Experiments with exotic nuclei II

MICHIGAN STATE UNIVERSITY

Advancing Knowledge. Transforming Lives.

Thursday

Friday

Excited states

Experimental considerations: Reactions

Collectivity

Coulomb excitation

Single-particle degrees of freedom

Transfer and knockout

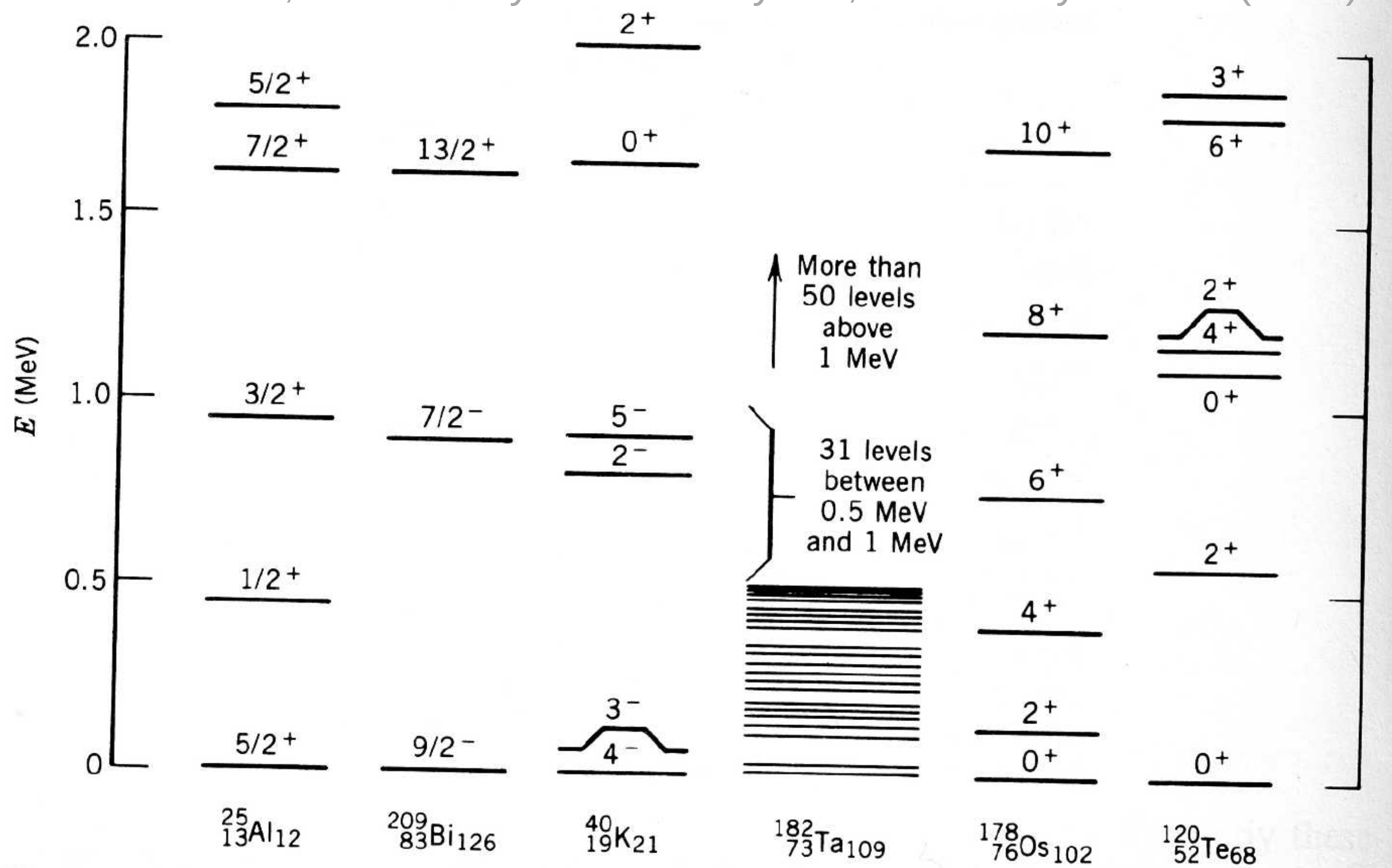
Excited-state lifetimes

Excited states

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

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

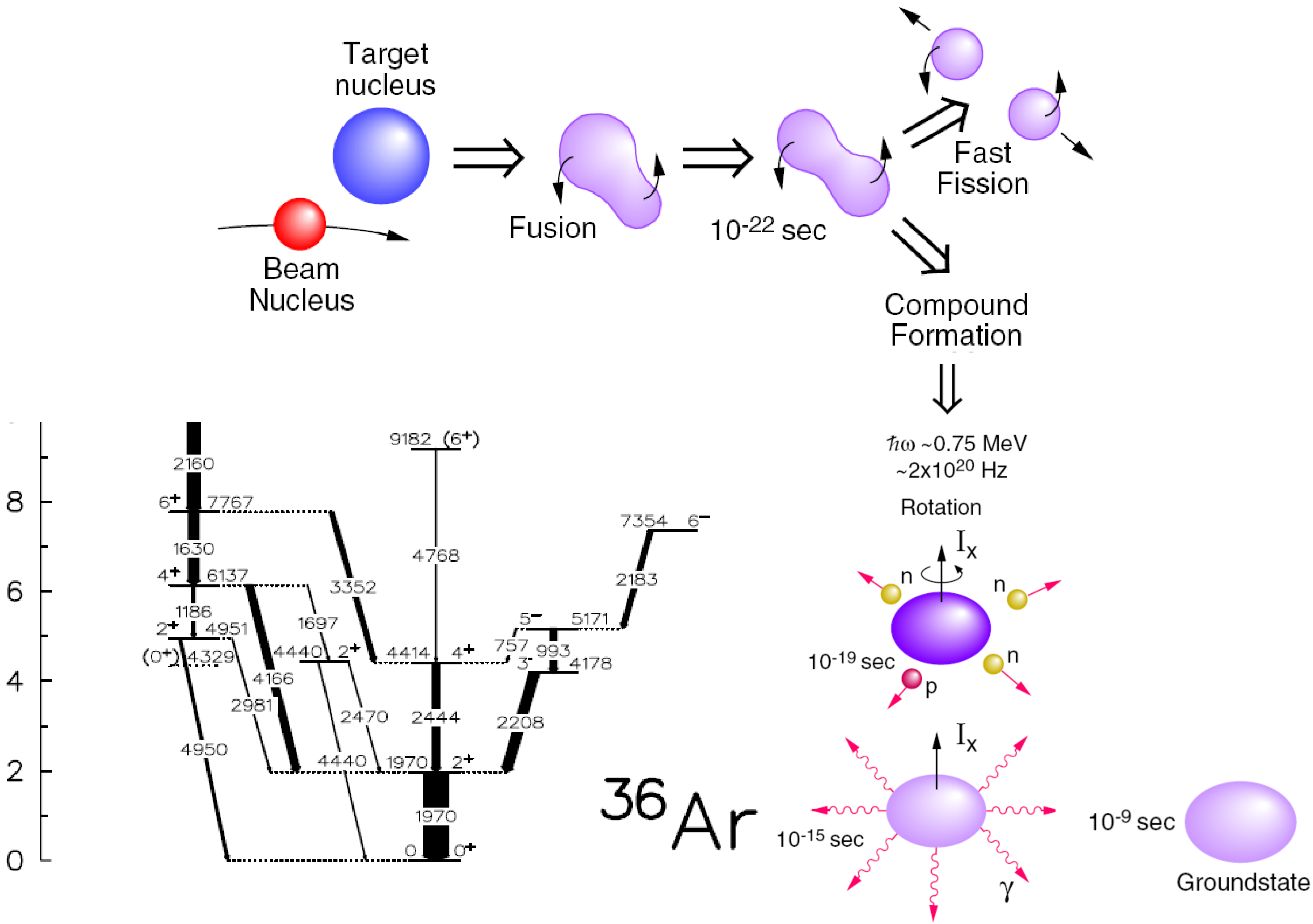


- In nuclei, the energy scales are close:

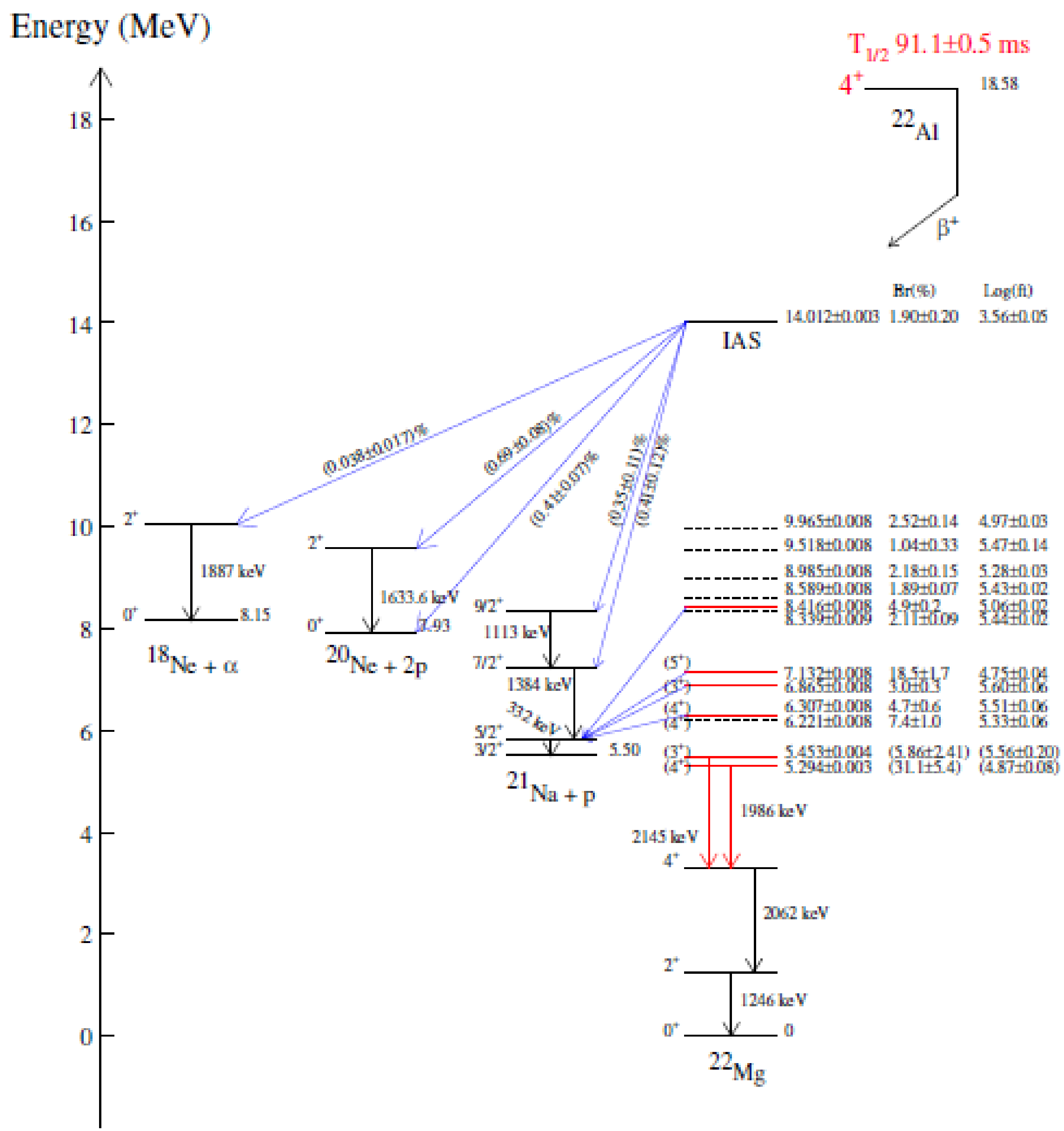
$E_{rot} \sim E_{vib} \sim E_{sp}$ (MeV)

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

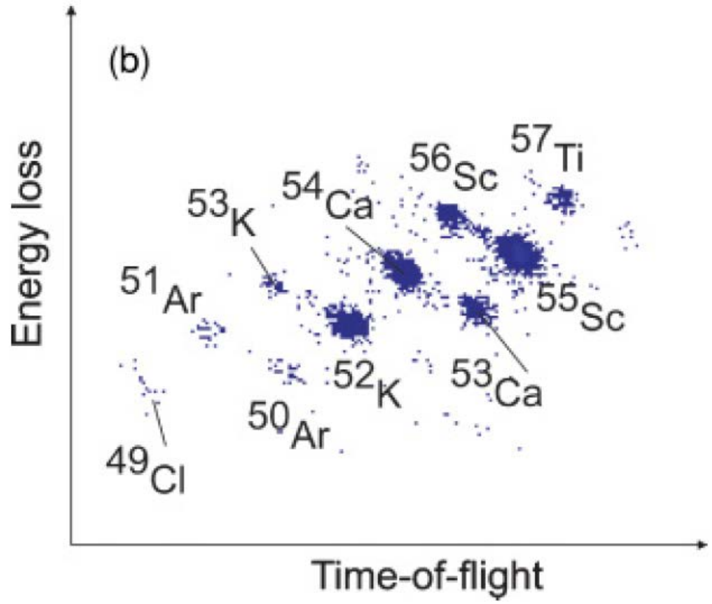
Population of excited states - Reactions



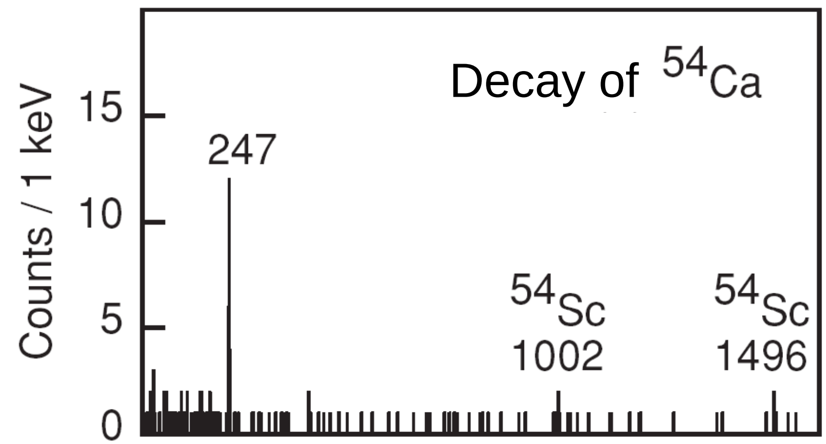
Population of excited states - Decays

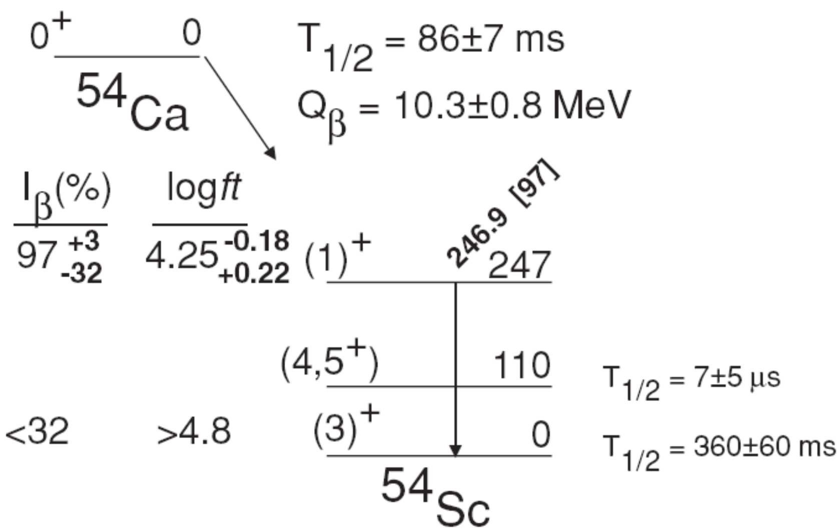


Excited states populated in β decay
Selectivity through selection rules



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



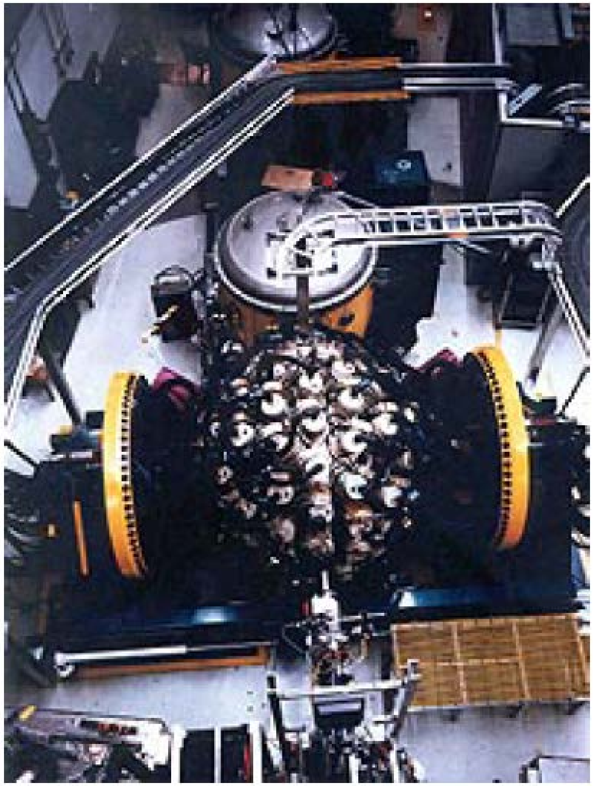


Selection rules in β decay, any textbook

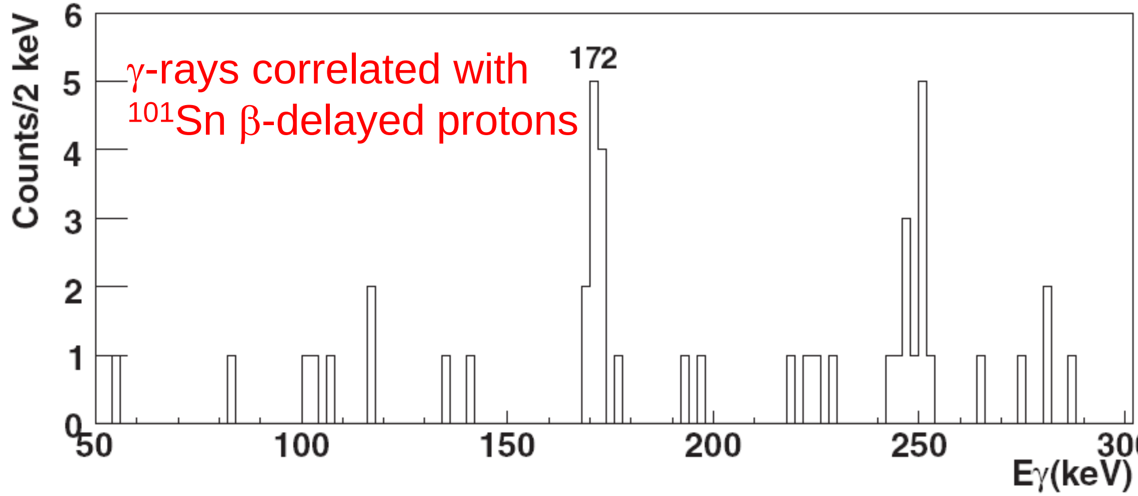
Type	ΔJ	Δπ
Allowed	0,1	no
First Forbidden	0,1,2	yes
Second Forbidden	1,2,3	no
Third Forbidden	2,3,4	yes
Fifth Forbidden	3,4,5	no

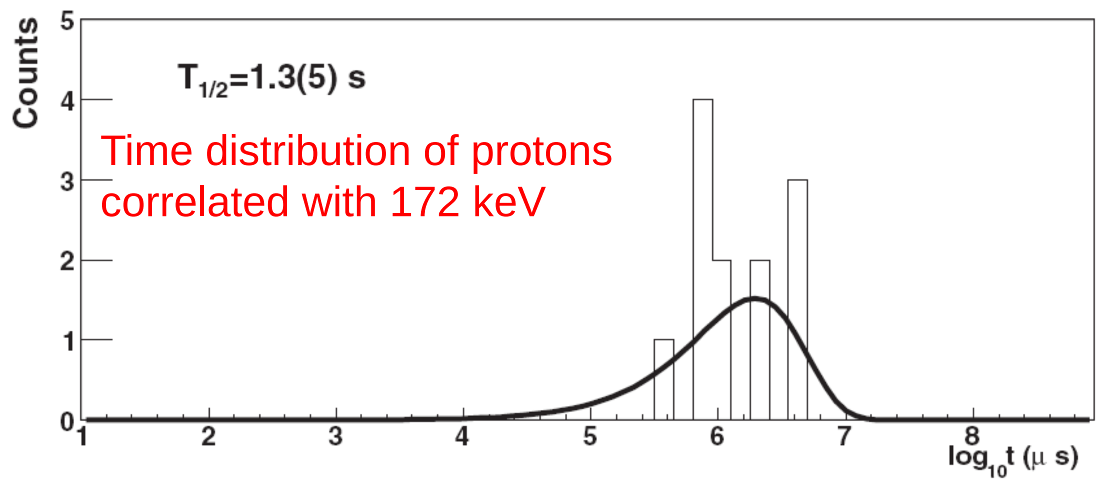
P. F. Mantica et al., PRC 77, 014313 (2008)

γ-ray spectroscopy tagged with β-delayed protons



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





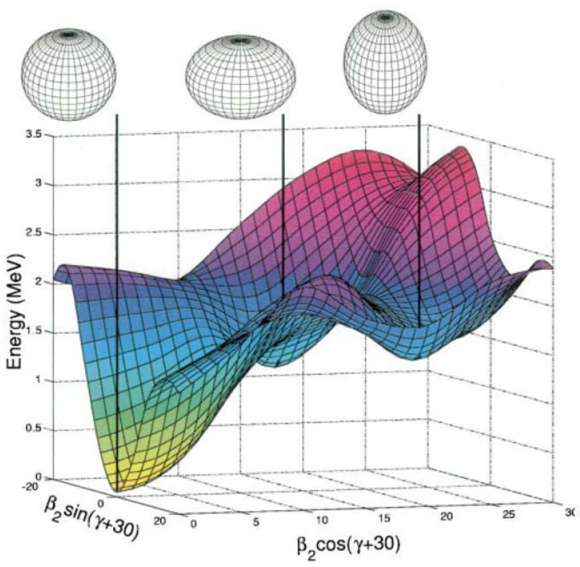
Single-neutron states above doubly magic ^{100}Sn:

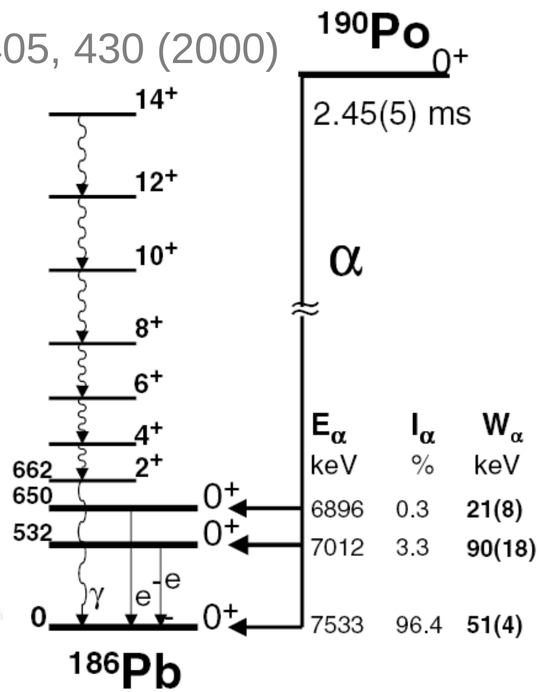
$d_{5/2} – g_{7/2}$ ~ 172 keV

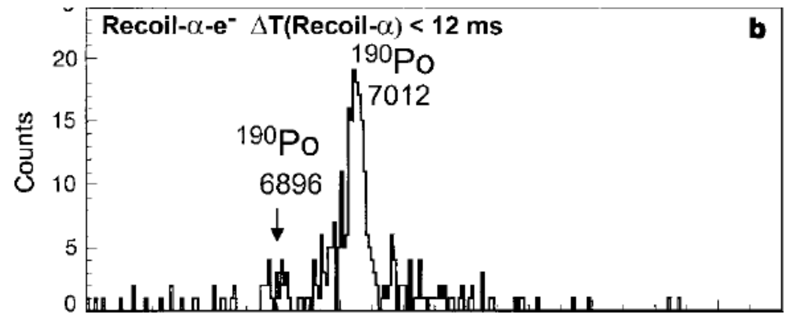
D. Seweryniak et al., PRL 101, 022504 (2007)

Excited states populated following α and proton emission

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

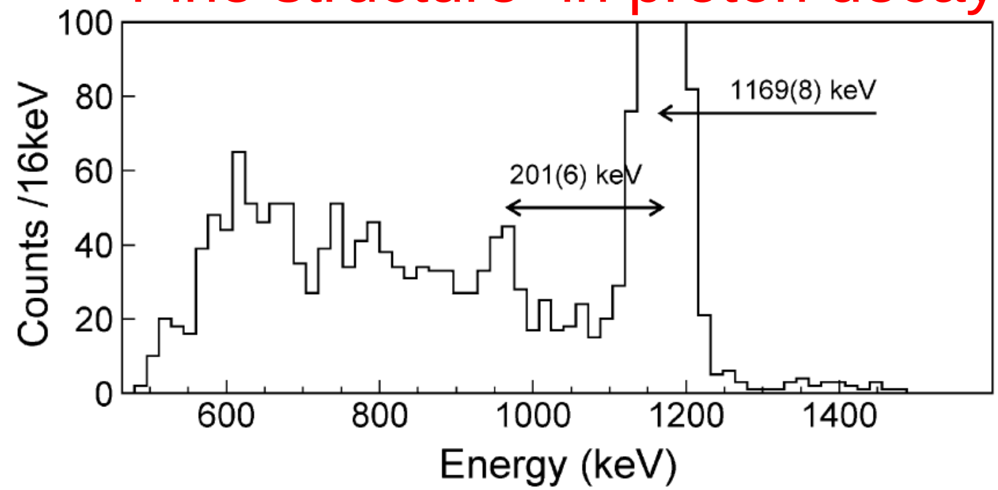






Ground state and first excited state (201 keV) of ^{140}Dy populated in proton decay of ^{141}Ho

“Fine structure” in proton decay



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

Structure information from excited states

As one indicator of shell closures

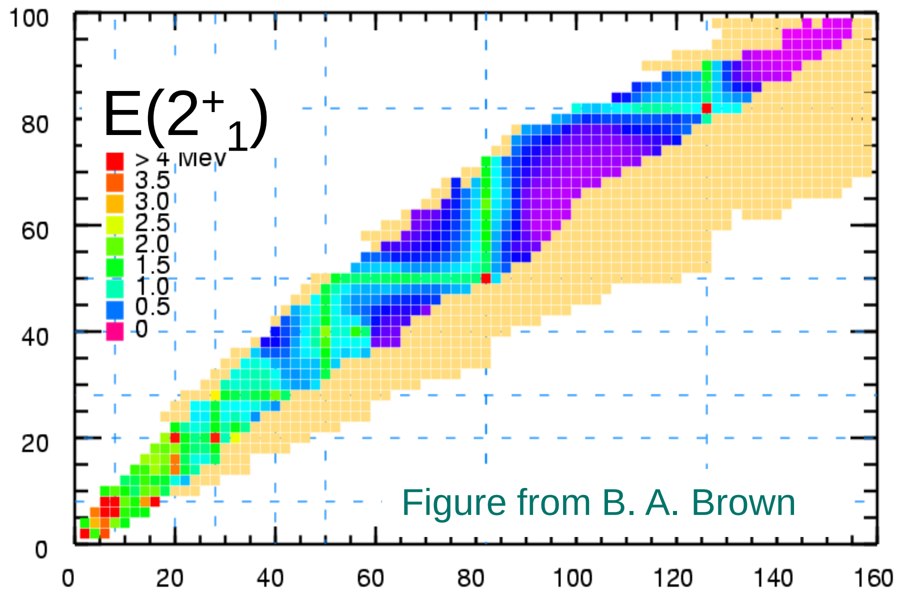
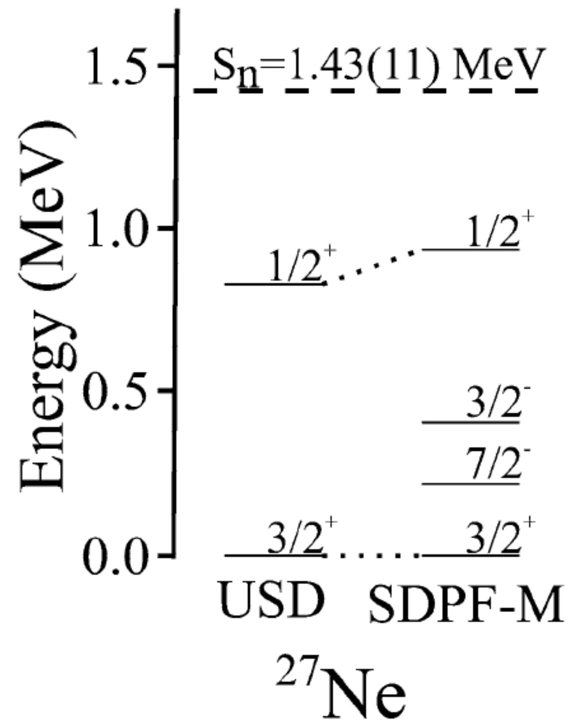


Figure from B. A. Brown

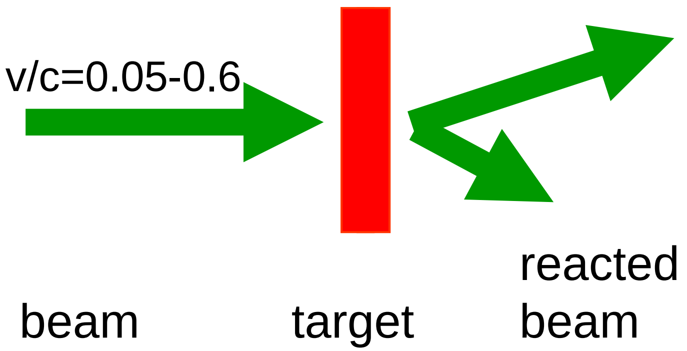
Guide model calculations



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

Experimental considerations: *Reactions*

Nuclear reactions – cross section



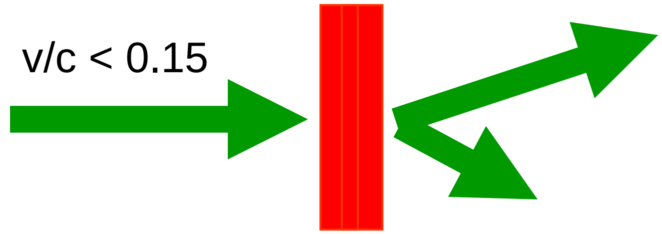
- Reactions
  - Inelastic scattering
  - Nucleon transfer
  - Fusion, fusion-evaporation
  - Breakup/fragmentation

- The choice of the target depends on the reaction that 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

- 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

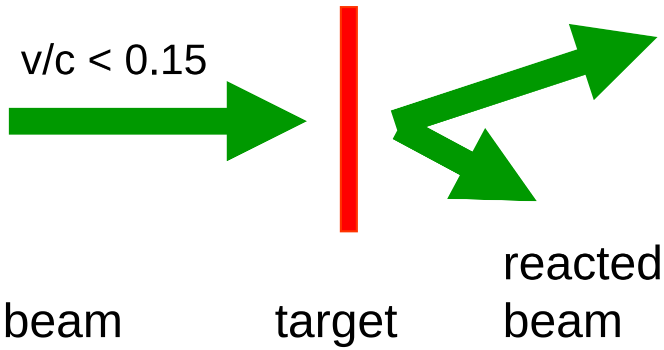


- Fast beams and thick targets
  - Increased luminosity
  - Use γ-ray spectroscopy to identify final states in thick-target experiments
  - Event-by-event identification
  - Mainly single-step reactions since the interaction time between target and projectile is small

- 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/cm^2 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

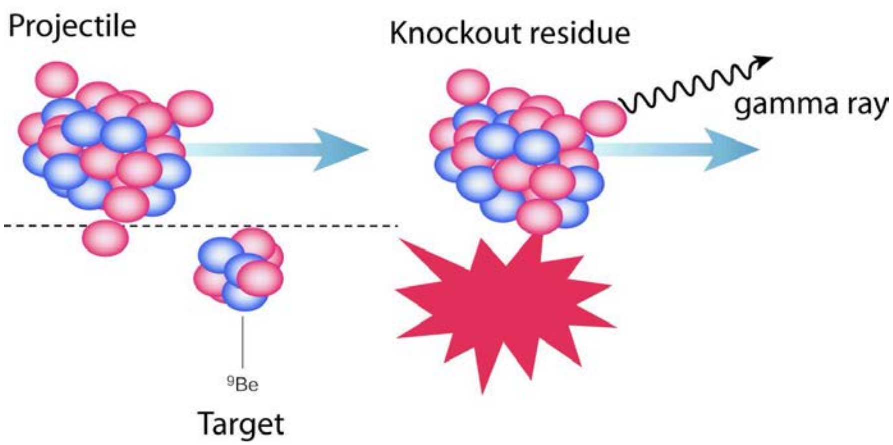
- Beam energies around the Coulomb barrier
  - Thin targets required
  - Multi-step reactions are possible
  - High angular-momentum transfer typical

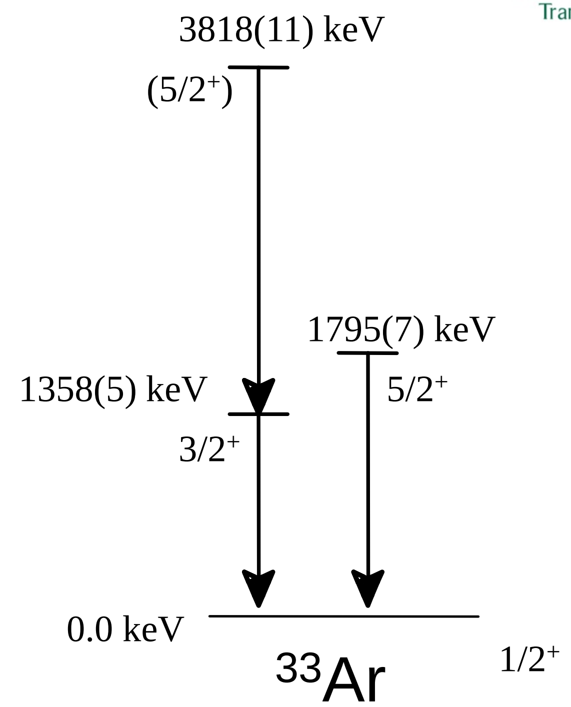
- Example

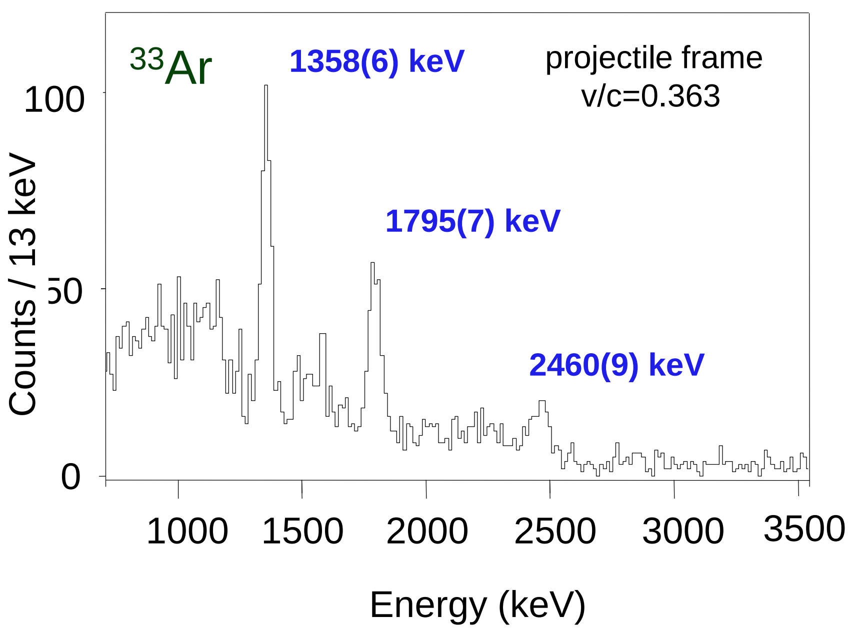
  $\sigma = 100$ mbarn

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

Excited states

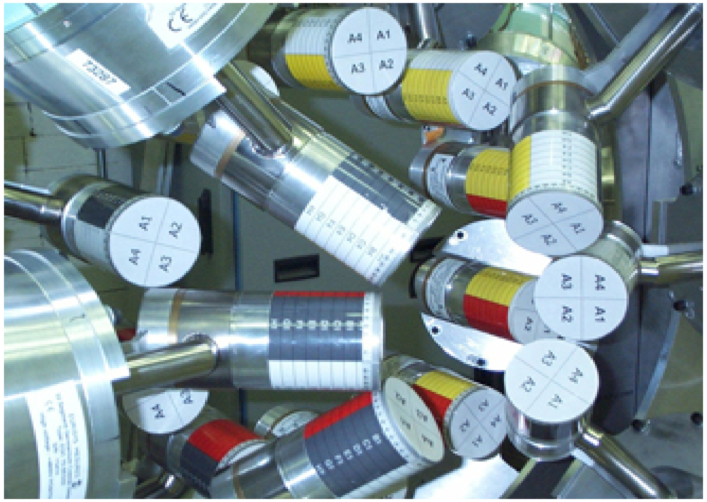


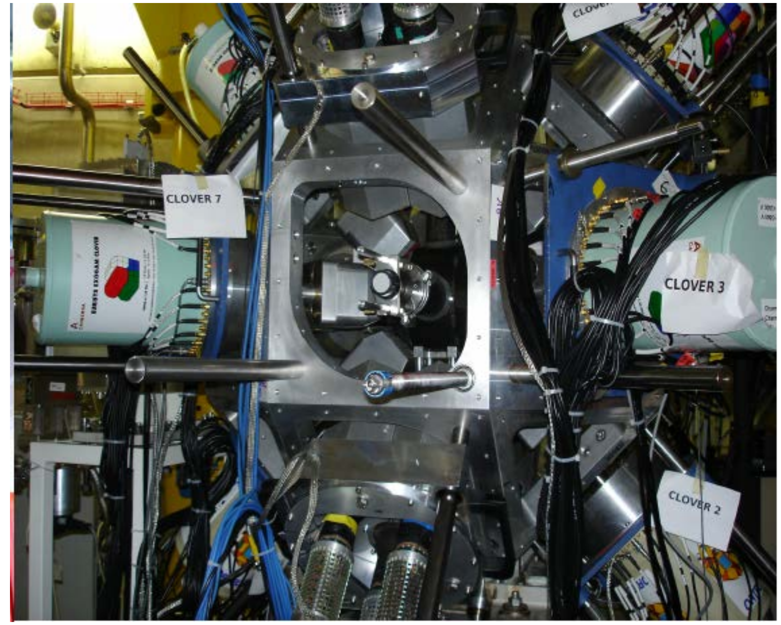


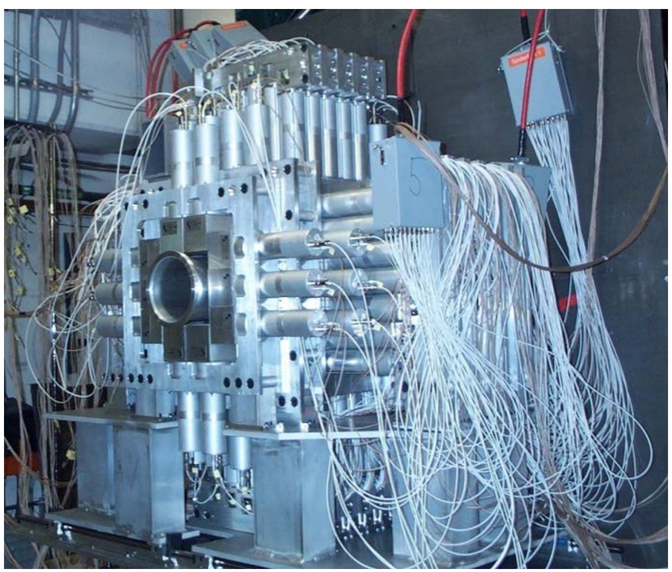


- Tag the population of excited states by measuring the decay γ rays. The γ-ray energy gives the energy difference between two states.

Gamma-rays to tag the final state

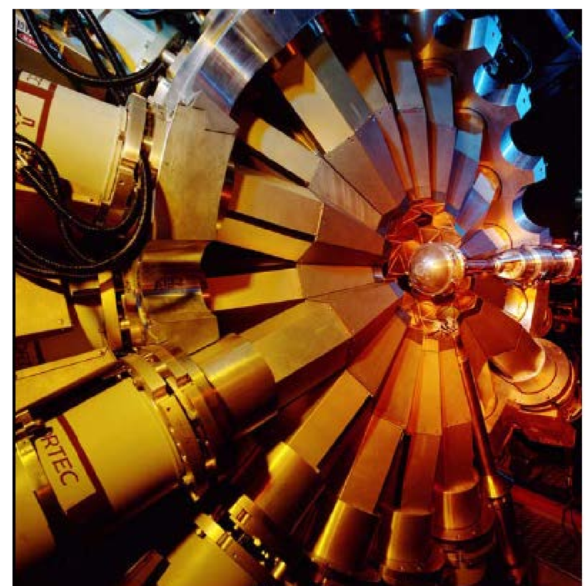






Germanium detectors:
Superior energy resolution, but low efficiency

Scintillator-based:
High-efficiency, moderate resolution

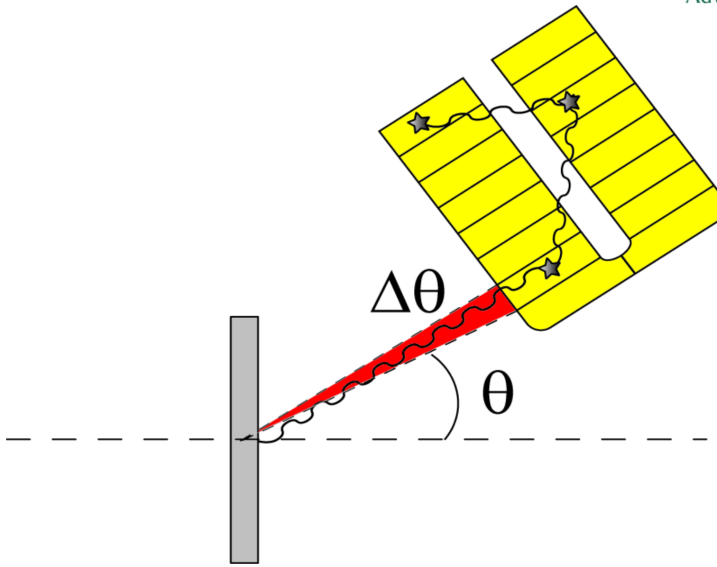


Emission in flight: Doppler shift!

NSCL NSF MICHIGAN STATE UNIVERSITY Advancing Knowledge. Transforming Lives.

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

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



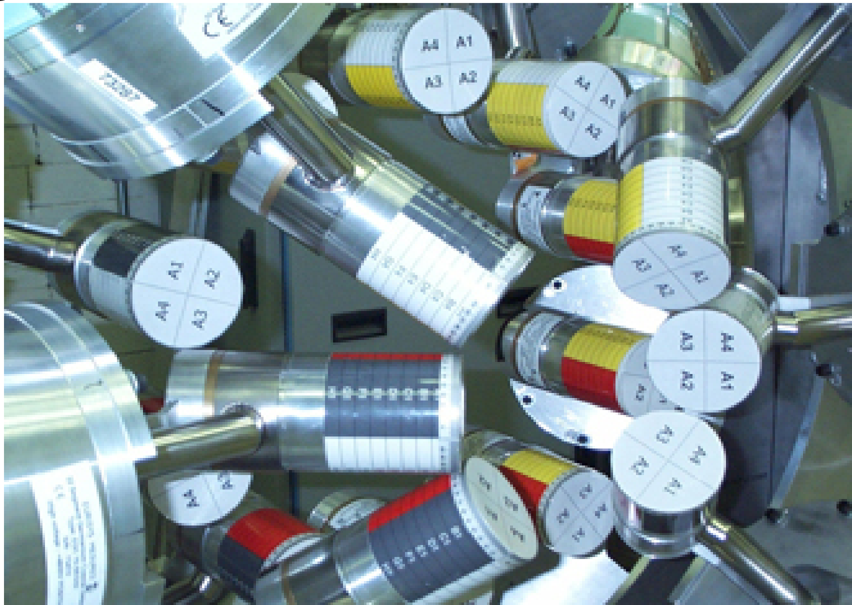
E_0 γ-ray energy in the source frame

E γ-ray energy in the lab frame

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

θ_0 γ-ray angle of emission

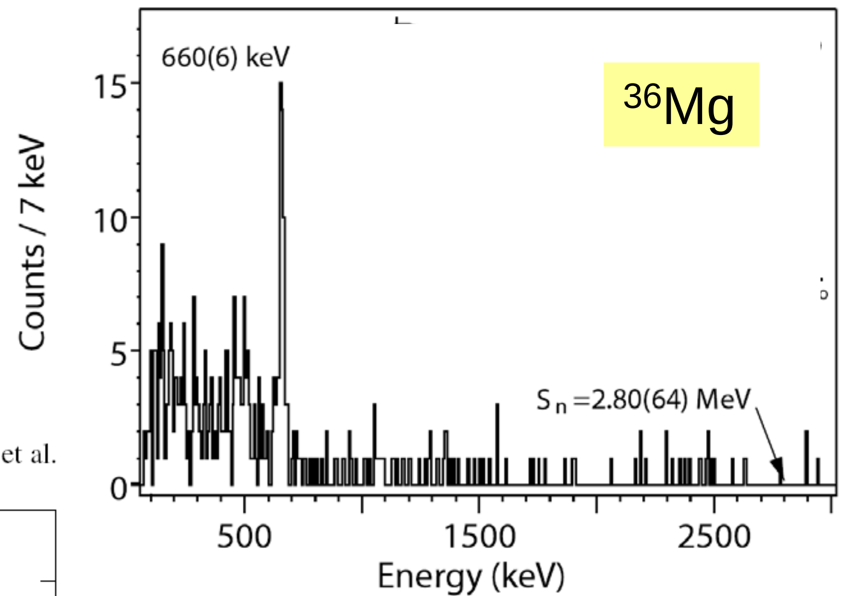
Example: SeGA geometry (NSCL)



Gamma-rays to tag the final state

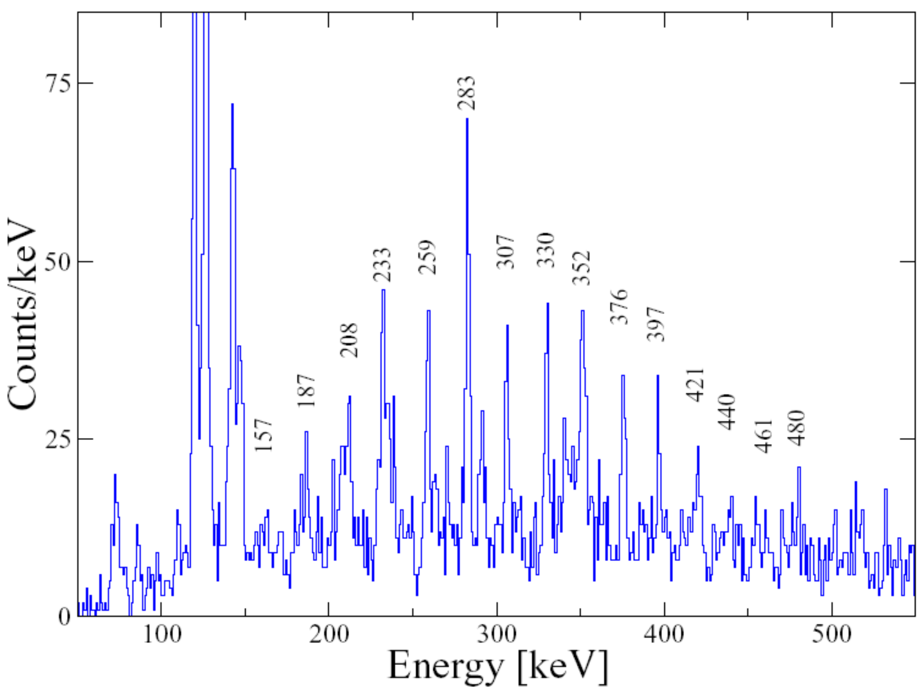
^{38}Si-2p at 83 MeV/u, SeGA @ NSCL

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



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

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

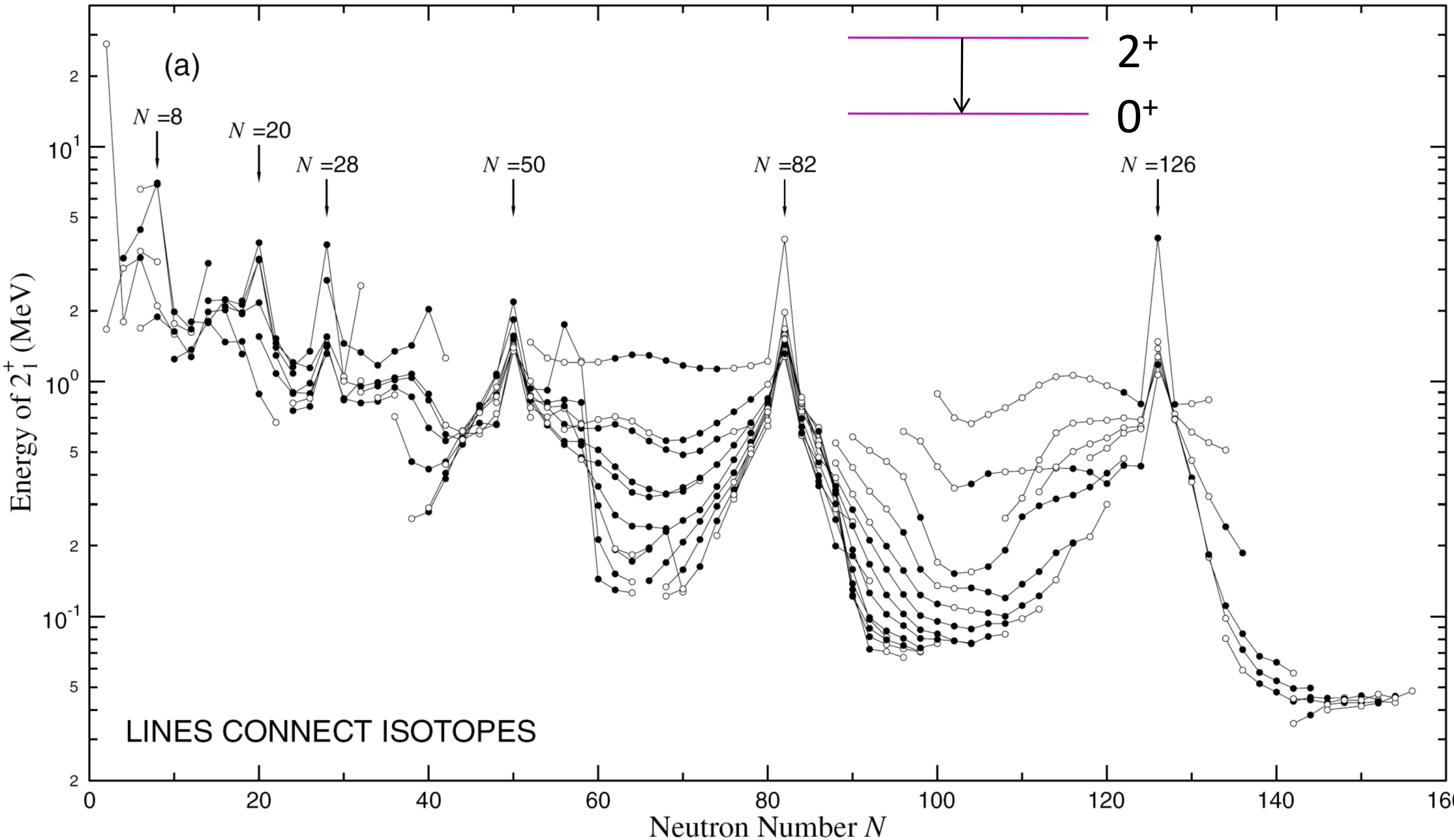


Low-energy fusion-evaporation reaction to produce ^{253}No. Many excited states are populated.

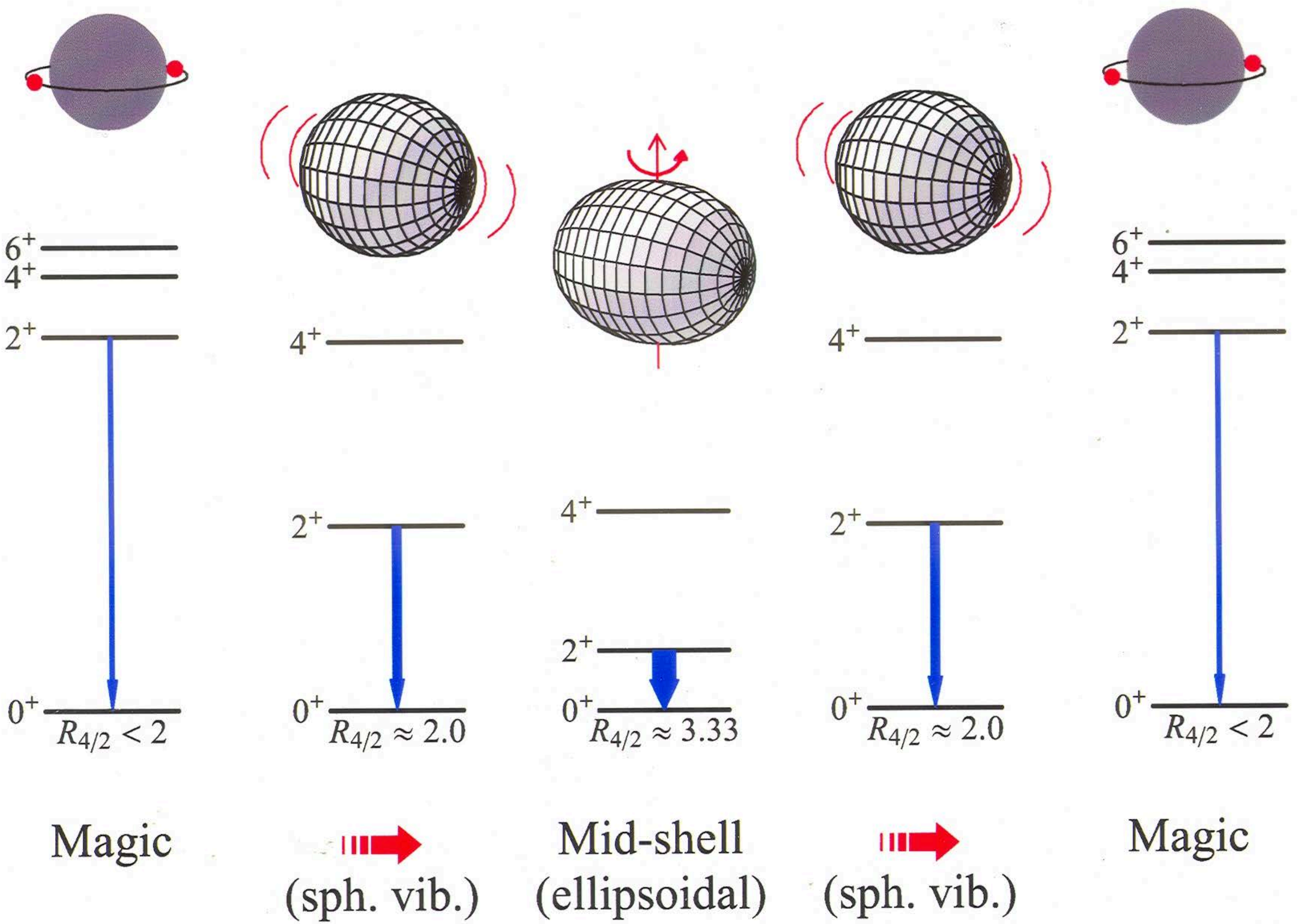
Collective excitations

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

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



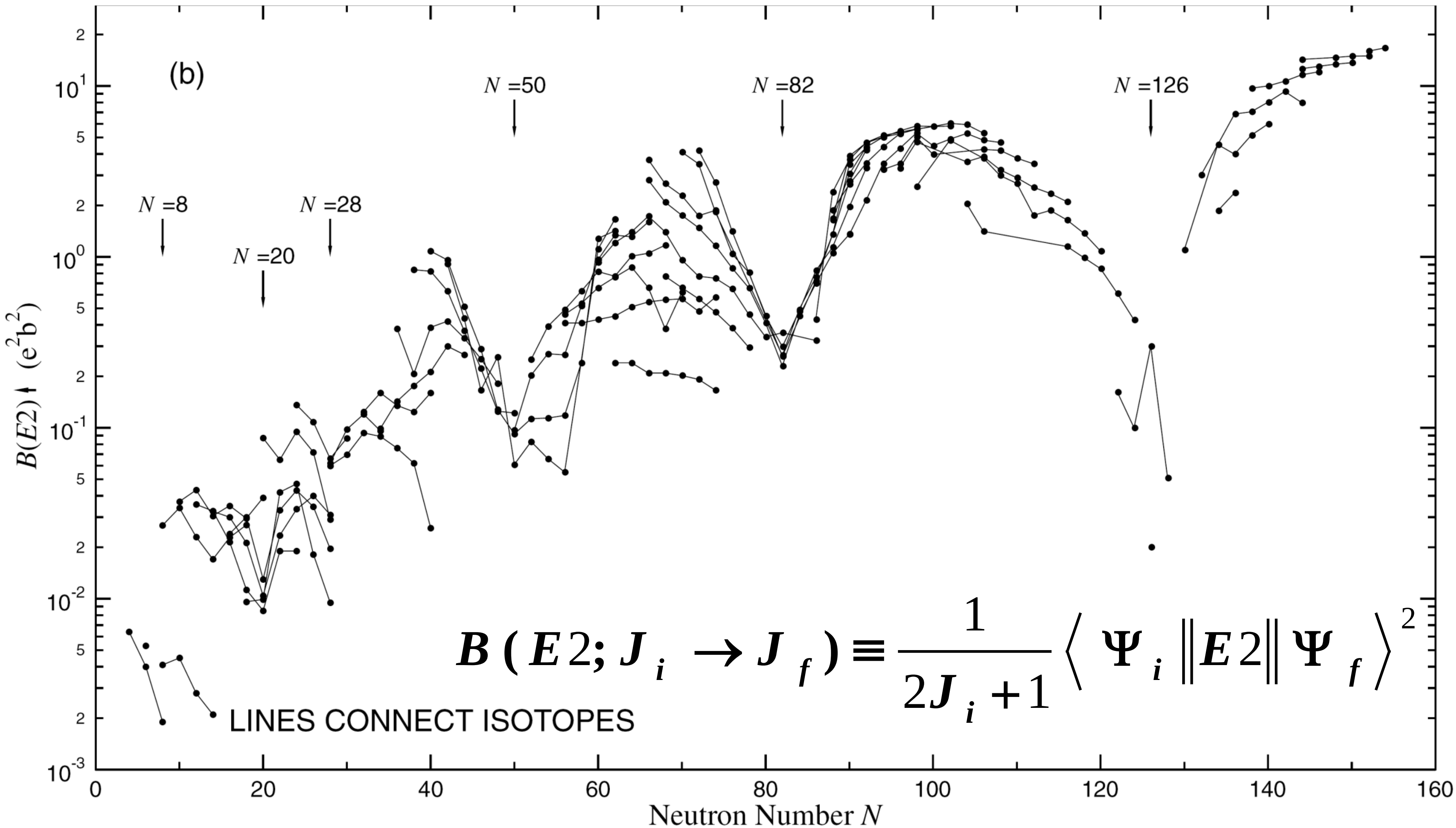
Even-even nuclei: 2^+ states are typically the first excited state on top of 0^+ ground states



Adapted from Rick Casten

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

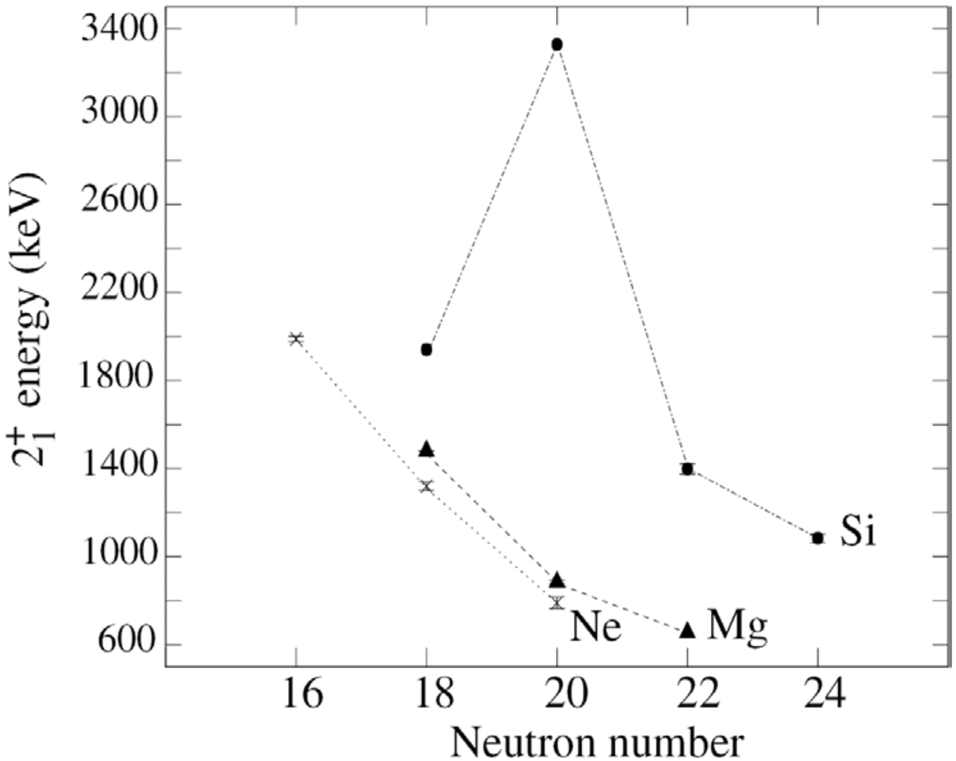
S. Raman et al., Atomic Data & Nuclear Data Tables 78, 1



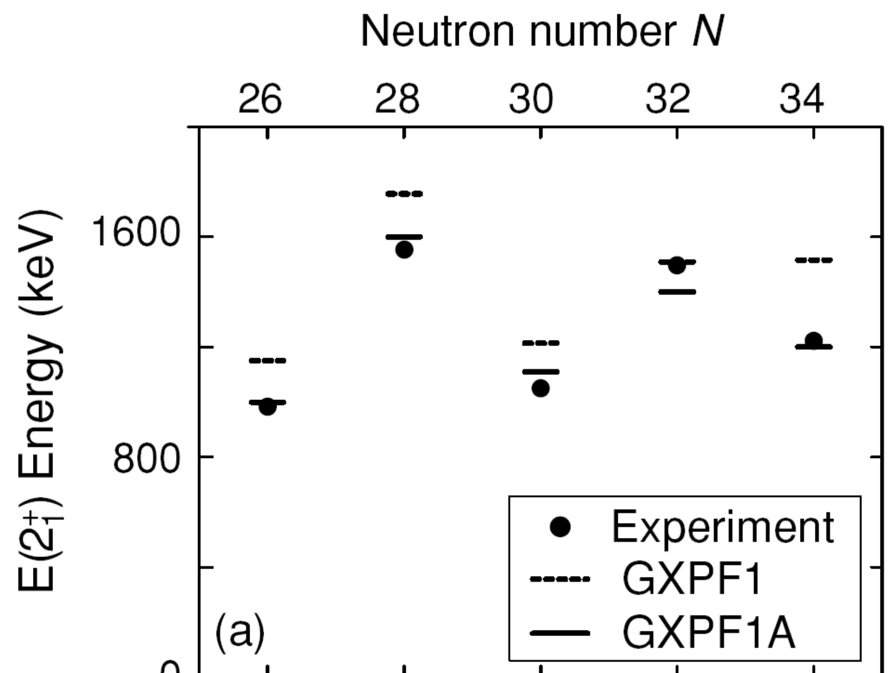
$$B(E2; J_i \rightarrow J_f) \equiv \frac{1}{2J_i+1} \left\langle \Psi_i \left\| E2 \right\| \Psi_f \right\rangle^2$$

Examples of changes in shell structure

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



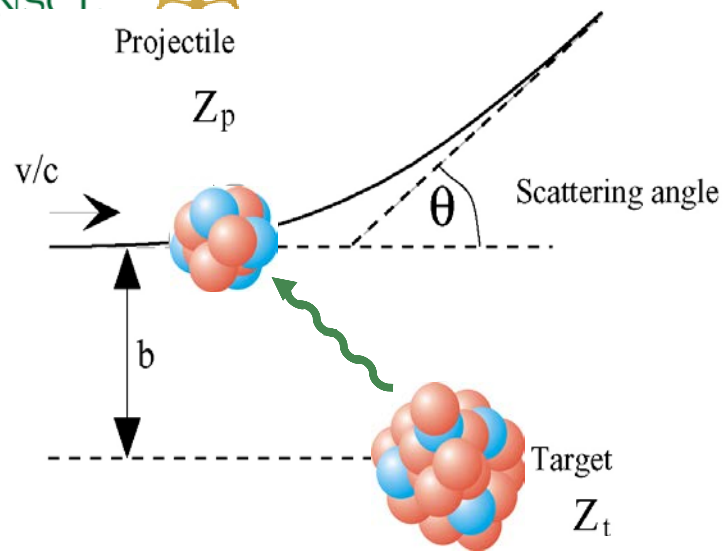
N=32 is a new magic number in the Ti isotopes

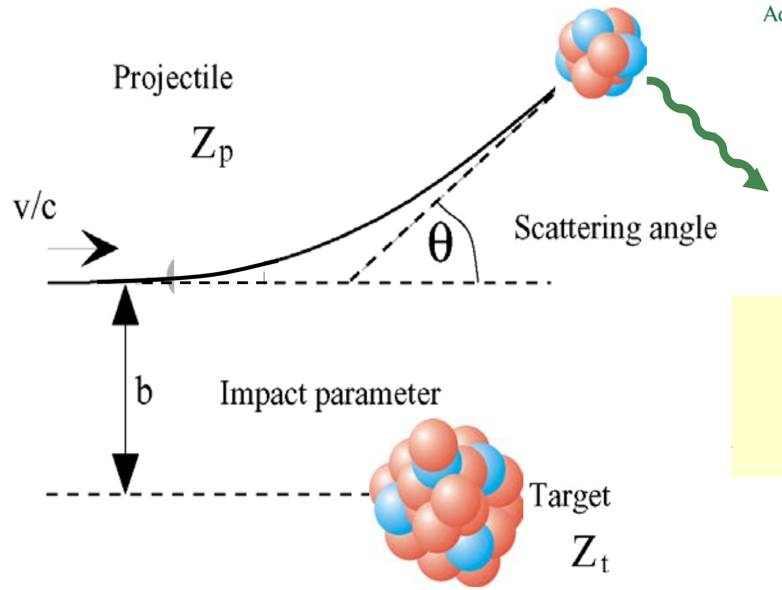


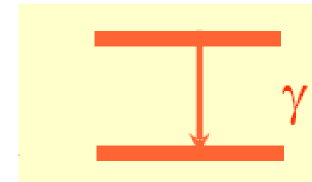
N=20 is not a good shell closure anymore in Mg and Ne isotopes

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, ISAC-II, CARIBU, Hie-ISOLDE):
E_x, $B(\sigma\lambda)$ excitation strength, band structures
($0^+ \rightarrow 2^+ \rightarrow 4^+ \rightarrow 6^+$)

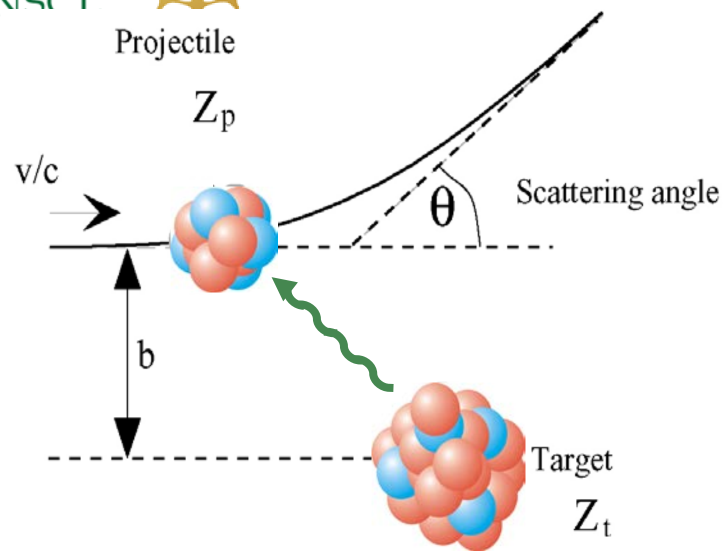
$$V_C(MeV) = \frac{1.44 \times Z_1 \times Z_2}{r(fm)}$$

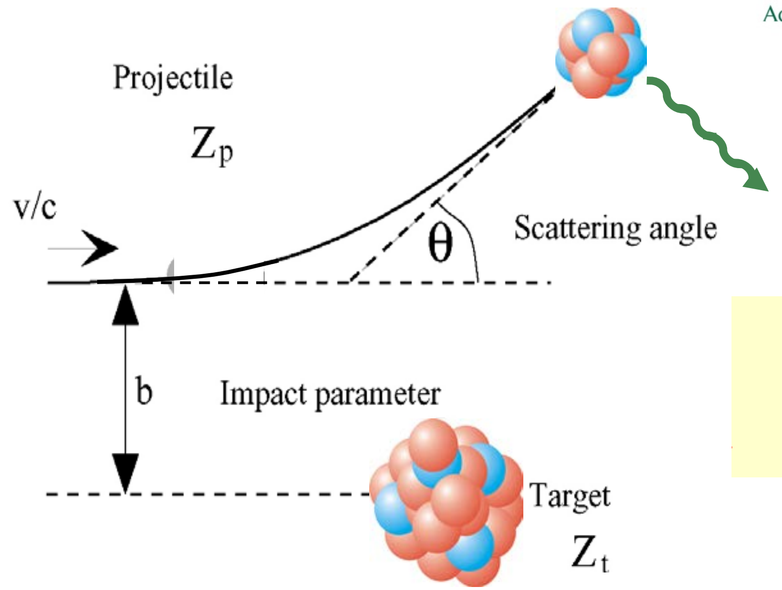
Beam energies well below the Coulomb barrier (ISOLDE, HRIBF):
Usually only the first 2^+ state accessible

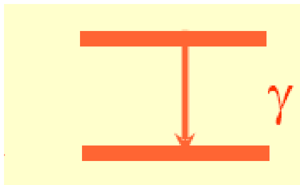
$$r(fm) \sim 1.2(A_1^{1/3} + A_2^{1/3})$$

A. Goergen, J. Phys. G 37, 103101 (2010)
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

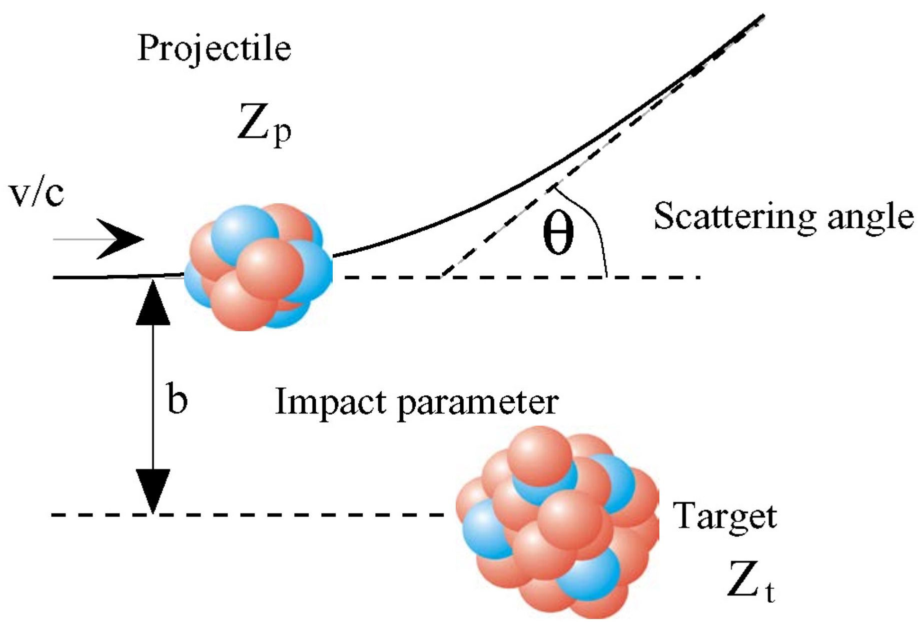
How can this still be Coulomb excitation?

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)

$$b_{\rm min} = \frac{a}{\gamma} \cot(\theta_{\rm max}^{\rm cm}/2)$$

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

Experiment:

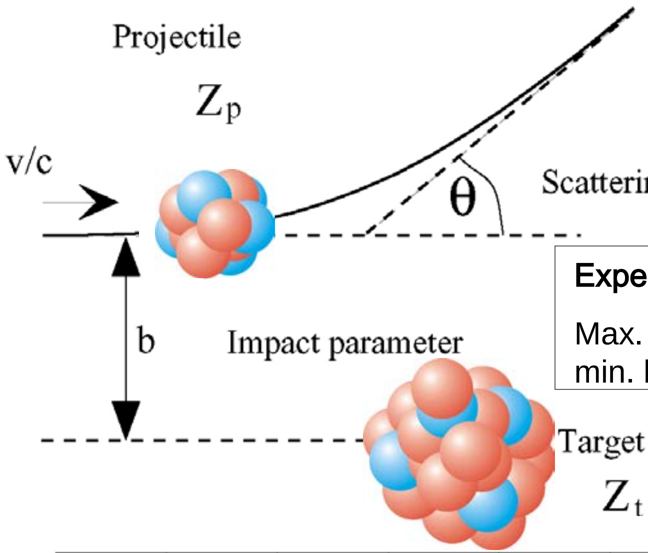
Maximum scattering angle determines minimum b. Restrict analysis to events at the most forward scattering angles so that b(θ) >R_{int}

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

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

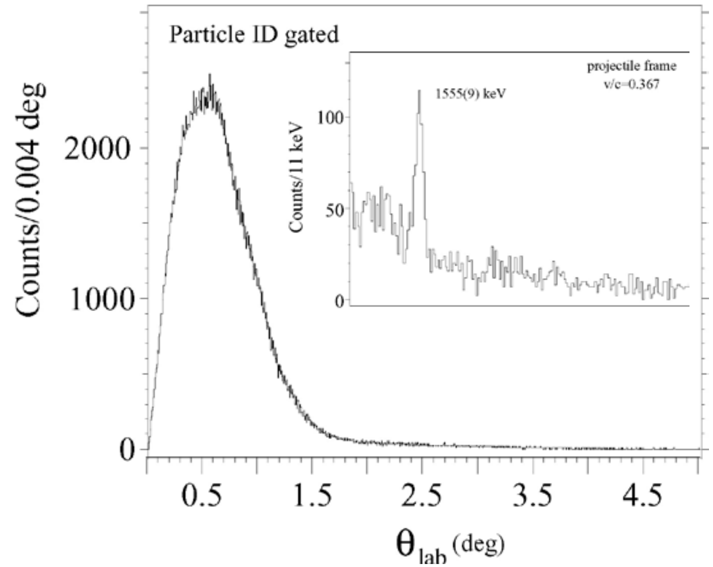
Advancing Knowledge. Transforming Lives.

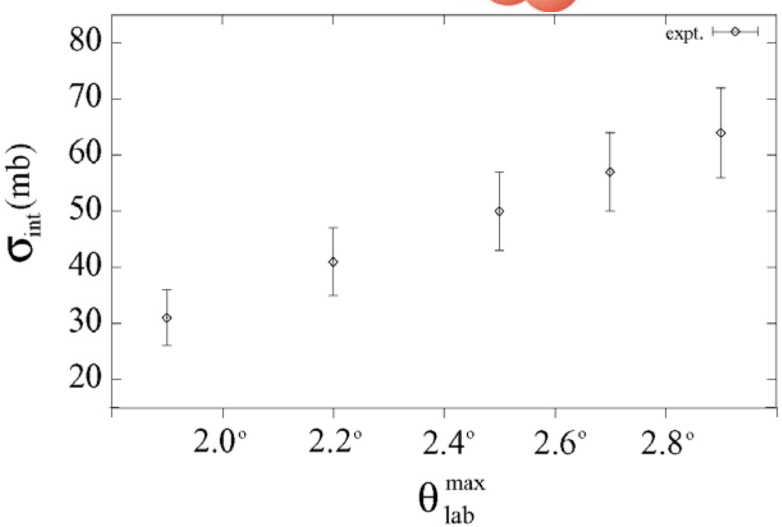
A. Gade *et al.*, PRC 68, 014302 (2003)

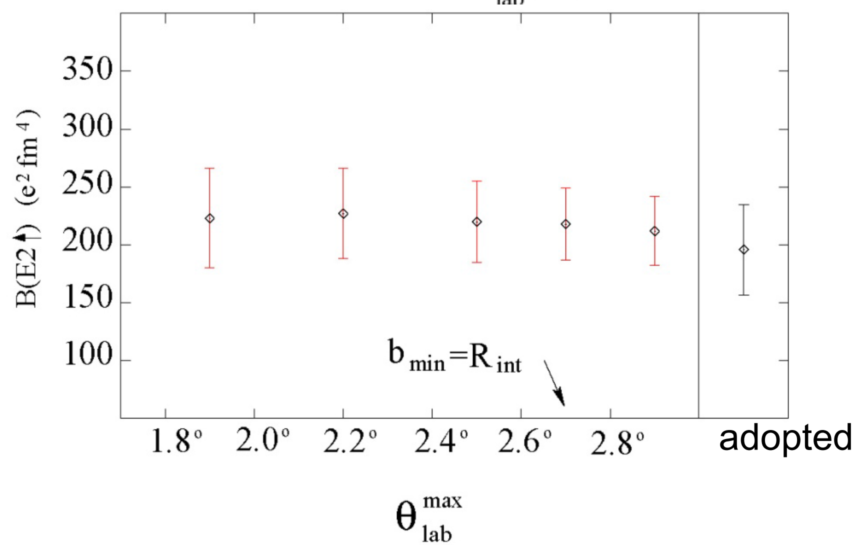


Experiment:

Max. θ determines min. b



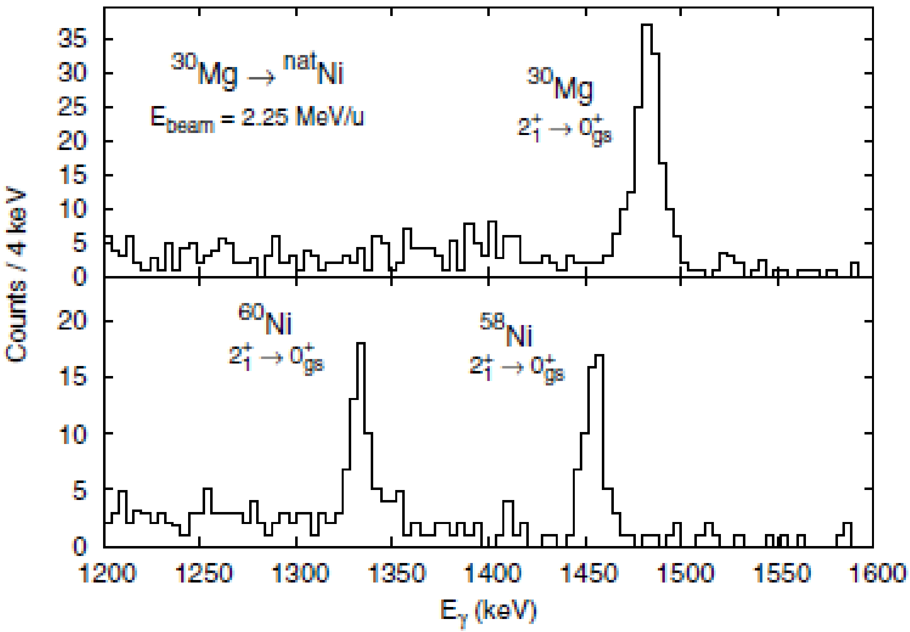




A. Winther and K. Alder, NPA 319, 518 (1979)

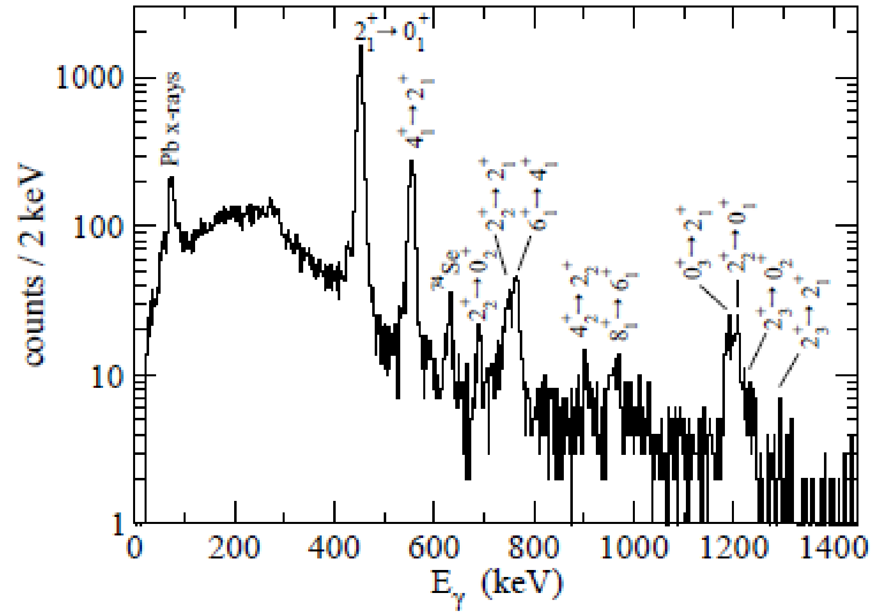
Low-energy Coulomb excitation
Example: ^{30}Mg + ^{58,60}Ni and ^{78}Kr + ^{208}Pb

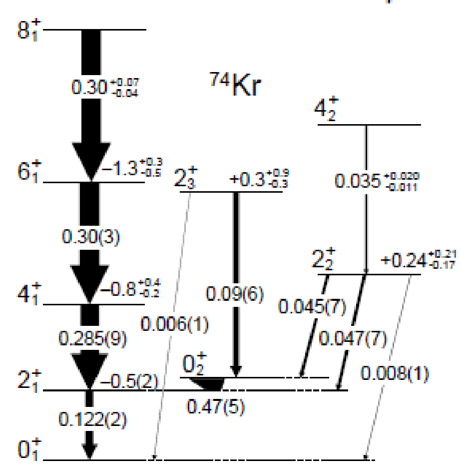
O. Niedermaier *et al.*, PRL 94, 172501 (2005)



^{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

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



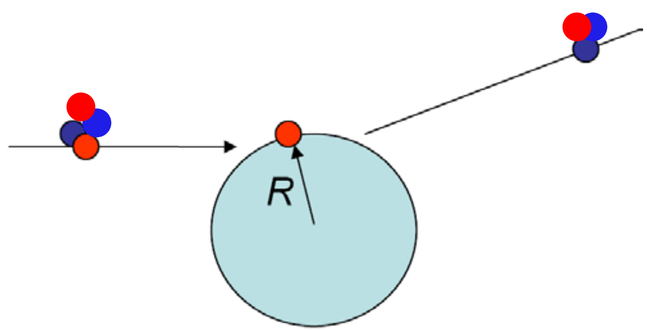


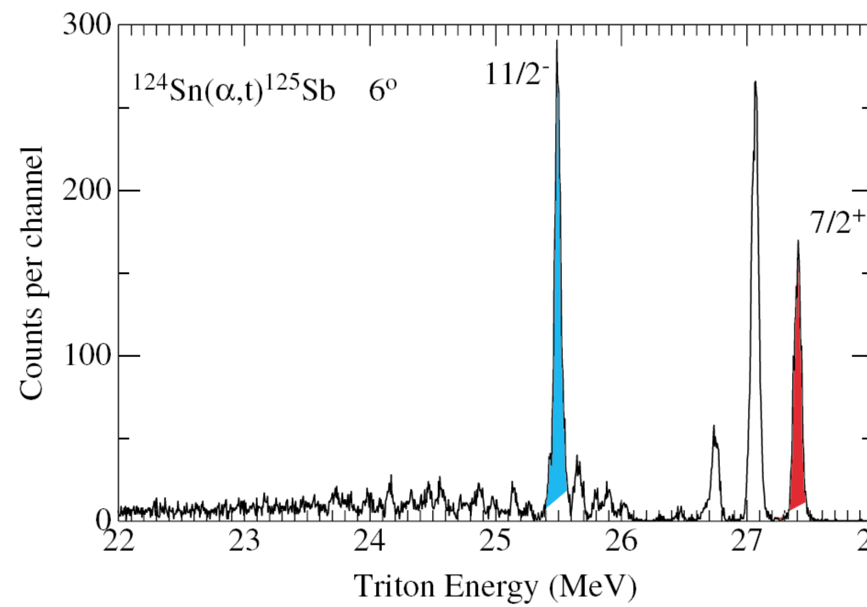
^{74}Kr multistep Coulex at 4.7 MeV/u on 1mg/cm^2 ^{208}Pb target at GANIL.
Data analysis done in a χ^2 minimization with a coupled channels code (GOSIA)

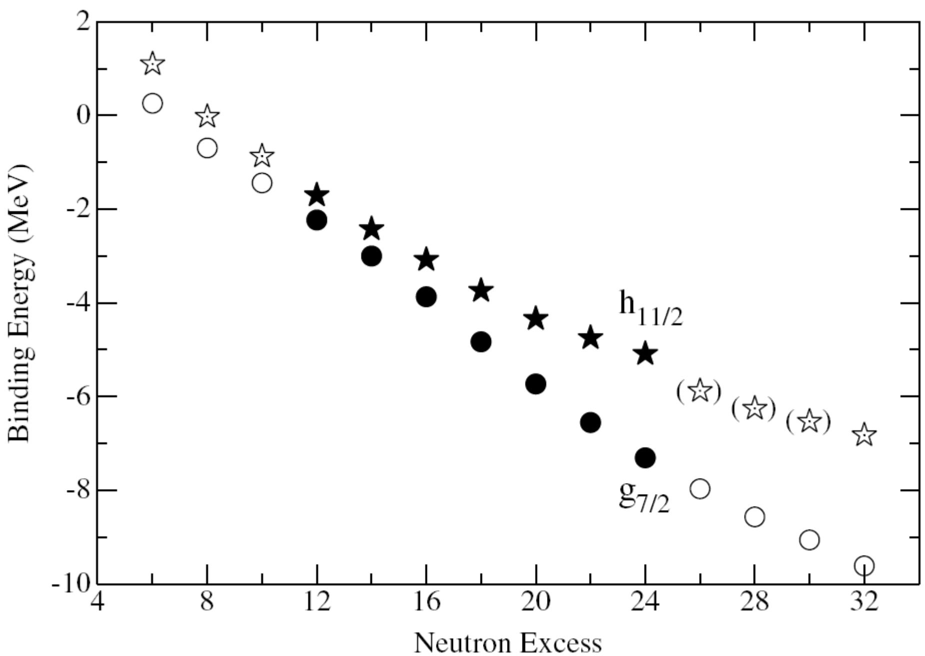
E. Clement *et al.*, PRC 75, 054314 (2005)

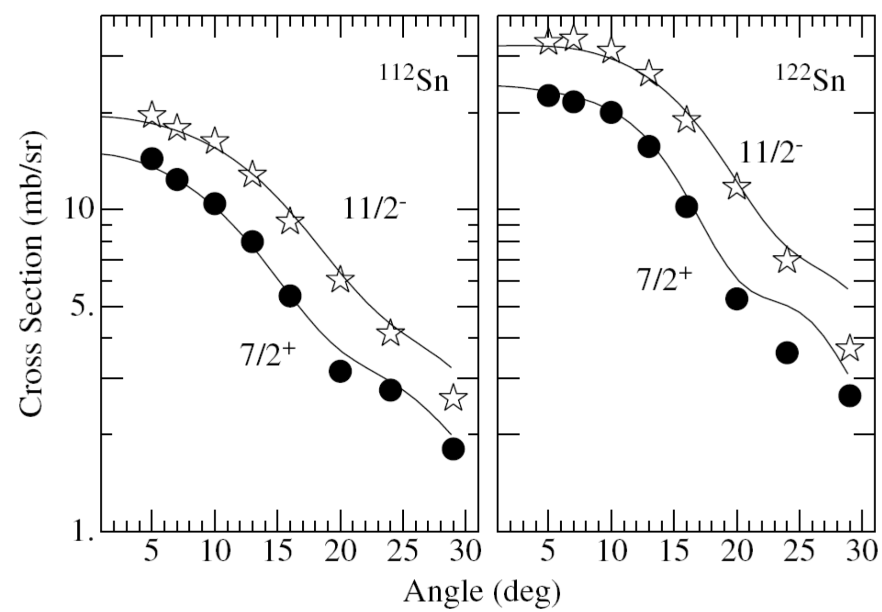
Single-particle states

Low-energy transfer reactions



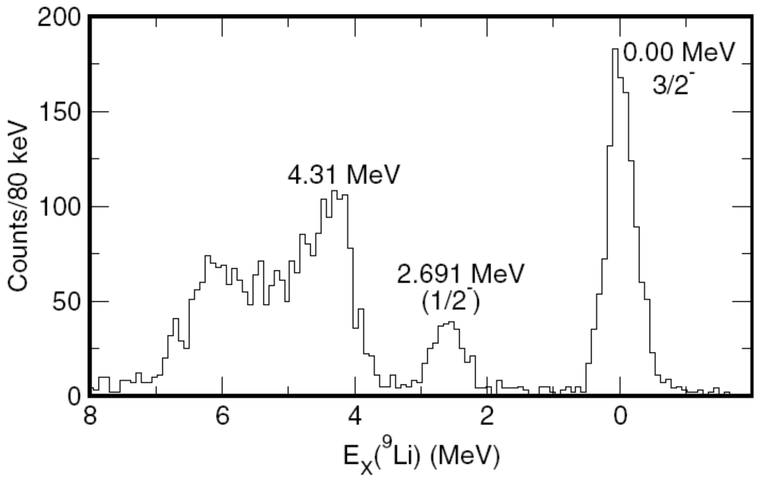






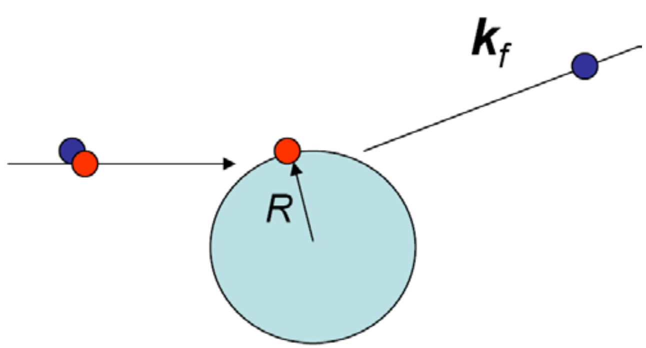
Low-energy transfer reactions

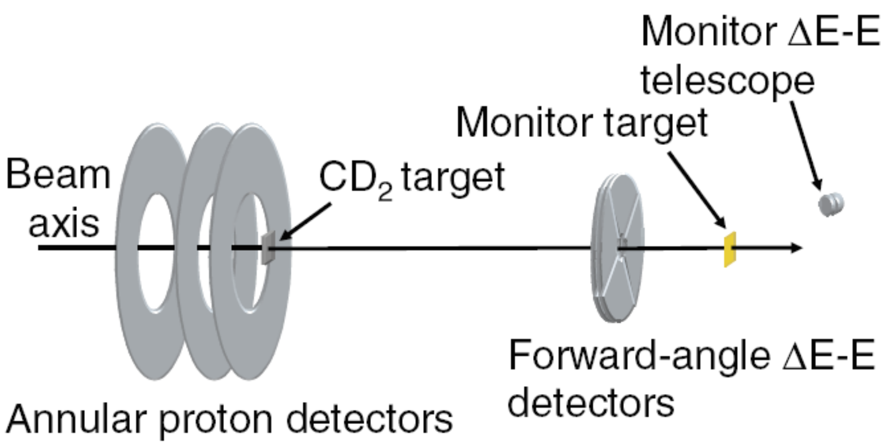
A. H. Wuosmaa et al., PRL 94, 082502 (2005)



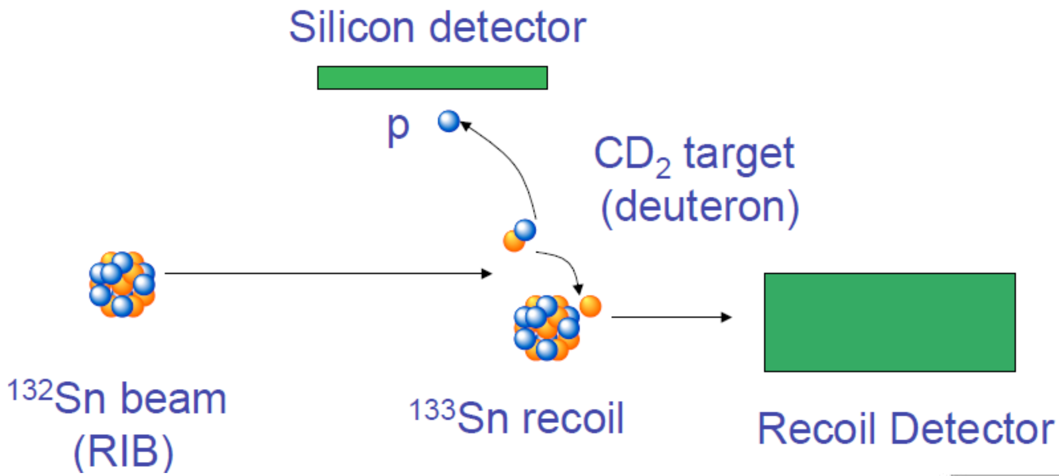
Low-energy inverse-kinematics transfer experiment

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



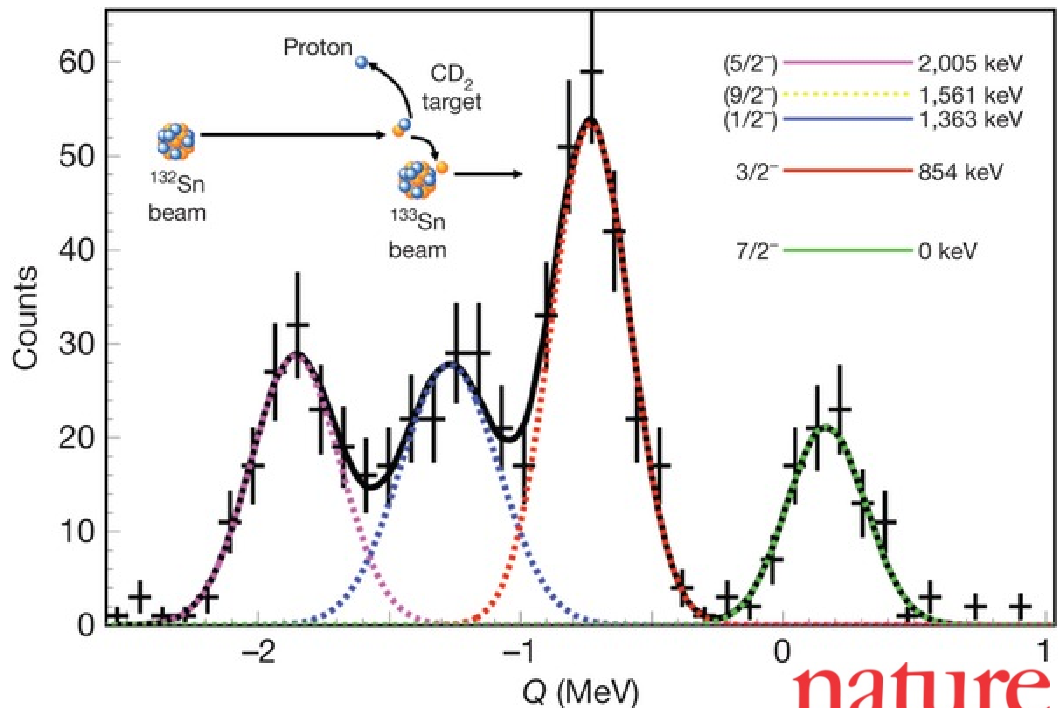


Low-energy transfer reactions – $^{132}Sn(d,p)^{133}Sn$ at HRIBF



Q-value spectrum for the $^{132}Sn(d,p)^{133}Sn$ reaction at 54° in the centre of mass.

- 4.77 MeV/u ^{132}Sn produced and accelerated at HRIBF bombarded a 160μg/cm^2 CD_2 target. Exit-channel proton detection with ORRUBA Si strip detectors under 69-107^o polar angles



KL Jones *et al.* *Nature* **465**, 454-457 (2010) doi:10.1038/nature09048

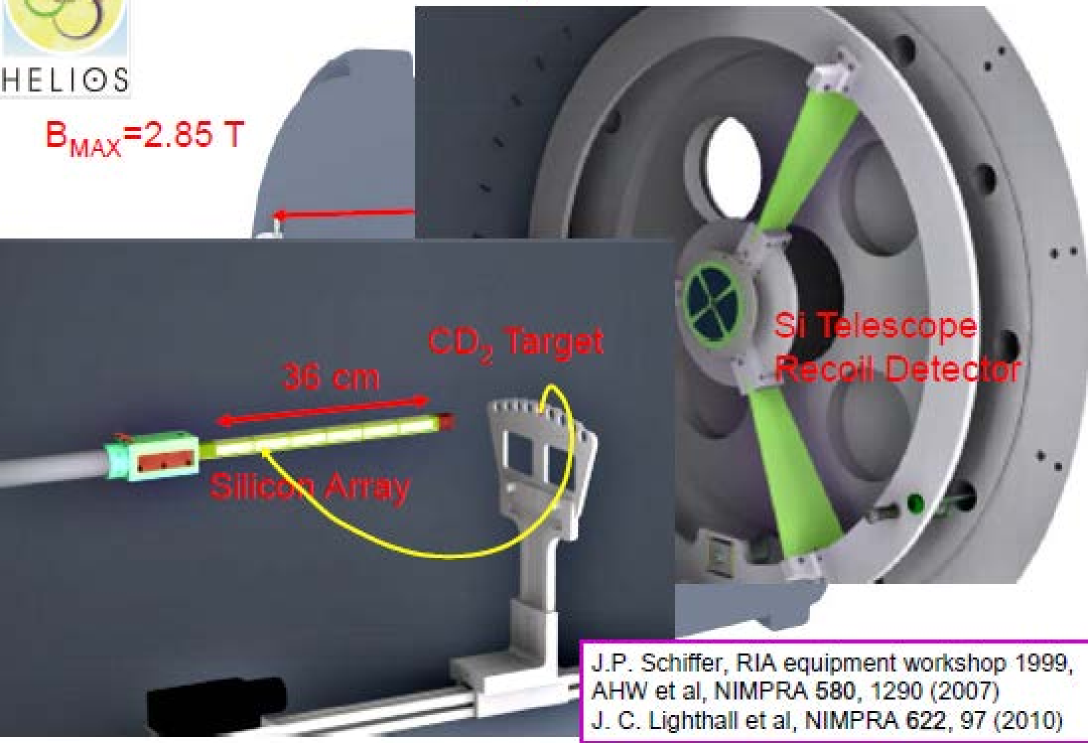
New kids on the block I
HELIOS

MICHIGAN STATE UNIVERSITY
Advancing Knowledge. Transforming Lives.

HELIcal Orbit Spectrometer -HELIOS

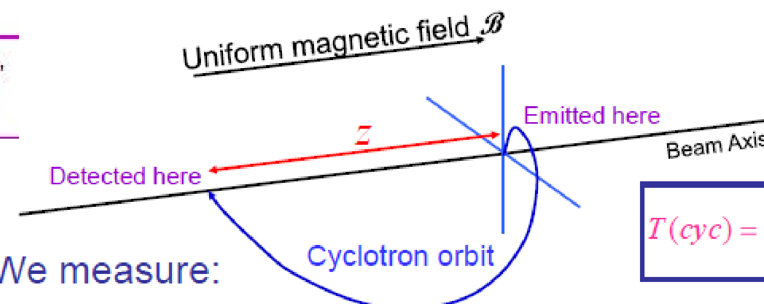
HELIOS

B_{MAX}=2.85 T



J.P. Schiffer, RIA equipment workshop 1999,
AHW et al, NIMPRA 580, 1290 (2007)
J. C. Lighthall et al, NIMPRA 622, 97 (2010)

In a magnetic field with HELIOS



$$T(cyc) = \frac{2\pi m}{qB}$$

We measure:
E_{lab}, z, TOF
We deduce:
E_{CM}, θ_{CM}

$$z \propto \cos\theta_{CM}$$

$$E_{lab} = E_{CM} - A + Bz$$

$$\Delta E_{lab} = \Delta E_{CM}$$

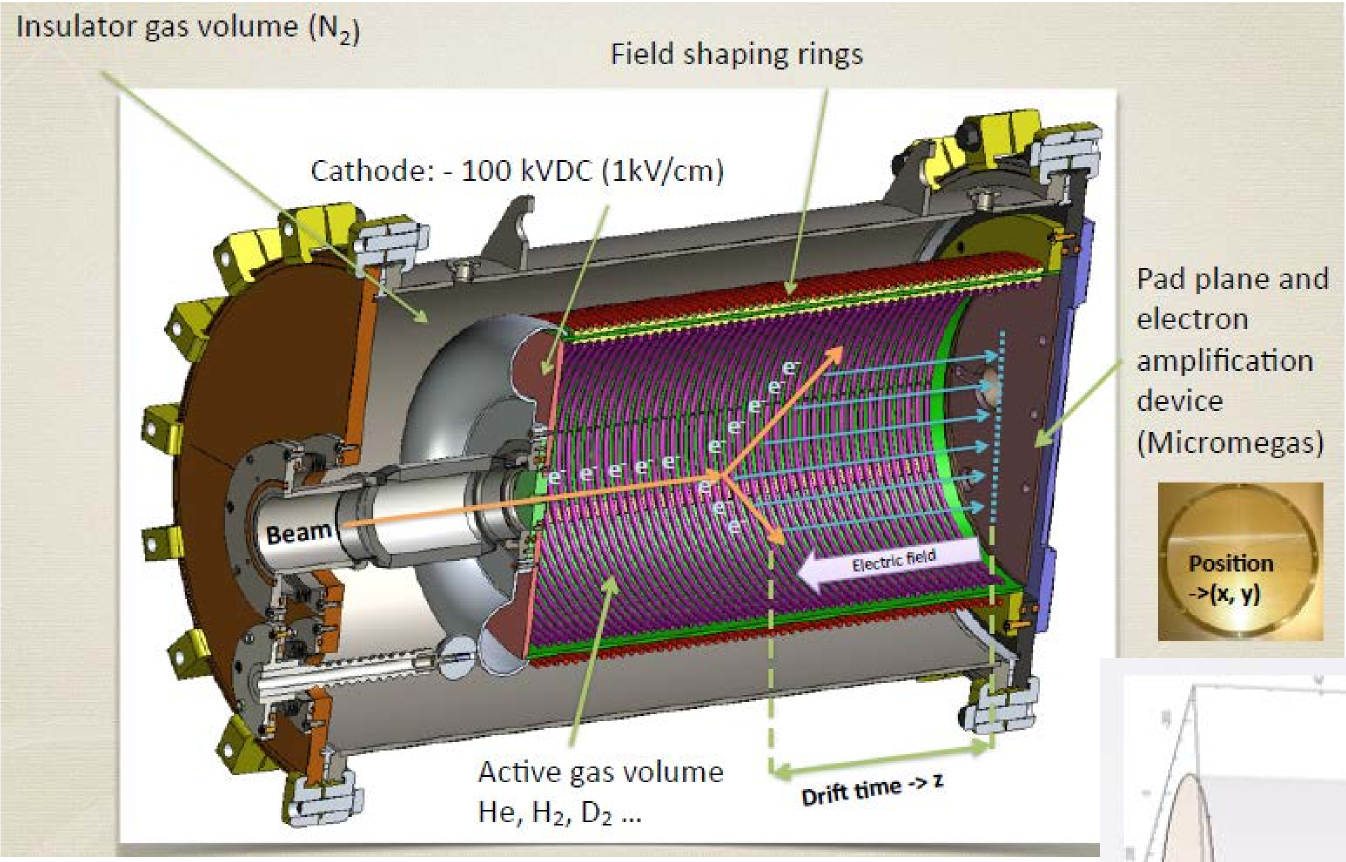
For a given state

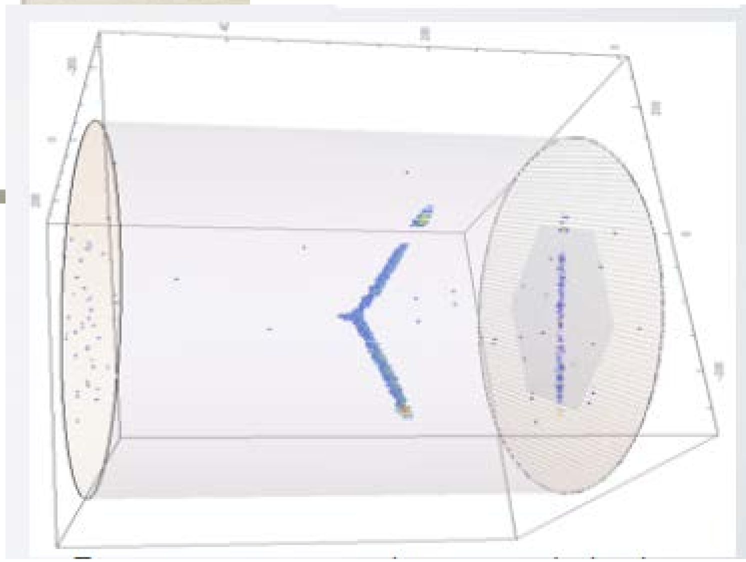
For two states at fixed z

NSCL NSF

New kids on the block II
Time projection chambers

MICHIGAN STATE UNIVERSITY
Advancing Knowledge.
Transforming Lives.

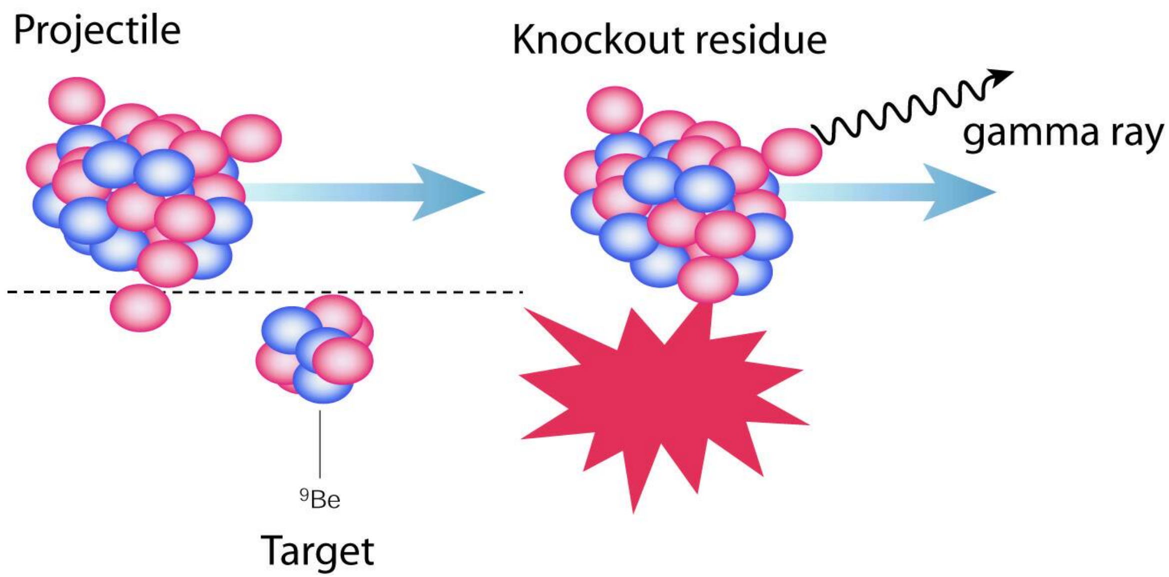


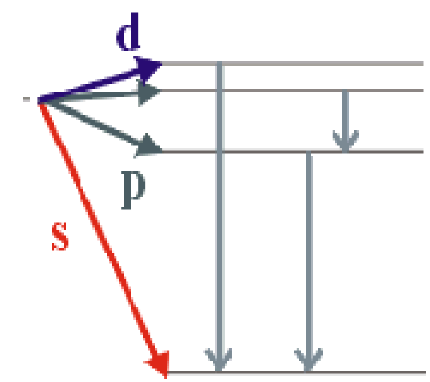


One-nucleon knockout
A direct reaction

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

  Straight-line trajectories



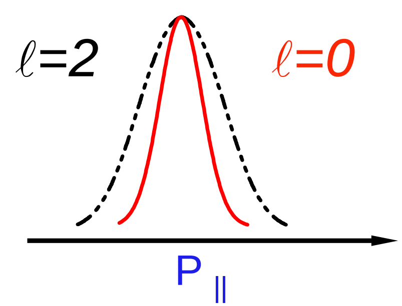


residue moment distribution
→ ℓ-value of knocked-out n

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

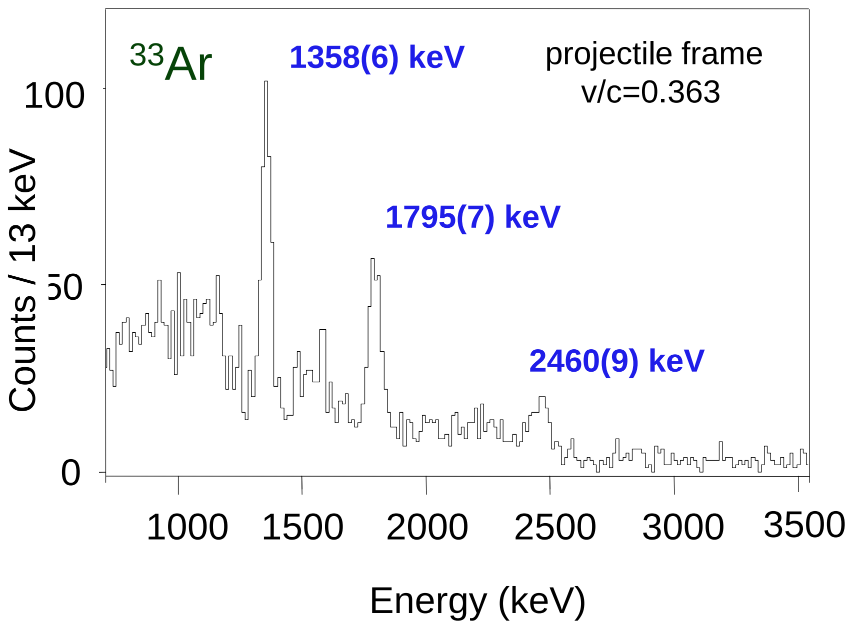
$$\sigma(nl^{\pi}) = C^2S(j, nl^{\pi})\ \sigma_{sp}(j, S_n)$$

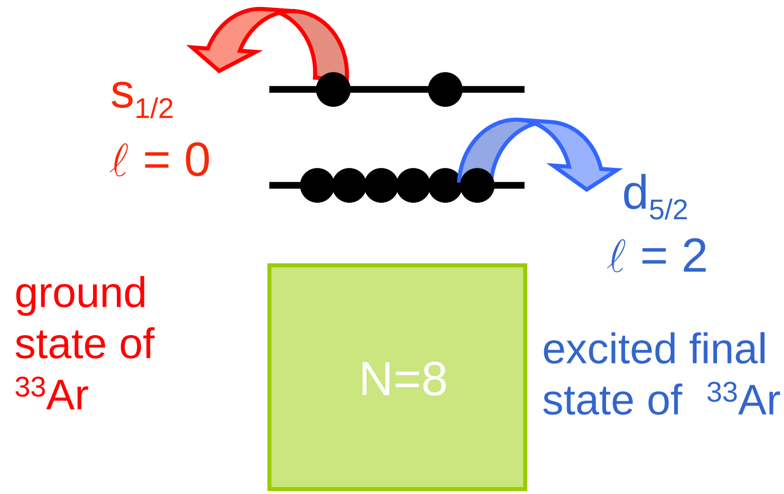
\# nucleons in orbit   reaction cross section



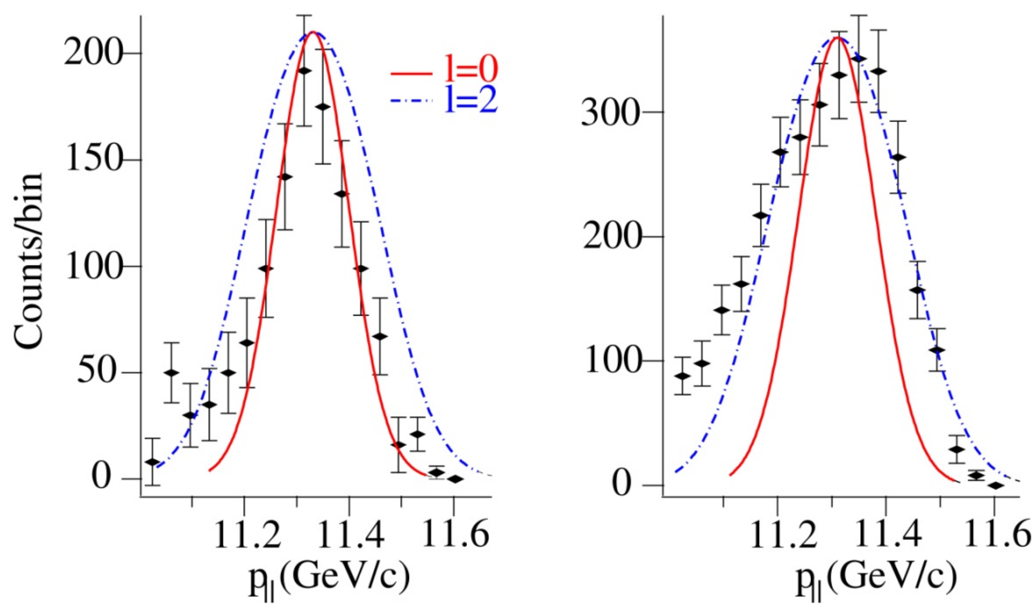
P.G. Hansen and B.M. Sherrill, NPA 693 ,133 (2001).
P.G. Hansen and J. A. Tostevin, Annu. Rev. of Nucl. and Part. Sci. 53, 219 (2003).

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





	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).

NSCL

Michigan State University

Advancing Knowledge. Transforming Lives.

Lifetimes of excited states

Can provide information on collective and single-particle degrees of freedom

Lifetimes of excited states

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

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

Some excited states live much longer: Isomers

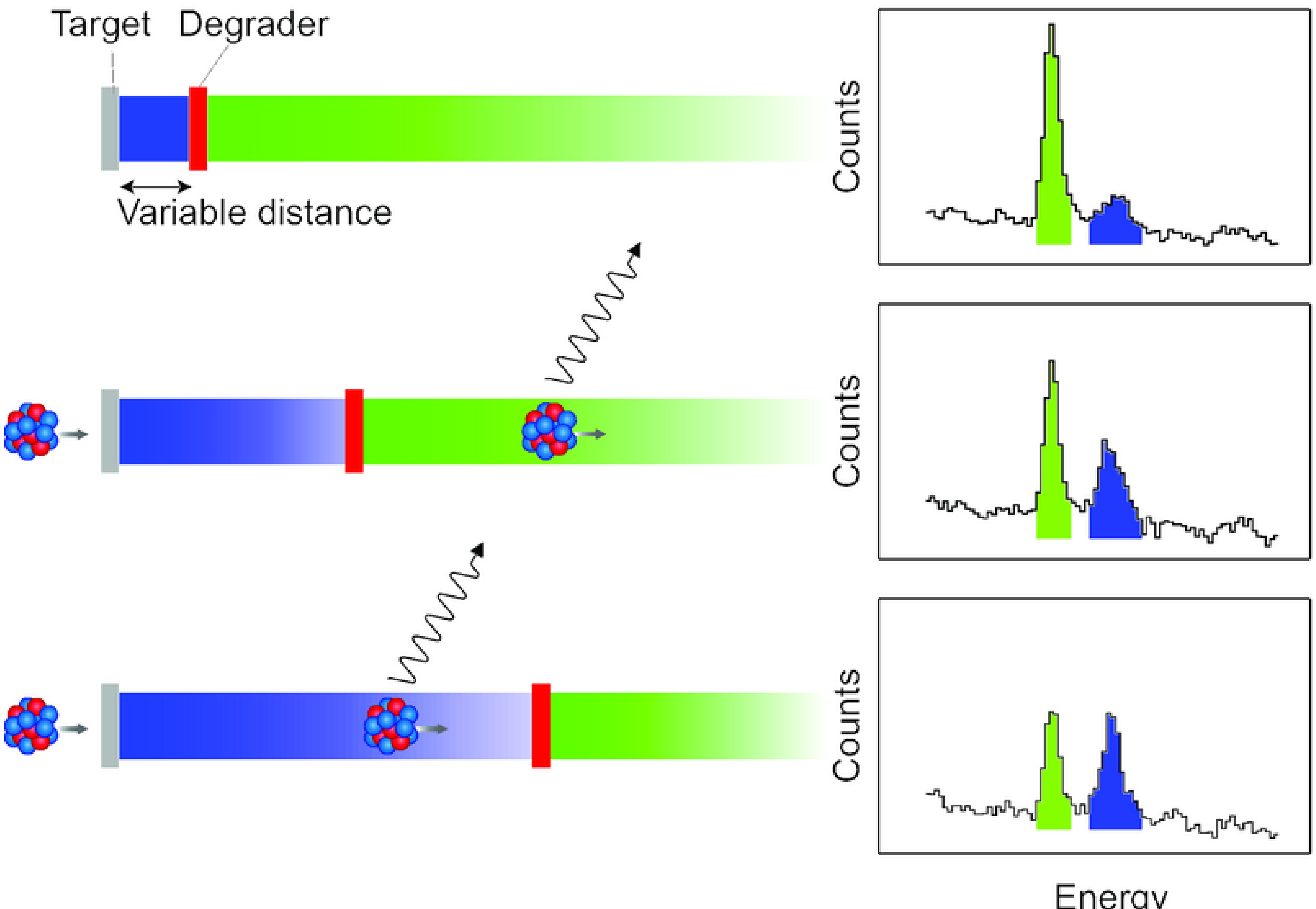
Table I: Examples of extreme isomers

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

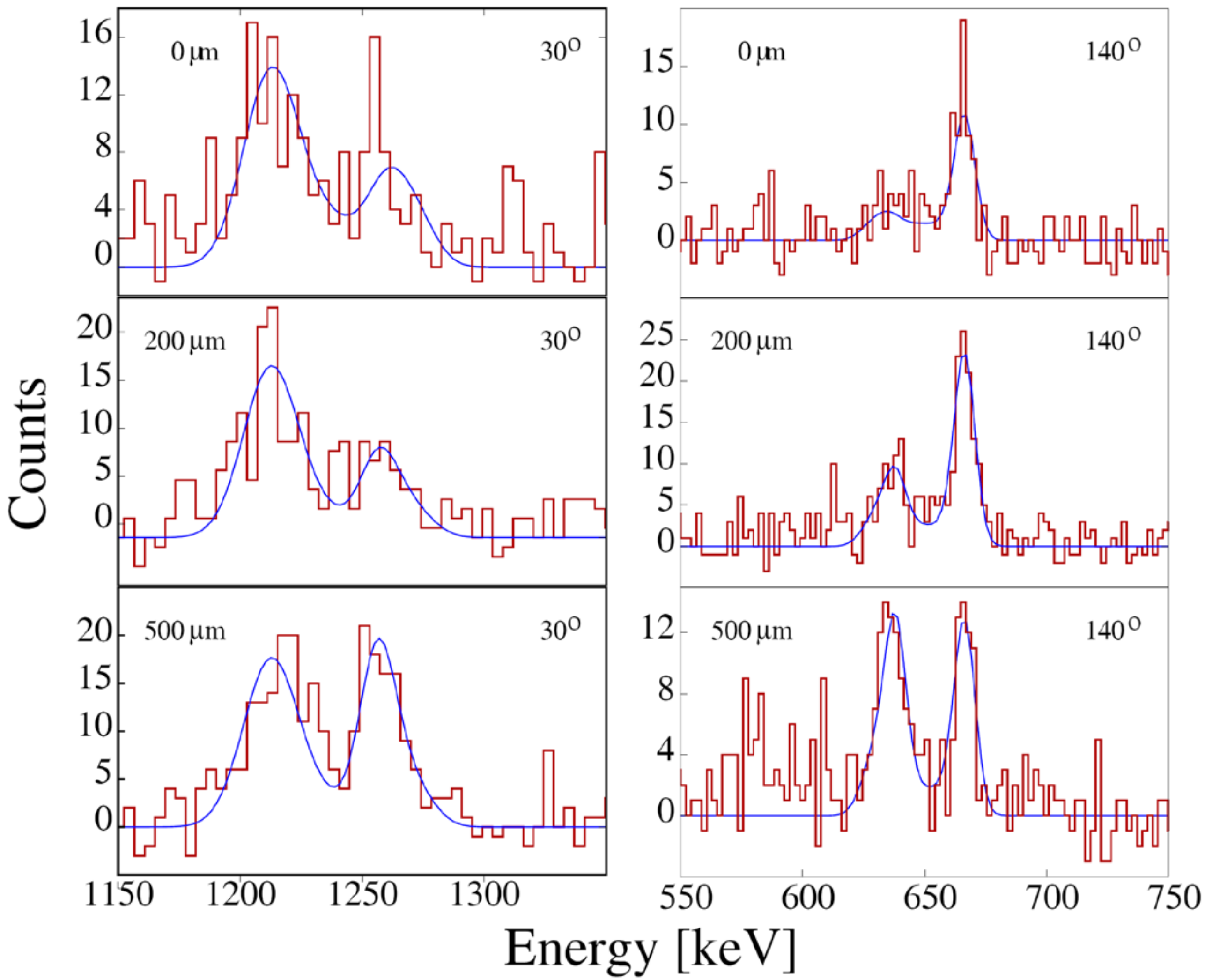
c=300 μm/ps β ~ 0.3c 10 ps ~ 1mm



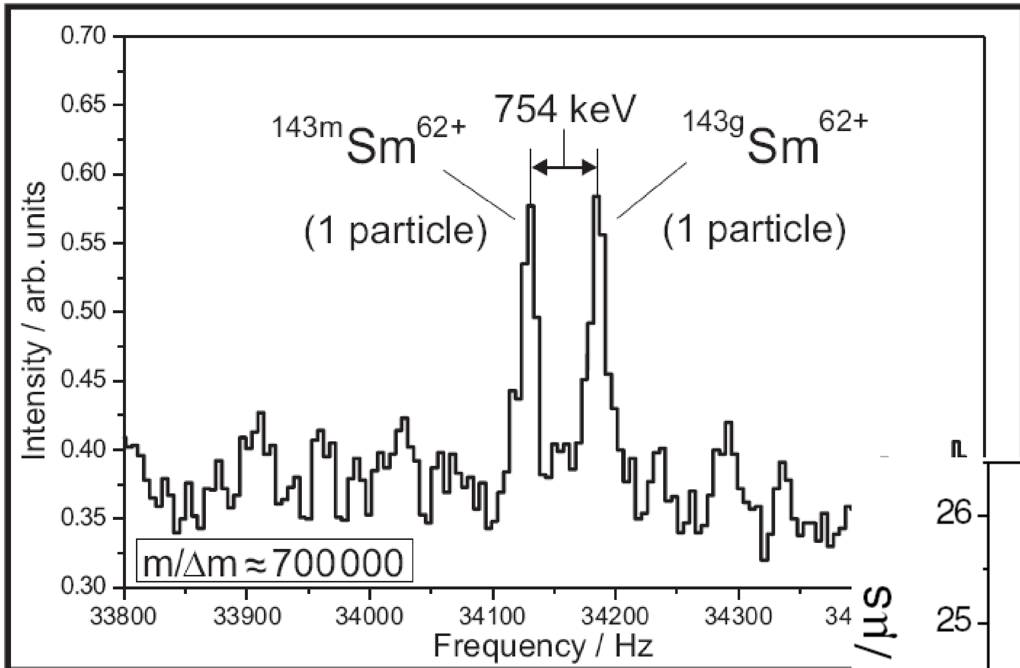
Adapted from K. Starosta

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

τ=3.2(5) [ps]

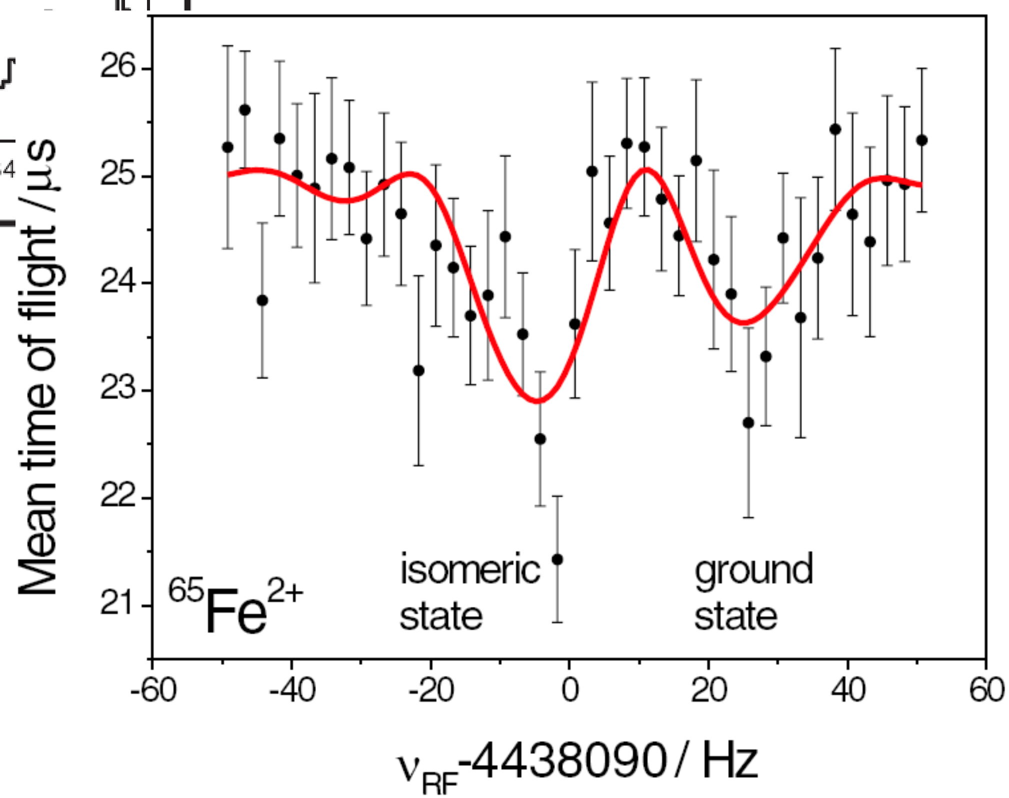


Long-lived excited states – isomers
Back to storage rings and penning traps



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

Take away

- Excited states provide valuable information on the evolution of nuclear structure
  - Population of excited states in various schemes
- Reactions – powerful tools
  - Observables related to the collective degree of freedom
  - Single-particle structure from direct reactions
- Life-times of excited states
  - Different experimental approaches