Nuclear Structure III
experiment

MICHIGAN STATE UNIVERSITY
Advancing Knowledge. Transforming Lives.

Sunday

Monday

Thursday

Low-lying excited states

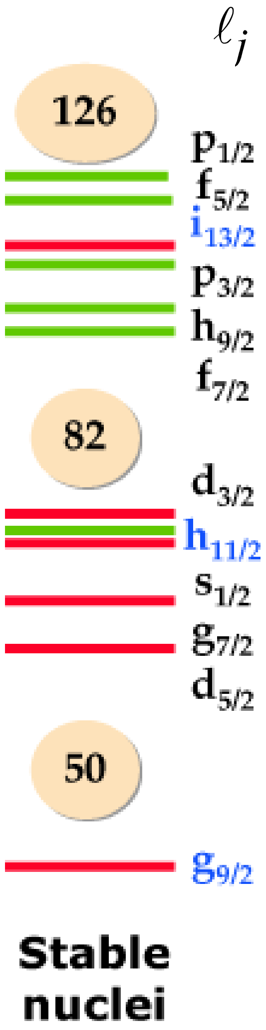
Collectivity and the single-particle degrees of freedom

Collectivity studied in Coulomb excitation

Direct reactions to study single-particle states

Friday

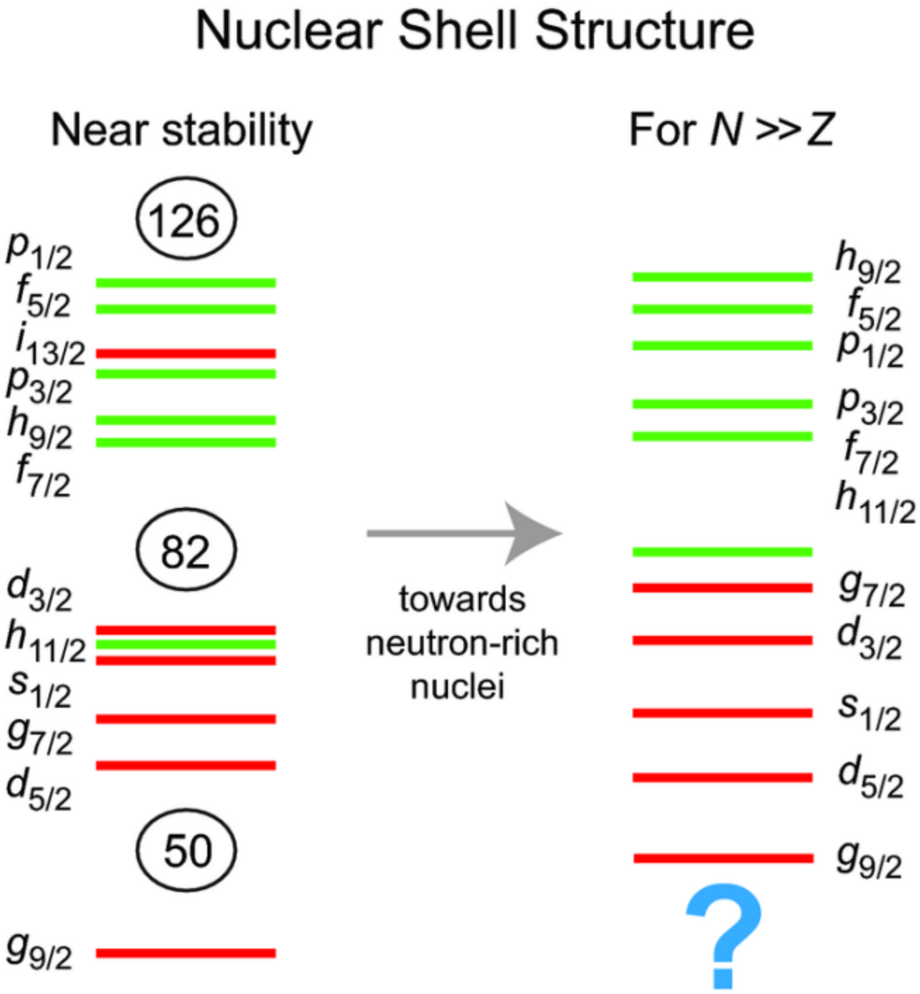
Shell Structure and Magic Numbers

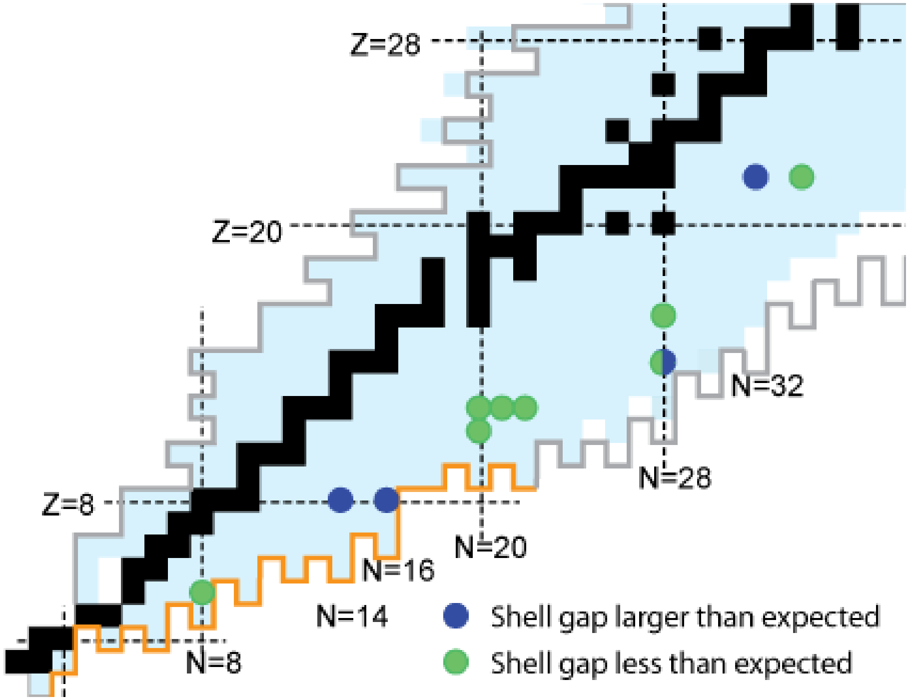


- Single-particle levels in nuclei
  The single-particle levels of this fermionic system are grouped. Large, stabilizing gaps between groups of single-particle states occur at certain occupation numbers of the orbits with a “magic number” of protons and neutrons
- Magic numbers
  Numbers of neutrons and protons in nuclei which correspond to particularly stable structures (2, 8, 20, 28, 50, 82, 126)
- $\ell = 0, 1, 2, 3, \ldots$
  s, p, d, f, ...
- Experimental signatures of nuclear shells
  - low capture cross sections
  - little collectivity
  - more tightly bound than neighboring nuclei

Maria Goeppert-Mayer, Phys. Rev. **75**, 1969 (1949)
O. Haxel, Phys. Rev. **75**, 1766 (1949)

Shell structure – magic numbers





- Mean field near stability
- Strong spin-orbit term

- Mean field for $N \gg Z$?
- Reduced spin-orbit
- Diffuse density
- Tensor force

Excited states

Collective excitation: all nucleons outside a closed shell contribute coherently to the excitation (vibration, rotation)

Single-particle excitation: Excited states are formed by rearranging one or a few nucleons in their orbits

K. S. Krane, Introductory Nuclear Physics, John Wiley & Sons (1988)

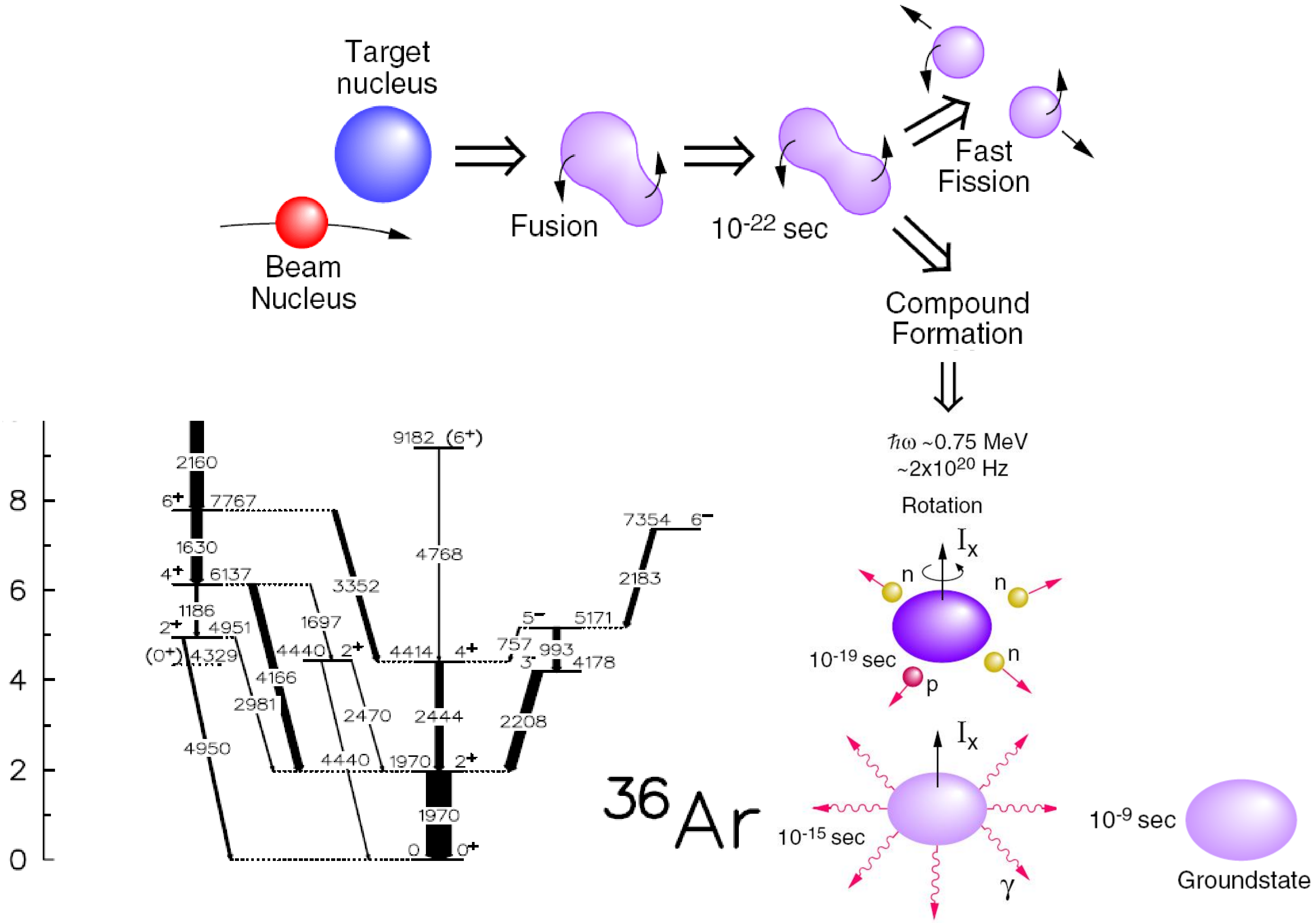
Fig. 3.19

- In nuclei, the energy scales are close:

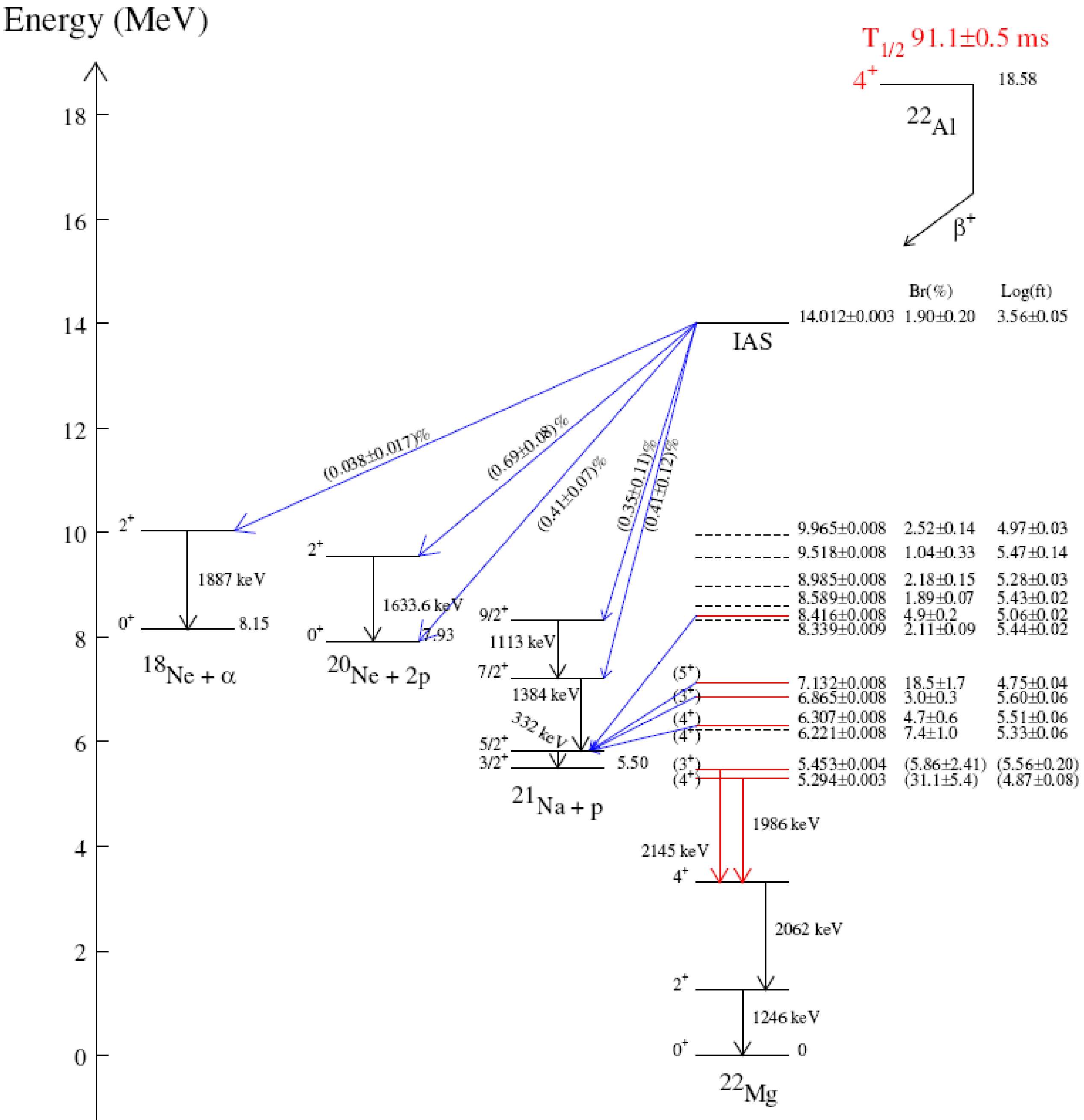
$E_{rot} \sim E_{vib} \sim E_{sp}$ (MeV)

Collective and single-particle excitation can be separated but interact strongly

Population of excited states - Reactions

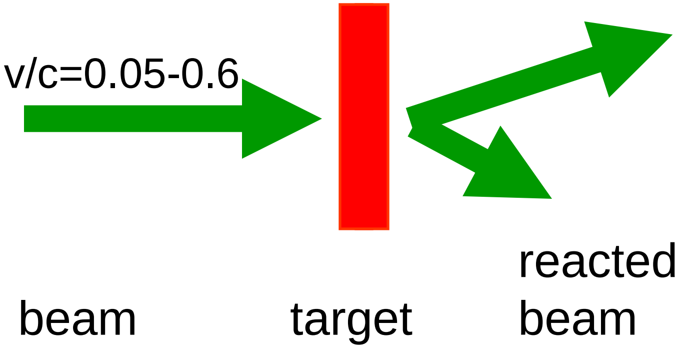


Population of excited states - Decays



Experimental considerations: *Reactions*

Nuclear reactions – cross section



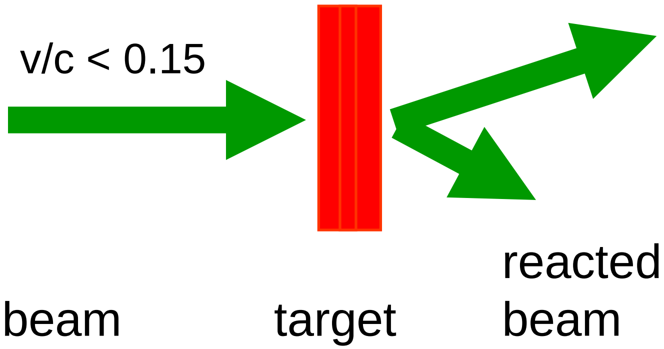
- The choice of the target depends on the reaction hat is desired

- $N_R = \sigma \times N_T \times N_B$
  - σ Cross section
  - N_T Atoms in target
  - N_B Beam rate
  - N_R Reaction rate

- Reactions
  - Inelastic scattering
  - Nucleon transfer
  - Fusion, fusion-evaporation
  - Breakup/fragmentation

- Experimental task
  - Identify and count incoming beam
  - Identify and count reacted beam
  - Tag the final state of the reaction residue
  - Measure scattering angles and momentum distributions

Nuclear reactions – experimental considerations I

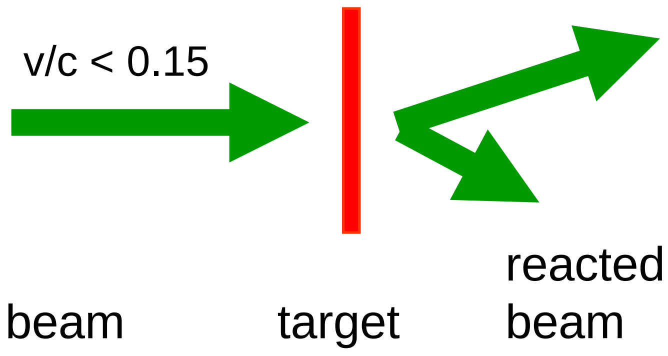


- Fast beams and thick targets
  - Increased luminosity
  - Use γ-ray spectroscopy to identify final states in thick-target experiments
  - Event-by-event identification
  - Mainly single-step reactions since the interaction time between target and projectile is small

- Typical reactions
  - Relativistic Coulomb excitation (single-step)
  - One- and two-nucleon knockout reaction
  - Coulomb breakup
  - Charge-exchange reactions

- Example
  σ = 100 mbarn
  - $N_T = 1.5 \times 10^{21}$ (500mg/cm² Au target)
  - $N_B = 6.5 \times 10^3$ Hz
  - N_R =1 Hz

Nuclear reactions – experimental considerations II



- Typical reactions
  - Fusion and fusion-evaporation reactions
  - Nucleon transfer reactions
  - Multiple Coulomb excitation
  - Deep-inelastic scattering

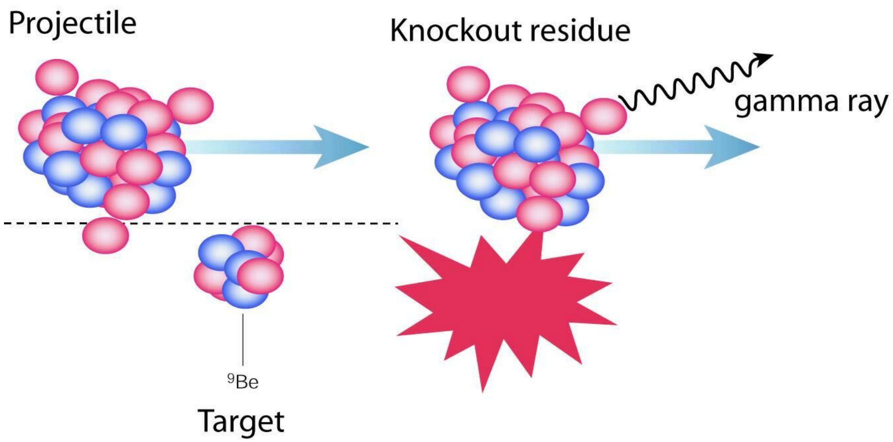
- Beam energies around the Coulomb barrier
  - Thin targets required
  - Multi-step reactions are possible
  - High angular-momentum transfer typical

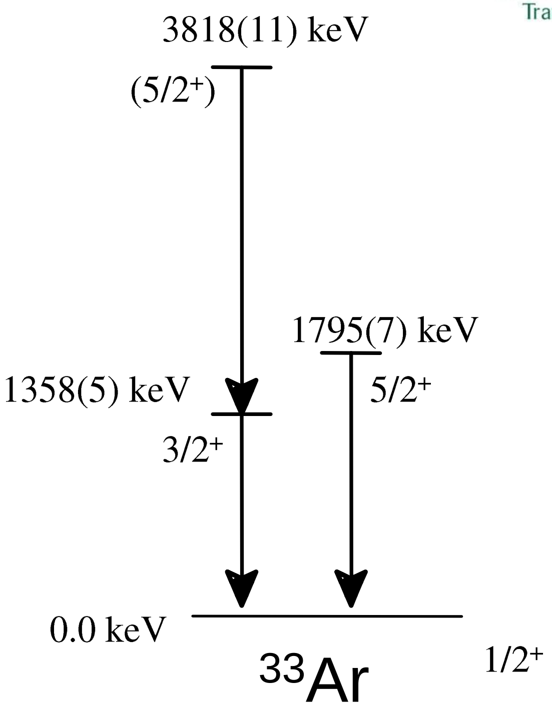
- Example

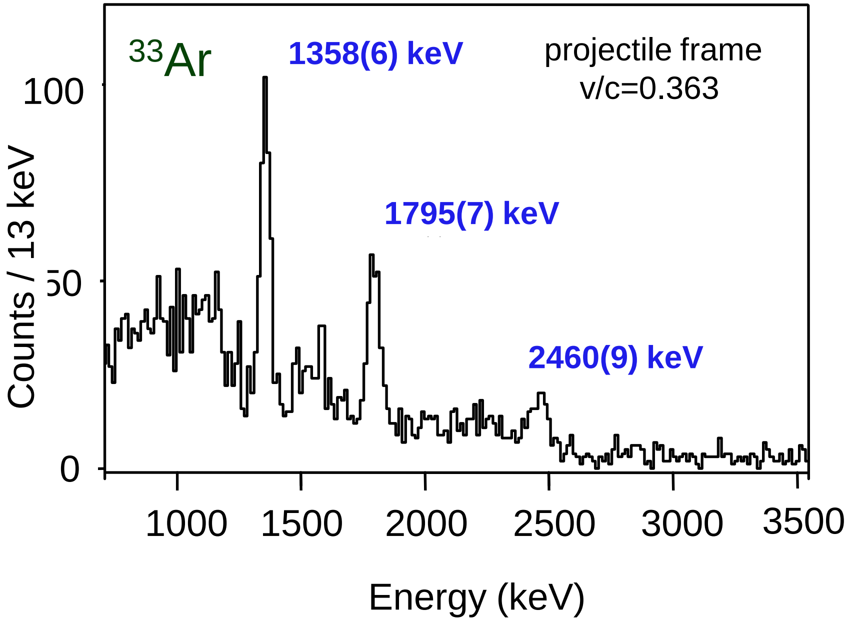
  σ = 100 mbarn

  - $N_T = 1 \times 10^{19}$ (3mg/cm² Au target)
  - $N_B = 1 \times 10^6$ Hz
  - $N_R = 1$ Hz

Excited states







- Tag the population of excited states by measuring the decay γ rays. The γ-ray energy gives the energy difference between two states.

Gamma-rays to tag the final state

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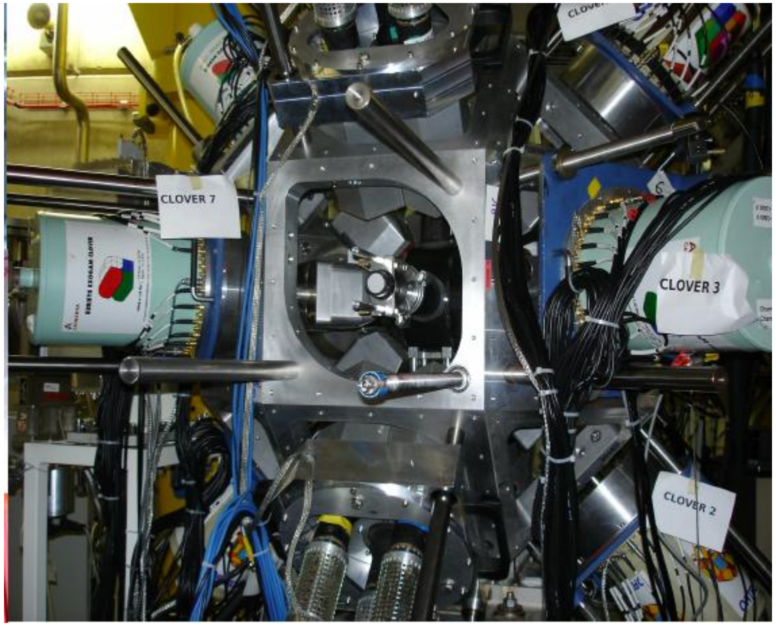
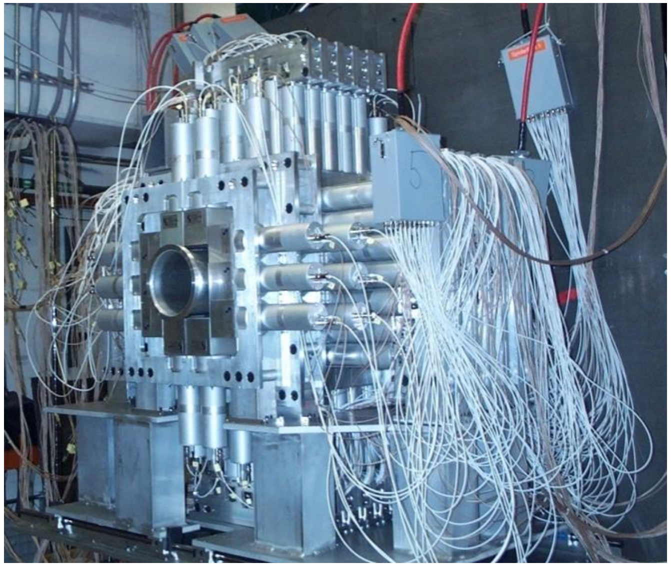
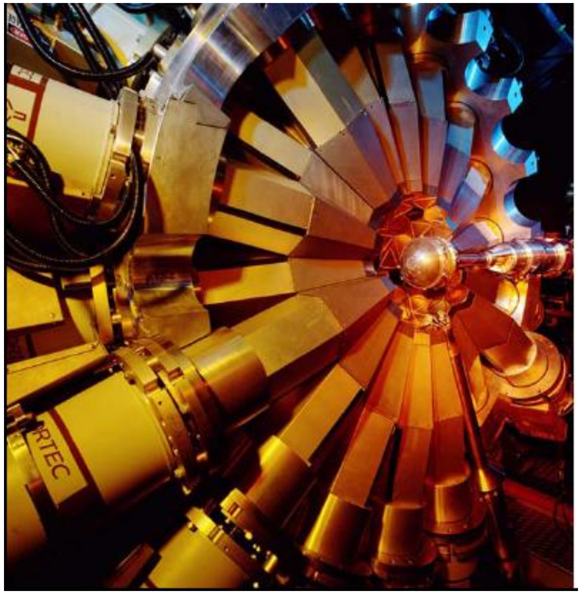




Germanium detectors:
Superior energy resolution, but low efficiency

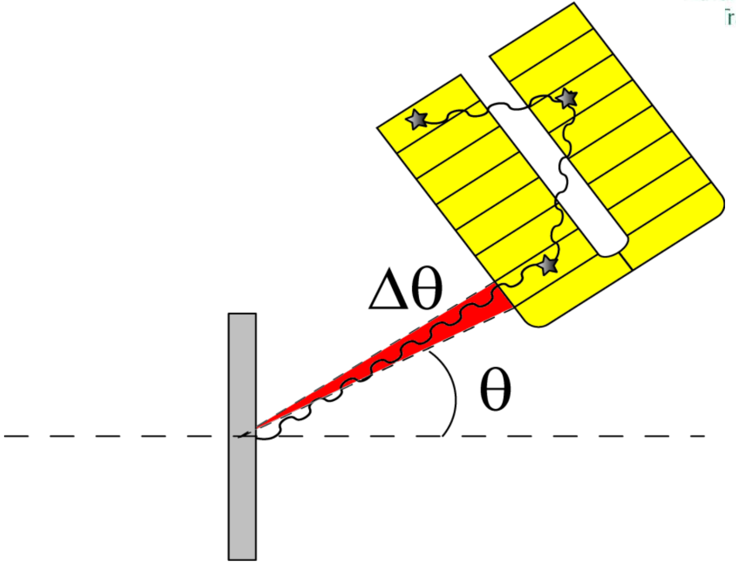
Scintillator-based:
High-efficiency, moderate resolution



Emission in flight: Doppler shift!

$$E = E_0 \frac{\sqrt{1-\beta_0{}^2}}{1-\boldsymbol{\beta}_0\cdot\mathbf{e}}$$

$$\boldsymbol{\beta}_0\cdot\mathbf{e} = \left|\boldsymbol{\beta}_0\right|\cos\theta_0$$



E_0 γ-ray energy in the source frame

E γ-ray energy in the lab frame

$\boldsymbol{\beta}_0$ velocity of the source

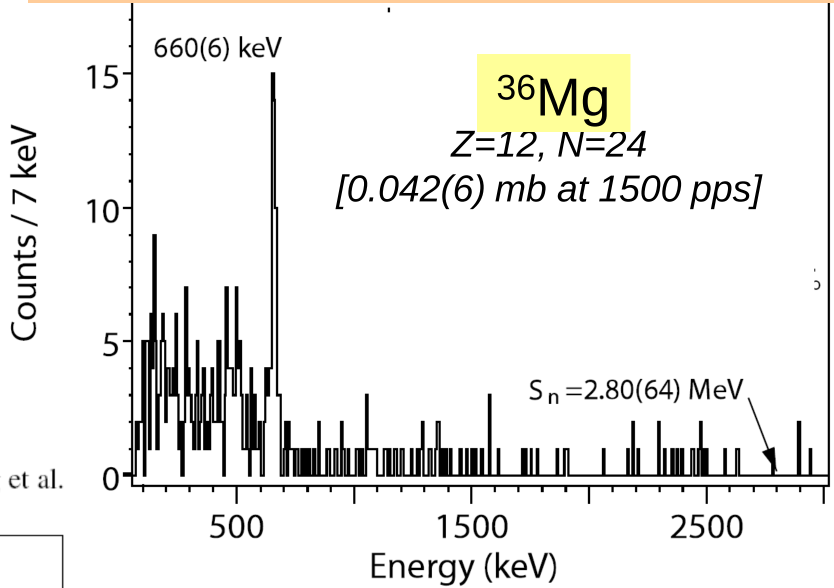
θ_0 γ-ray angle of emission

Example: SeGA geometry (NSCL)

Gamma-rays to tag the final state

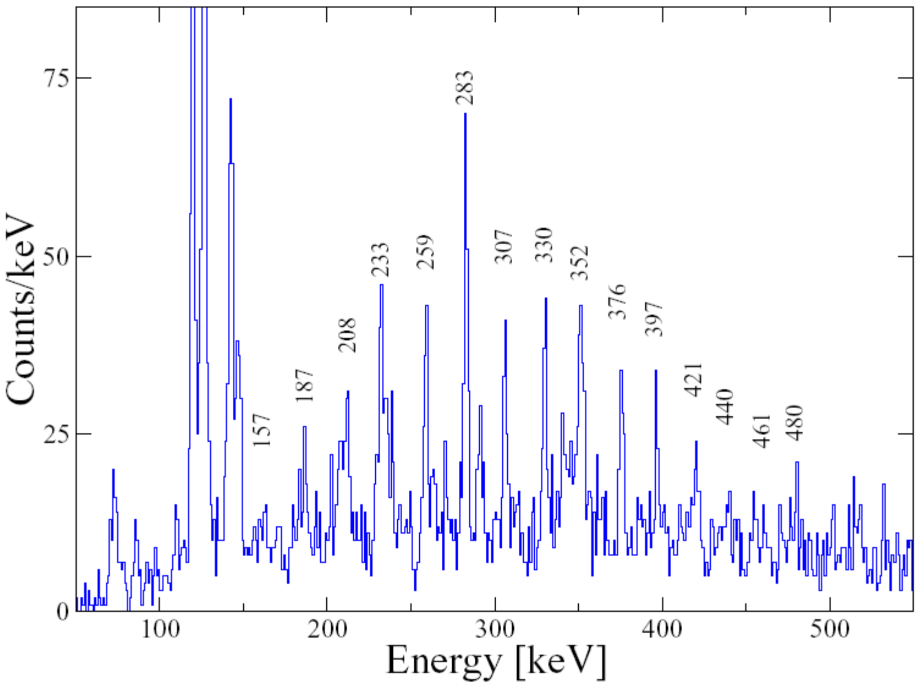
Two-proton knockout to ^{36}Mg.
Only the first excited state was observed.

^{38}Si-2p at 83 MeV/u, SeGA @ NSCL



A. Gade et al., PRL 99, 072502 (2007)

^{48}Ca + ^{207}Pb ⇒ ^{253}No + 2n, JUROGAM+RITU+GREAT, R.-D. Herzberg et al.

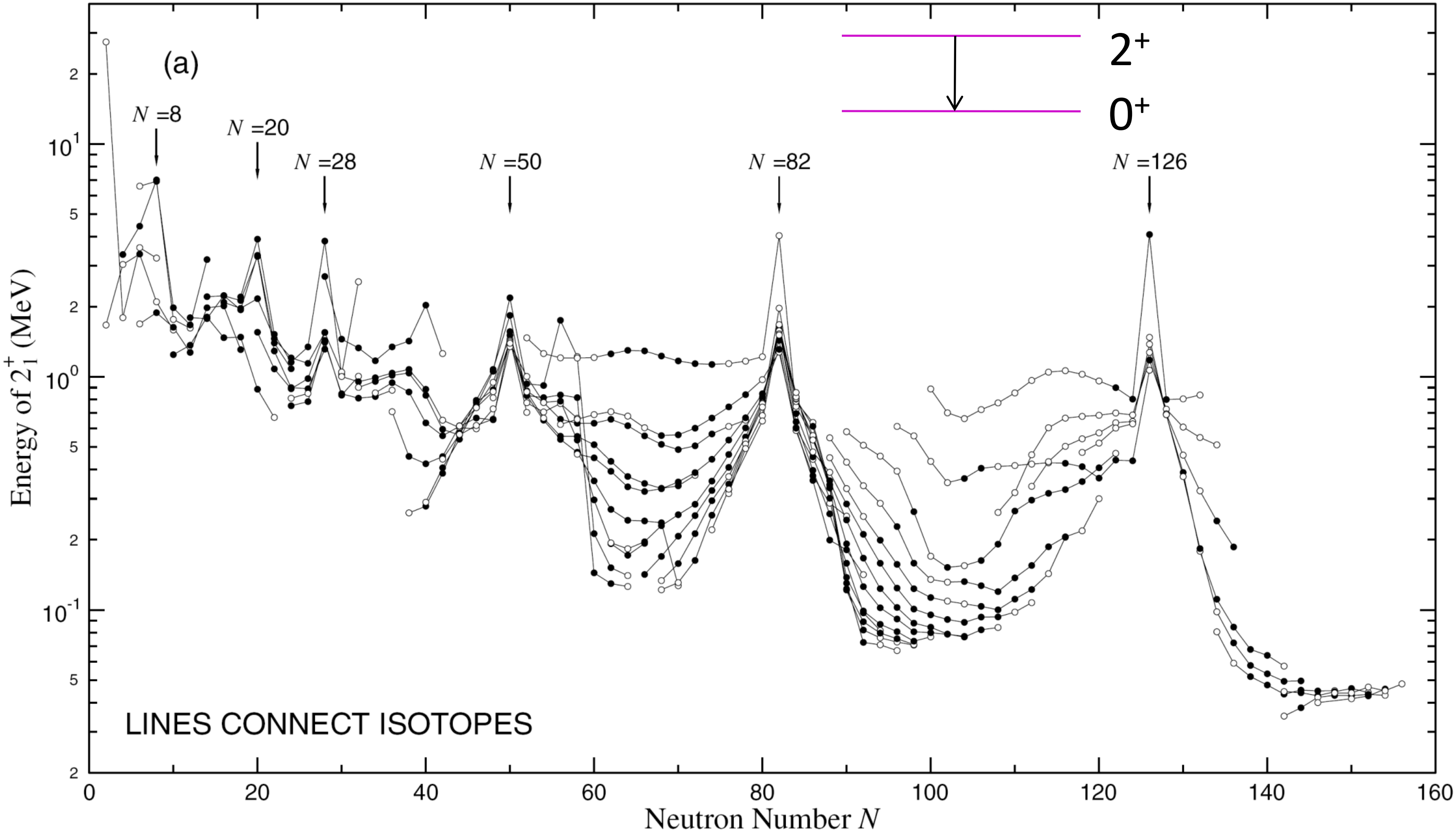


Low-energy fusion-evaporation reaction to produce ^{253}No. Many excited states are populated.

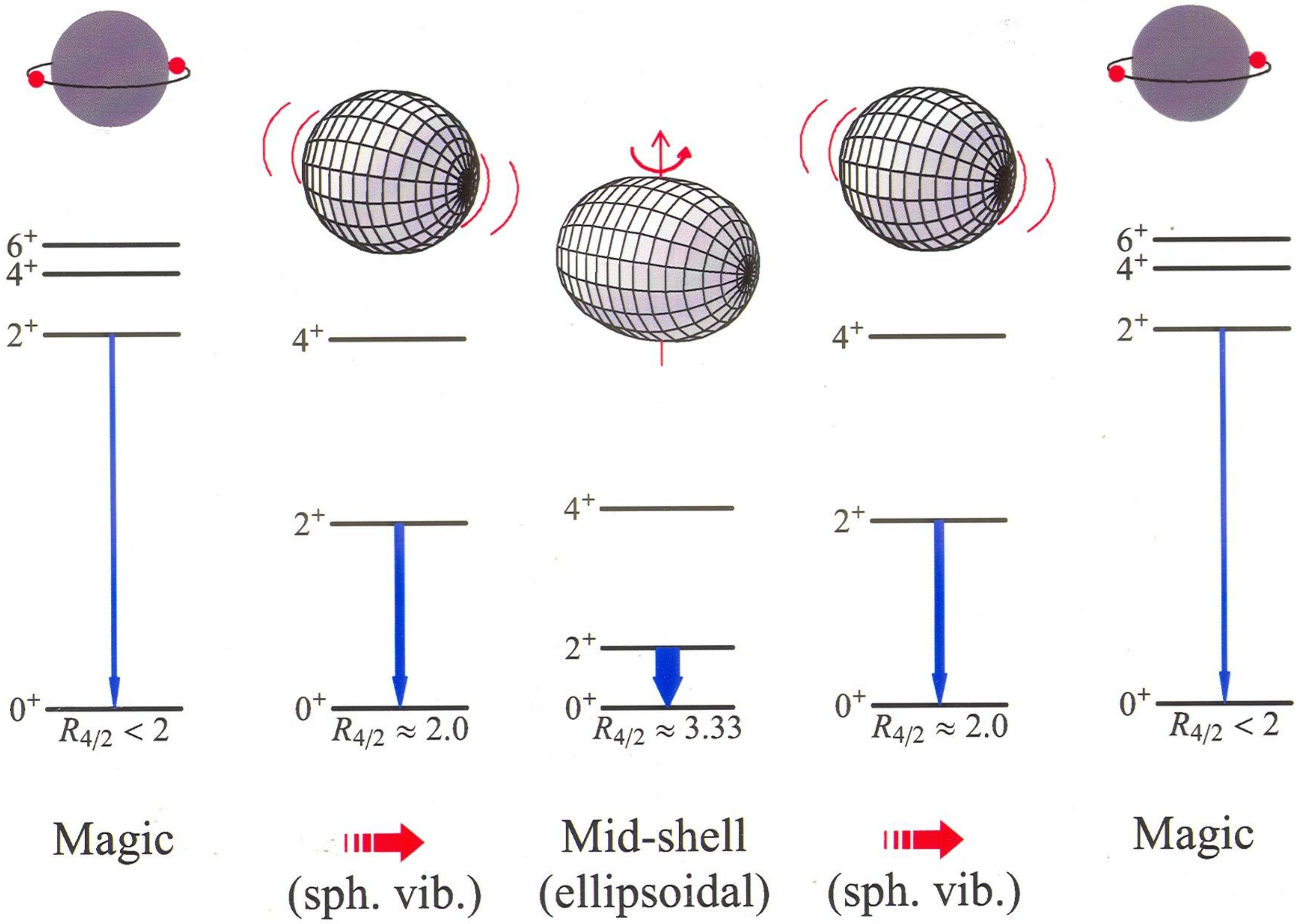
Collective excitations

Even-even nuclei: 2^+_1 state energy as an indicator of shell structure

S. Raman et al., Atomic Data & Nuclear Data Tables 78, 1



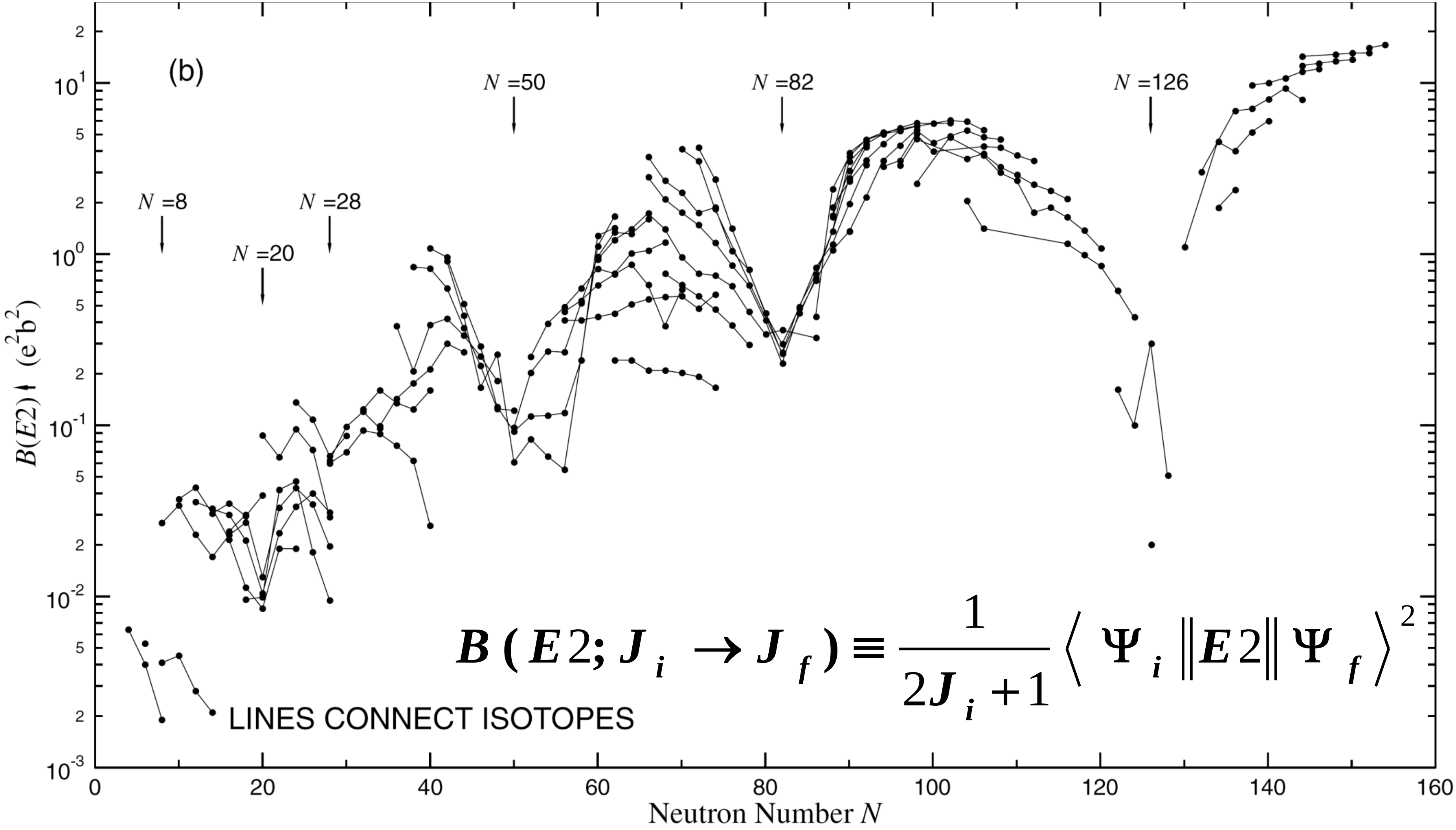
Even-even nuclei: 2^+ states are typically the first excited state on top of 0^+ ground states



Adapted from Rick Casten

Even-even nuclei: 2^+_1 excitation strength as an indicator of shell structure

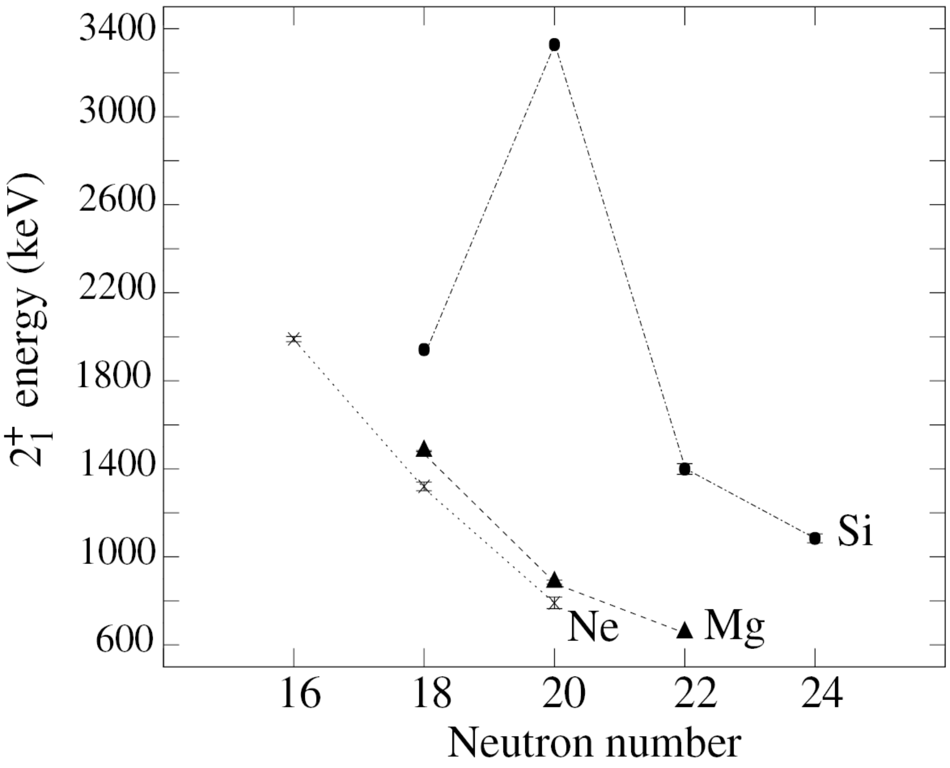
S. Raman et al., Atomic Data & Nuclear Data Tables 78, 1



$$B(E2;J_i \rightarrow J_f) \equiv \frac{1}{2J_i+1}\left\langle \Psi_i \left\| E2 \right\| \Psi_f \right\rangle^2$$

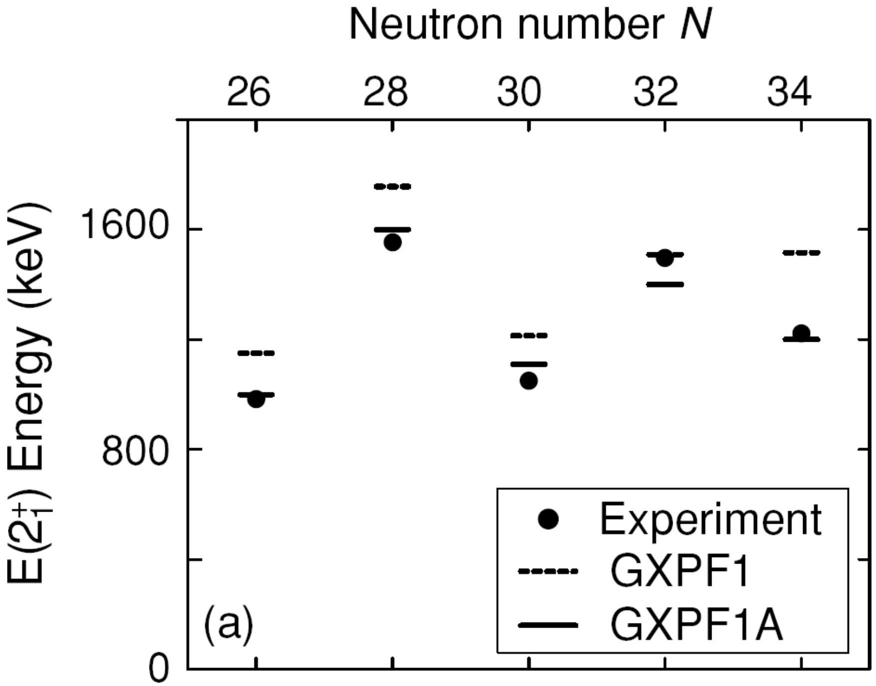
Examples of changes in shell structure

A. Gade and T. Glasmacher, Prog. In Part. and Nucl. Phys. 60, 161 (2008)



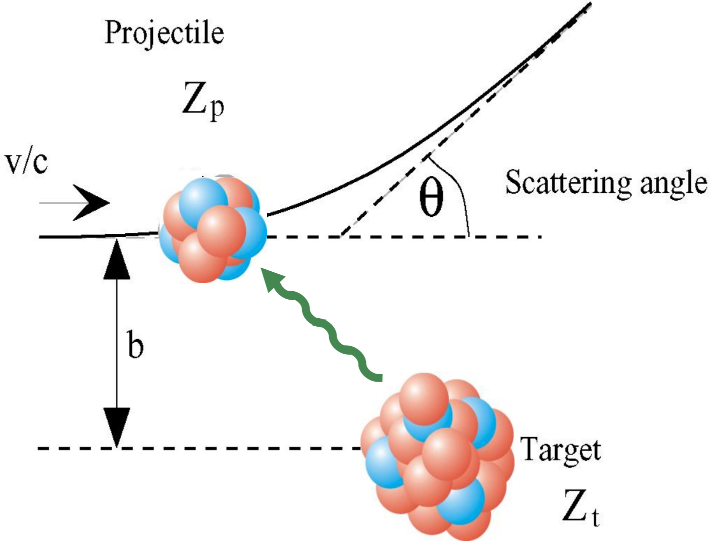
N=20 is not a good shell closure anymore in Mg and Ne isotopes

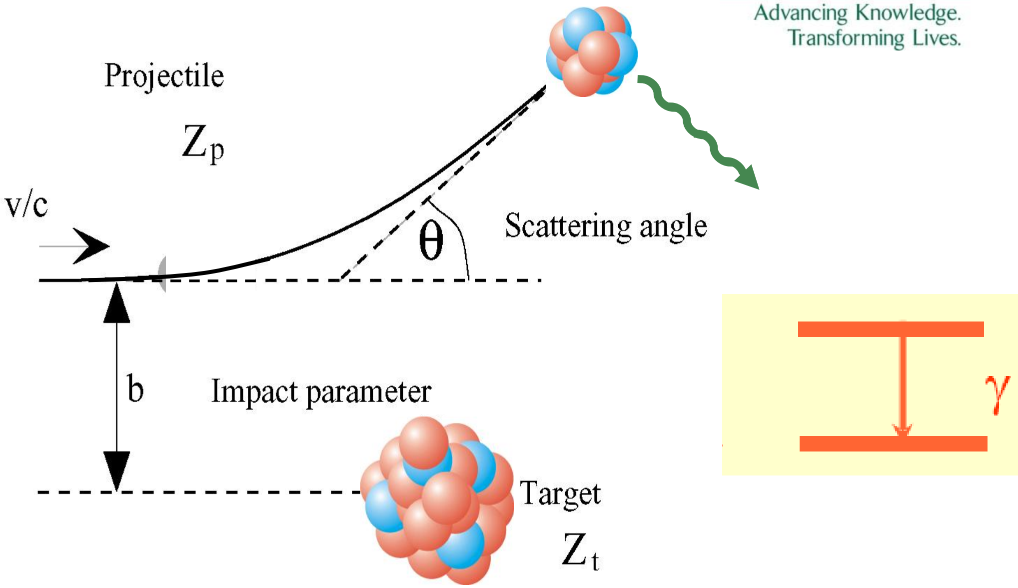
N=32 is a new magic number in the Ti isotopes



D.-C. Dinca et al., PRC 71, 041302 (2005)

Low-energy projectile Coulomb excitation





Exchange of virtual photons mediates excitation

Measure de-excitation γ-rays

Beam energies at the Coulomb barrier (SPIRAL):

E_x, B(σλ) excitation strength, band structures
(0^+ → 2^+ → 4^+ → 6^+)

Beam energies well below the Coulomb barrier (ISOLDE, HRIBF):

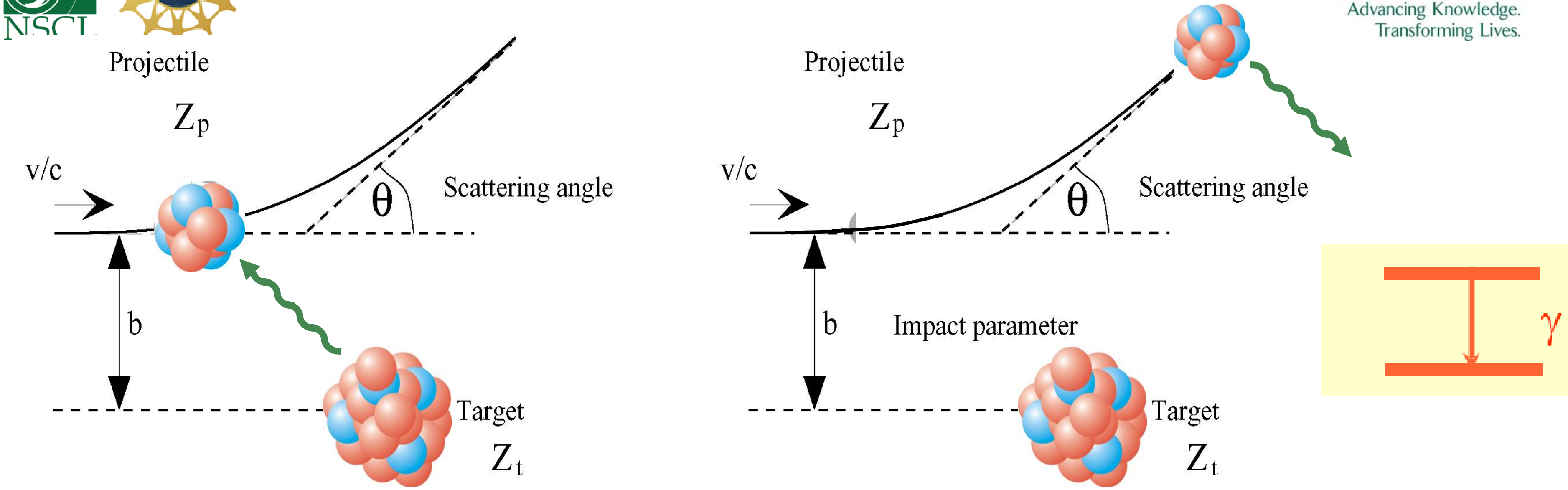
Usually only the first 2^+ state accessible

$$V_C(MeV) = \frac{1.44 \times Z_1 \times Z_2}{r(fm)}$$

$$r(fm) \sim 1.2(A_1^{1/3} + A_2^{1/3})$$

D. Cline, Annu. Rev. Part. Sci. 36, 683 (1986)

High-energy projectile Coulomb excitation



Exchange of virtual photons mediates excitation

Measure de-excitation γ-rays

Intermediate and relativistic energies (NSCL, RIKEN, GANIL, GSI): $E(2^+_1)$, $B(E2,0^+ \rightarrow 2^+_1)$ excitation strength, two-step to 4^+ heavily suppressed (short interaction time at high beam energies)

BUT: the collision between target and projectile happens above the Coulomb barrier for every target-projectile combination

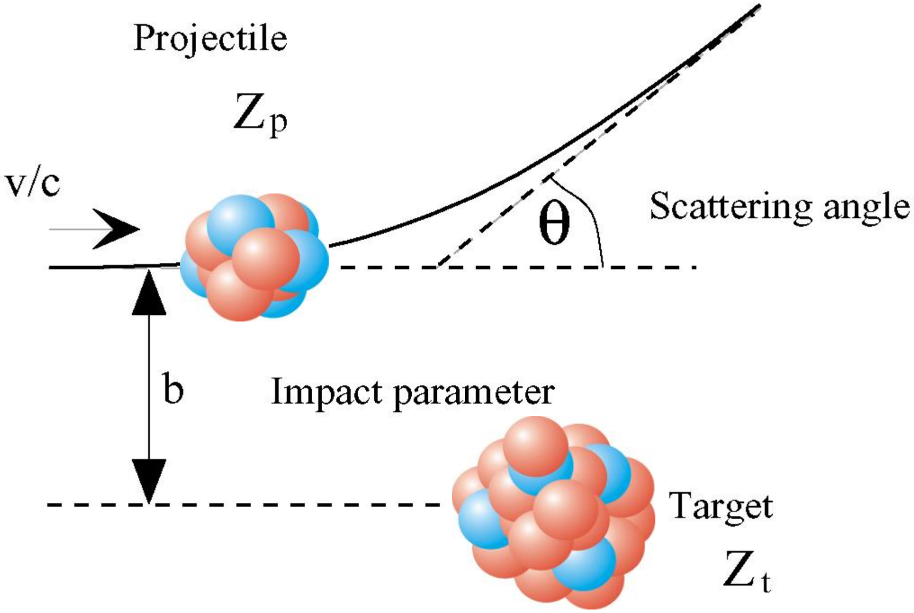
How can this still be Coulomb excitation?

T. Glasmacher, Annu. Rev. Part. Sci. 48, 1 (1998)

How can it be Coulomb excitation at energies above the Coulomb barrier ?!

At NSCL, RIKEN, GSI … the collision between target and projectile happens above the Coulomb barrier for every target-projectile combination

But: electromagnetic interaction dominates for b > R_{int}



For given v/c:

impact parameter b=b(θ)

$$b_{\min} = \frac{a}{\gamma} \cot(\theta^{\mathrm{cm}}_{\max}/2)$$

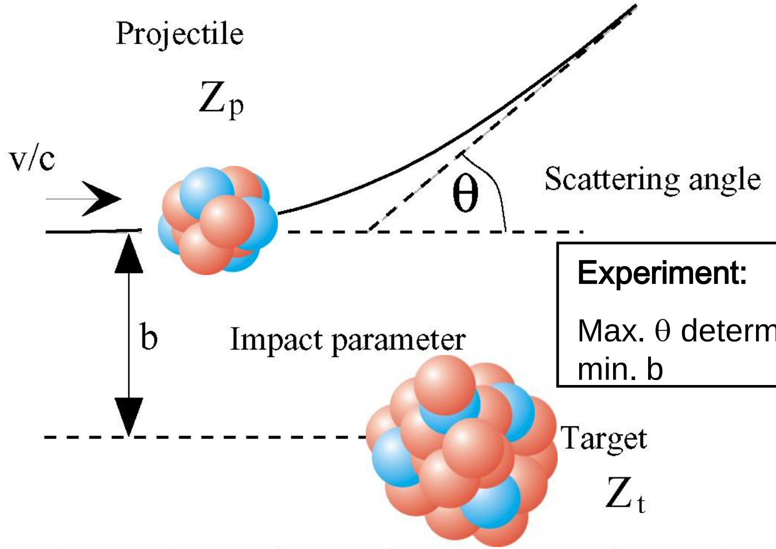
$$a = \frac{Z_p Z_t e^2}{\mu v^2}$$

Experiment:

Maximum scattering angle determines minimum b. Restrict analysis to events at the most forward scattering angles so that b(θ) >R_{int}

T. Glasmacher, Annu. Rev. Part. Sci. 48, 1 (1998)

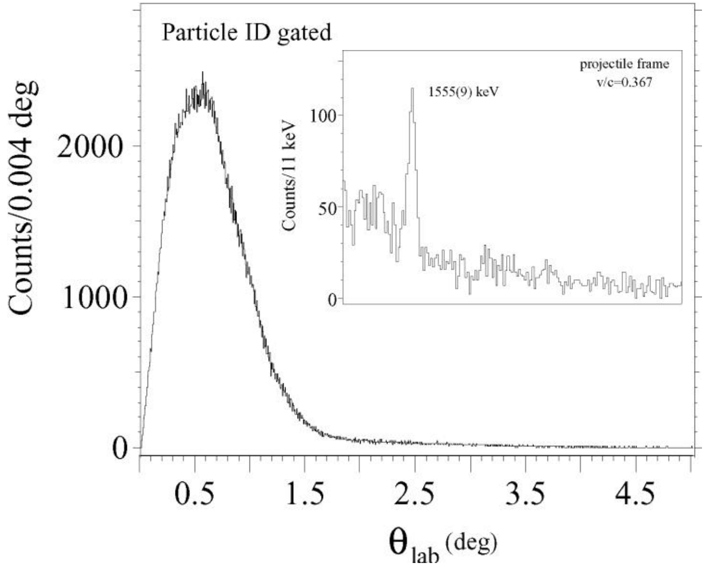
Intermediate-energy Coulomb excitation
Example: ^{46}Ar + ^{197}Au

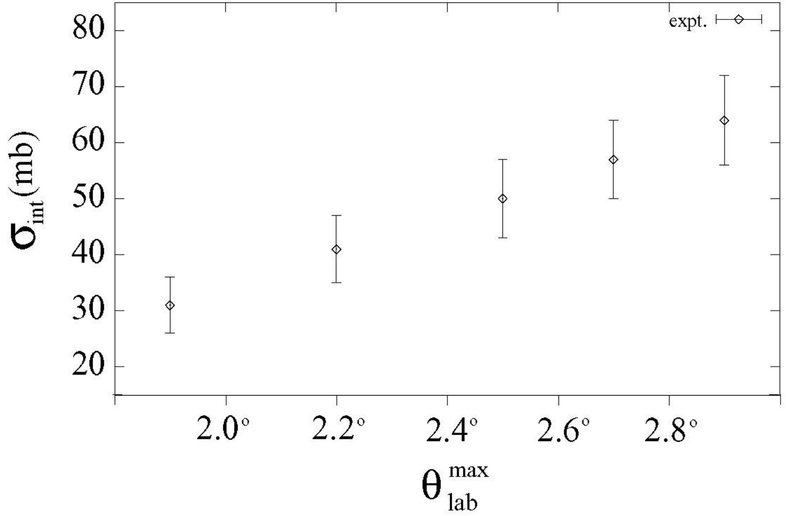


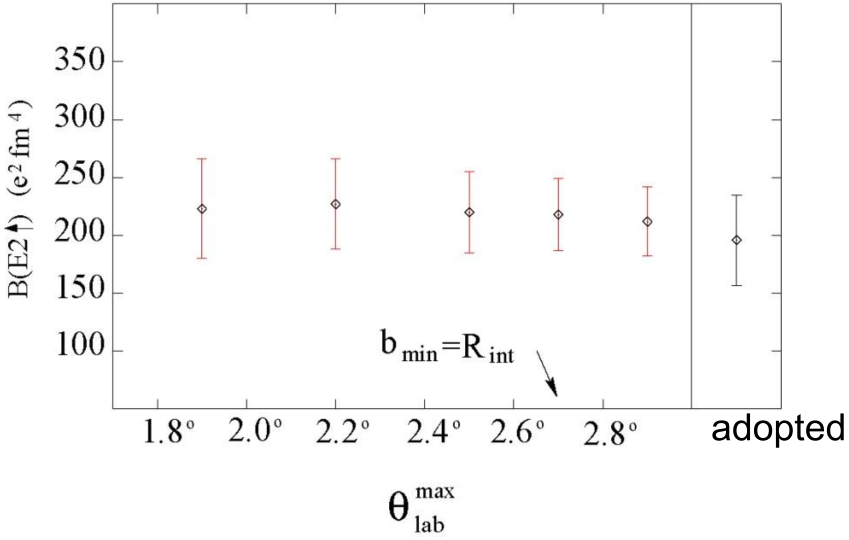
Experiment:

Max. θ determines min. b

A. Gade *et al.*, PRC 68, 014302 (2003)



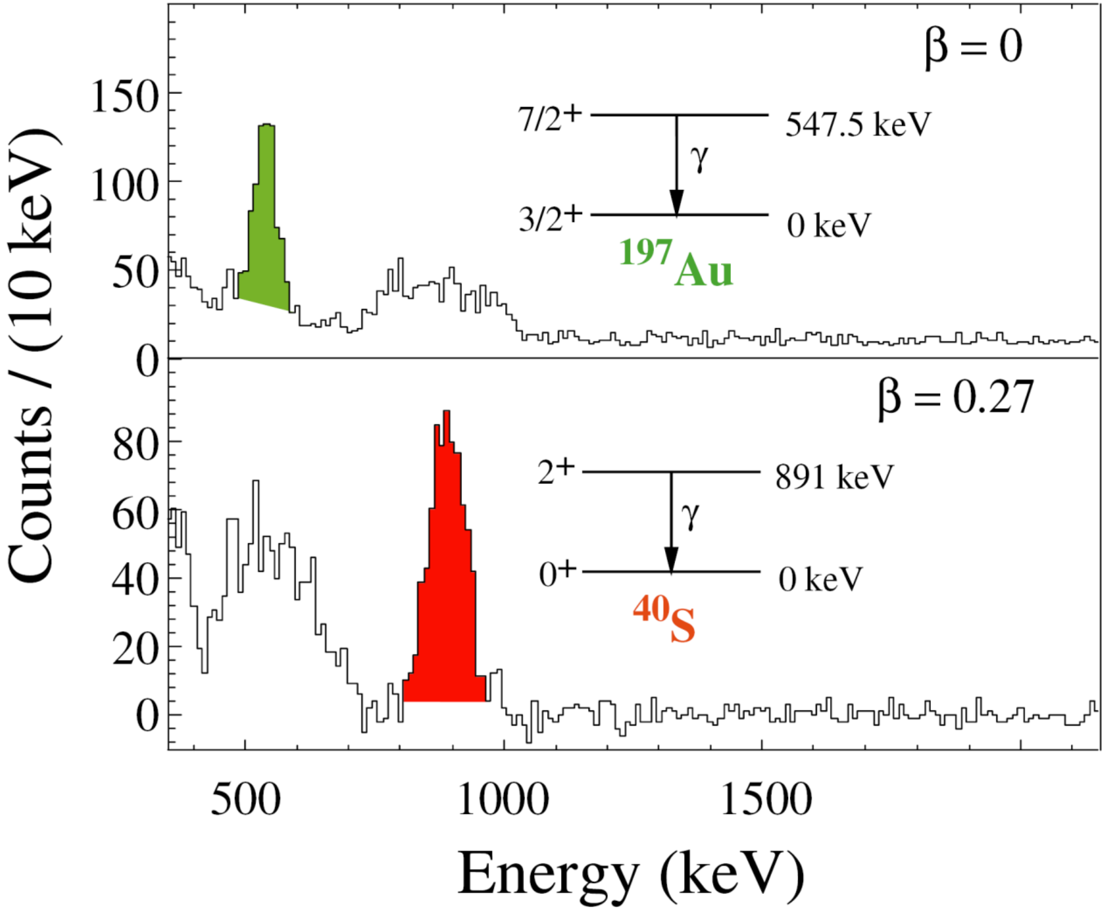




A. Winther and K. Alder, NPA 319, 518 (1979)

Target excitation

$^{40}S + ^{197}Au$

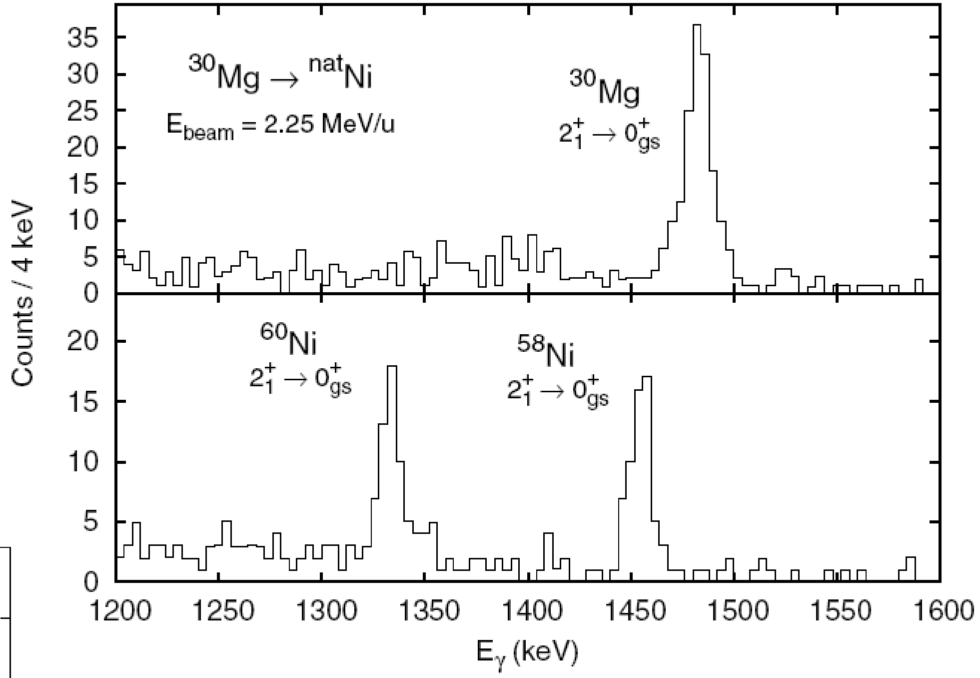


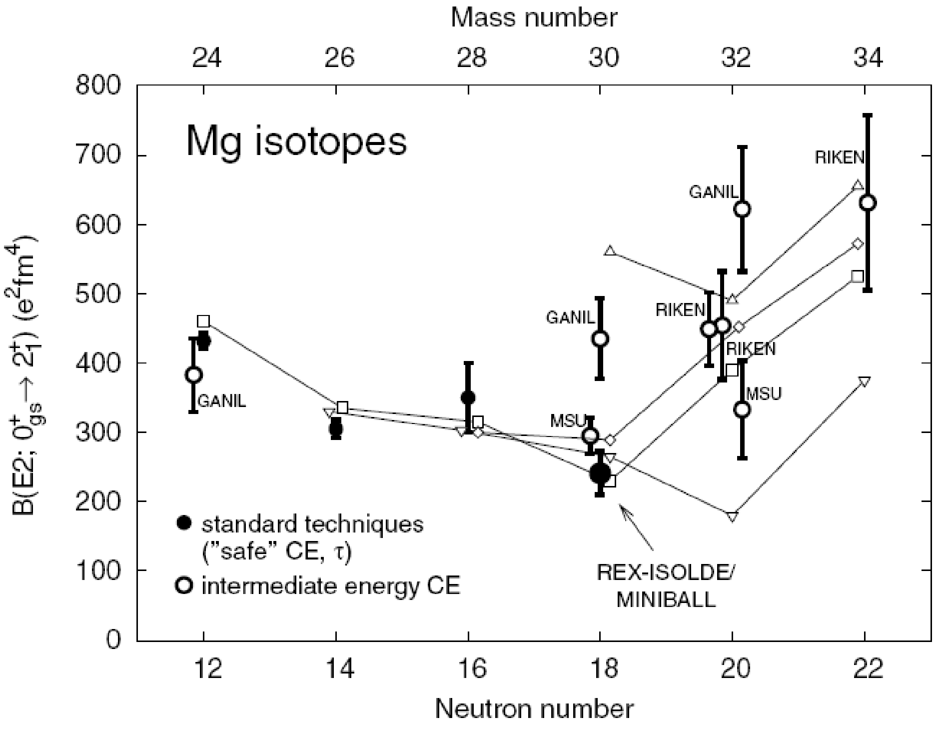
H. Scheit et al., PRL 77, 3967 (1996)

Low-energy Coulomb excitation
Example: ^{30}Mg + ^{58,60}Ni

^{30}Mg at 2.25 MeV/nucleon on natural Ni target (1.0 mg/cm^2)
From REX-ISOLDE at CERN
γ-ray detection with MINIBALL.
Particle detection with CD-shaped double-sided Si strip detector

O. Niedermaier *et al.*, PRL 94, 172501 (2005)





$$\frac{\sigma_{CE}(^{30}\mathrm{Mg})}{\sigma_{CE}(^{58,60}\mathrm{Ni})} = \frac{\epsilon_\gamma(^{58,60}\mathrm{Ni})}{\epsilon_\gamma(^{30}\mathrm{Mg})} \frac{W_\gamma(^{58,60}\mathrm{Ni})}{W_\gamma(^{30}\mathrm{Mg})} \frac{N_\gamma(^{30}\mathrm{Mg})}{N_\gamma(^{58,60}\mathrm{Ni})},$$

Applications

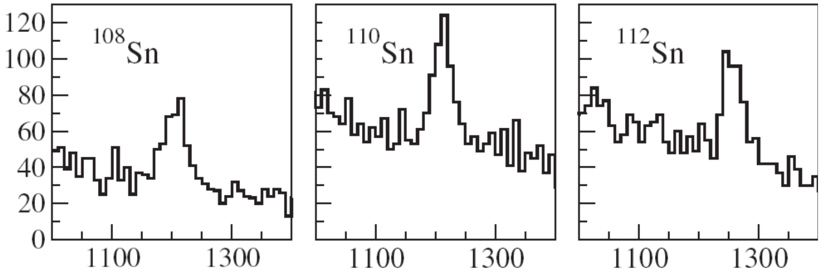
Approaching N=Z=50 and N=50 in Ge isotopes

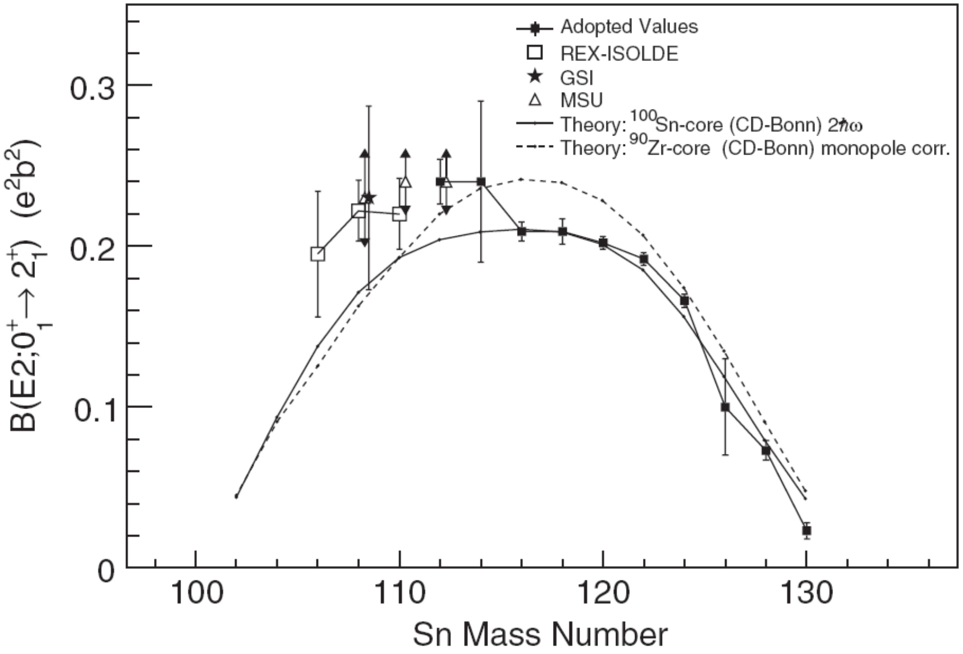
NSCL: intermediate-energy Coulex

GSI: relativistic Coulex

ISOLDE: barrier-energy Coulex

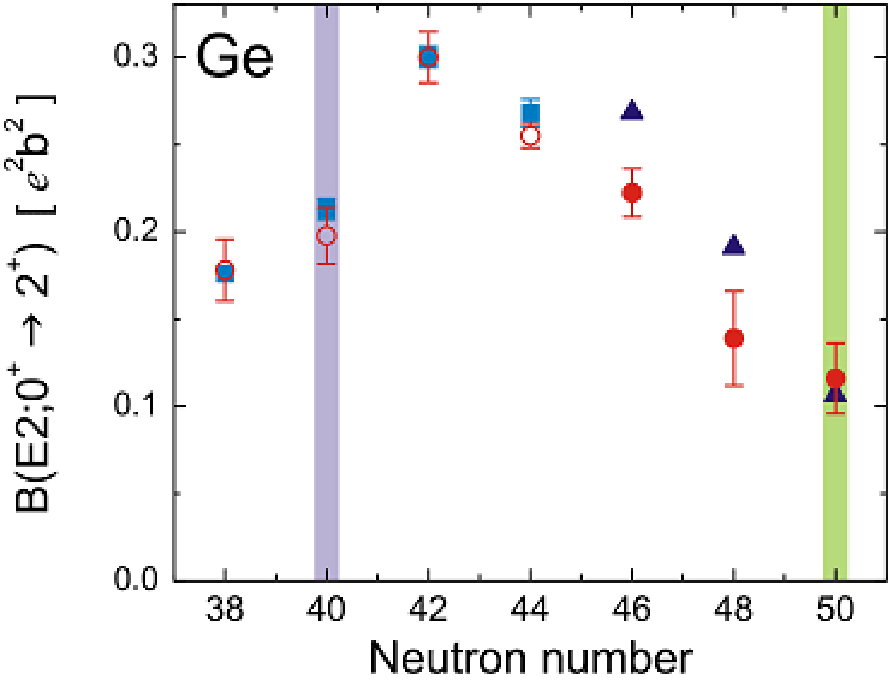
C. Vaman et al., PRL 99, 162501 (2007)





A. Ekstrom et al., PRL 101, 012502 (2008)

$^{78\text{-}82}$Ge Coulomb excitation below the barrier at HRIBF



E. Padilla-Rodal et al., PRL 94, 122501 (2005)

Structure information from excited states

As one indicator of shell closures

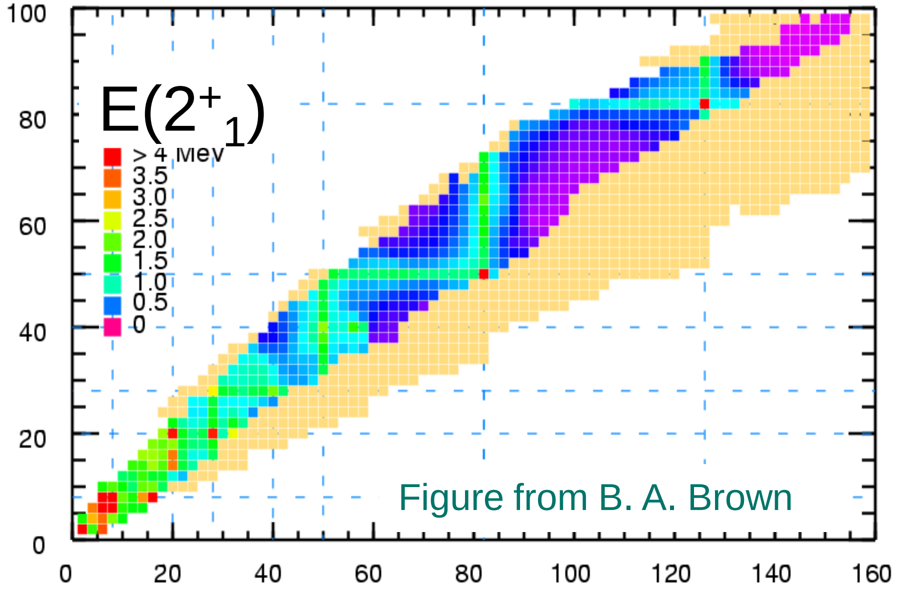
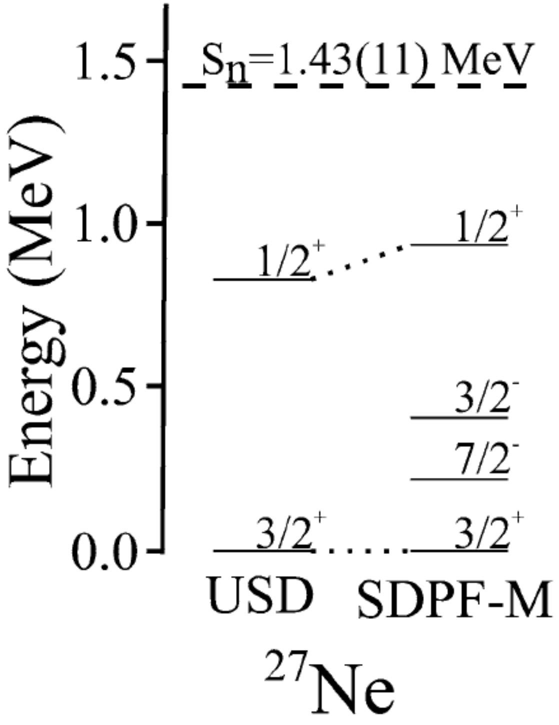


Figure from B. A. Brown

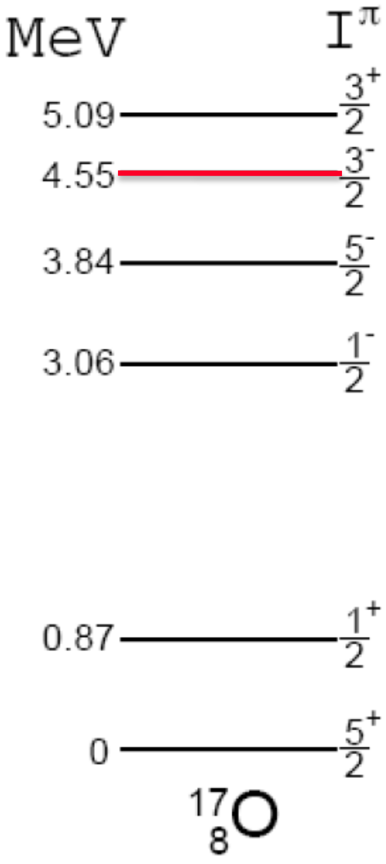
Guide model calculations

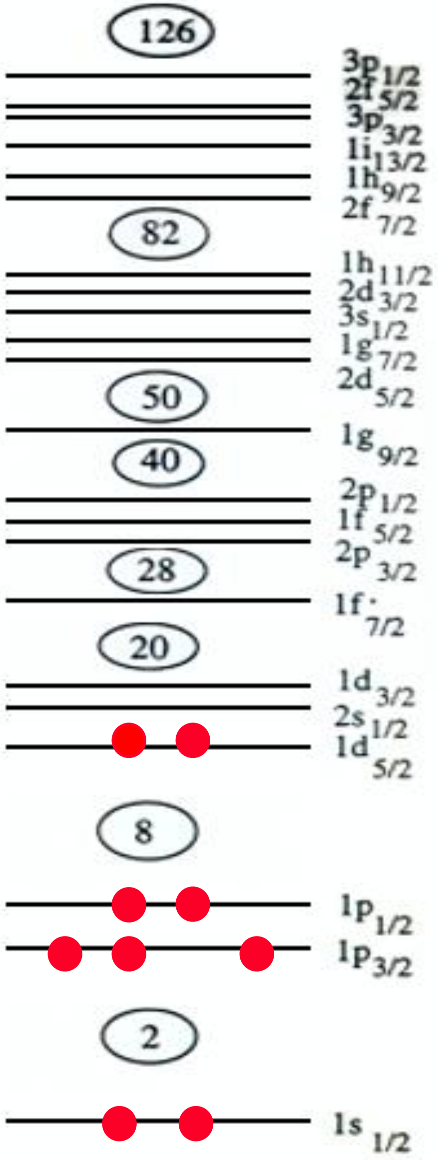


J. R. Terry et al., Phys. Lett. B 640, 86 (2006)

Single-particle states

Excited states in nuclei with one nucleon outside a magic number

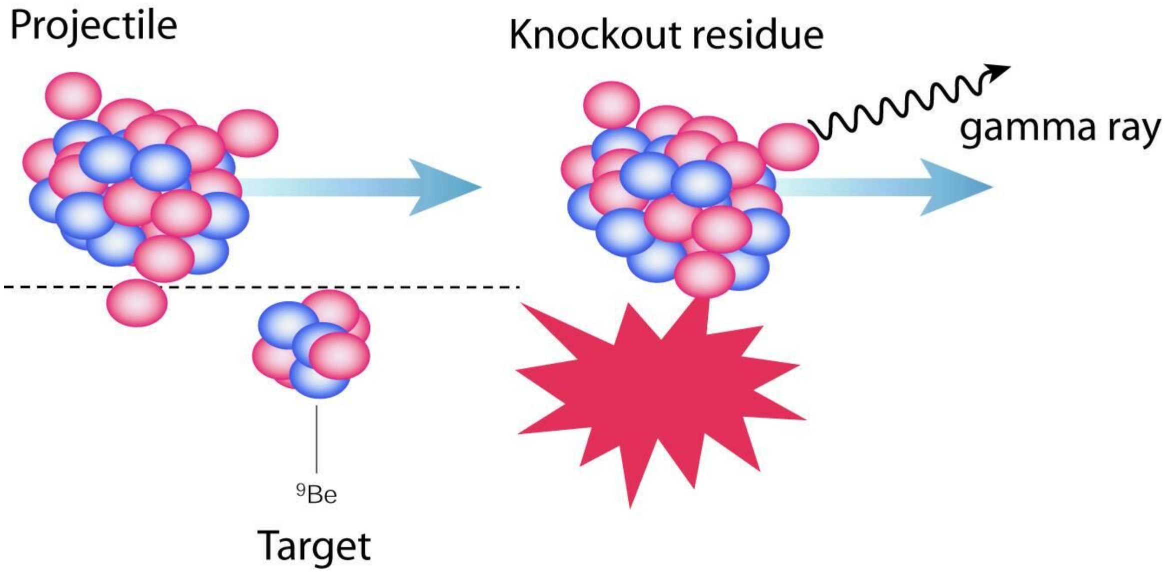


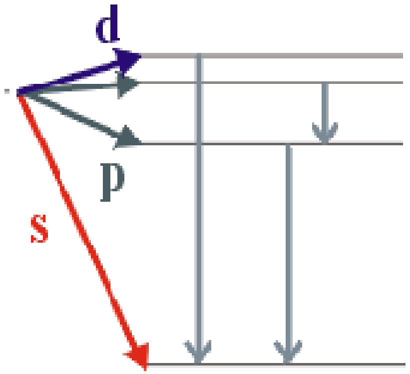


One-nucleon knockout
A direct reaction

- **more than 50 MeV/nucleon:**

  Straight-line trajectories





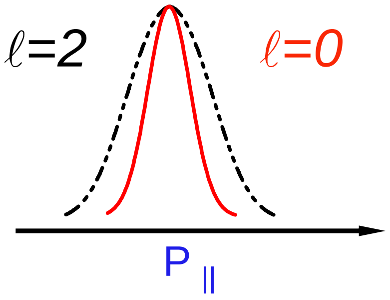
residue moment distribution

→ ℓ-value of knocked-out n

P.G. Hansen, PRL 77, 1016 (1996)

$$\sigma(nl^{\pi}) = C^2S(j,nl^{\pi})\;\sigma_{sp}(j,S_n)$$

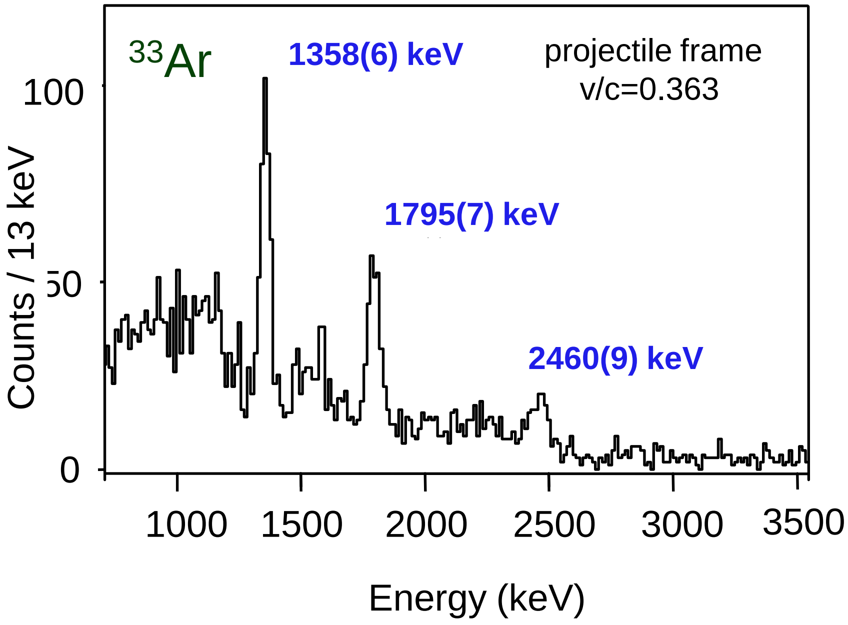
\# nucleons in orbit reaction cross section

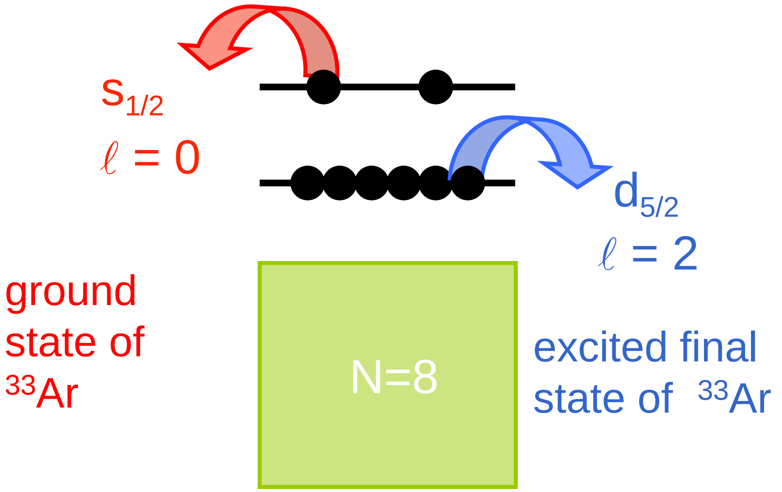


P.G. Hansen and B.M. Sherrill, NPA 693 ,133 (2001).

P.G. Hansen and J. A. Tostevin, Annu. Rev. of Nucl. and Part. Sci. 53, 219 (2003).

Spectroscopy in one-nucleon knockout
Example: ^{9}Be(^{34}Ar,^{33}Ar)X





$s_{1/2}$
$\ell = 0$

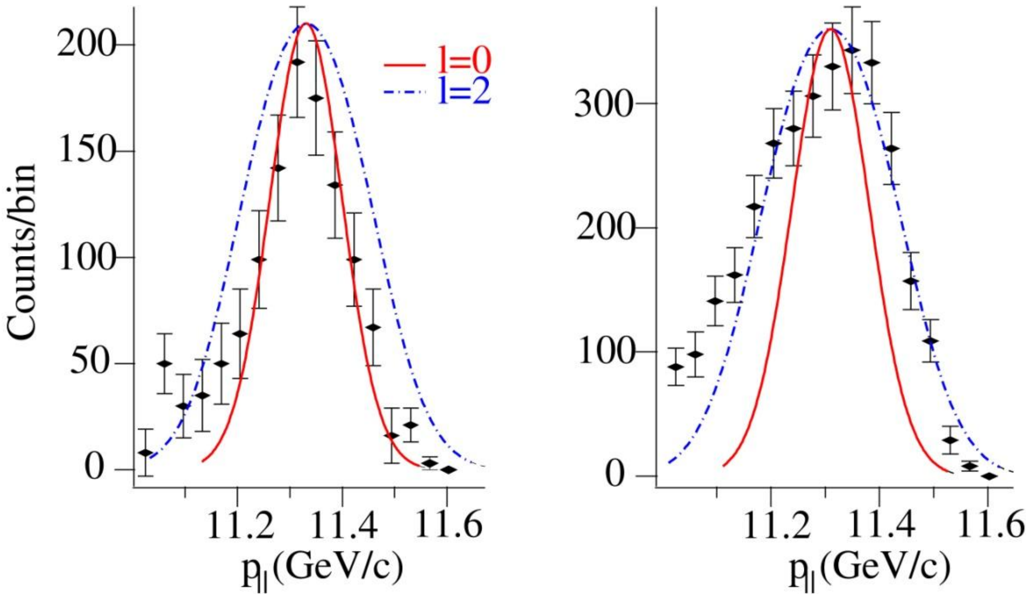
ground state of ^{33}Ar

N=8

$d_{5/2}$
$\ell = 2$

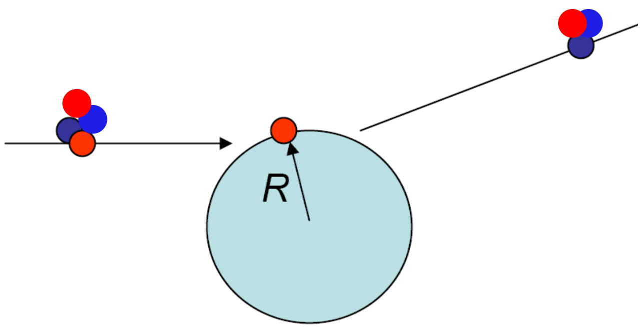
excited final state of ^{33}Ar

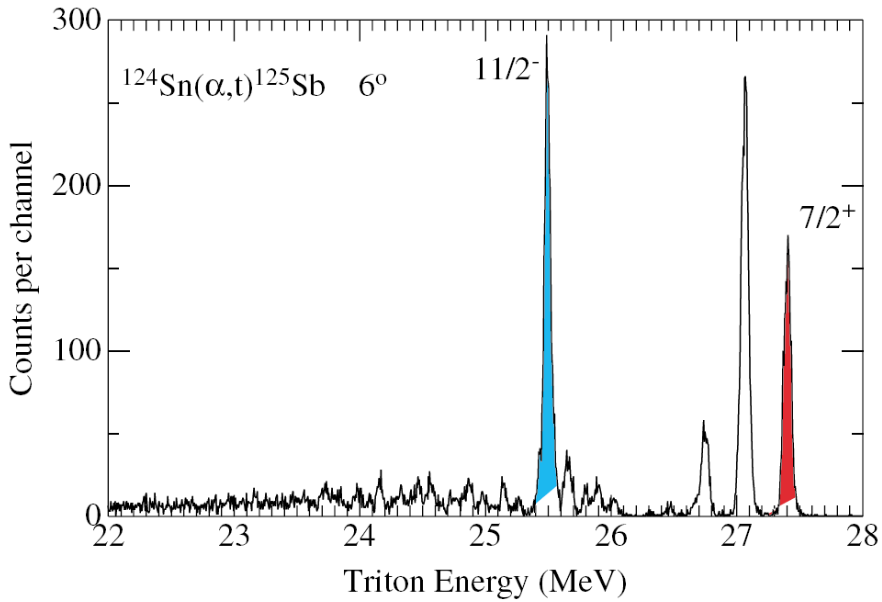
	BR (%)	σ_{exp} (mb)	C^2S_{exp}
$1/2^+$	30.2(46)	4.7(9)	0.38(6)
$3/2^+$	20.2(44)	3.2(8)	0.36(9)
$5/2^+$	31.7(31)	4.9(7)	0.56(8)
$(5/2^+)$	17.9(30)	2.8(6)	>0.34(7)

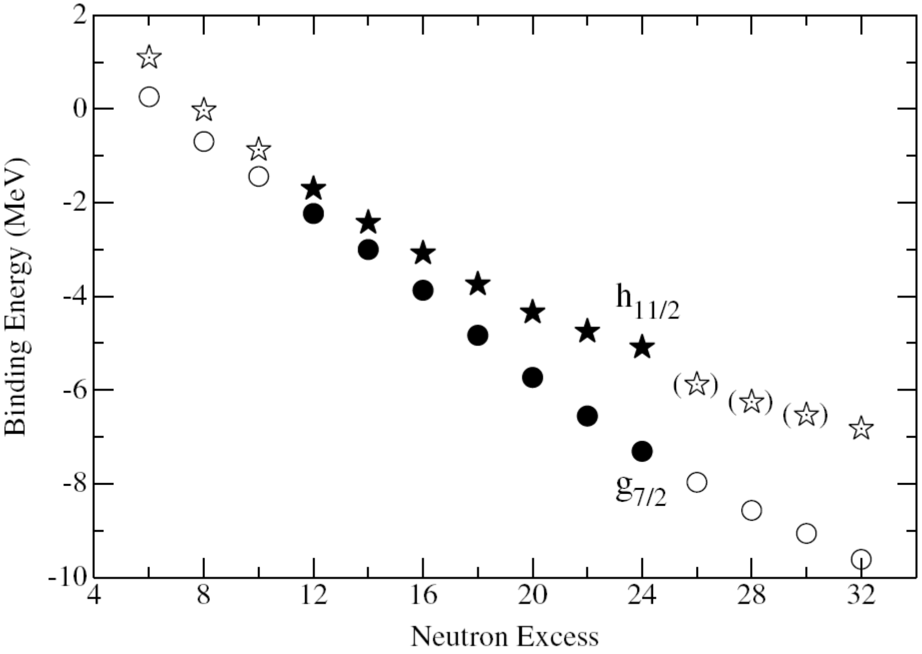


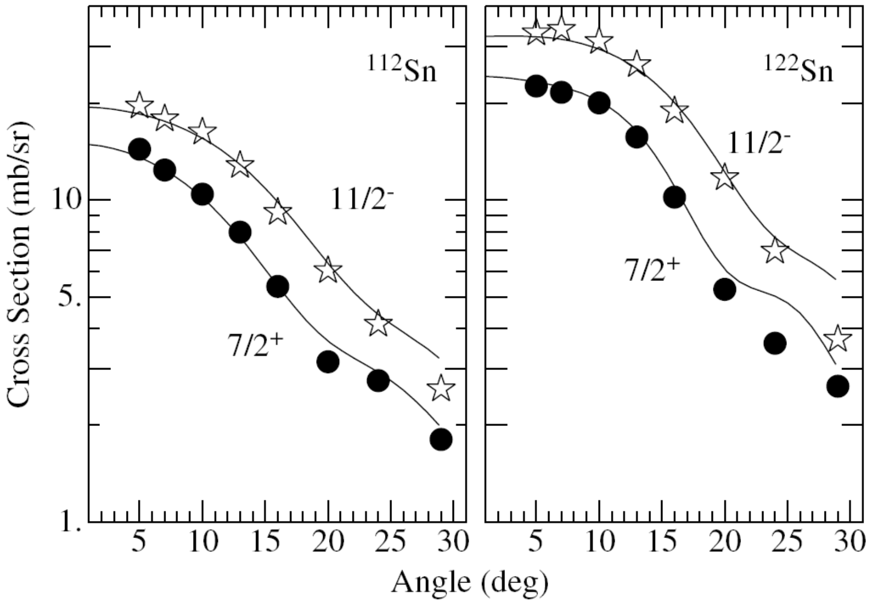
A. Gade *et al*., PRC 69 034311 (2004).

Low-energy transfer reactions



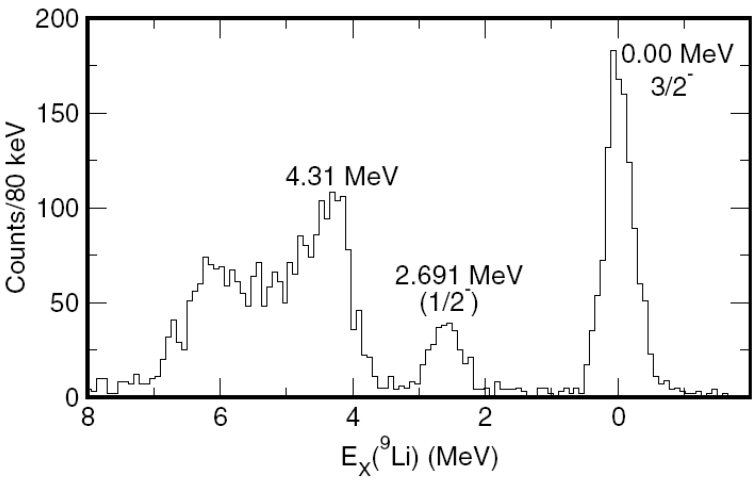






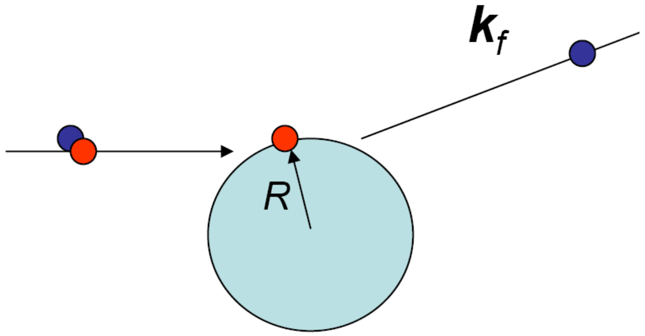
Low-energy transfer reactions

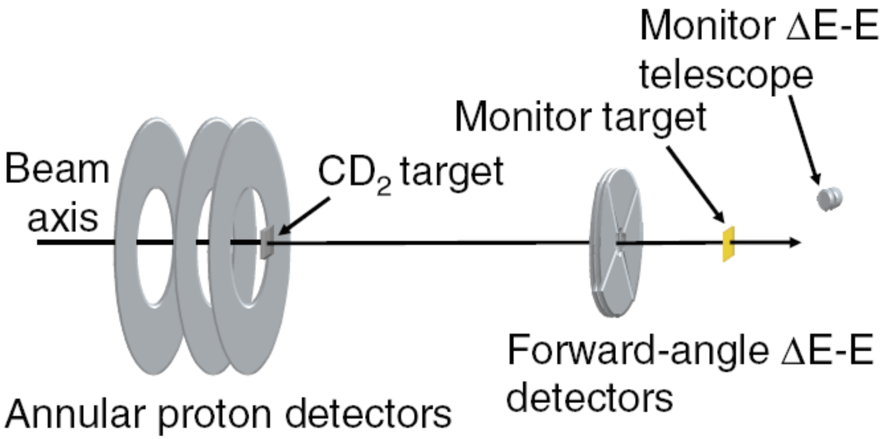
A. H. Wuosmaa et al., PRL 94, 082502 (2005)



Low-energy inverse-kinematics transfer experiment

- $^2H(^8Li,p)^9Li$ at ANL
- Proton angular distribution measured
- Quantitative spectroscopic information obtained

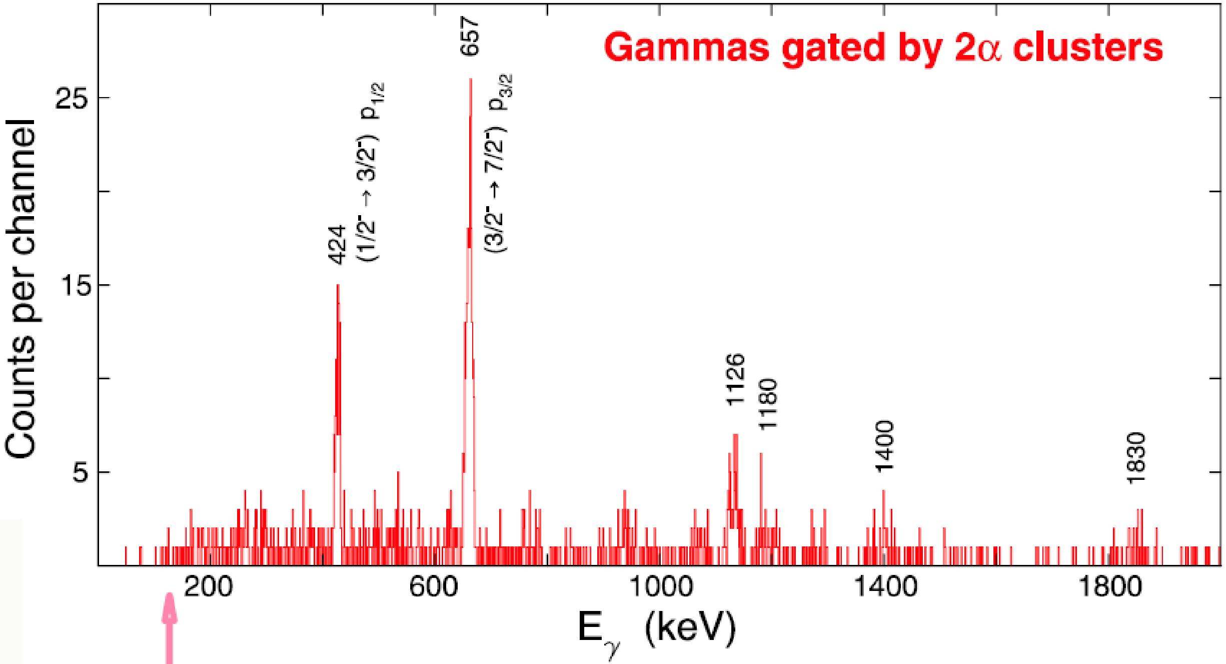


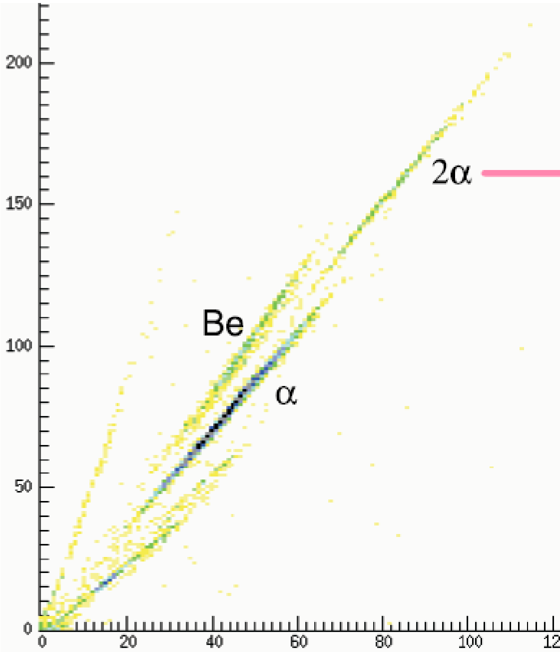


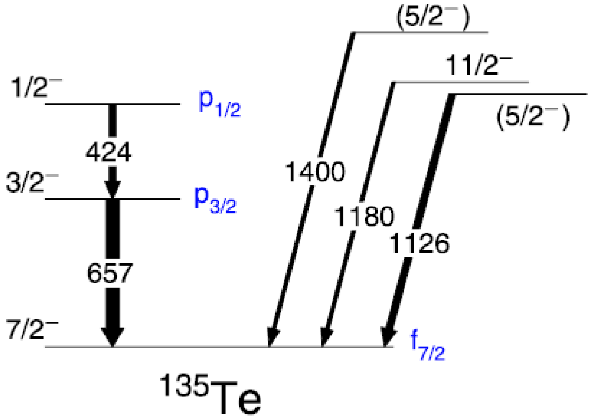
HI-induced low-energy transfer at HRIBF
A really smart trigger

Heavy-ion induced transfer

- ^{9}Be(^{134}Te,^{8}Be)^{135}Te at HRIBF@ORNL
- Gamma-ray detection in coincidence with 2α clusters







D.C. Radford et al., EPJ A15, 171 (2002)

Lifetimes of excited states

Lifetimes of excited states

Lifetimes of excited 2^+ states in even-even nuclei: picosecond range

$$\tau_\gamma = 40.81 \times 10^{13} E^{-5} [B(E2)\uparrow/\mathrm{e}^2\mathrm{b}^2]^{-1}$$

Some excited states live much longer: Isomers

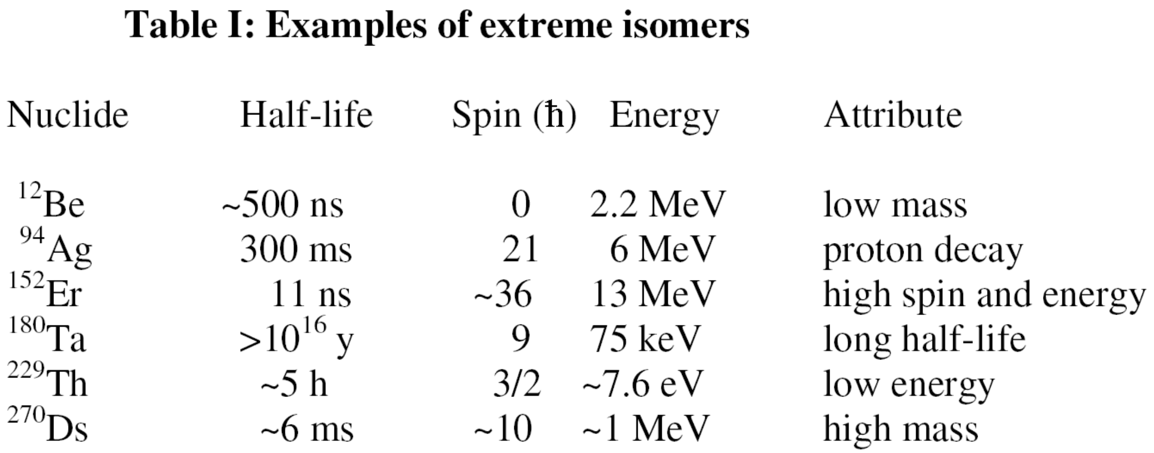


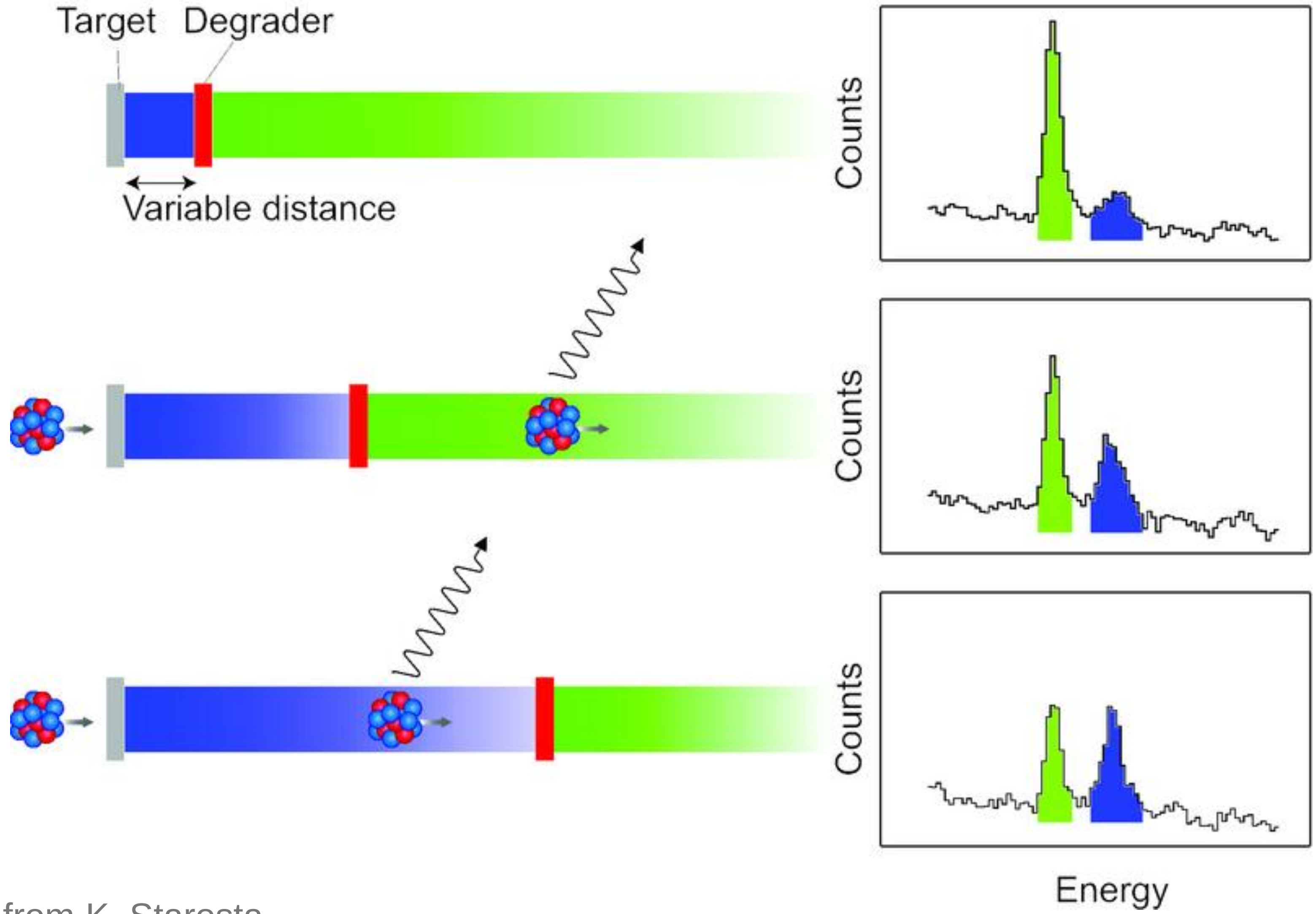
Table I: Examples of extreme isomers

Nuclide	Half-life	Spin (ħ)	Energy	Attribute
^{12}Be	~500 ns	0	2.2 MeV	low mass
^{94}Ag	300 ms	21	6 MeV	proton decay
^{152}Er	11 ns	~36	13 MeV	high spin and energy
^{180}Ta	>10^{16} y	9	75 keV	long half-life
^{229}Th	~5 h	3/2	~7.6 eV	low energy
^{270}Ds	~6 ms	~10	~1 MeV	high mass

From P.M. Walker and J. J. Carroll, Nuclear Physics News 17, 11-15 (2007)

Plunger lifetime measurements

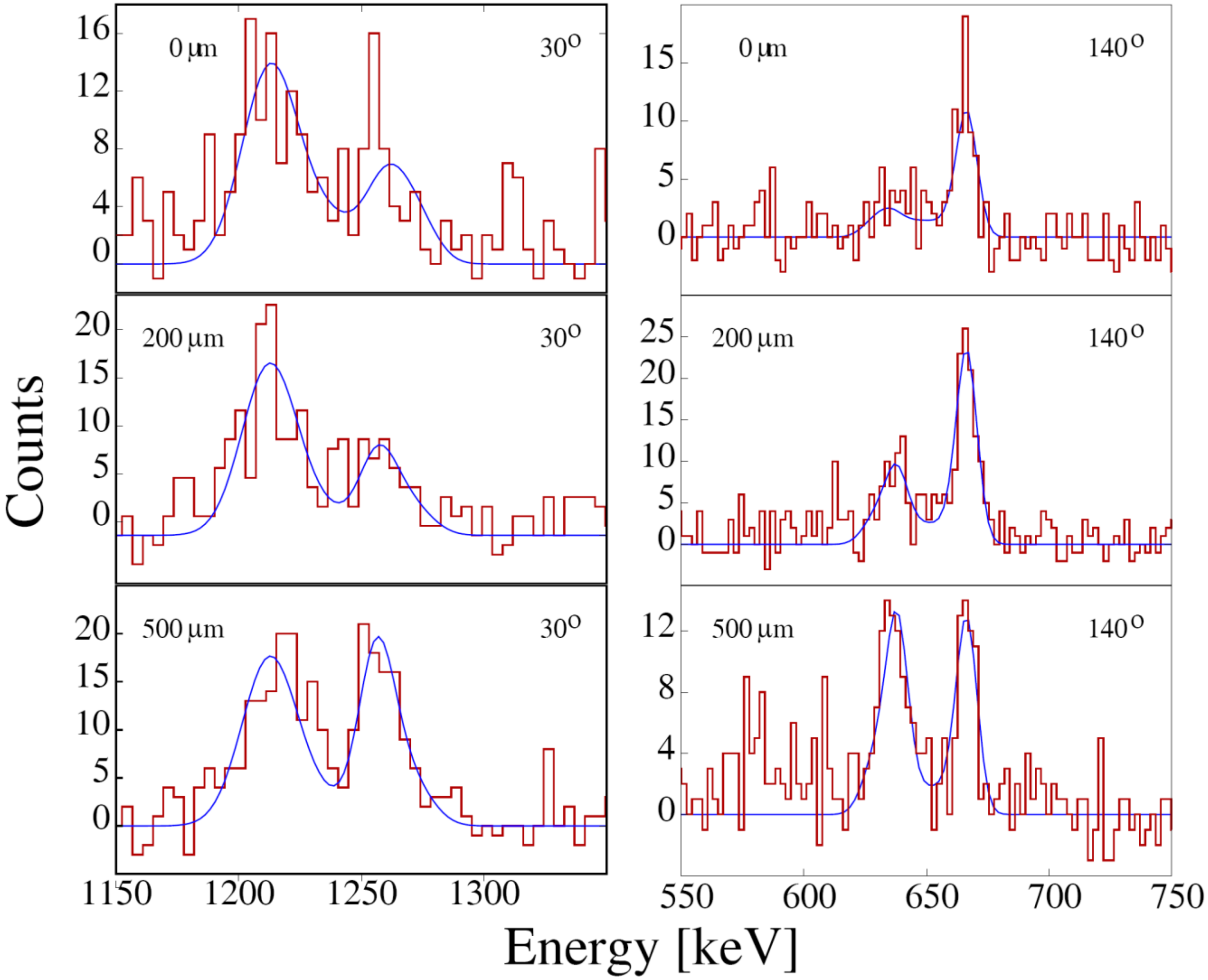
c=300 µm/ps **β ~ 0.3c** **10 ps ~ 1mm**



Adapted from K. Starosta

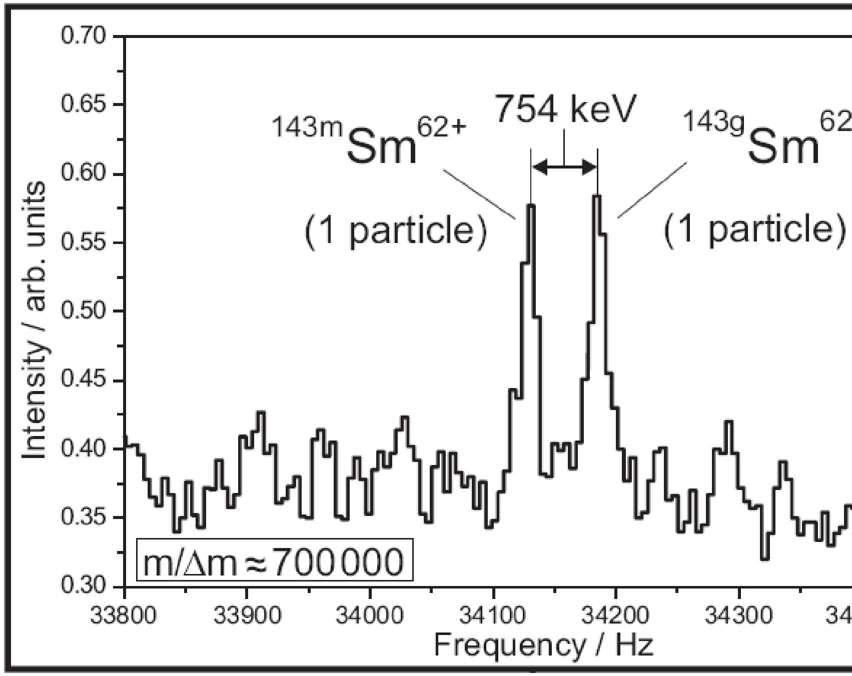
Line shapes and lifetimes
Example: ^{64}Ge $2^+_1 \rightarrow 0^+_1$

τ=3.2(5) [ps]



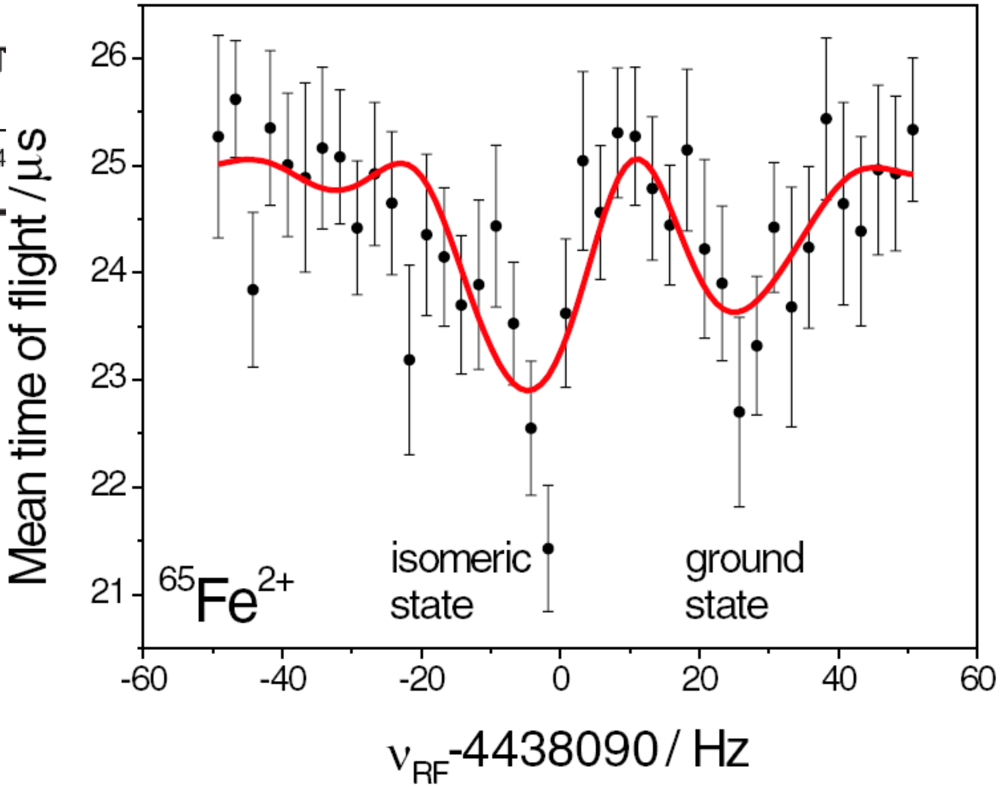
Long-lived excited states – isomers

Back to storage rings and penning traps



F. Bosch, Lect. Notes Phys. 651, 137(2004)

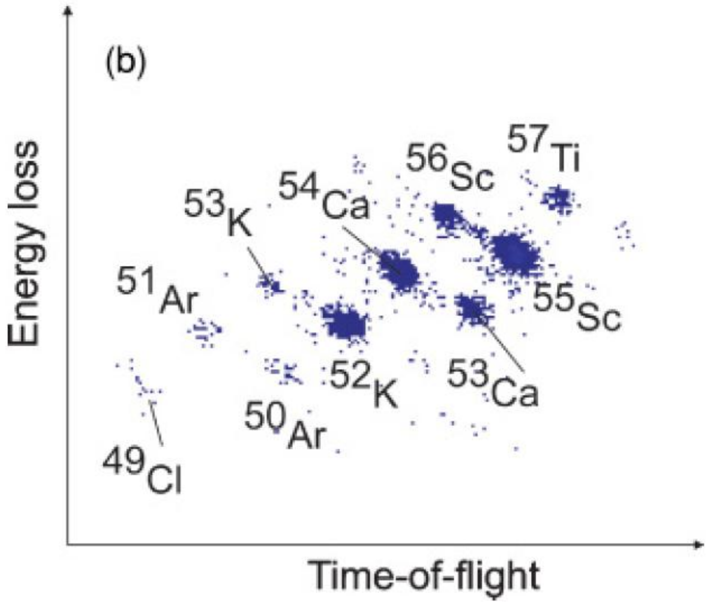
M. Block et al., PRL 100, 132501 (2008)



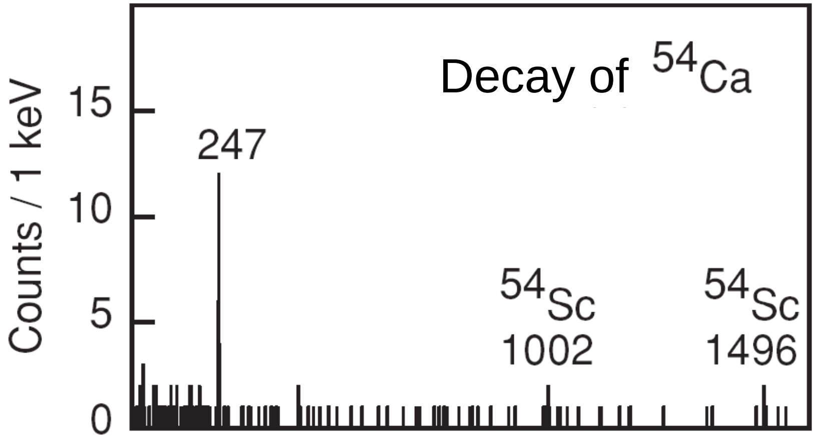
Isomers: decay hindered by nuclear structure (selection rules, energy, …) → long lifetime

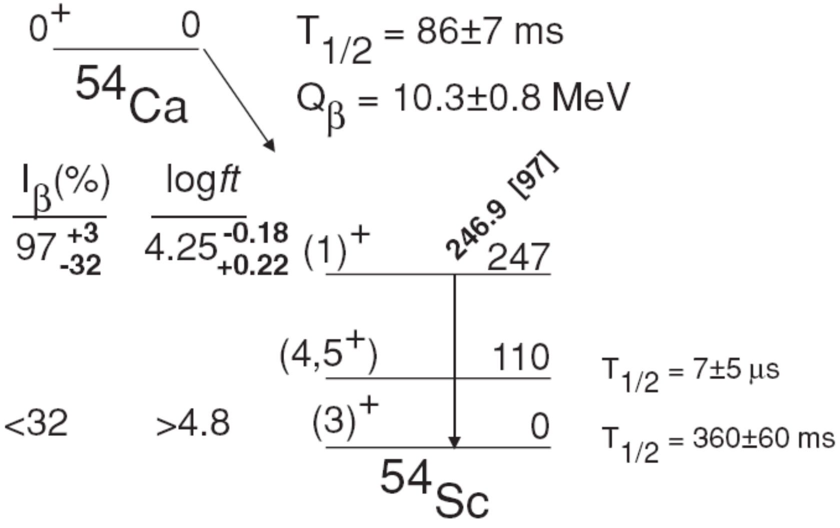
Excited states populated in decays

Excited states populated in β decay
Selectivity through selection rules



Total number of ^{54}Ca implants: 654 only



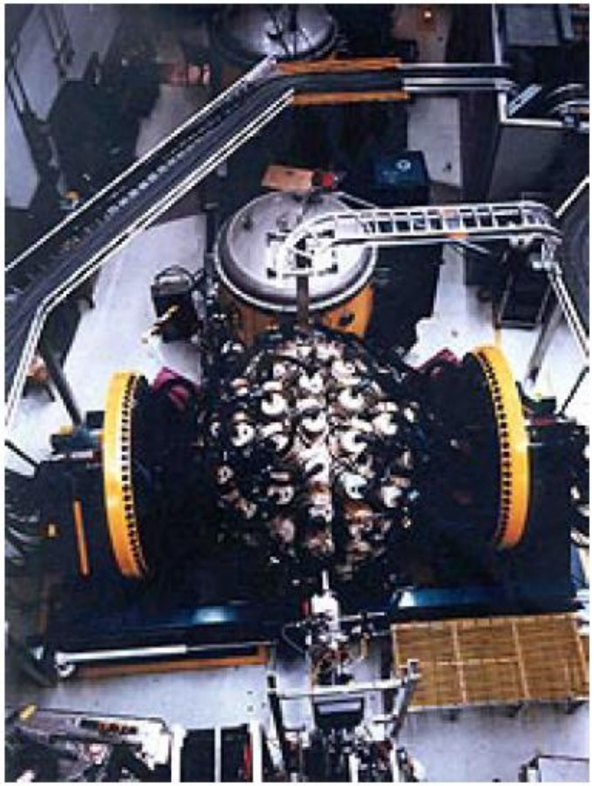


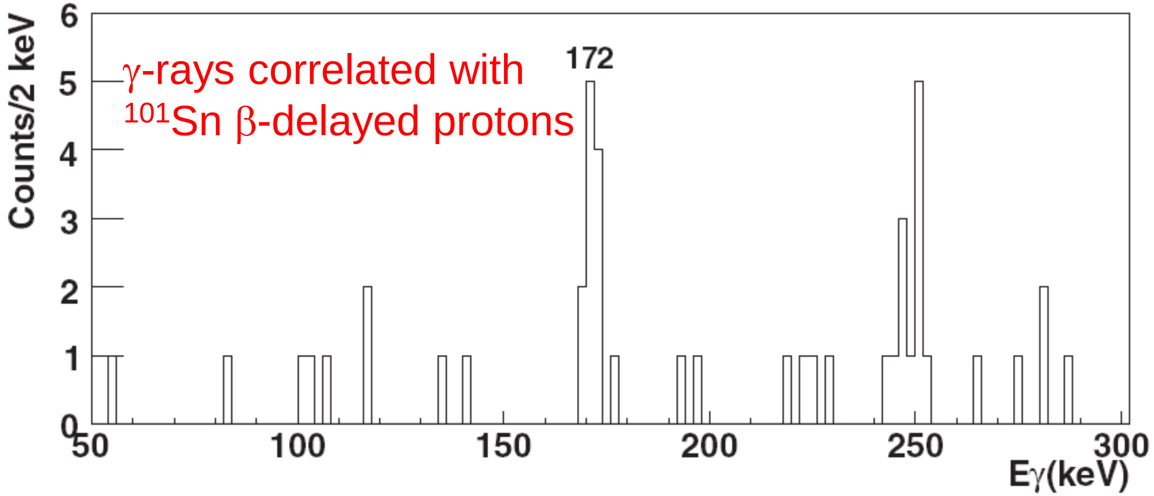
Selection rules in β decay, any textbook

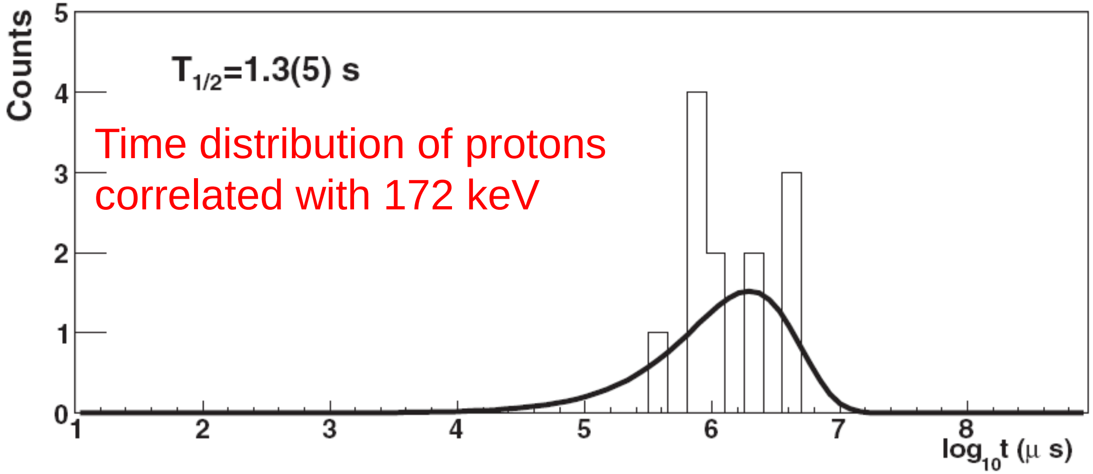
Type	ΔJ	Δπ
Allowed	0,1	no
First Forbidden	0,1,2	yes
Second Forbidden	1,2,3	no
Third Forbidden	2,3,4	yes
Fifth Forbidden	3,4,5	no

P. F. Mantica et al., PRC 77, 014313 (2008)

γ-ray spectroscopy tagged with β-delayed protons




^{58}Ni+^{46}Ti at 192 MeV (ATLAS/ANL)



Single-neutron states above doubly magic ^{100}Sn:

$d_{5/2} – g_{7/2}$ ~ 172 keV

D. Seweryniak et al., PRL 101, 022504 (2007)

Excited states populated following α and proton emission

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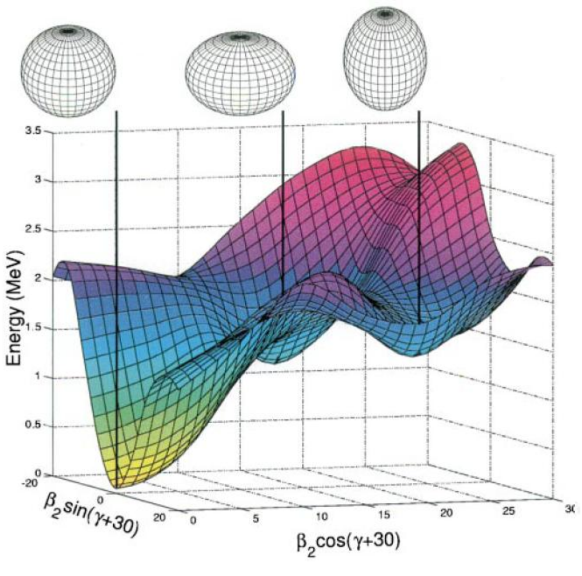
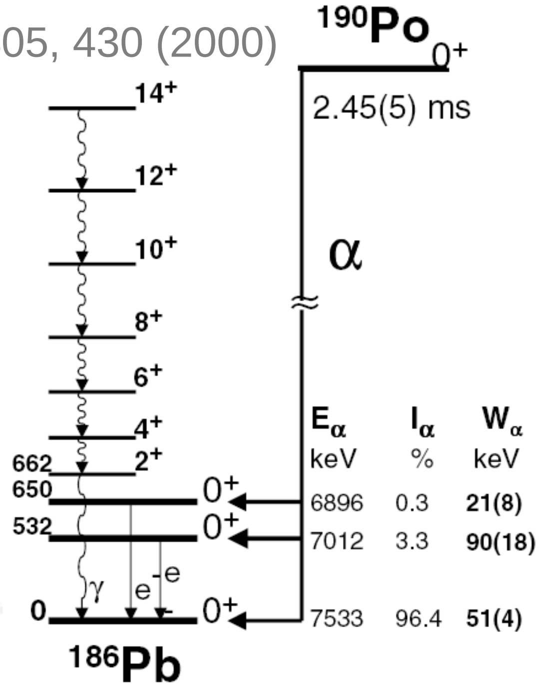
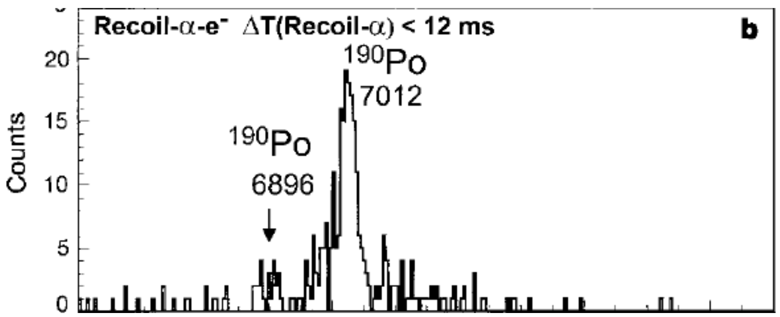
A. N. Andreyev et al., Nature 405, 430 (2000)

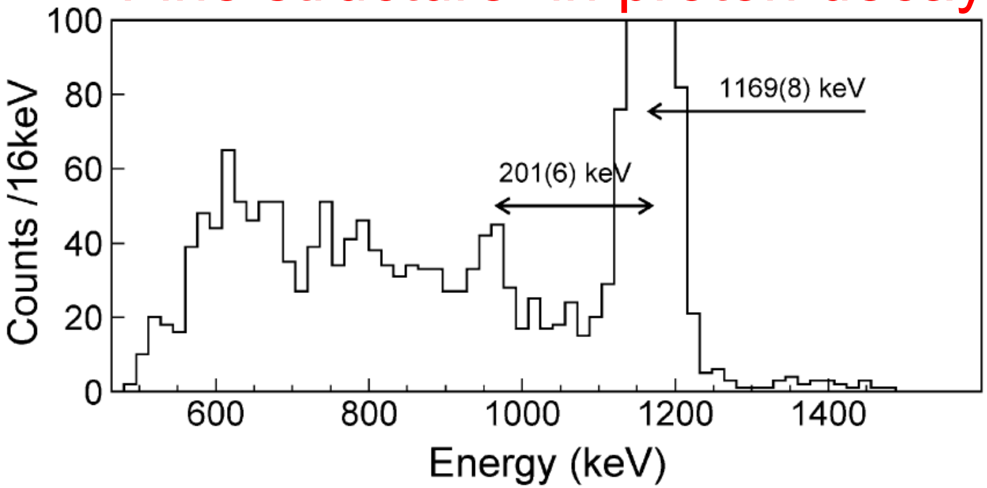




Eα keV	Iα %	Wα keV
6896	0.3	**21(8)**
7012	3.3	**90(18)**
7533	96.4	**51(4)**



“Fine structure” in proton decay



Ground state and first excited state (201 keV) of ^{140}Dy populated in proton decay of ^{141}Ho

M. Karny et al., PLB 664, 52 (2008)

Take away

- Excited states provide valuable information on the evolution of nuclear structure
    - Gamma-ray spectroscopy to tag the excited state
    - Observables related to the collective degree of freedom
    - Single-particle structure from direct reactions

- Life-times of excited states
    - Different experimental approaches

- Population of excited states in decays (selectivity)

Related review articles

Coulomb excitation (low energy and intermediate energy)

- Nuclear shapes studied by Coulomb excitation, D. Cline, Annu. Rev. Part. Sci. 36, 683 (1986)
- Coulomb excitation at intermediate energies, T. Glasmacher, Annu. Rev. Part. Sci. 48, 1 (1998)

Direct reactions with exotic beams

- Direct reactions with exotic nuclei, P.G. Hansen and J.A. Tostevin, Annu. Rev. Part. Sci. 53, 219 (2003)

In-beam gamma-ray spectroscopy with fast beams

- In-beam nuclear spectroscopy of bound states with fast exotic ion beams, A. Gade and T. Glasmacher, Prog. In Part. and Nucl. Phys. 60, 161 (2008)