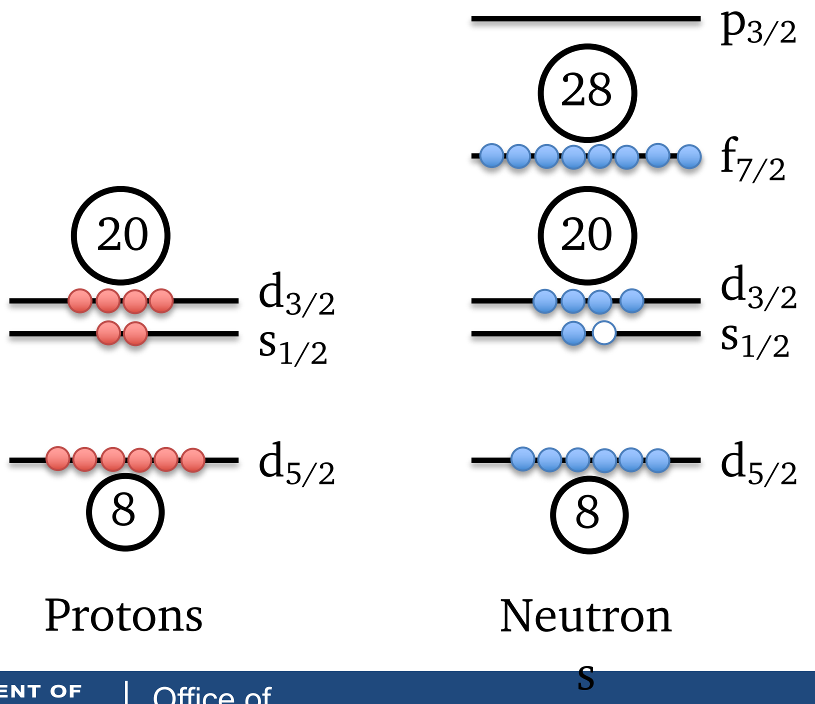
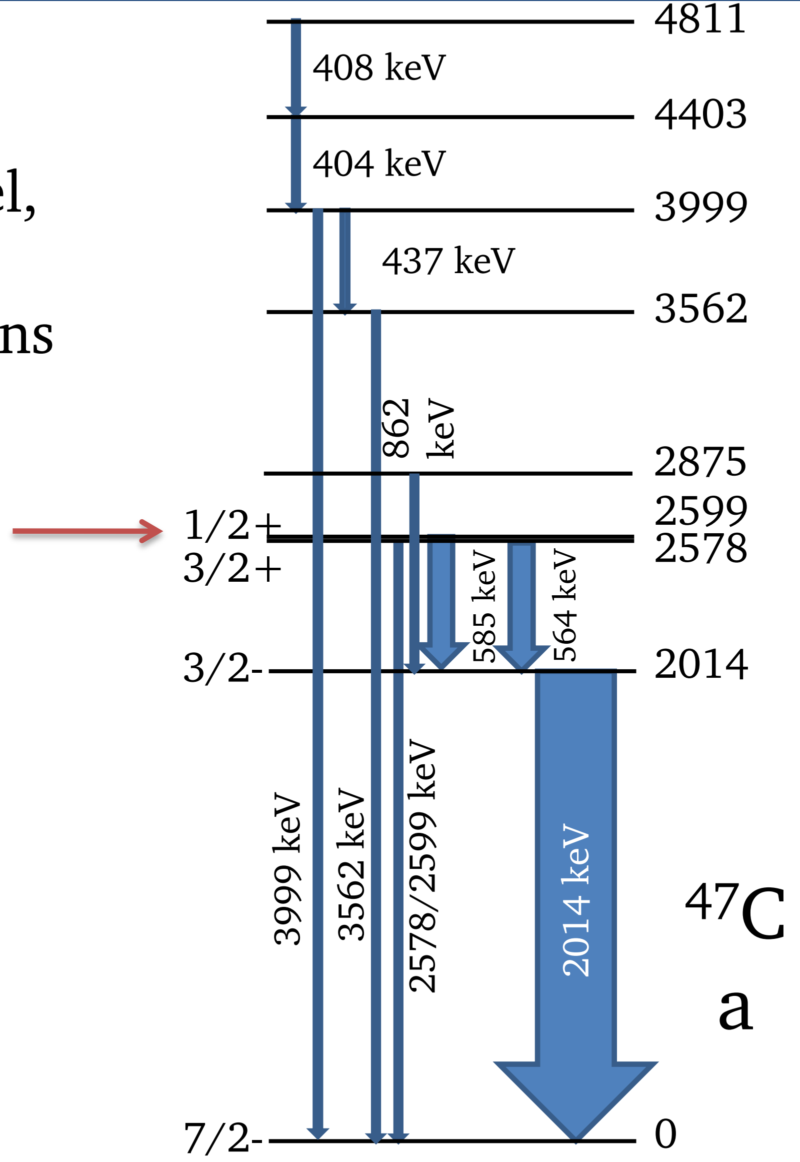




Nuclear excitations

Collective excitations

- Many nucleons outside a closed shell contribute coherently to excitations
- Vibrations and rotations (for non-spherical nuclei) have excitation energies comparable to single-particle energy excitations

> *The nucleus can quiver, ring or even "breathe"; the coordinated motion of the nuclear particles reveals much about the forces between them. Six modes of vibration have been detected so far*

Nuclear vibration

Treat nuclear vibrations as time-dependent deformation

$$R(\theta,\phi) = R_0\left(1 + \sum_{\lambda=0}^{\infty}\sum_{\mu=-\lambda}^{\lambda} \alpha^*_{\lambda\mu} Y_{\lambda\mu}(\theta,\phi)\right)$$

$$H_{\text{vib}} = \frac{1}{2}\sum_{\lambda\mu}\left(B_\lambda|\dot{\alpha}_{\lambda\mu}|^2 + C_\lambda|\alpha_{\lambda\mu}|^2\right)$$

n=3 ——— 0,2,3,4,6+

n=2 ——— 0,2,4+

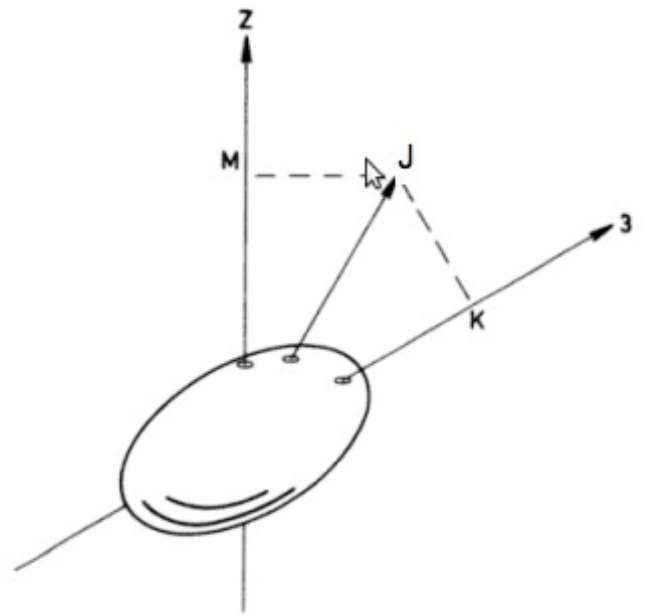
n=1 ——— 2+

——— 0+

Give rise to characteristic excitation spectra – vibration phonons couple as angular momenta

i.e. Quadrupole vibrations

Nuclear rotation

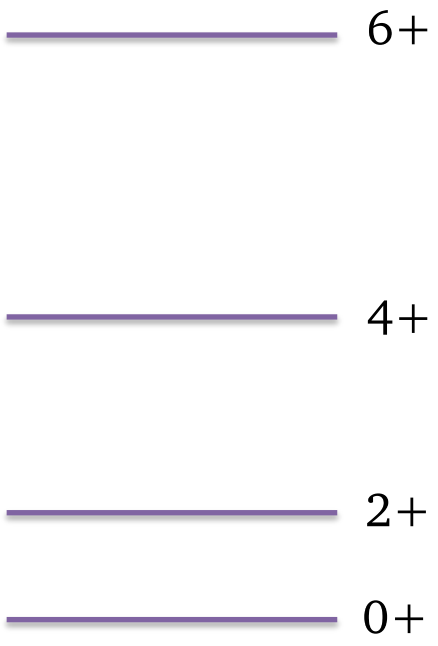


From A. Bohr and B. R. Mottelson.
Nuclear structure, volume 2

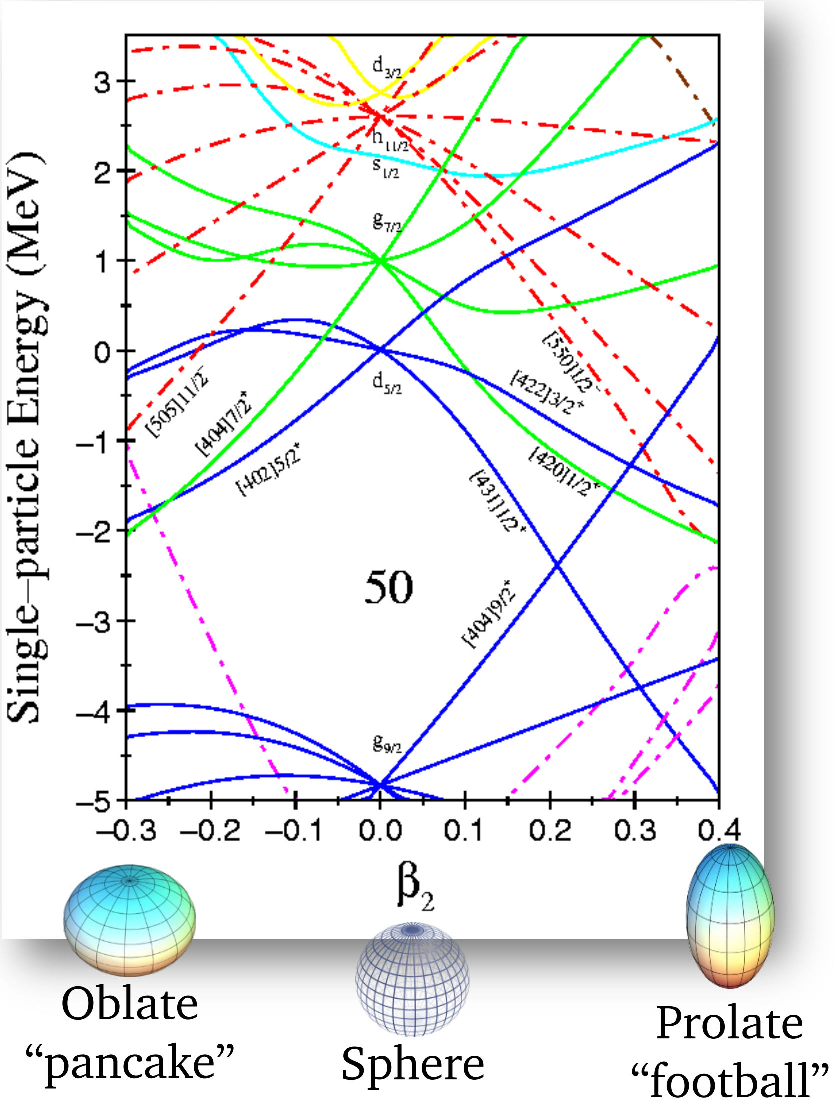
Deformed nuclei can also undergo collective rotational motion; nuclear rotation is parameterized in the same way as classical rotors

$$\boxed{E_{rot}(J) = \hbar^2/2I \times J(J+1)}$$

I = Moment of inertia

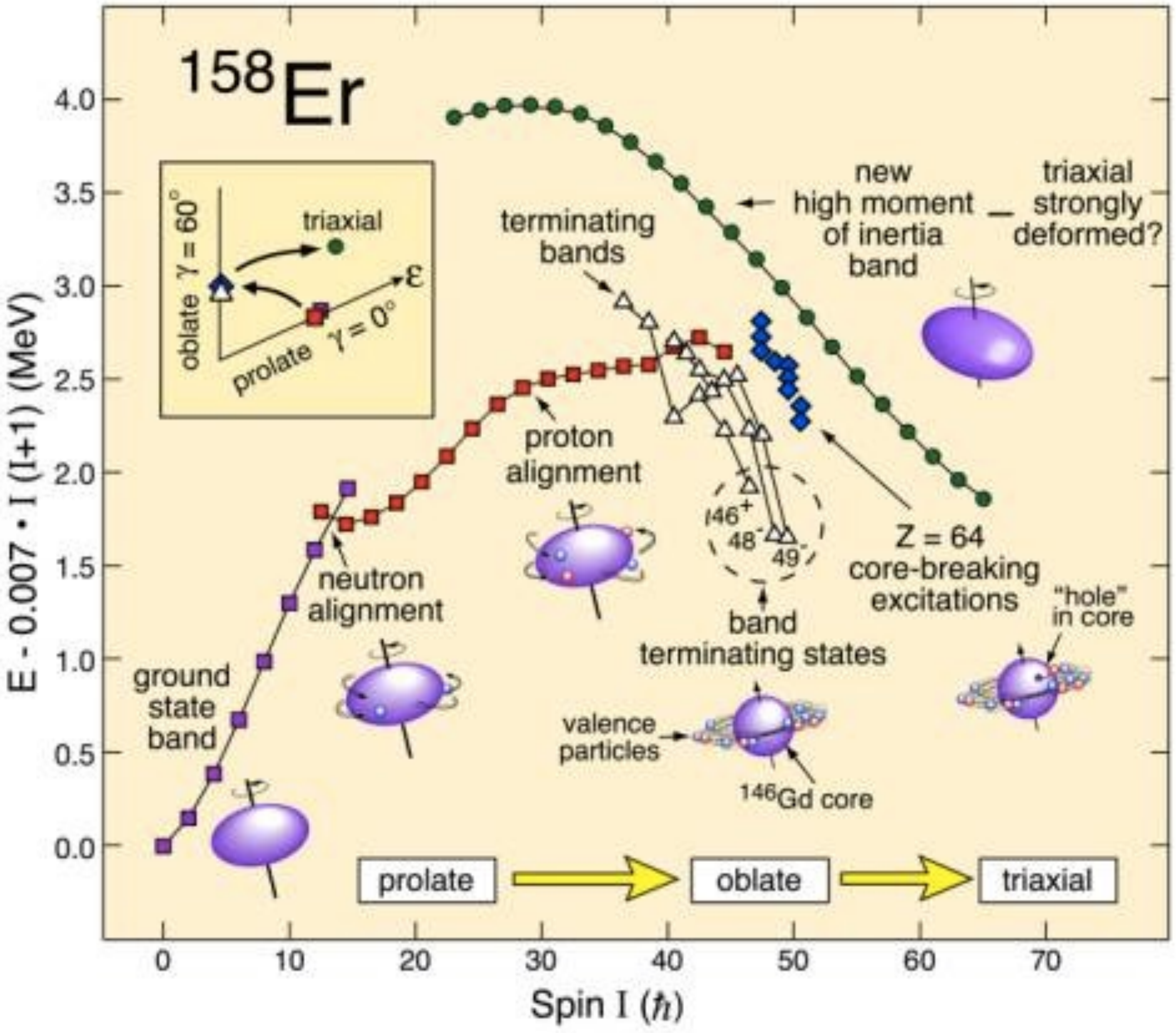


Deformation and the Nilsson model



- Nuclear rotation is a collective excitation, but interfaces to single-particle structure
- Nilsson model is a shell-model description in a deformed basis, which provides a good description in well-deformed nuclei

Moment of inertia in nuclei

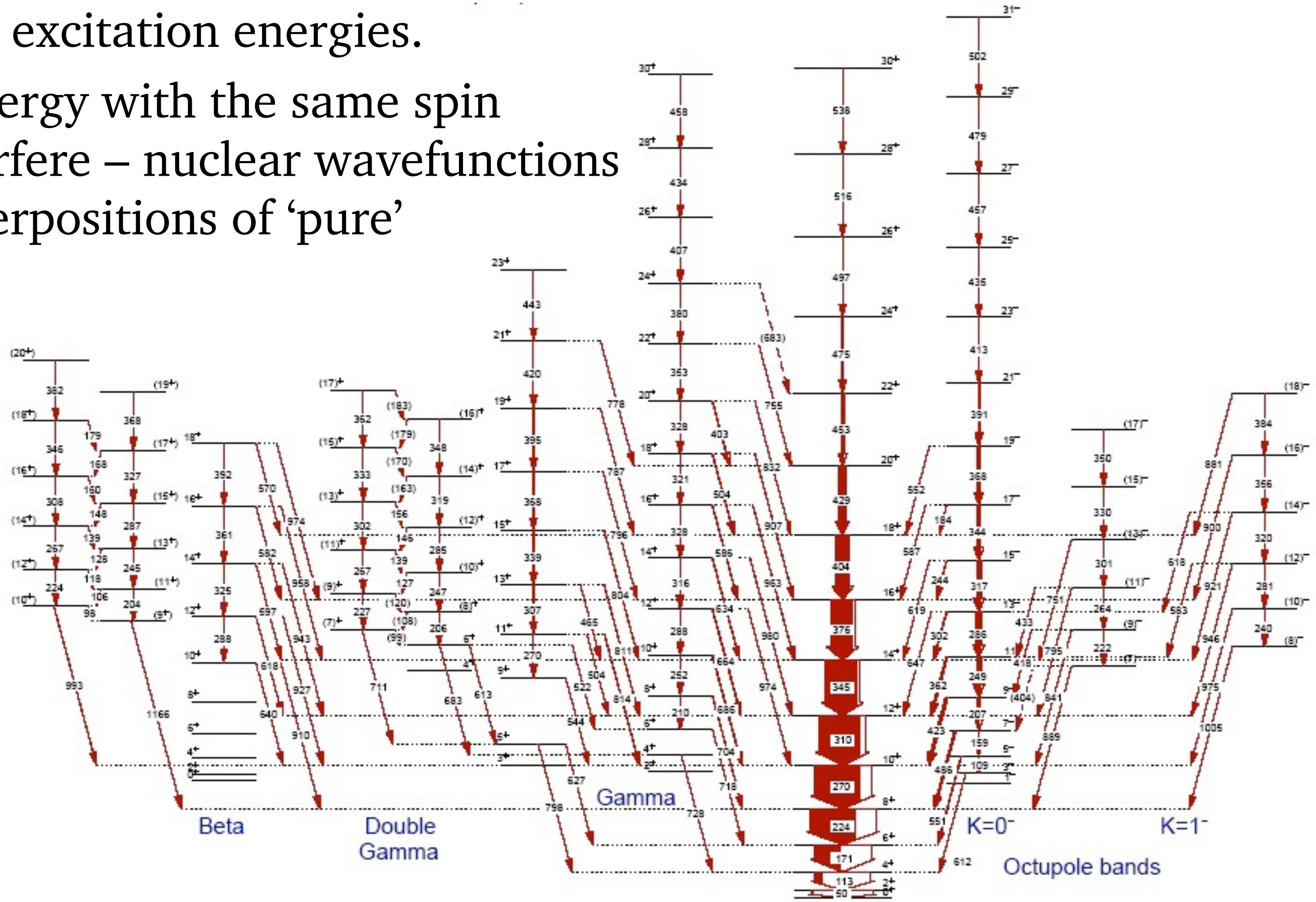


- Rigid body estimate for the moment of inertia is consistently larger than experimental data
- Irrotational flow value (like a liquid drop…) is too small
- Data puts the nuclear moment of inertia between these two limits; moment of inertia dynamic

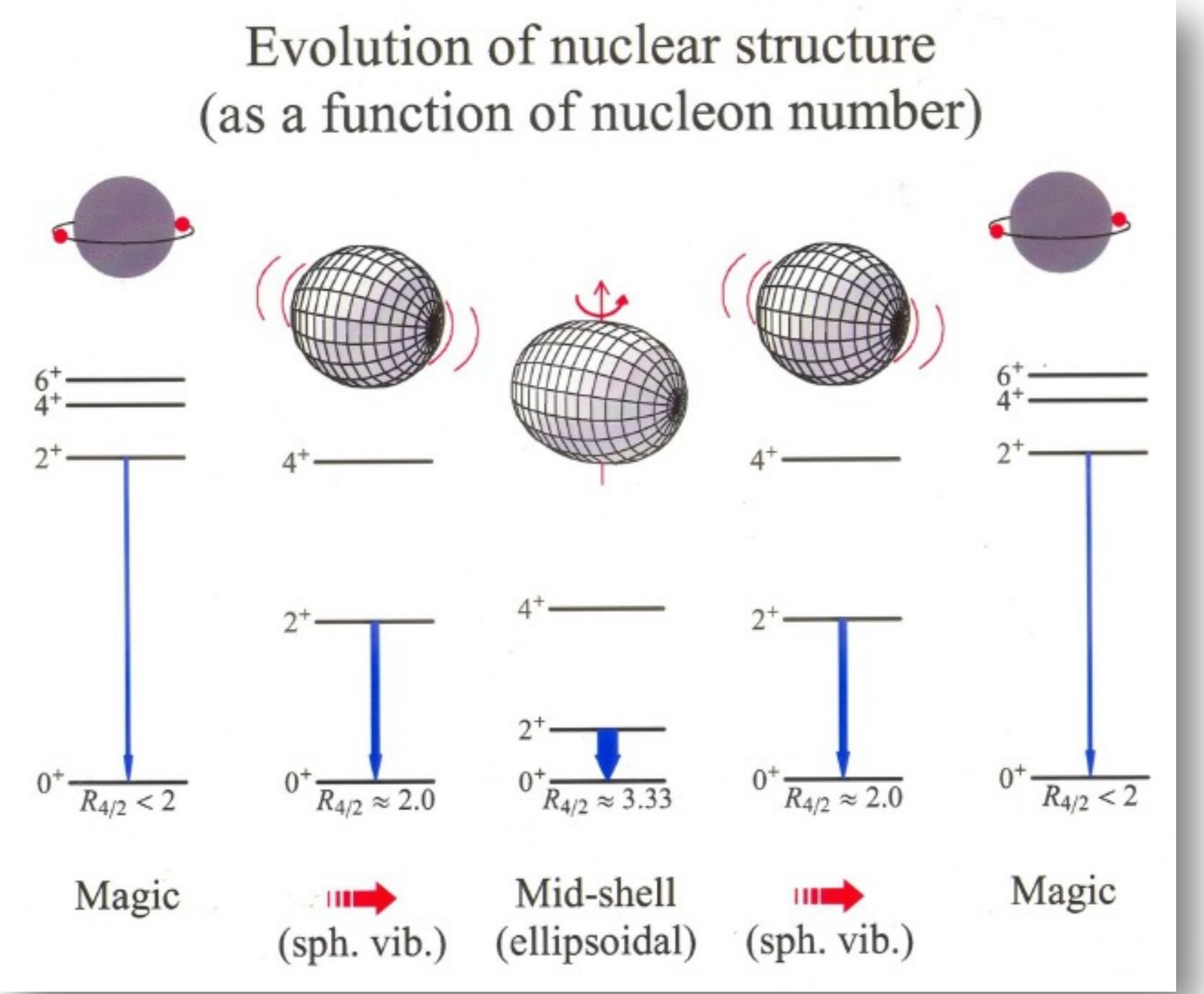
Excitations in the real world

Nuclei are not limited to a single type of excitation – vibration, rotation and single-particle configurations all coexist at similar excitation energies.

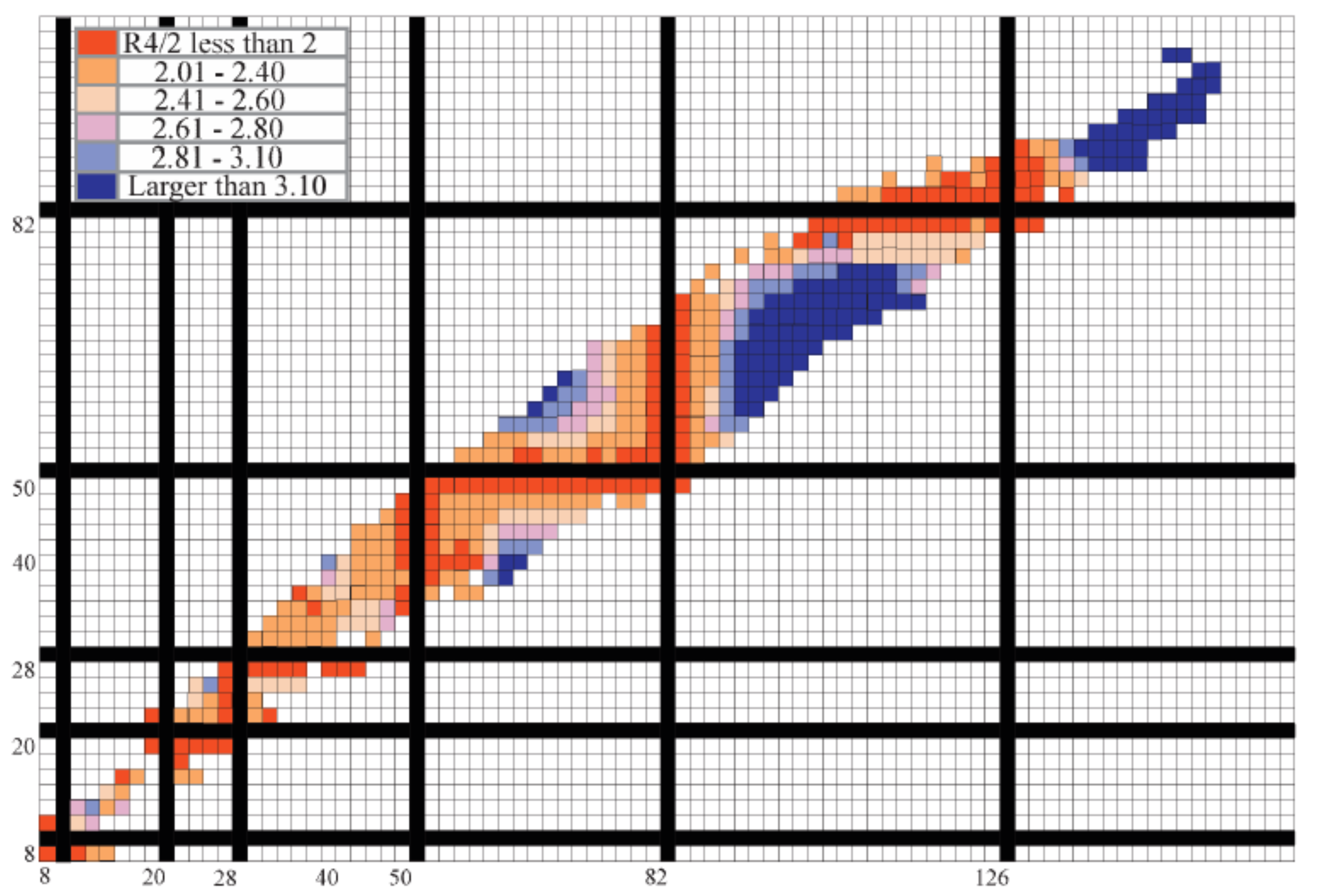
States near in energy with the same spin interact and interfere – nuclear wavefunctions are complex superpositions of 'pure' configurations.



Simple patterns still tell us about structure



$R_{4/2}$ – A powerful ratio



Question!

- In ^{42}Si, a gamma-ray from 2+ to 0+ is observed at 742 keV, and a gamma-ray from the 4+ state to the 2+ state is observed at 2032 keV. What can we say about the excitation?
  (A) Nothing
  (B) It's pretty rotational – deformed
  (C) It seems vibrational
  (D) It's unbound

Question!

- In ^{42}Si, a gamma-ray from 2+ to 0+ is observed at 742 keV, and a gamma-ray from the 4+ state to the 2+ state is observed at 1431 keV. What can we say about the excitation?

  (A) Nothing

  (B) It's pretty rotational – deformed

  (C) It seems vibrational

  (D) It's unbound

$$E(4+)/E(2+) = (1431 + 742)\,\mathrm{keV} / 742\,\mathrm{keV} = 2.9$$

Studying Level Schemes

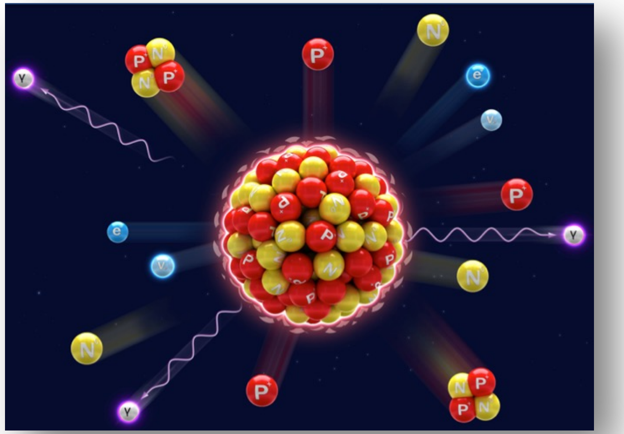
Studying Level Schemes

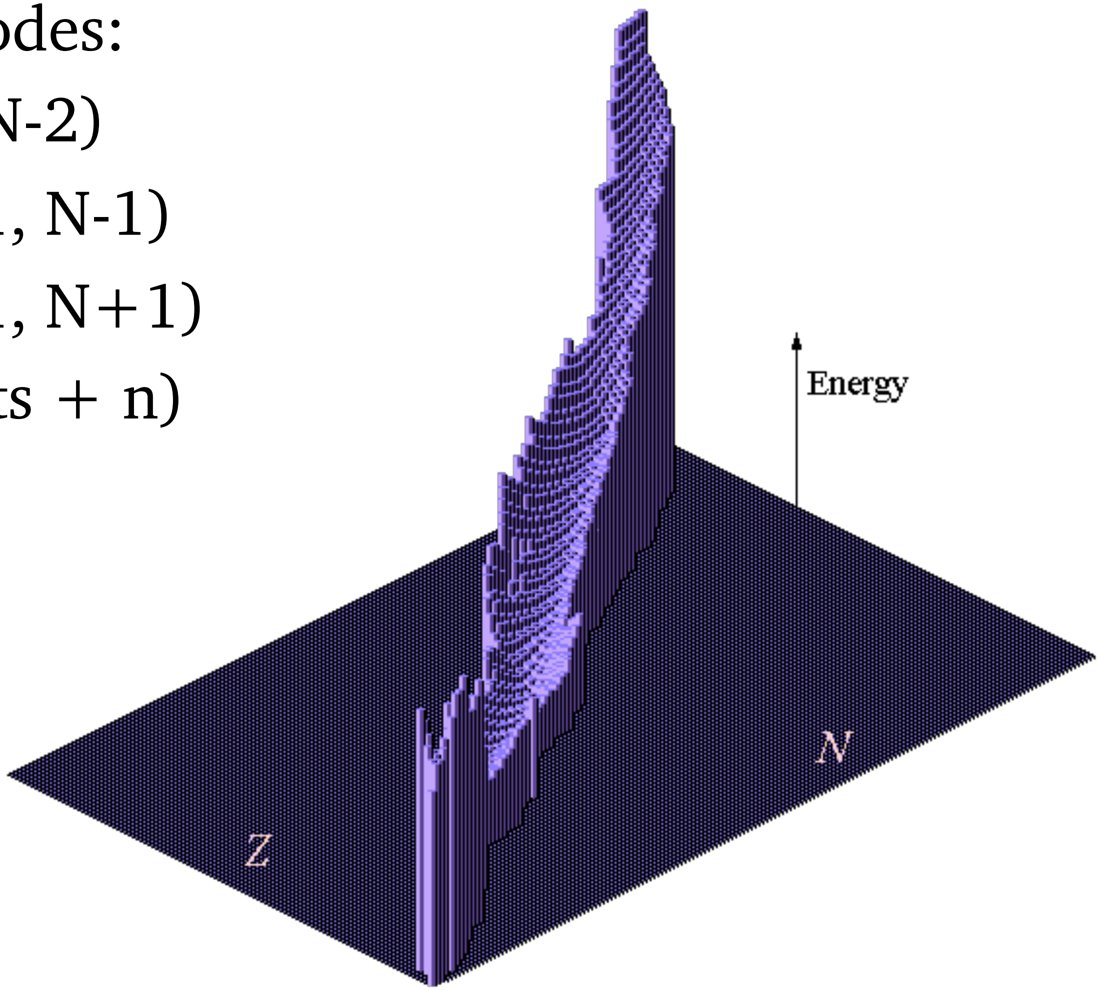
Nuclear Decay

Nuclear ground-state decay

Nuclei decay toward stability (and a lower energy state) via one of four basic decay modes:

- Alpha decay (--> Z-2, N-2)
- Beta(-) decay (--> Z+1, N-1)
- Beta(+) decay (--> Z-1, N+1)
- Fission (--> 2 fragments + n)
- 1p & 2p radioactivity



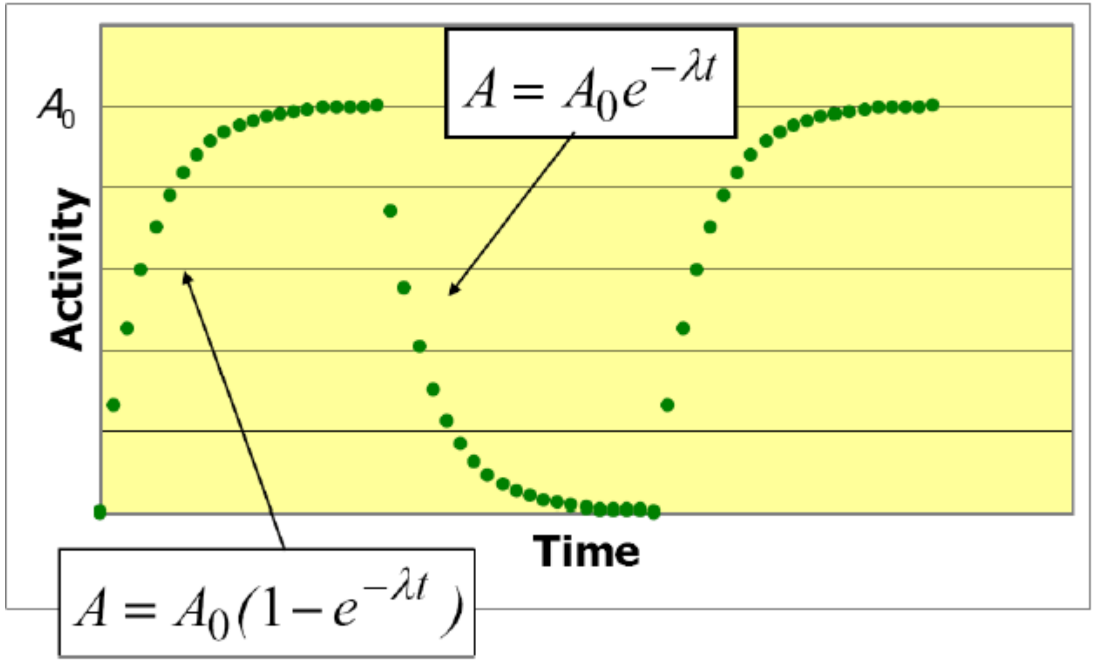


Decay observables

- Nuclear decay measurements allow access to a number of observables
  - Half-life information for decaying state
  - Energies for emitted particles (spectroscopic information in daughter nucleus)
  - Gamma-rays de-exciting daughter states populated in decay
    - Excited state spins and parities based on selection rules for primary decay and subsequent gamma decay

Decay half-lives

All radioactive decay modes obeys Poisson statistics and are described by straight-forward differential equations.



A = -dN/dt = λN

$t_{1/2} = \ln(2) / \lambda$

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Nuclear excited state decay

- Excited states in nuclei can decay in a number of ways:
  - β^+, β^-, electron capture (EC) -- $^{177}Lu^m$
  - Particle emission -- $^{53}Co^m$, $^{211}Po^m$
  - Fission $^{239}Pu^m$
  - Internal conversion
  - Gamma-ray emission

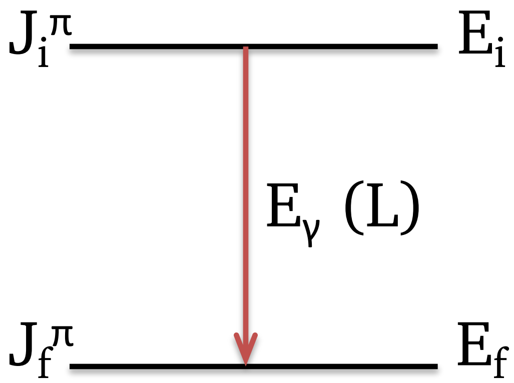
Dominant Excited State Decay

- Excited states in nuclei can decay in a number of ways:
  - β^+, β^-, electron capture (EC) -- $^{177}Lu^m$
  - Particle emission -- $^{53}Co^m$, $^{211}Po^m$
  - Fission $^{239}Pu^m$
  - Internal conversion
  - Gamma-ray emission

Nuclear properties from gamma-ray studies

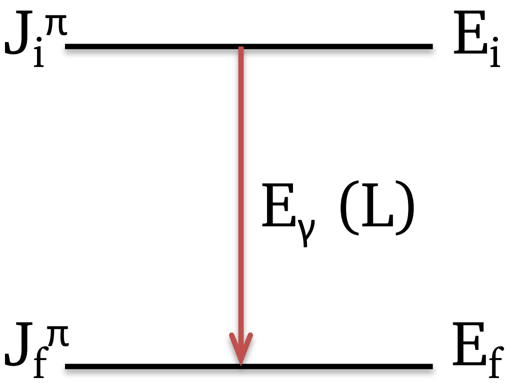
- Coincidence relation --> Level schemes
- Angular distribution/correlation --> Multipolarity, spin
- Doppler shifts --> excited state lifetimes
- Linear polarization --> E/M, parity
- Intensity of transitions --> B(E2)

Selection Rules



$$E_\gamma = E_i - E_f$$
$$|J_i - J_f| \le L \le J_i + J_f$$
$$\Delta\pi(EL) = (-1)^L$$
$$\Delta\pi(ML) = (-1)^{L+1}$$

Selection Rules



$$E_\gamma = E_i - E_f$$
$$|J_i - J_f| \leq L \leq J_i + J_f$$
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The transition probability for at state decaying by transition of multipole order L is:

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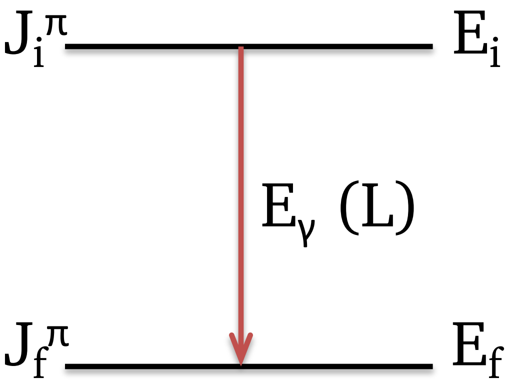

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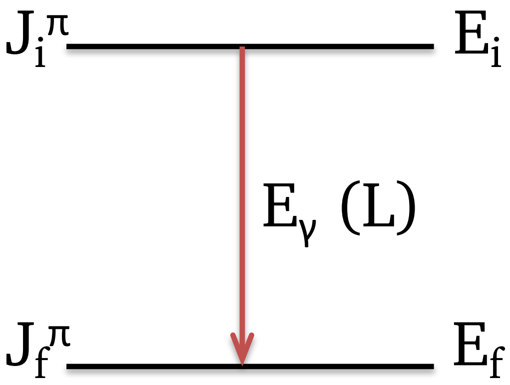

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Weisskopf estimates

$$B(E2 : J_i \rightarrow J_f) = \frac{1}{2J_i+1}\langle\psi_f||E2||\psi_i\rangle^2$$

$$T(E1) = 1.03 \times 10^{24} A^{2/3} E_\gamma^3$$

$$T(E2) = 7.28 \times 10^{7} A^{4/3} E_\gamma^5$$

$$\cdots$$

$$T(M1) = 3.15 \times 10^{13} E_\gamma^3$$

$$T(M2) = 2.24 \times 10^{7} A^{4/3} E_\gamma^5$$

$$\cdots$$

Lifetimes and Gamma Decay

- The bulk of electromagnetic (gamma) transitions have lifetimes of $10^{-15} – 10^{-13}$ s
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Question!

- What would you expect to be the dominant character of the gamma-ray transition linking the second 0^+ excited state at 1.06 MeV in ^{32}Mg with the ground state (0^+)?
  (A) E1
  (B) M2
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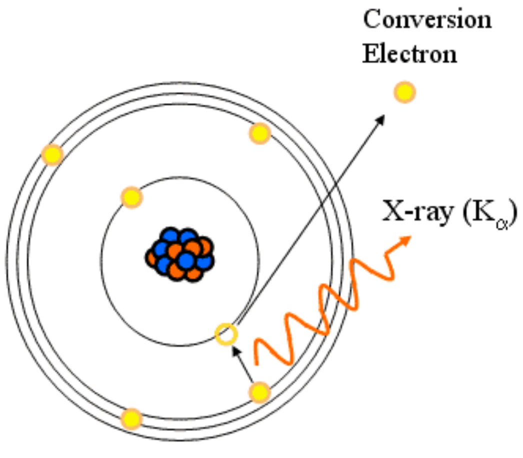
Gamma rays must carry at least one ~ of angular momentum – cannot link two 0+ states
When gamma transition is not possible, internal conversion is an alternative electromagnetic transition.



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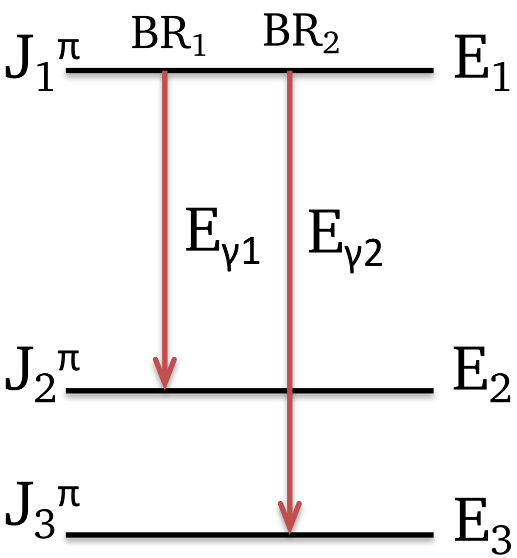

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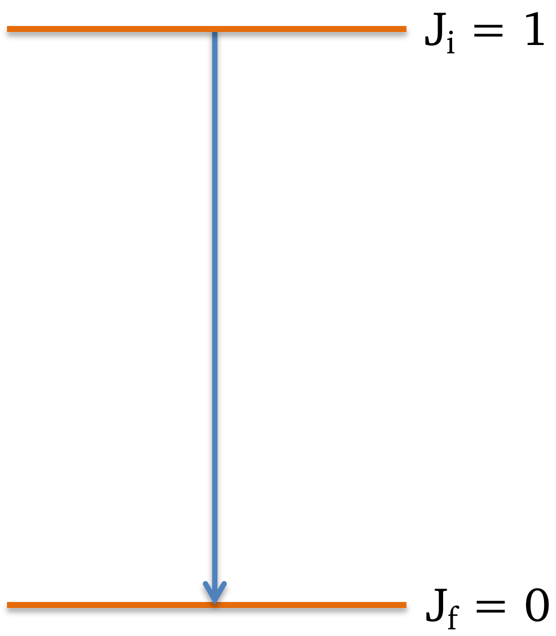
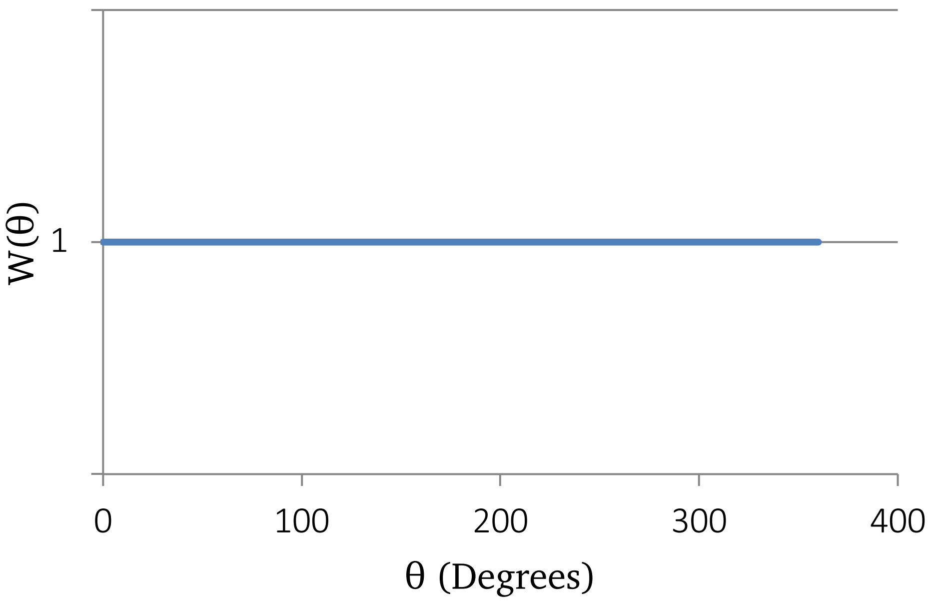
- Knowledge of J_i and J_f limit the multipolarity (L) of gamma-ray transitions
- To measure multipole order (L) we can measure angular distributions
- To determine E vs. M we need to measure polarization of the transition

Gamma-Ray Angular Distributions

- Angular distribution of a gamma-ray depends on the values of m_i and m_f





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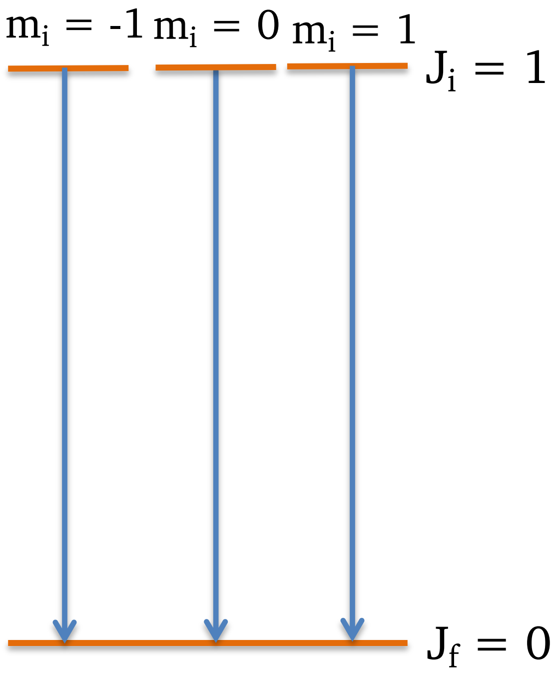
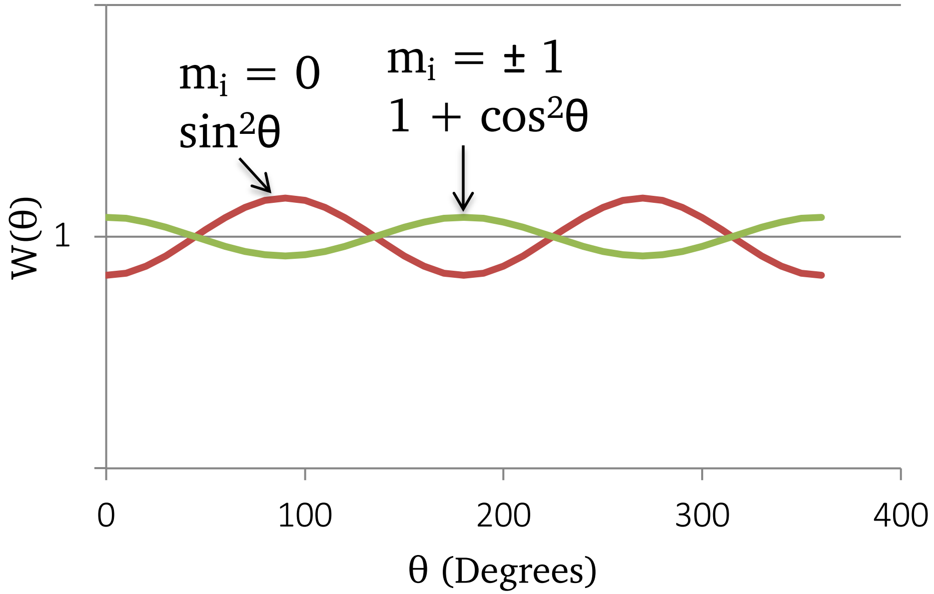
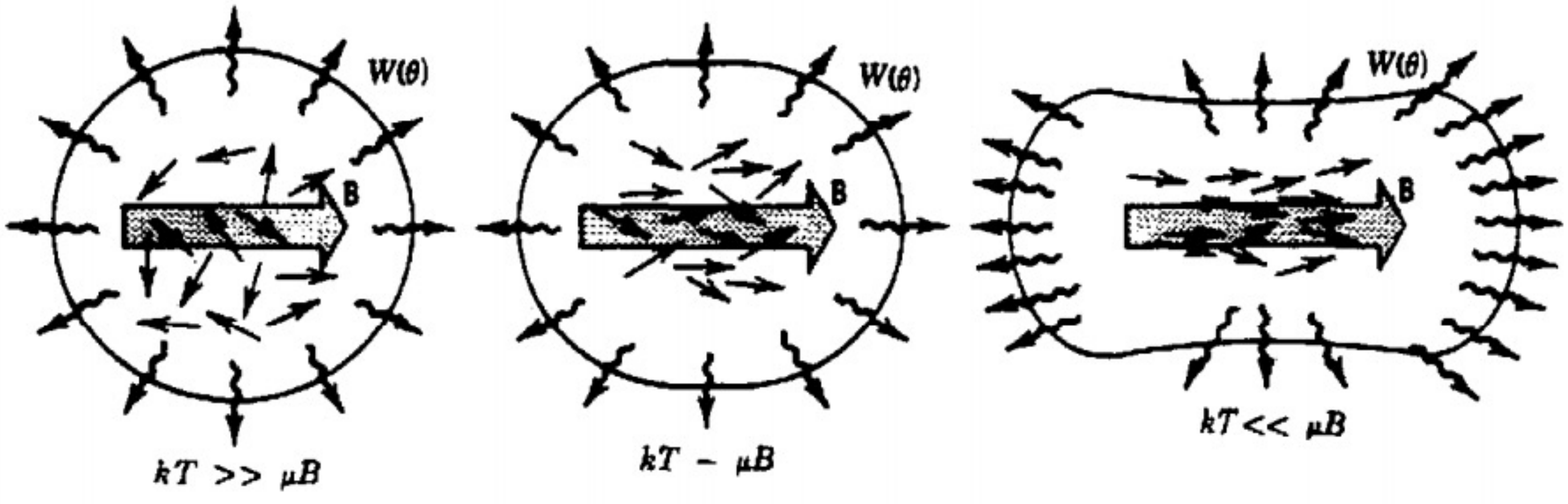




Gamma-Ray Angular Distributions

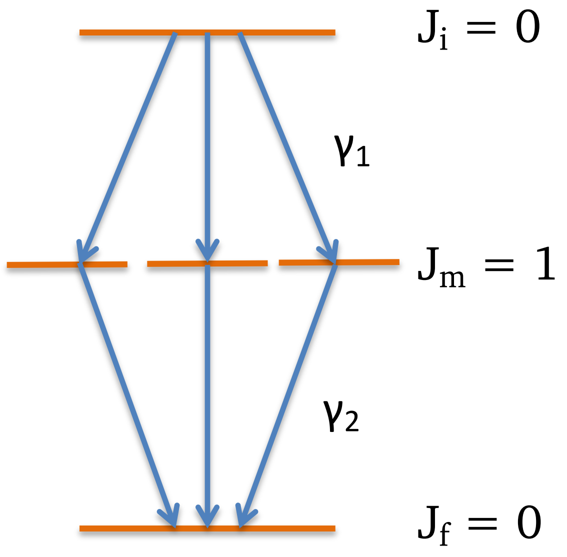
- If we produce unequal populations $p(m_i)$ angular distributions $W(\theta)$ will be non-constant

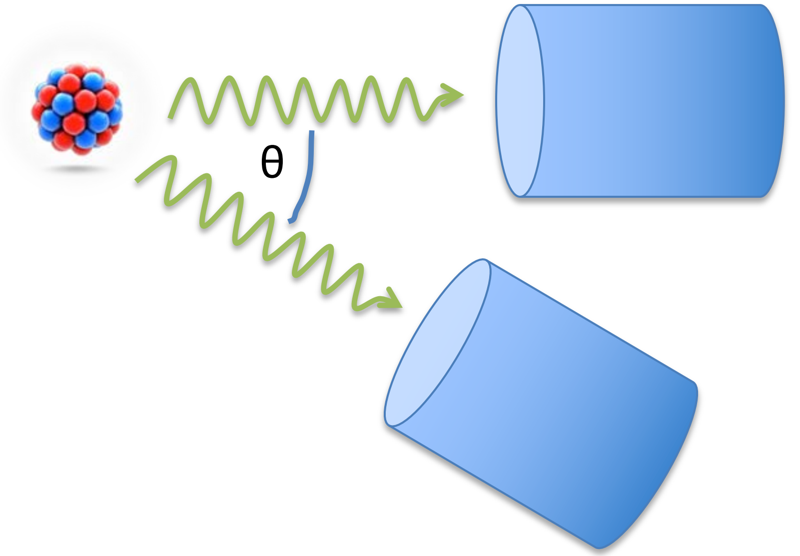
Nuclear Orientation



Gamma-Ray Angular Correlations

- Observation of a previous radiation selects an unequal mixture of populations $p(m_i)$

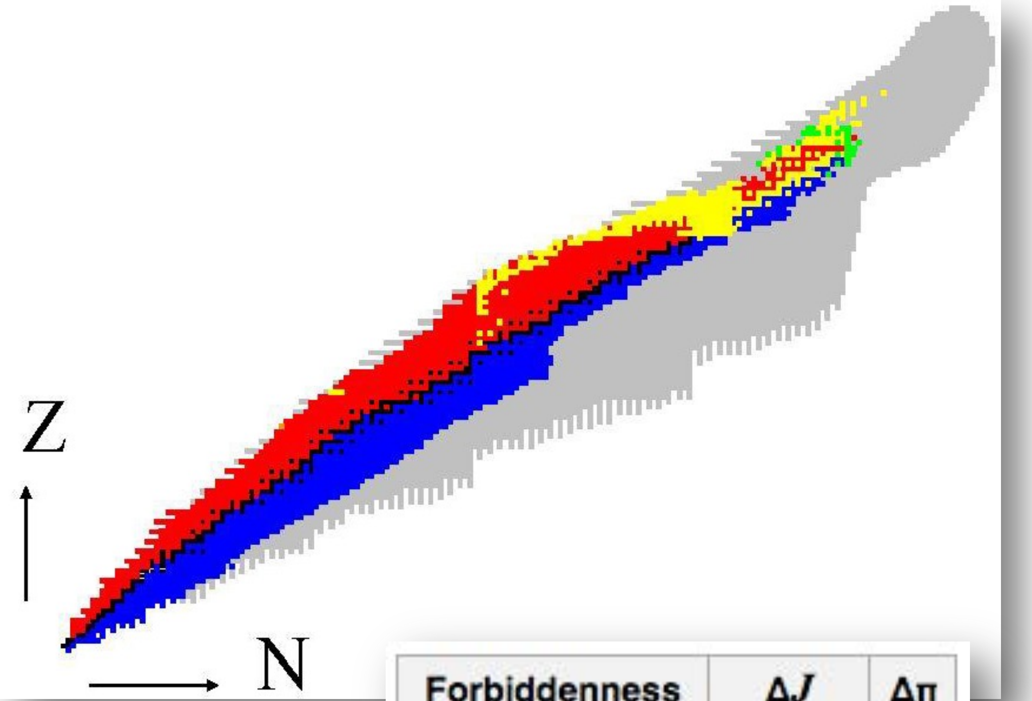




- First gamma defines z-axis -- $\theta_1 = 0$
- $p(m_m) = 0$ for $m_m = 0$
- Distribution of γ_2 relative to γ_1 is $m = \pm 1 \text{ --> } m = 0$
- $W(\theta) \text{ --> } 1 + \cos^2\theta$

Back to β decay…

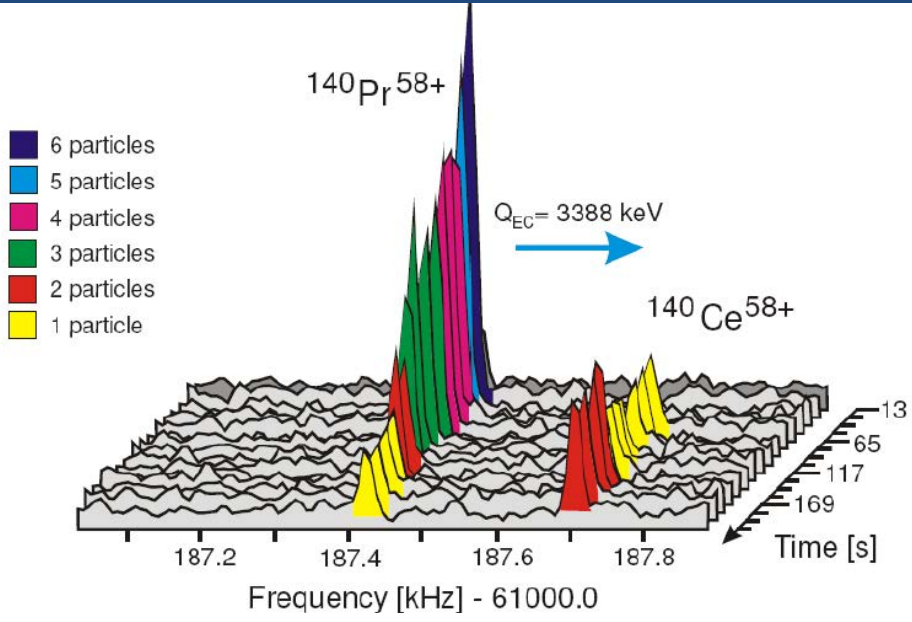
- The majority of nuclides on the chart decay via β^+ or β^- decay
  - n --> p + β^- + ν_e
  - p --> n + β^+ + ν_e
- We can consider β-decay (and other decays) as a tool to populate excited states in daughter nuclei, but with a unique selectivity

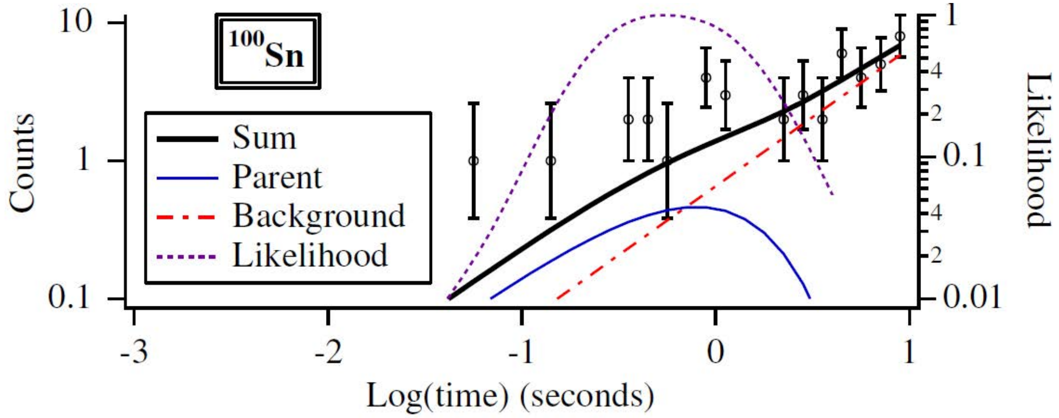


Forbiddenness	ΔJ	Δπ
Superallowed	$0^+ \rightarrow 0^+$	no
Allowed	0, 1	no
First forbidden	0, 1, 2	yes
Second forbidden	1, 2, 3	no
Third forbidden	2, 3, 4	yes

β-decay half-lives

- even with the most limited statistics, half-lives can be extracted
- the equations of exponential decay are well known and can be applied using statistical techniques such as maximum likelihood to obtain half-lives from tens of observed decays

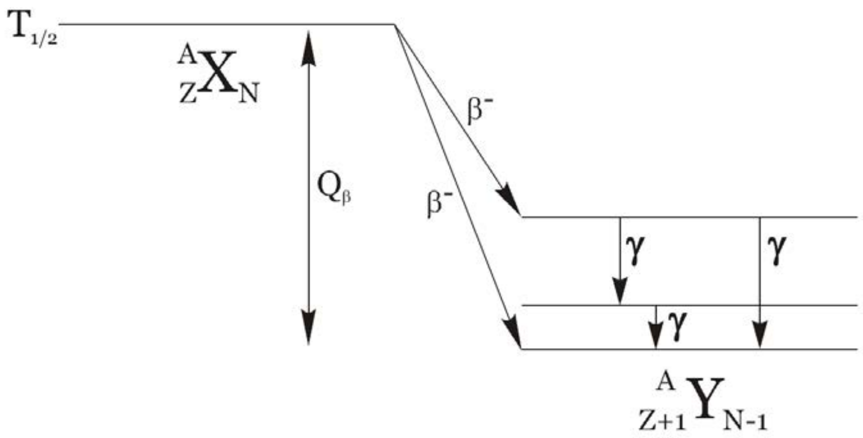




D. Bazin et al., PRL 101, 252501 (2008).
F. Bosch et al., Int. J. Mass Spectr. 251, 212 (2006).

Implantation β decay spectroscopy

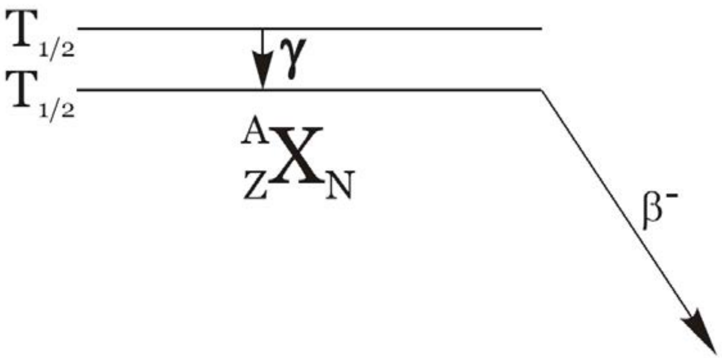
β-Delayed Gamma Spectroscopy



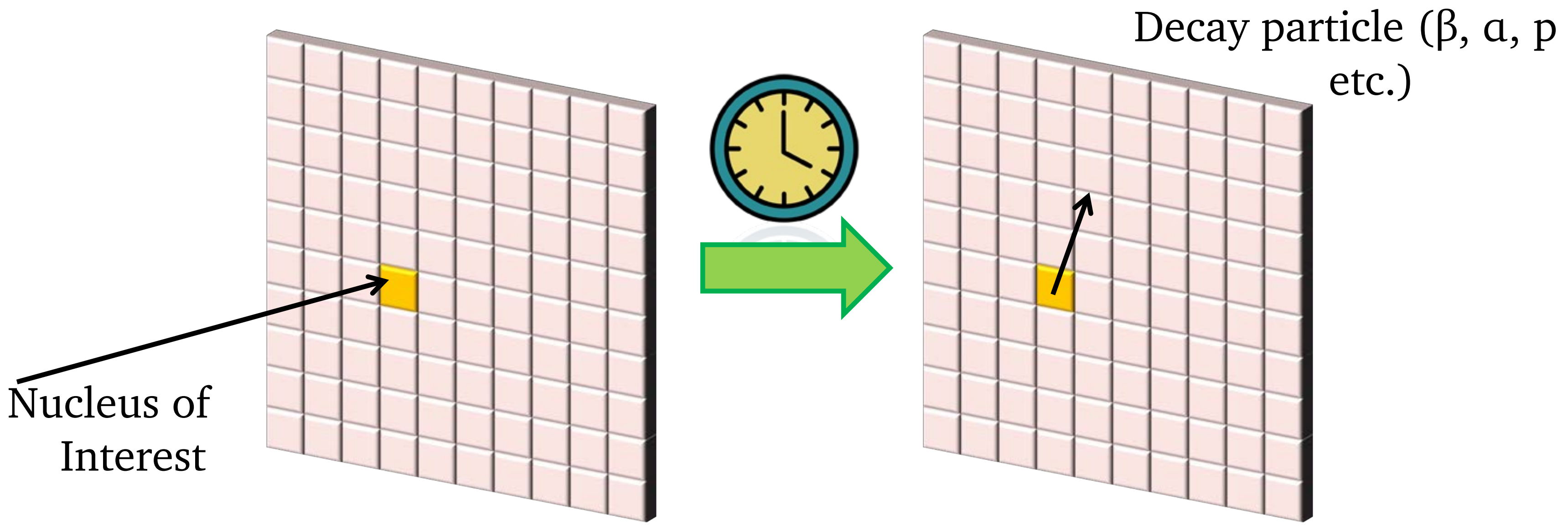
• gamma rays following decay events provide information on low-level structure of daughter nuclei

Isomeric Decay

• depending on the production mechanism, nuclei may be produced in long-lived excited states (isomeric states)
• a TAC for implantation-gamma provides the possibility for isomer lifetime determination, if you look for gammas following an implantation

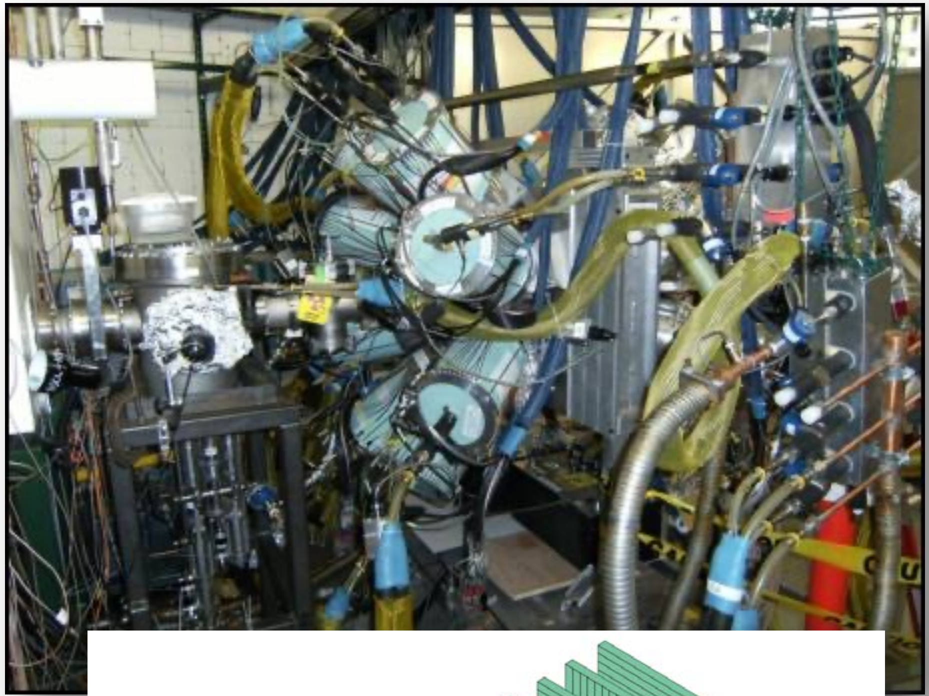


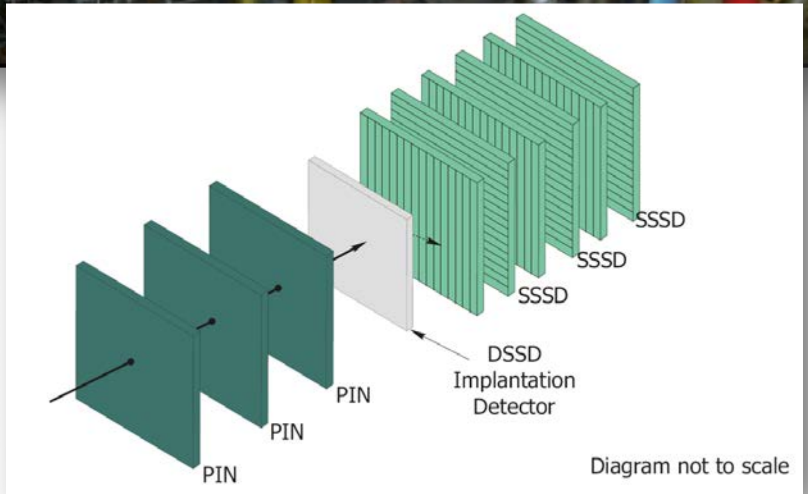
Implant-decay correlation technique

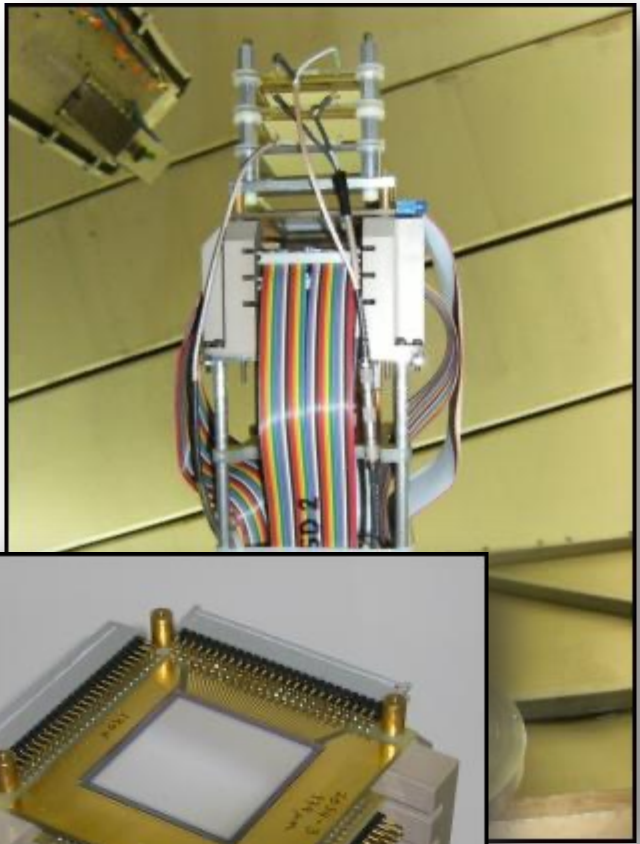


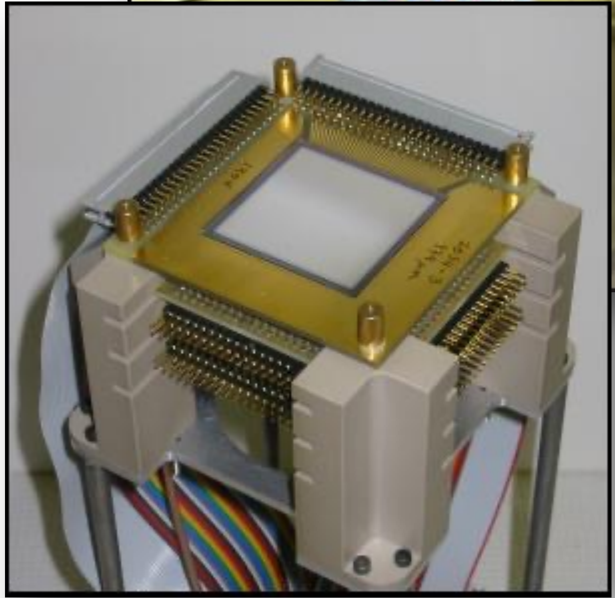
The use of highly-segmented detectors (usually Si) allows temporal and spatial correlations between implanted nuclei, and their subsequent decays → detect the implant and the decay to obtain half-lives and information on levels in the daughter relative to the parent ground state

β-decay spectroscopy set-up: NSCL



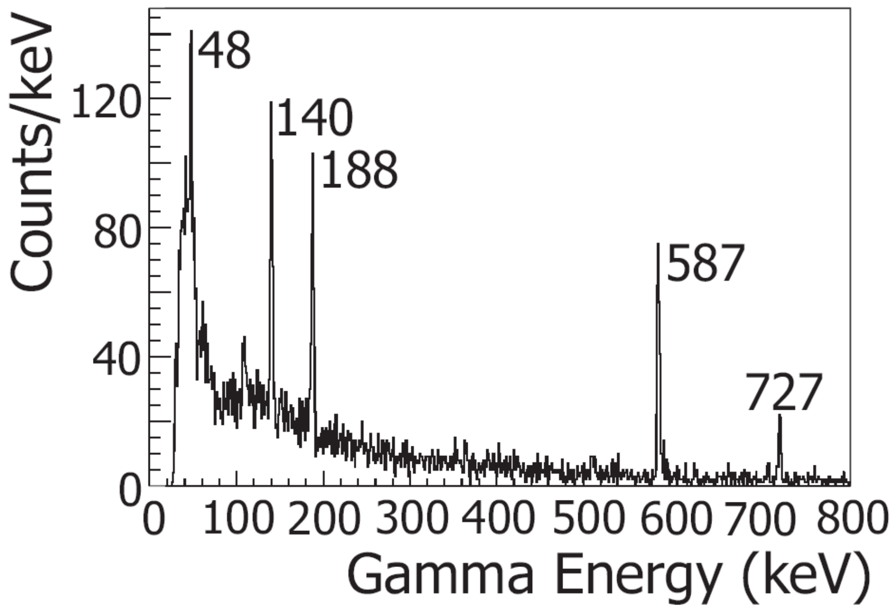


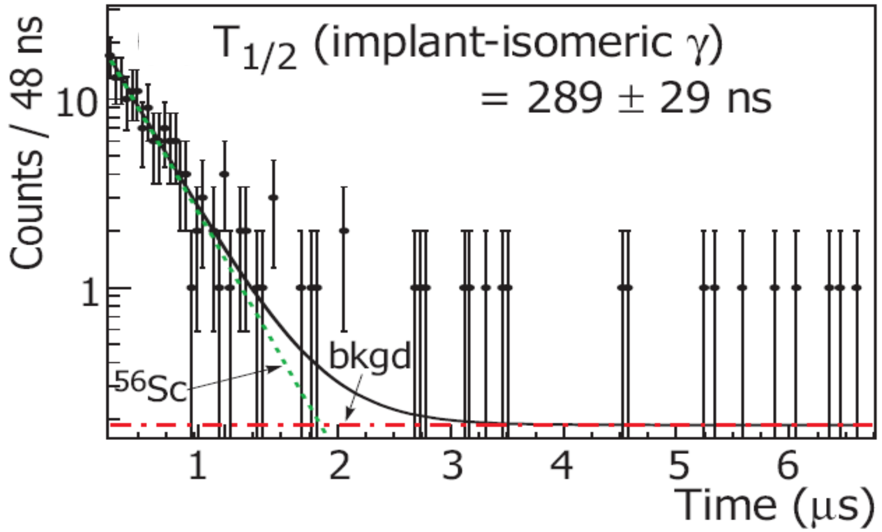




β-decay spectroscopy: complex example

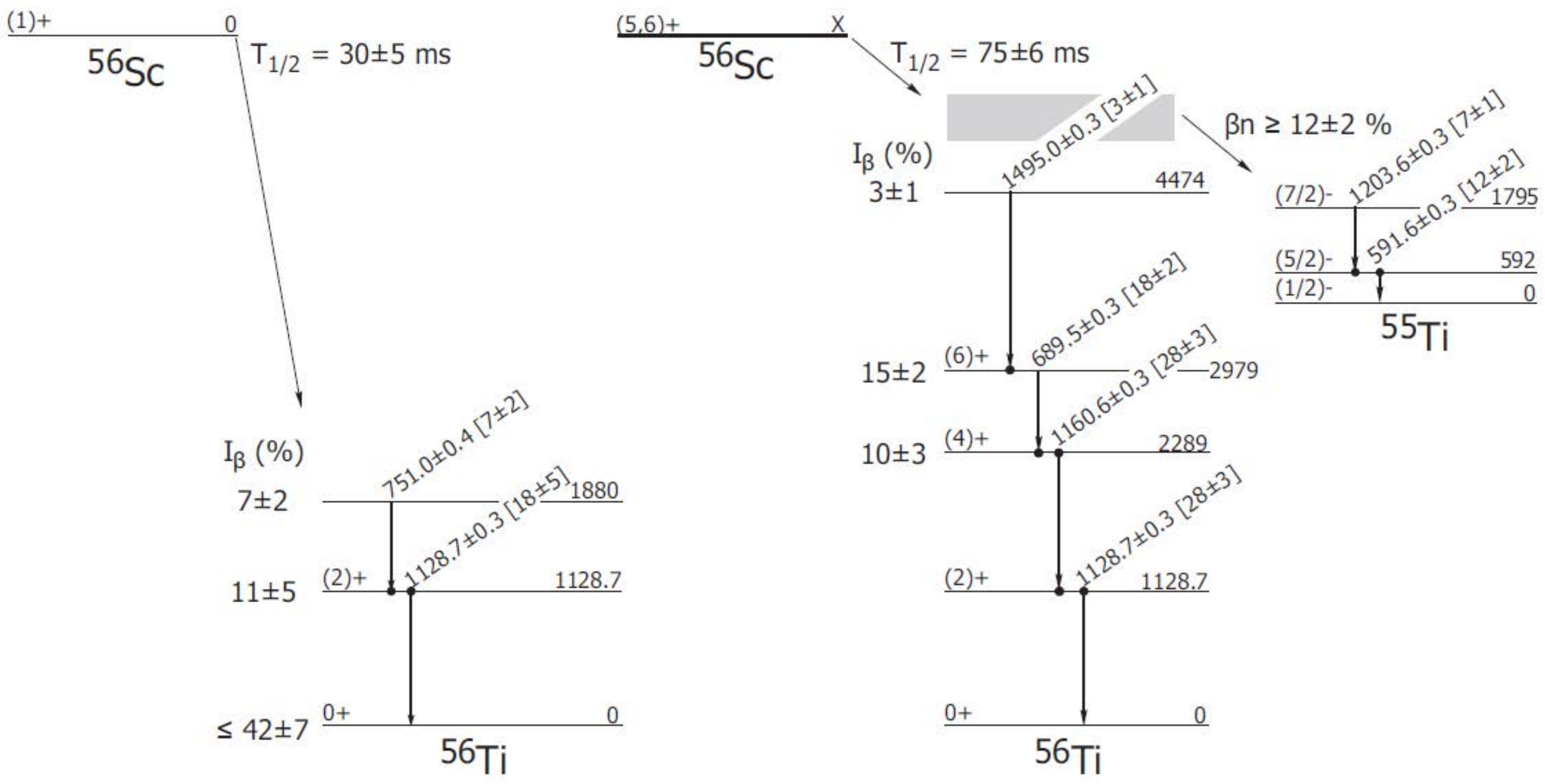
A. Look at the gamma-rays in coincidence with the nucleus of interest (^{56}Sc) implantations – by fitting half-lives of the isomer, and through gamma-gamma correlations, build up a level scheme, and can get relative spin-parities for the states in ^{56}Sc





HLC et al., PRC 82, 014311 (2010).

β-decay spectroscopy: complex example



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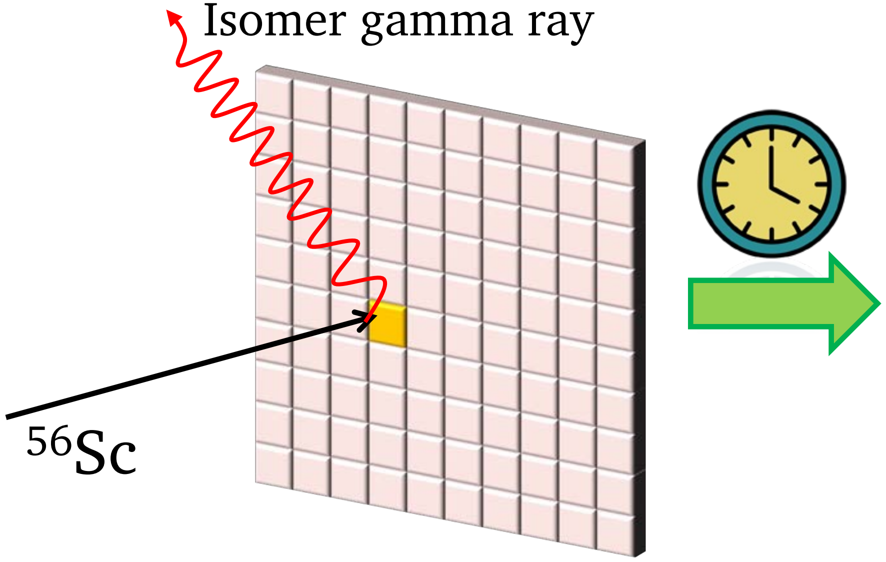
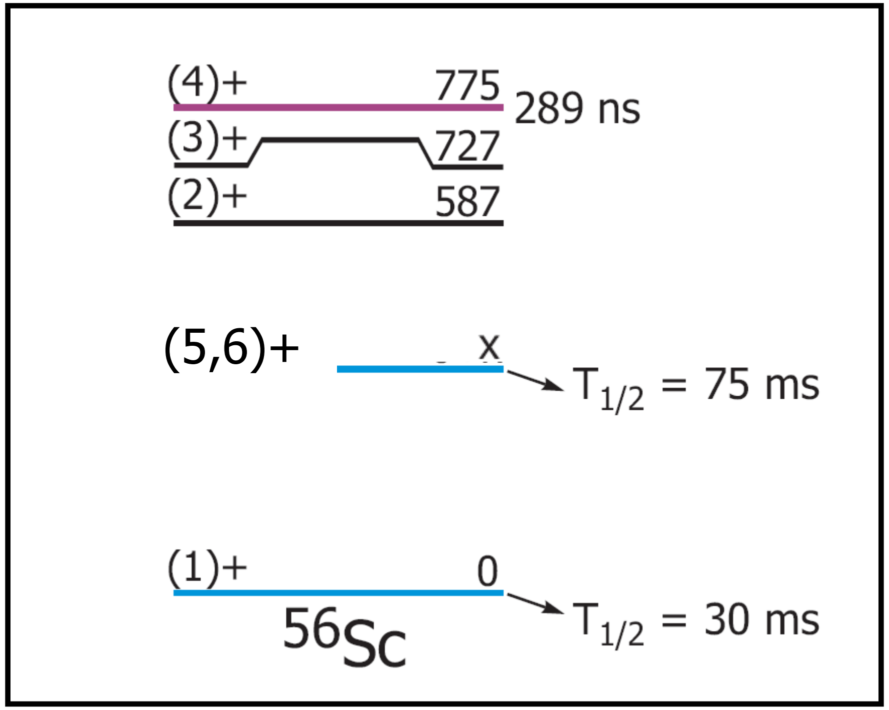
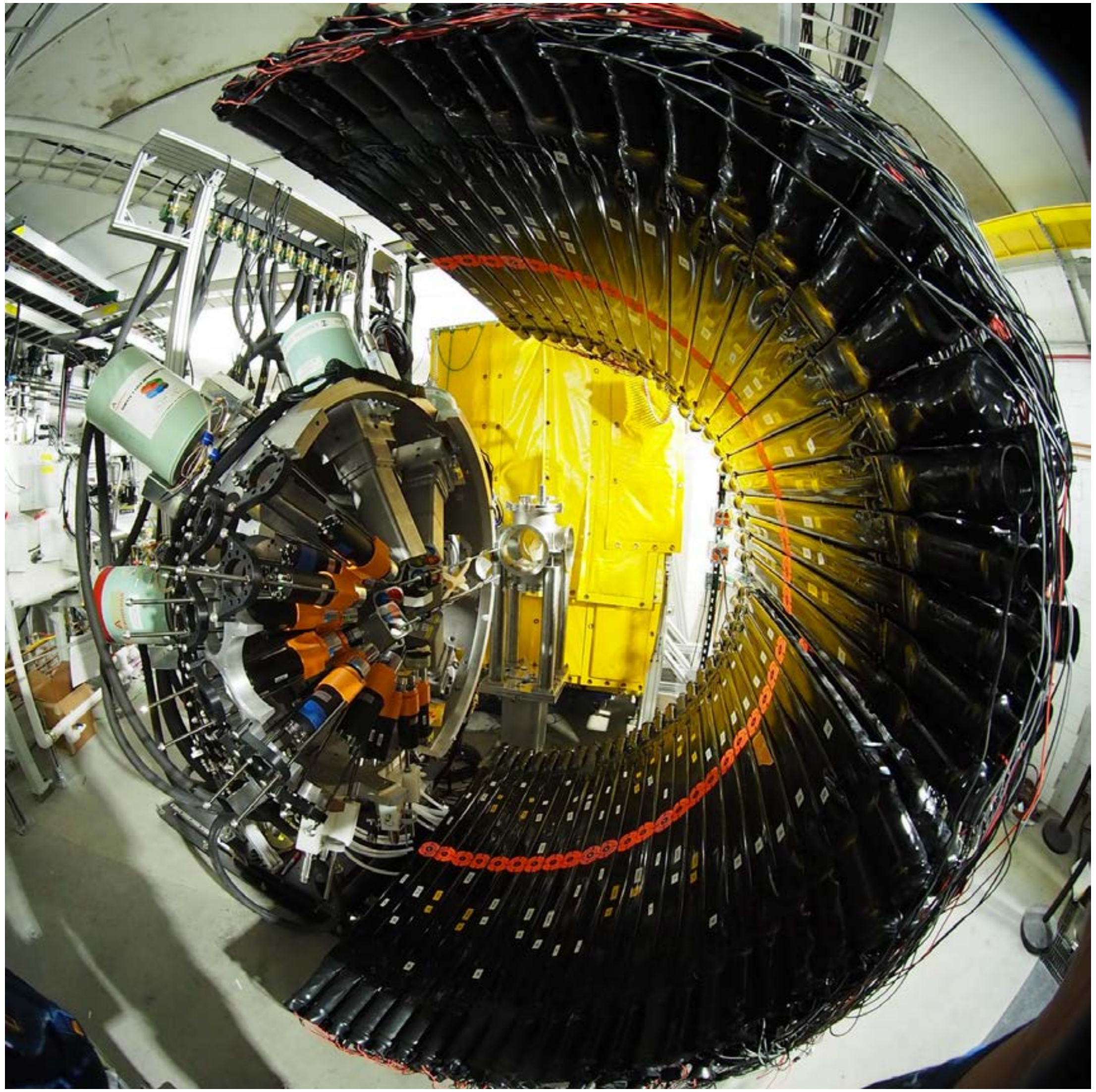
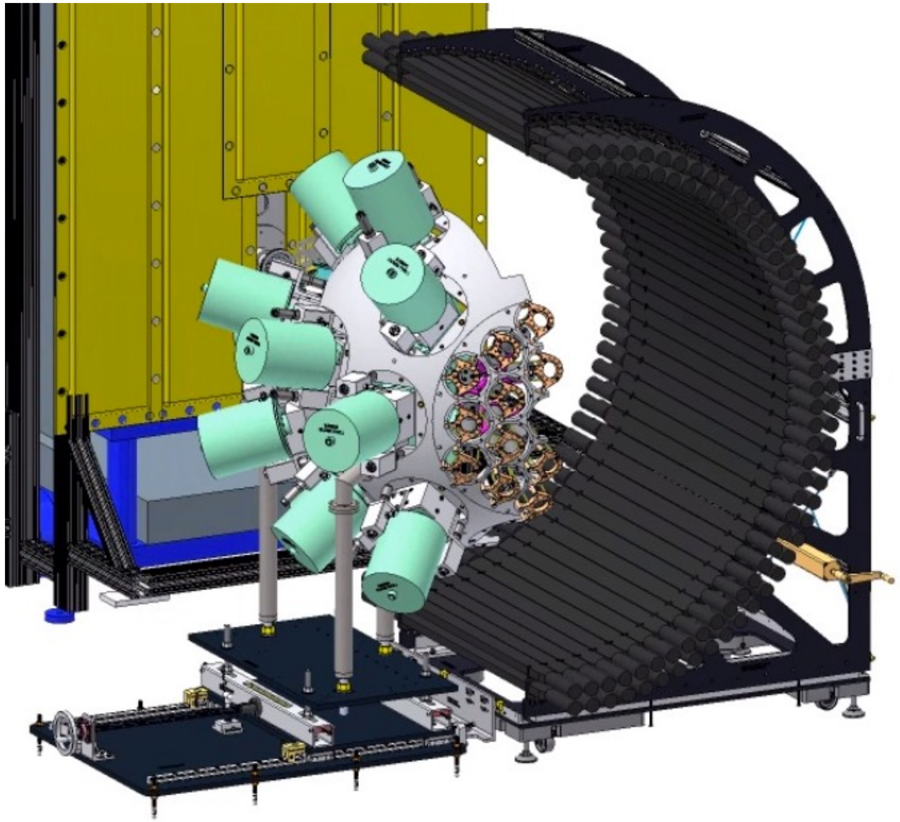




D. Gate on implantations that came in coincidence with isomer gamma-rays and look at half-life → determine which state the isomer populates, and fix the spin/parity

β-decay spectroscopy at FRIB

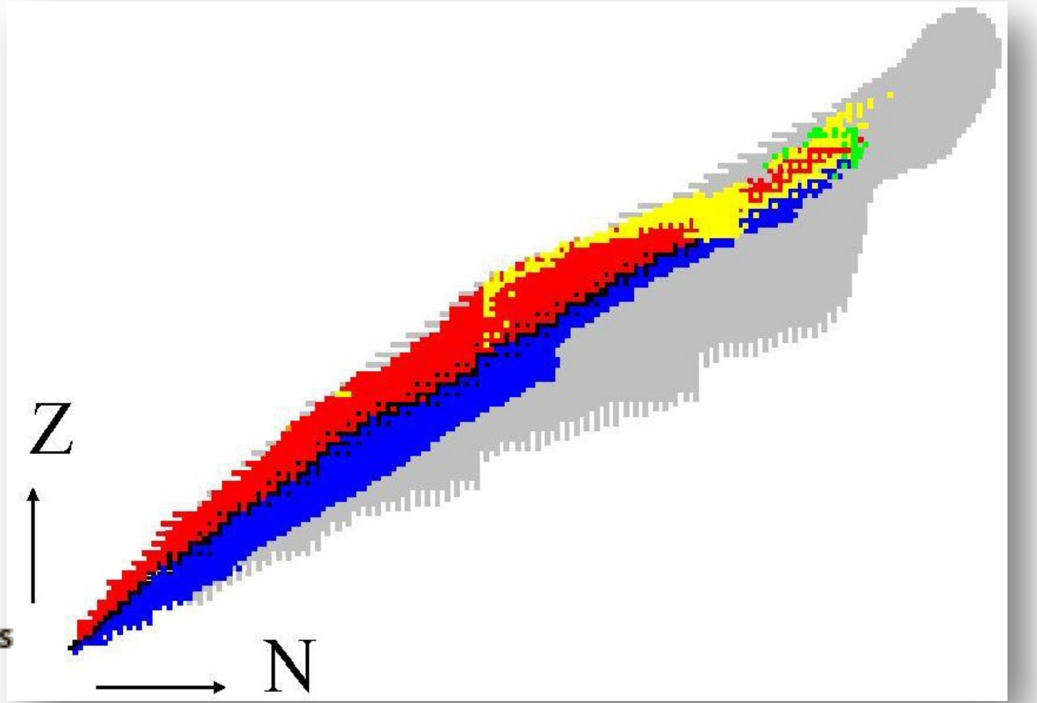


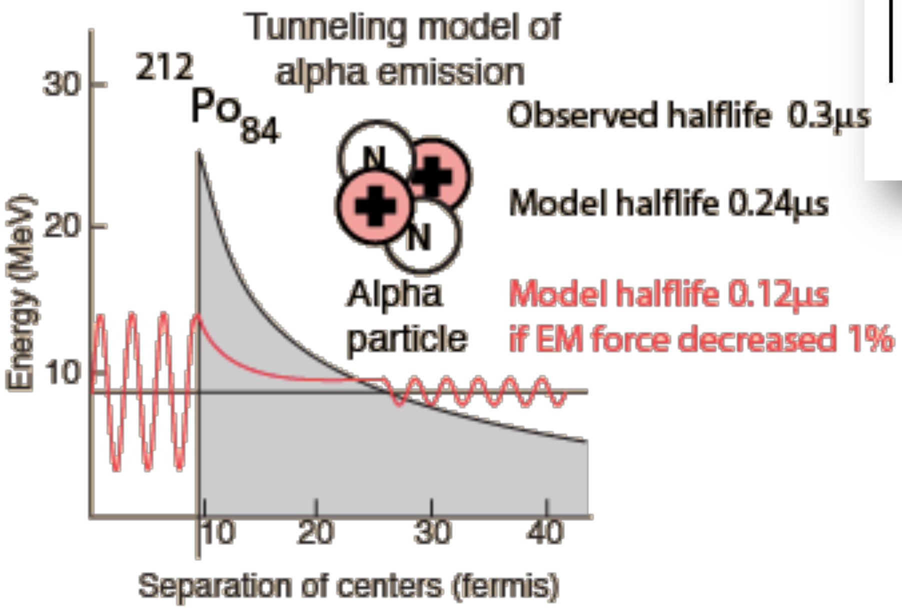


The FRIB Decay Station initiator (FDSi) is being led by ORNL and UTK, and includes (in addition to HPGe), fast timing scintillators, neutron-detection and possibilities for TAS measurements

Alpha decay

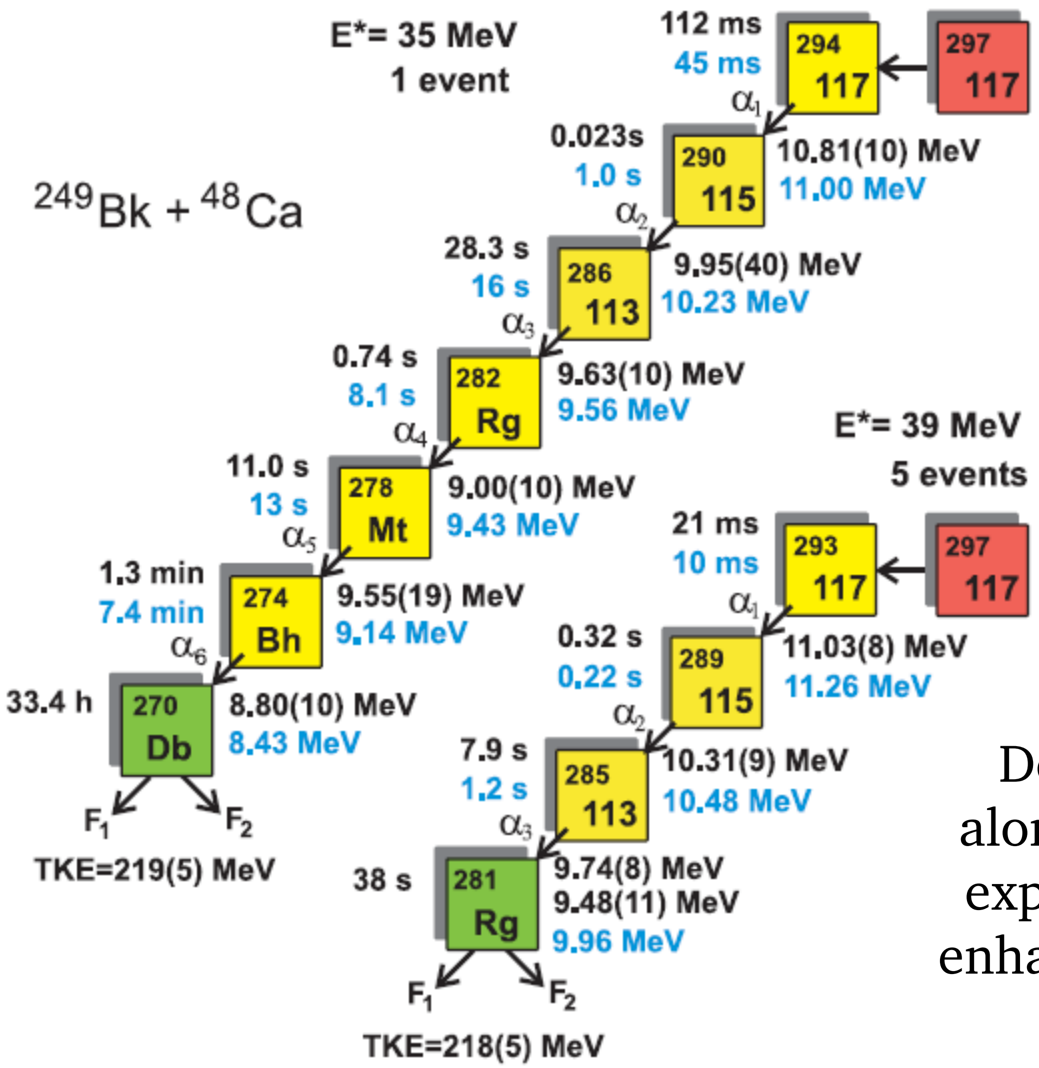
- α decay occurs only in heavier systems on the nuclear chart
- Alpha decay however probes different aspects of the nuclear forces





- Different selectivity in the process --> favour low L alpha emission

Alpha decay – heavy element structure



Yu. Ts. Oganessian et al., PRL 104, 142502 (2010).

The heaviest nuclei decay via emission of ‘heavy’ particles – alpha decay – or by spontaneous fission

Since alphas and fission products are relatively easy to detect, even a single nucleus can provide significant information

Decay properties of element 117 alone, from only 6 events, provide experimental evidence supporting enhanced stability beyond Z = 111

The heaviest nuclei – patience required!

Selected for a Viewpoint in *Physics*
PRL **104**, 142502 (2010) PHYSICAL REVIEW LETTERS week ending 9 APRIL 2010

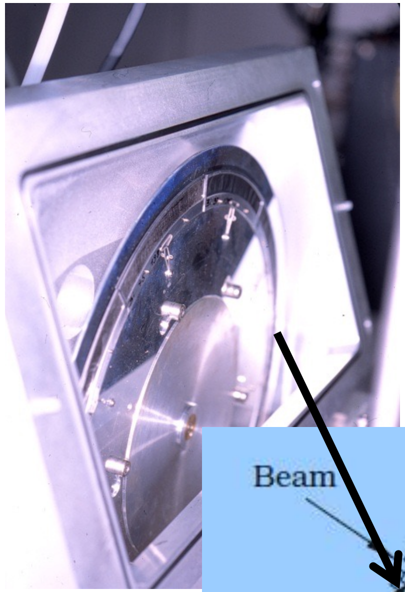
Synthesis of a New Element with Atomic Number $Z = 117$

Yu. Ts. Oganessian,[1,*] F. Sh. Abdullin,[1] P. D. Bailey,[2] D. E. Benker,[2] M. E. Bennett,[3] S. N. Dmitriev,[1] J. G. Ezold,[2] J. H. Hamilton,[4] R. A. Henderson,[5] M. G. Itkis,[1] Yu. V. Lobanov,[1] A. N. Mezentsev,[1] K. J. Moody,[5] S. L. Nelson,[5] A. N. Polyakov,[1] C. E. Porter,[2] A. V. Ramayya,[4] F. D. Riley,[2] J. B. Roberto,[2] M. A. Ryabinin,[6] K. P. Rykaczewski,[2] R. N. Sagaidak,[1] D. A. Shaughnessy,[5] I. V. Shirokovsky,[1] M. A. Stoyer,[5] V. G. Subbotin,[1] R. Sudowe,[3] A. M. Sukhov,[1] Yu. S. Tsyganov,[1] V. K. Utyonkov,[1] A. A. Voinov,[1] G. K. Vostokin,[1] and P. A. Wilk[5]

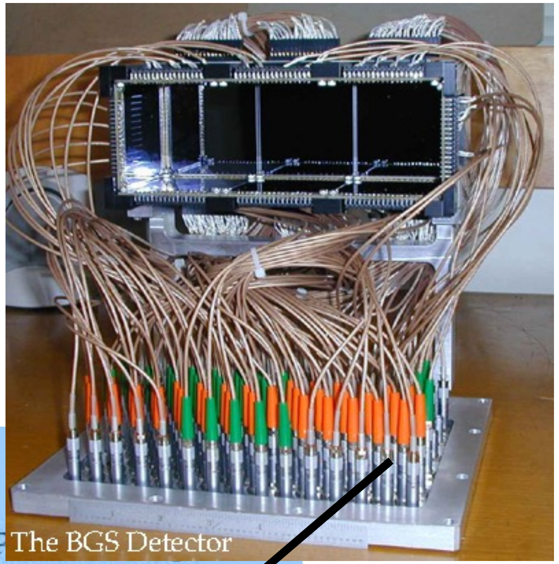
[1]*Joint Institute for Nuclear Research, RU-141980 Dubna, Russian Federation*
[2]*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[3]*University of Nevada Las Vegas, Las Vegas, Nevada 89154, USA*
[4]*Department of Physics and Astronomy, Vanderbilt University, Nashville, Tennessee 37235, USA*
[5]*Lawrence Livermore National Laboratory, Livermore, California 94551, USA*
[6]*Research Institute of Atomic Reactors, RU-433510 Dimitrovgrad, Russian Federation*
(Received 15 March 2010; published 9 April 2010)

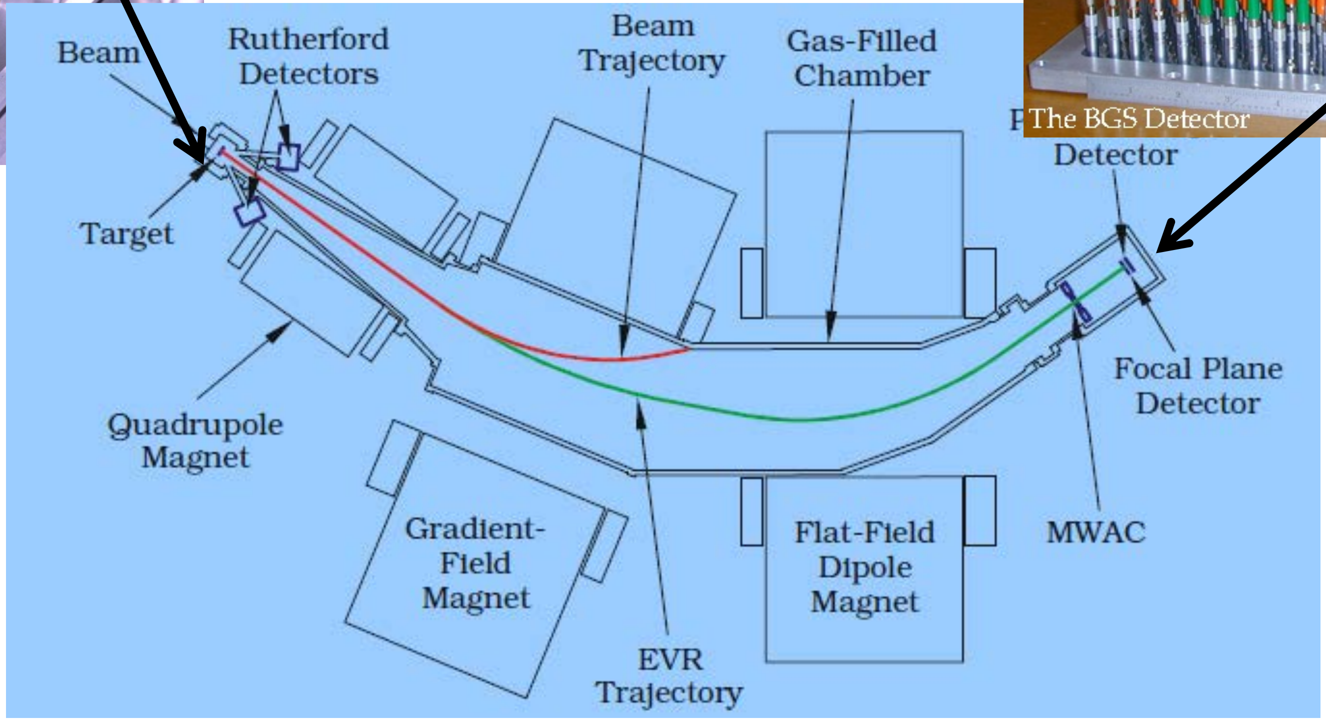
Experiment ran for 70 days, ^{48}Ca at 7 x 10^{12} ions/second on ^{249}Bk
→ 5 observed decay chains for ^{293}117 and 1 for ^{294}117,
corresponding to cross-sections of 0.5pb and 1.1pb

Spectroscopy of heavy elements

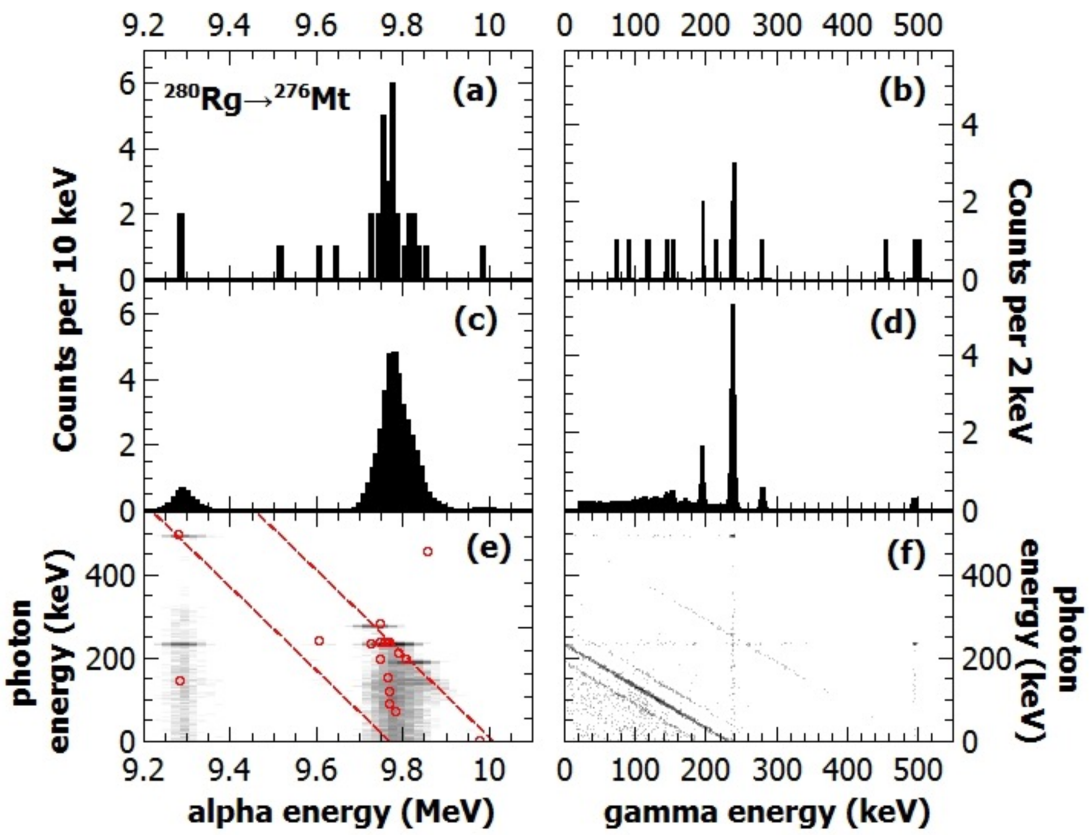


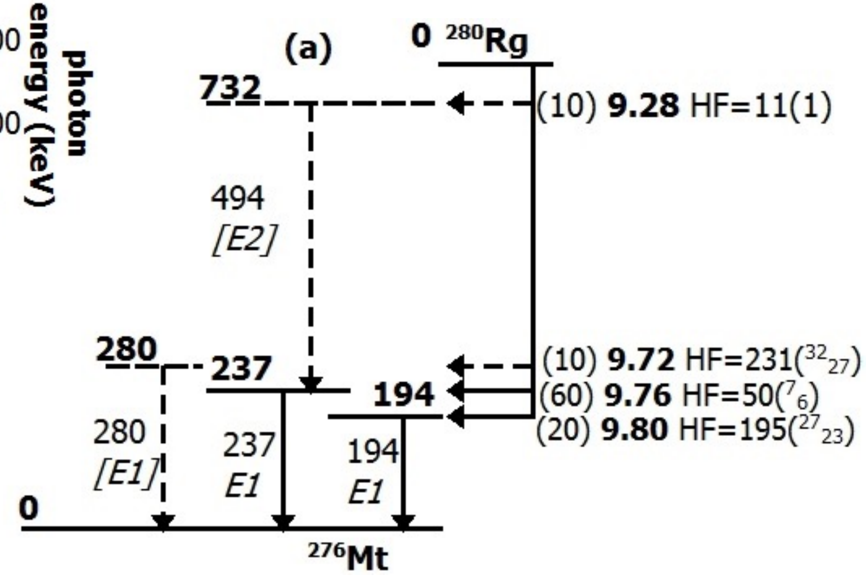
Efficiency is critical!! Gas-filled separators 'collect' charge states, high efficiency separation, and Si box-type arrays provide high efficiency for detecting residues.





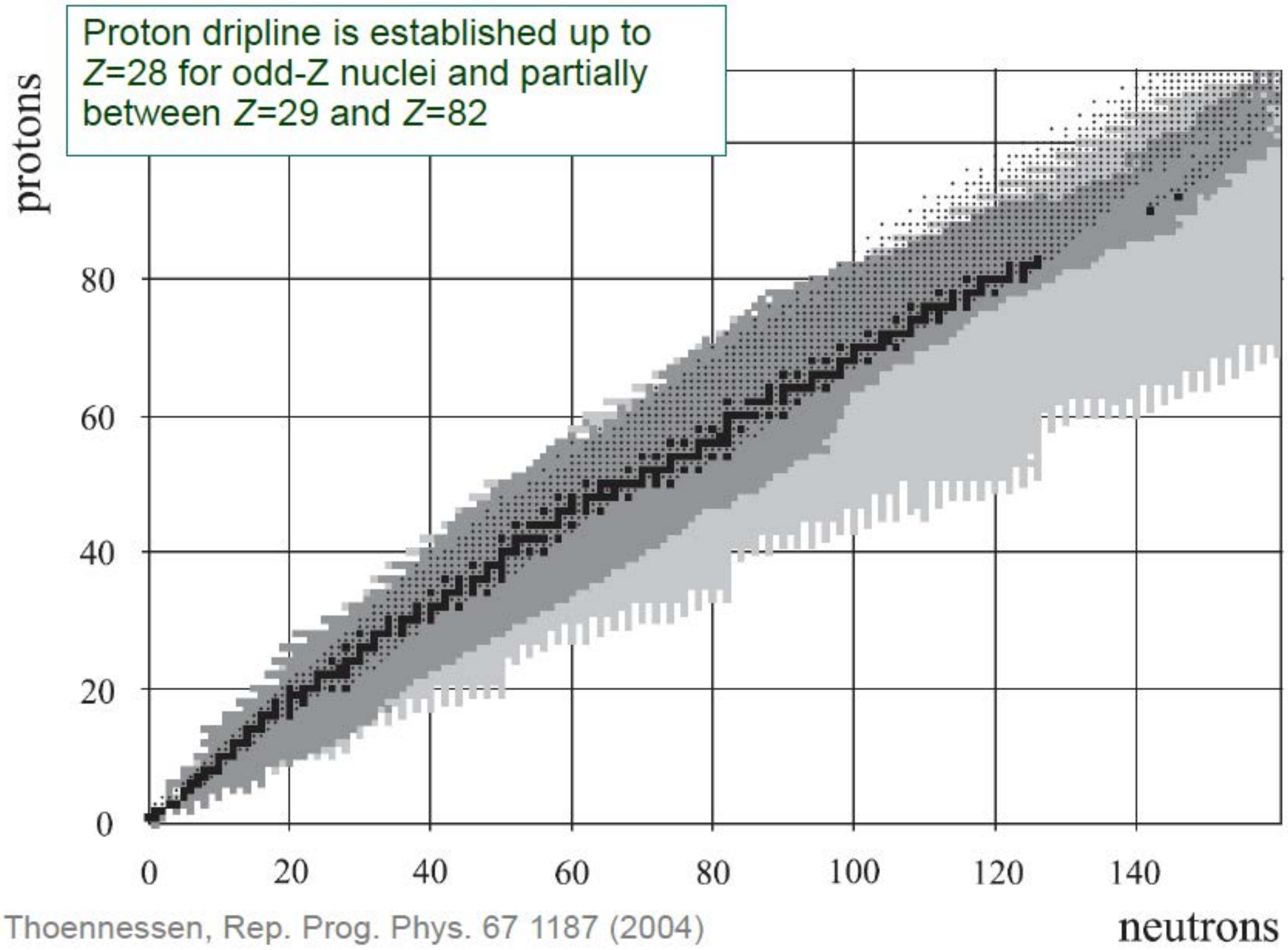
Spectroscopy from element 115





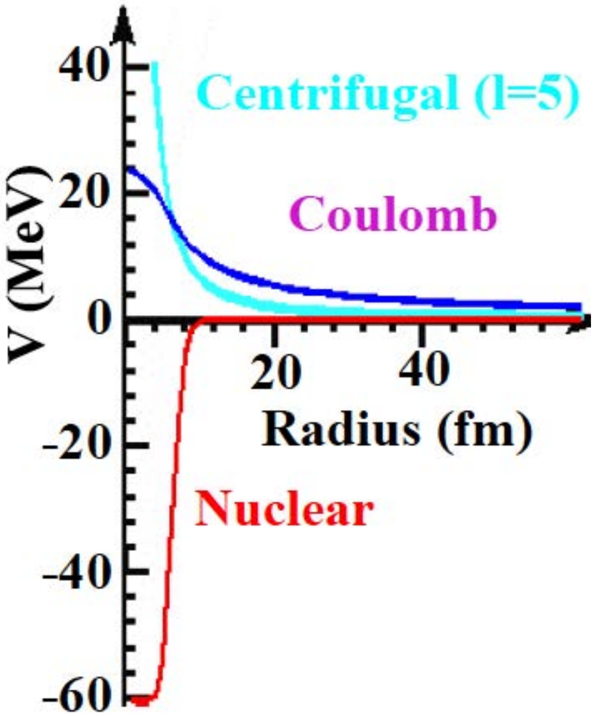
J. M. Gates et al.

Proton dripline

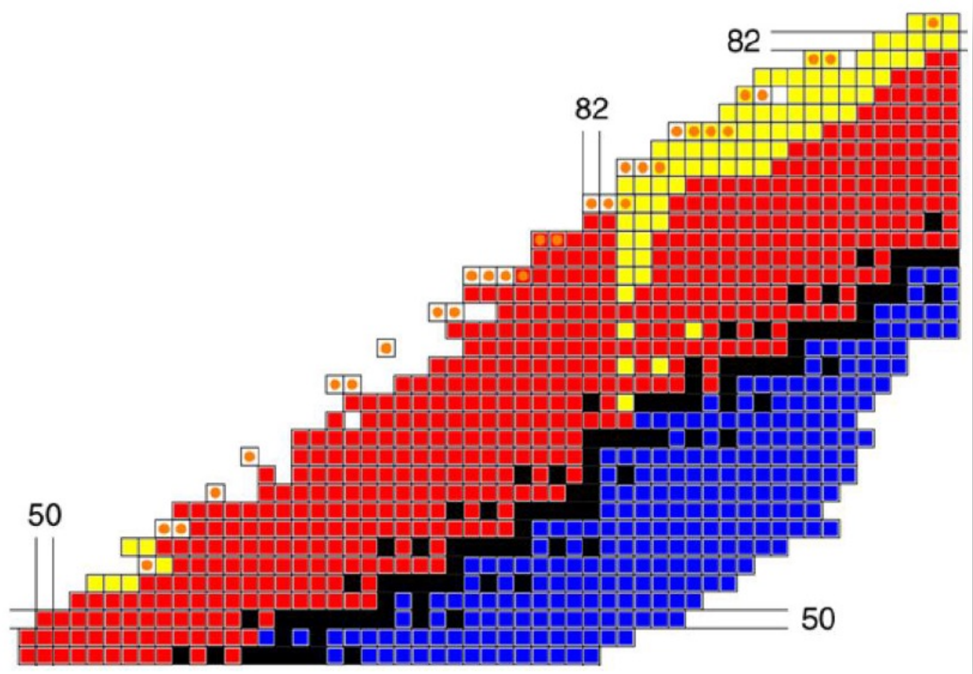


Thoennessen, Rep. Prog. Phys. 67 1187 (2004)

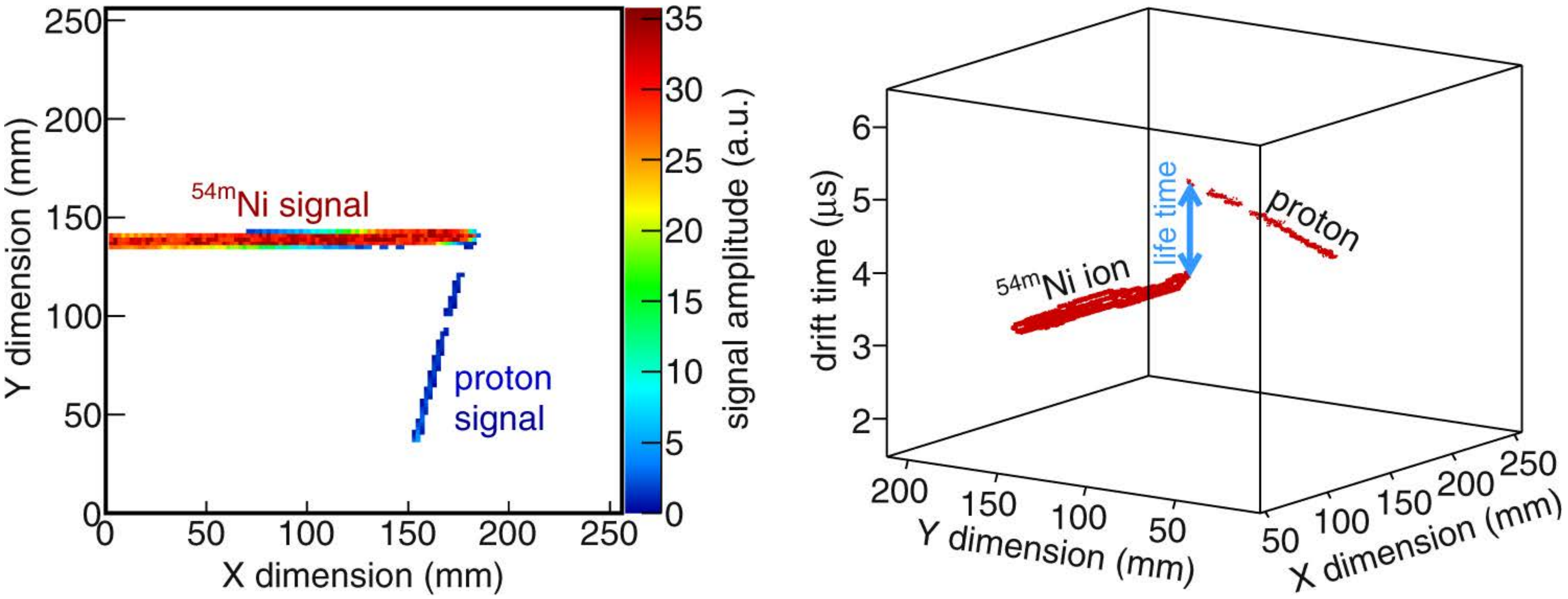
Proton decay



- Even when the Q value for proton removal becomes positive, proton emission is hindered due to the Coulomb (and centrifugal) barriers --> radioactivity



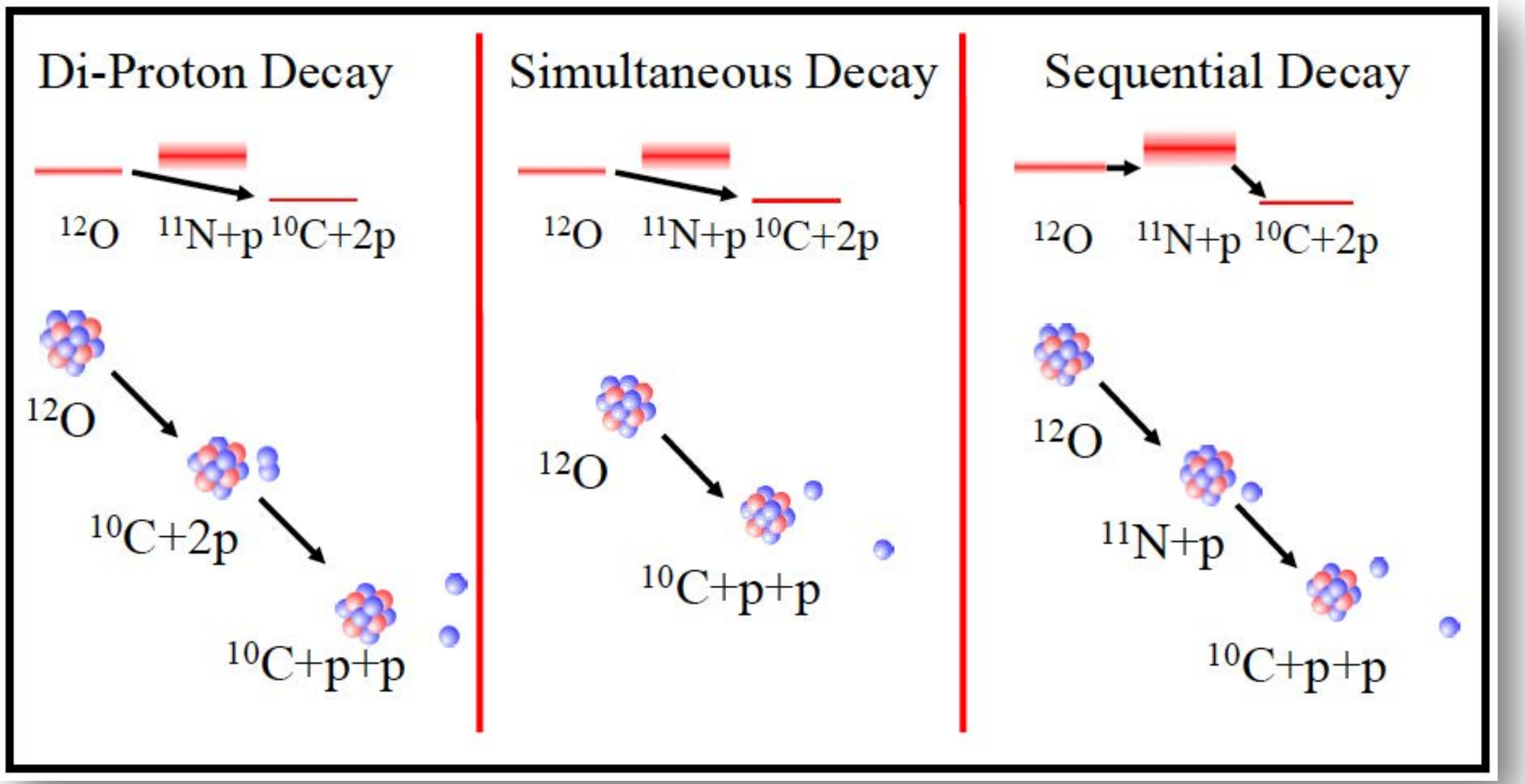
Proton emission branches in ^{54m}Ni



- A recent experiment with the ACTAR TPC measured proton decay from isomeric states in ^{54}Ni
- Data were reproduced reasonably well with shell-model calculations for the initial and final state wavefunctions and a barrier penetration model for the proton emission

J. Giovinazzo *et al.*, Nature Communications **12**, 4805 (2021).

2p decay



Di-Proton Decay
^{12}O
$^{11}N+p$
$^{10}C+2p$
^{12}O
$^{10}C+2p$
$^{10}C+p+p$
Simultaneous Decay
^{12}O
$^{11}N+p$
$^{10}C+2p$
^{12}O
$^{10}C+p+p$
Sequential Decay
^{12}O
$^{11}N+p$
$^{10}C+2p$
^{12}O
$^{11}N+p$
$^{10}C+p+p$

Summary

- Nuclear excitation spectra (energies, spins and parities of excited states) are fundamental experimental observables
- Patterns of excitation provide insight into symmetries and collective properties of nucleus
  - Vibrational spectra
  - Rotational spectra
  - Single-particle excitations
- Nuclear decay provides access to excitation spectra, as well as fundamental observable such as half-life