Nucleon-Transfer Reactions with Radioactive Ion Beams

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14-19 July 2017

Nuclear Physics with Stable and Radioactive Ion Beams

Lecture 1/3

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About myself

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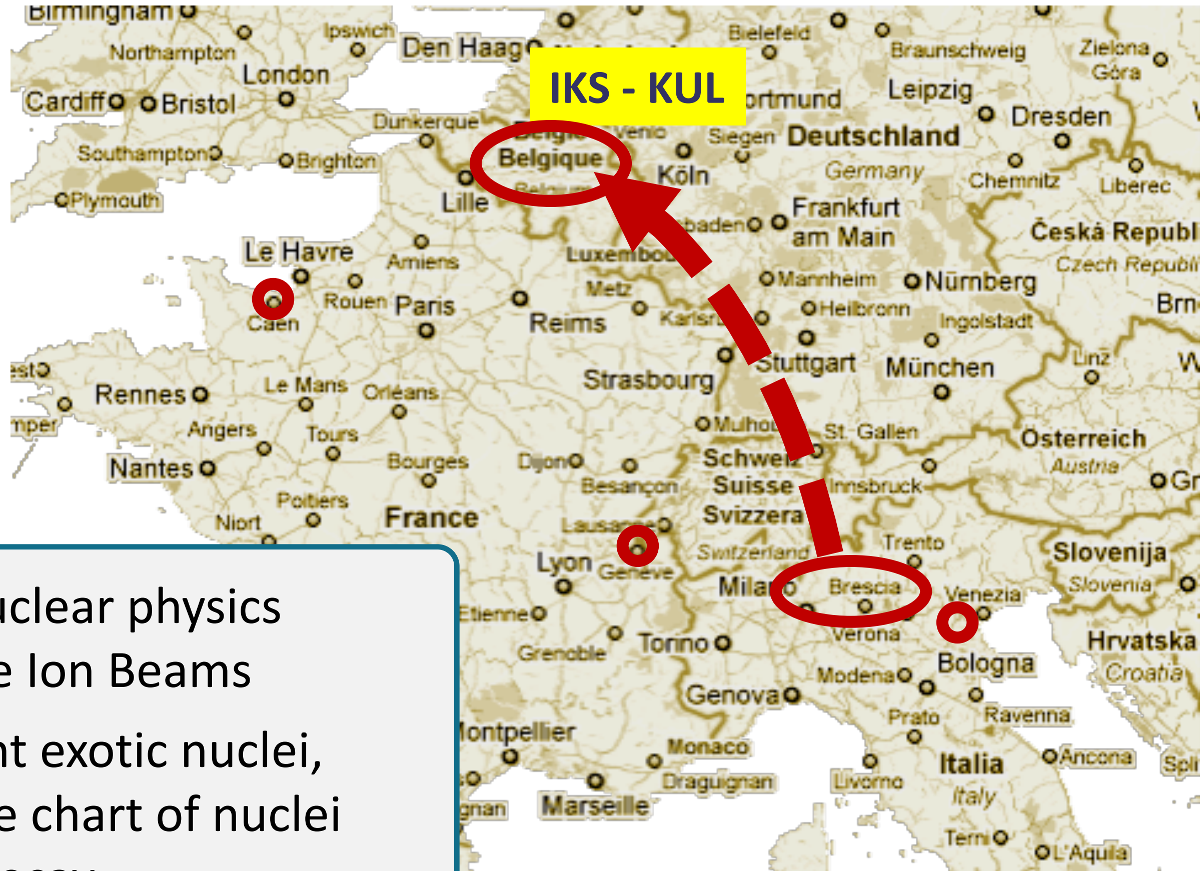
About myself



- Experimental nuclear physics with Radioactive Ion Beams
- Started with light exotic nuclei, moving up in the chart of nuclei Reactions and decay
- Development of new instruments

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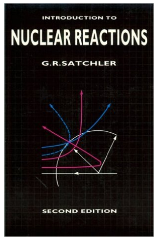
Contents

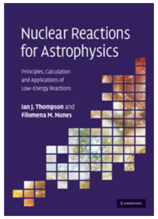
- Nuclear reactions
  - Types of reactions
  - Characteristics of direct reactions
- Why use transfer reactions
  - Information from reactions
  - Q-value, angular momentum, spectroscopic factors
- Reactions and RIBs
  - Motivations
  - Challenges: inverse kinematics
- Case studies
  - Light nuclei
  - Transfer and gammas Ne-Na
  - Mg and Ni, the 0^+s
  - Ni region
  - Sn region
  - …

References

Nuclear reactions

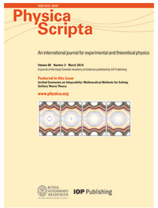


- GR Satchler
  Introduction to Nuclear Reactions
  MacMillan



- IJ Thompson and FM Nunes
  Nuclear Reactions for Astrophysics
  Cambridge University Press

Physics with RIBs



- Nobel Symposium 152:
  Physics with Radioactive Beams
  Physica Scripta T152

Survey of shell evolution far from stability

- O Sorlin and M-G Porquet
  Progress in Particle and Nuclear Physics 61 (2008) 602

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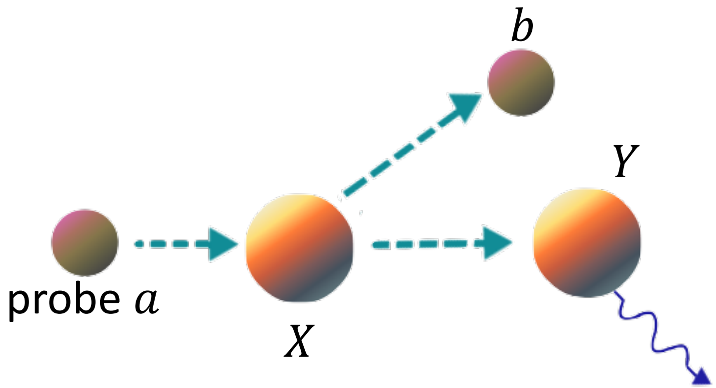
Nuclear reactions

- A nucleus X collides with a probe a (particle, γ-ray).
  In the collision they exchange energy, momentum and possibly mass
  As a result we obtain a product nucleus Y and some outgoing radiation b (particle, γ-ray)

$$a + X \rightarrow b + Y$$



- Alternative notation:

$$X(a, b)Y$$

  Puts the accent on the process (a, b)

- Two aspects:
  - study the reaction mechanism
  - use reactions to investigate the structure of nuclei ($\rightarrow$ use simple probes)

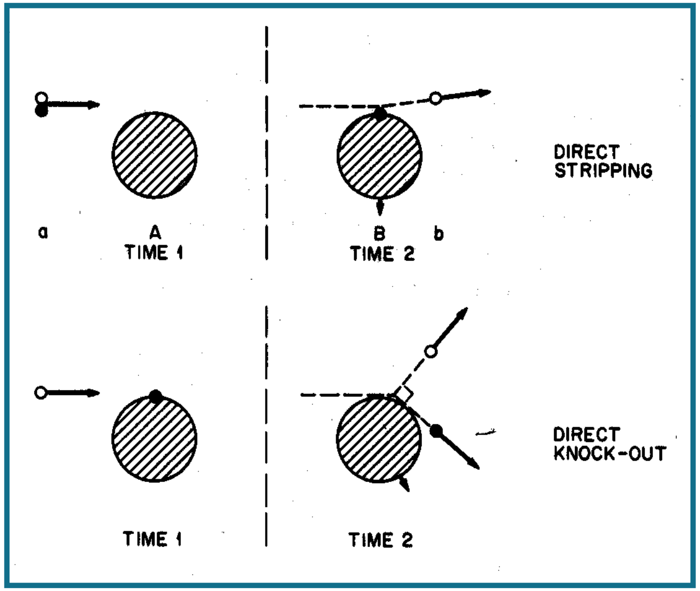
Types of reactions (list not exhaustive)

- Elastic scattering: $X(a,a)X$ — $^{12}C(p,p)^{12}C$ — $^{208}Pb(n,n)^{208}Pb$
  Always present!
- Inelastic scattering: $X(a,a')X^*$ — $^{12}C(p,p')^{12}C^*$ — $^{40}Ca(\alpha,\alpha')^{40}Ca^*$
- Rearrangement reactions: (ex)change of mass
  - Transfer reactions:
    - stripping $X\big((a+c),a\big)(X+c)$ — $^{12}C(d,p)^{13}C$
    - pick-up $(X+c)\big(a,(a+c)\big)X$ — $^{12}C(p,d)^{11}C$
  - Knock-out reactions: $X(a,ac)Y$ — $^{12}C(p,2p)^{11}B$
- Photo-disintegration: $X(\gamma,a)Y$ — $^{16}O(\gamma,\alpha)^{12}C$
- Capture reactions: $X(a,\gamma)Y$ — $^{14}N(\alpha,\gamma)^{18}F$

- Combination of particles: **partition**
- Partition with specified excited states: **channel**
- Different exit channels may be present (**open**) at the same time depending on conservation principles

Characteristics of direct reactions

- Direct reactions: inelastic scattering, transfer, breakup
  - Fast, only few nucleons involved
  - Likely to occur at small exit angles (peripheral)
  - Time scale $\tau \ll 10^{-22}$ s
  - Modelled as one-step processes
- Tend to probe the “valence” nucleons (depends on the energy)
- Very selective
  Provide information about the similarity between initial and final states



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  - Sn region
  - …

Information provided by reactions

- (all reactions)
  The *Q*-value (difference in kinetic energies)
  identifies the excitation energy of the populated state
- (direct reactions)
  The initial and final spins are connected through
  the transferred angular momentum, which can be measured
- (transfer reactions)
  The cross section is a measure of the weight
  of a given configuration within the populated state

Transfer reactions are an excellent spectroscopic probe:
they measure how much the wave function of a particular state
may be described by a single-particle motion within the nucleus

Conservation of energy

- $E_{k,i} + M_i c^2 = E_{k,f} + M_f c^2$
  where the masses include the excitation energy

- In the centre-of-mass system:

$$E'_{k,i} + \underbrace{\left(M_i c^2 - M_f c^2\right)}_{Q\text{-value for the } (i,f) \text{ channel}} = E'_{k,f} > 0 \quad \rightarrow \quad E'_{k,i} > -Q$$

Threshold for the (i, f) channel

- Q is usually calculated through the mass excess $\Delta = (M - A)c^2$

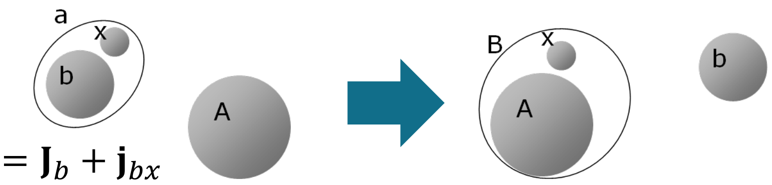
Example: ^{40}Ca(d,p)^{41}Ca:
Δ(^{40}Ca) = –34846 keV
Δ(^{41}Ca) = –35138 keV
Δ(d) = 13136 keV
Δ(p) = 7289 keV
→ Q = 6139 keV = 6.139 MeV

- In the laboratory system:
  $Q = E_{k,f} - E_{k,i}$
  → we can measure Q and thus
  identify the channel

Conservation of angular momentum (and parity)

- $\mathbf{J}_a + \mathbf{J}_A + \overrightarrow{\ell_\alpha} = \mathbf{J}_b + \mathbf{J}_B + \overrightarrow{\ell_\beta}$
  The <u>transferred angular momentum</u> in $a + A \rightarrow b + B$
  is defined as $\mathbf{l} = \overrightarrow{\ell_\alpha} - \overrightarrow{\ell_\beta}$

- Transfer reactions: $(b + x) + A \rightarrow b + (A + x)$ with $b + x = a,\ A + x = B$
  $\mathbf{l} = (\mathbf{J}_B - \mathbf{J}_A) + (\mathbf{J}_b - \mathbf{J}_a)$
  $\mathbf{l} = \mathbf{j}_{Ax} - \mathbf{j}_{bx}$
  $\rightarrow \mathbf{l} = \mathbf{l}_{Ax} - \mathbf{l}_{bx}$



$\mathbf{J}_a = \mathbf{J}_b + \mathbf{j}_{bx}$
$\mathbf{j}_{bx} = \mathbf{l}_{bx} + \mathbf{j}_x$

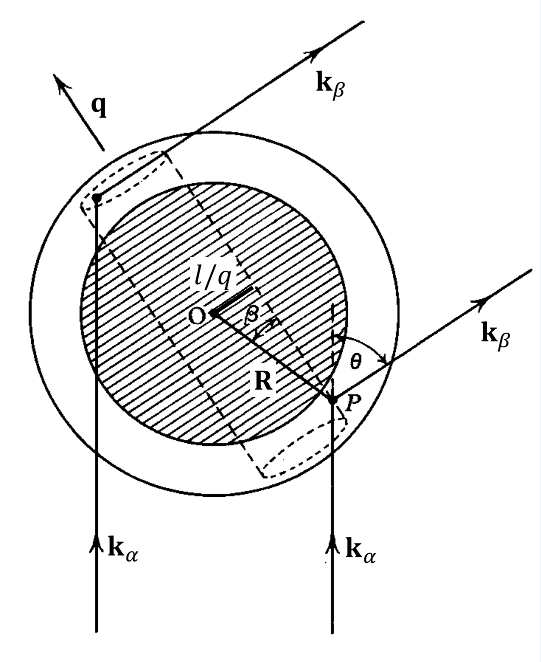
$\mathbf{J}_B = \mathbf{J}_A + \mathbf{j}_{Ax}$
$\mathbf{j}_{Ax} = \mathbf{l}_{Ax} + \mathbf{j}_x$

  $\rightarrow$ <u>l is constrained by the binding angular momenta</u>
  $\rightarrow$ <u>only few l participate for a given channel</u>
  For one-nucleon transfers, these binding angular momenta are directly given by the shell-model orbitals (s,p,d,g…)

- Also, for a given channel parity must be conserved:
  $\pi_a \pi_A \pi_b \pi_B = (-1)^l = (-1)^{l_{bx} + l_{Ax}}$
  $\rightarrow$ either only odd l (change of parity) or only even l participate

How to measure the transferred angular momentum

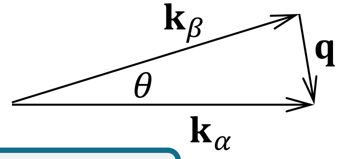
Semi-classical argument



- Reaction takes place on the surface of the target nucleus
- Transferred angular momentum: $\mathbf{l} = \mathbf{q} \times \mathbf{R}$
  where $\mathbf{q} = \mathbf{k}_\alpha - \mathbf{k}_\beta$ is the transferred momentum
- For a given populated state $\mathbf{q}$ is fixed in magnitude
  For a given observation angle $\mathbf{k}_\beta$ is fixed in direction
  → l/q is fixed (angle β between q and R is fixed)
  → events originate on two rings with radius l/q
- Conditions on the observation angle θ
  For $\mathbf{q} \ll \mathbf{k}_\alpha \approx \mathbf{k}_\beta$:
  - $q \approx \bar{k}\theta$ (with $\bar{k} = (k_\alpha + k_\beta)/2$ or $\bar{k} = \sqrt{k_\alpha k_\beta}$)
  - $l/q \leq R$ (reaction on the surface)

  we find

  $$\theta \geq l/\bar{k}R$$

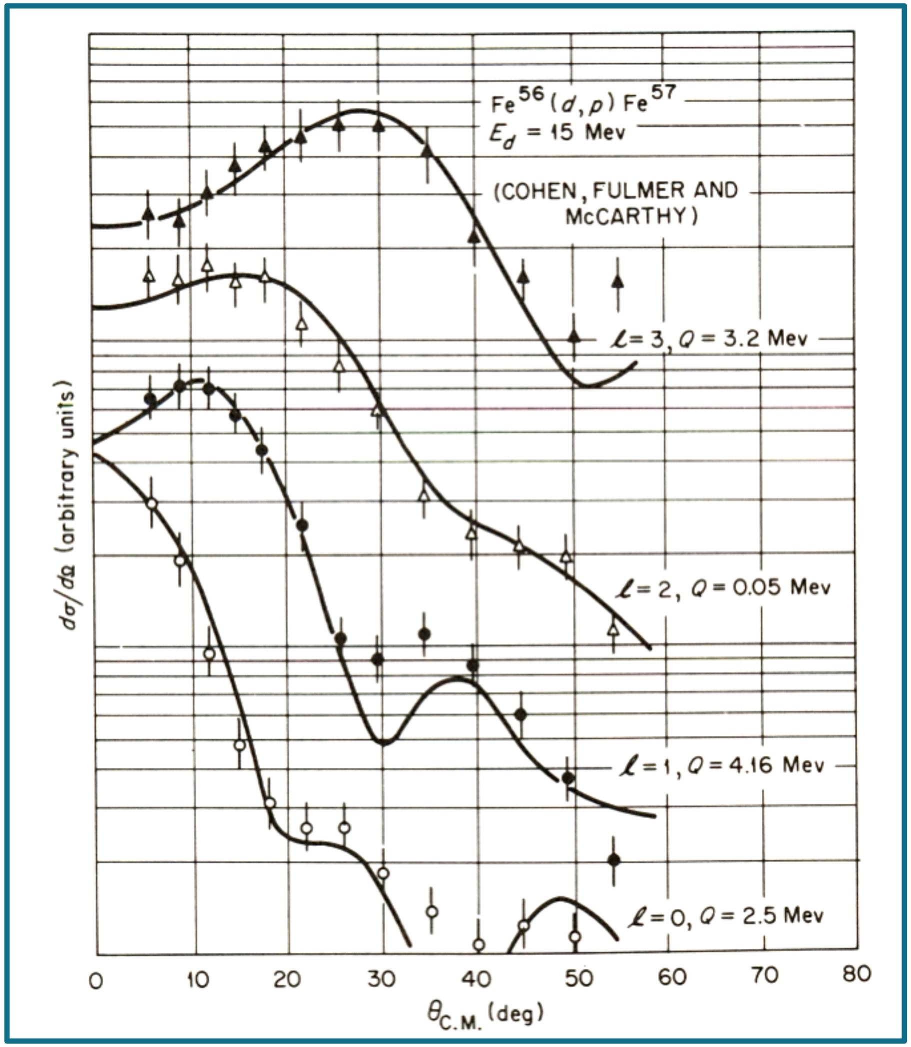


Relation between the transferred angular momentum and the scattering angle

- Also: constructive interference for $2R\theta = n\lambda \rightarrow \theta \approx n\pi/\bar{k}R$

How to measure the transferred angular momentum

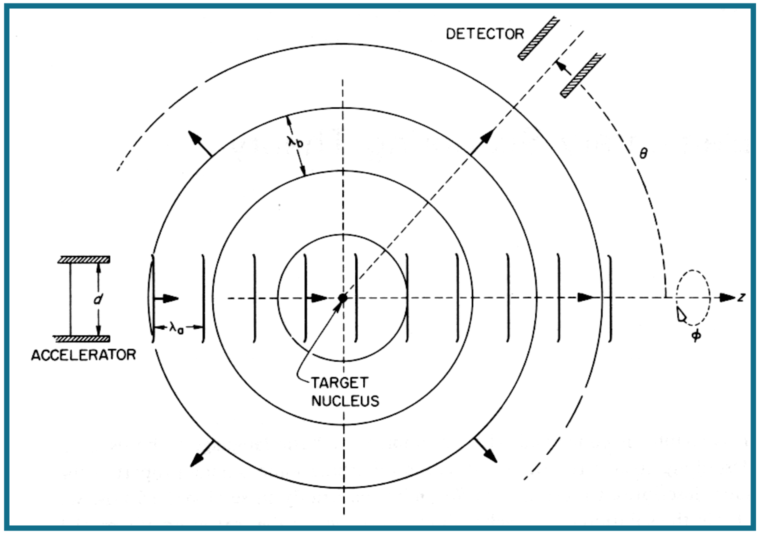
- First maximum for $\theta \approx l/\bar{k}R$
- Maxima separated by $\Delta\theta \approx \pi/\bar{k}R$



BL Cohen et al, Phys Rev 126 (1962) 698

Cross sections

- Solution of the scattering problem
  plane wave + modulated spherical wave
  $$\psi(\mathbf{r}) \xrightarrow{r\to\infty} e^{i\mathbf{k}\cdot\mathbf{r}} + f(\theta,\varphi)\frac{e^{ikr}}{r}$$
  scattering amplitude



- Cross section $d\sigma/d\Omega \propto |f(\theta,\varphi)|^2$

- Schrödinger equation:
  $(\nabla^2 + k^2)\psi(\mathbf{r}) = U(\mathbf{r})\psi(\mathbf{r})$
  has the (formal) solution
  $$\psi(\mathbf{r}) \xrightarrow{r\to\infty} e^{i\mathbf{k}\cdot\mathbf{r}} - \frac{e^{ikr}}{4\pi r}\int e^{-i\mathbf{k}'\cdot\mathbf{r}'}U(\mathbf{r}')\psi(\mathbf{r}')dr'$$
  (various ways to solve)

- For a transfer, $U(\mathbf{r})$ connects the initial and final states:
  $$U \approx \int \phi_a^*\phi_A^* V \phi_b \phi_B d\tau$$

Spectroscopic factors

$U \approx \int \phi_a^* \phi_A^* V \phi_b \phi_B d\tau$ integral on the internal states

- The important part is the overlap between ϕ_A and ϕ_B which is expressed by the spectroscopic factor (various definitions)
- For the transfer of a cluster x one assumes: $\phi_B = (\phi_A \phi_x)_{l_{Ax} j_{Ax}}$ and calculates the cross section accordingly
- "Experimental" spectroscopic factors can then be obtained as ratio of the measured cross section to the calculated one:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} = S_{(l_{Ax} j_{Ax})_{J_B}} \left(\frac{d\sigma}{d\Omega}\right)_{\text{cal}}$$

The spectroscopic factor is a measure of how much the populated state contains the "pure" cluster (single-particle) configuration

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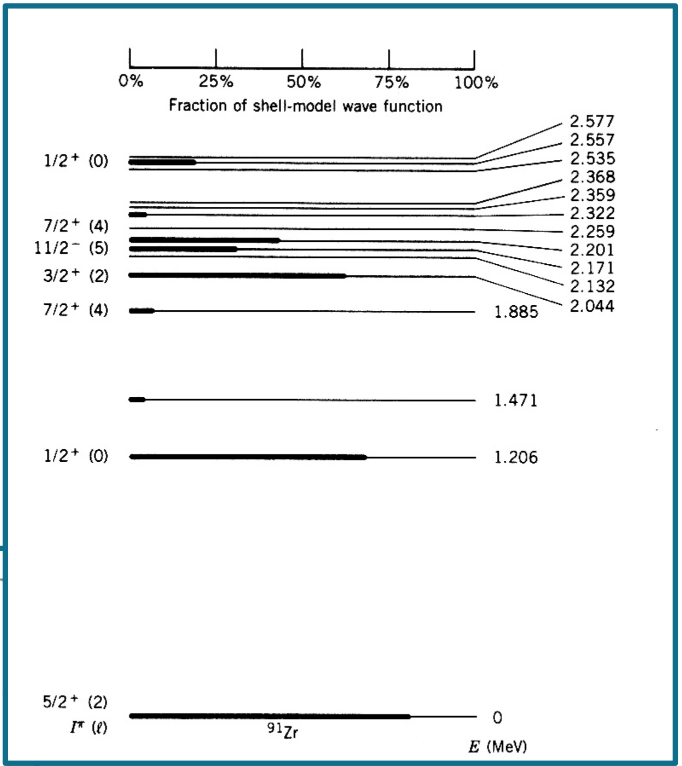
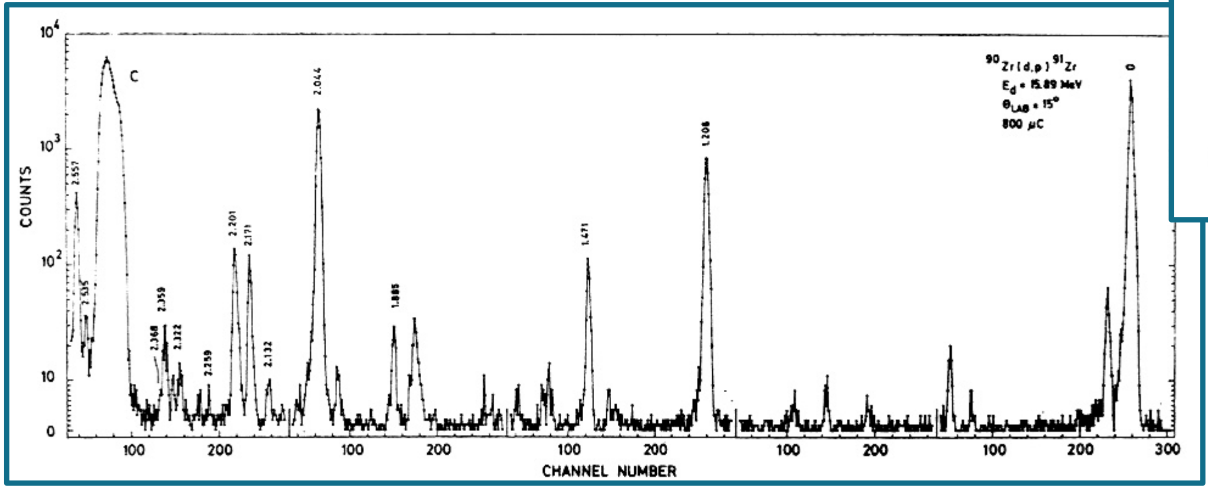
Spectroscopic factors

- Spectroscopic factors are obtained from cross sections (integral of the peaks)
- Angular distributions are fitted to extract l and normalised to the calculated ones to obtain S





HP Block et al, Nucl Phys A 273 (1976) 142

Spectroscopic factors - caution

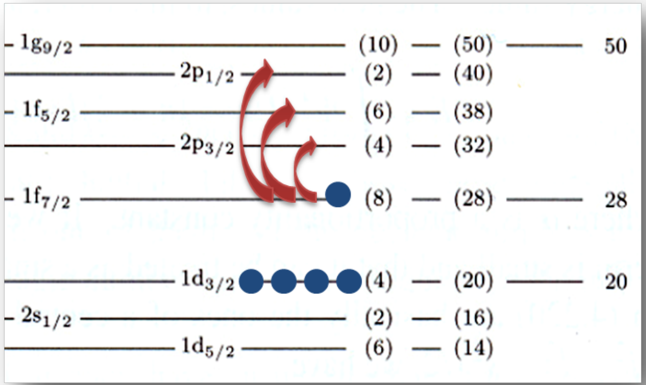
1. Absolute spectroscopic factors depend upon
   - the approximation used for the calculation (DWBA, ADWA, CRC...)
   - the potentials (interaction and binding)

→ usually, relative spectroscopic factors are used to derive structure information

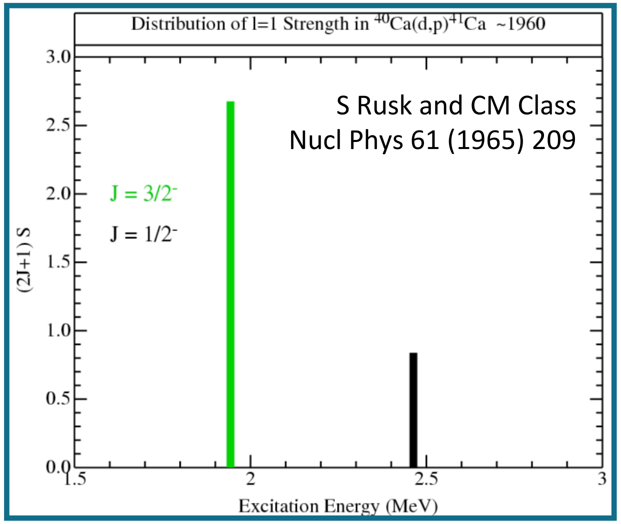
2. For pure "single-particle" states the spectroscopic factors satisfy sum rules
   However, a given configuration could be present
   in several excited states (fragmentation)
   and it is usually difficult to measure all the strength

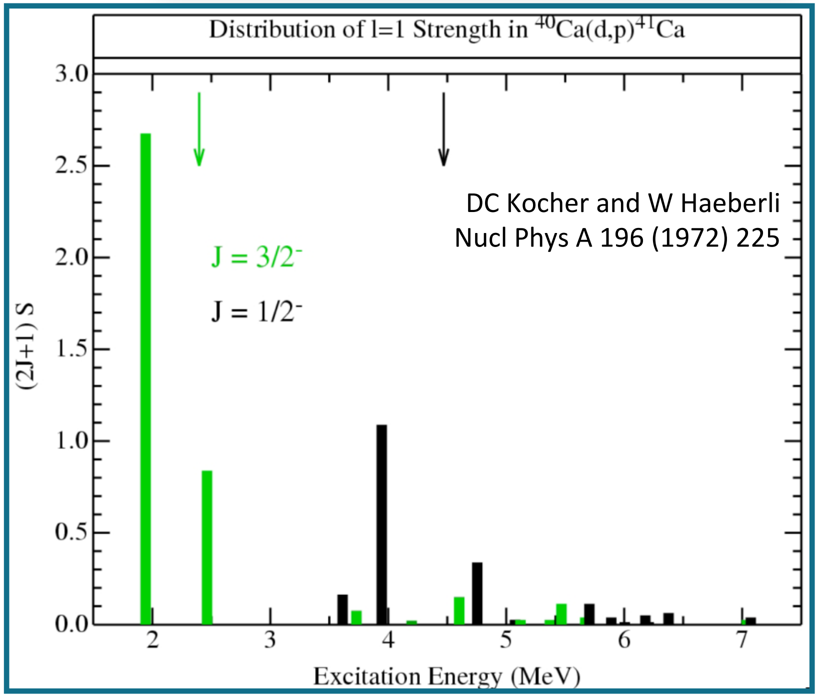
Strength fragmentation

- If the strength is fragmented: the single-particle energy is taken to be the **centroid** (mean energy, weighted by the spectroscopic factor)
- Need to detect as much strength as possible!



$$E_{s.p.} = \sum S_i E_i$$





Example: $p_{3/2}$-$p_{1/2}$ spin-orbit splitting in ^{41}Ca

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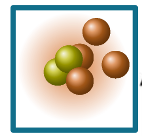
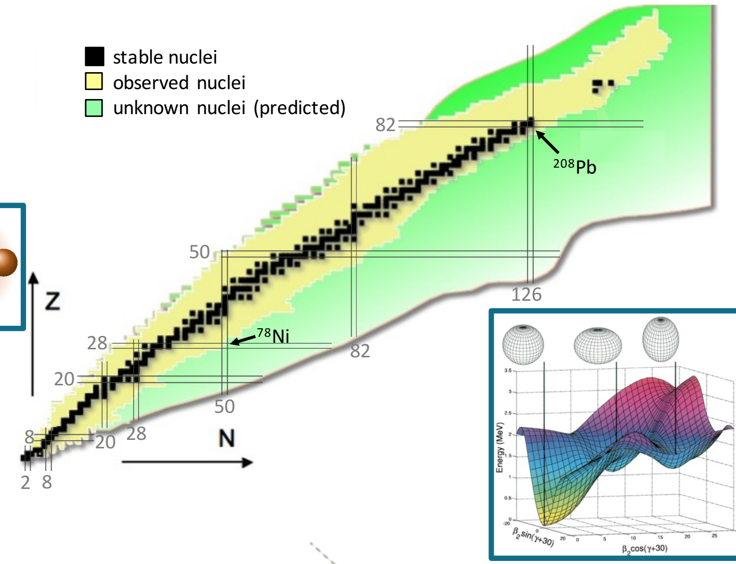
New physics far from stability

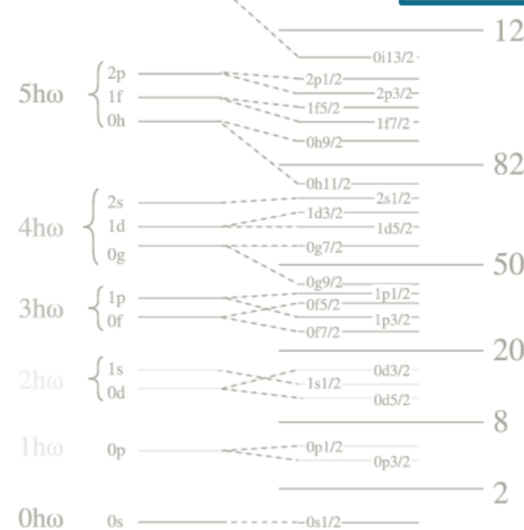
- Halos, cluster structures
- Shape transitions and coexistence (macroscopic picture)
- Changes in the shell structure





Why these changes?
An excess of neutrons or protons enhances particular aspects of the N-N interaction

- Matter distribution (shape potential well)
- Spin-orbit force
- Three-body forces
- Tensor interaction
- …



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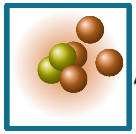

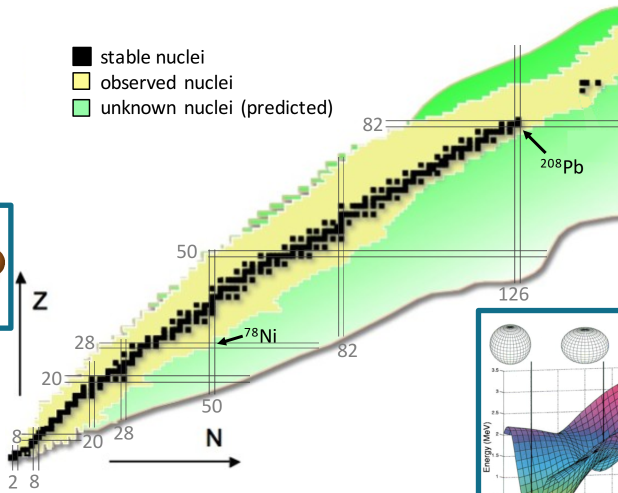

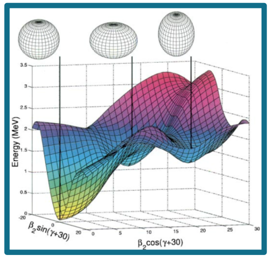

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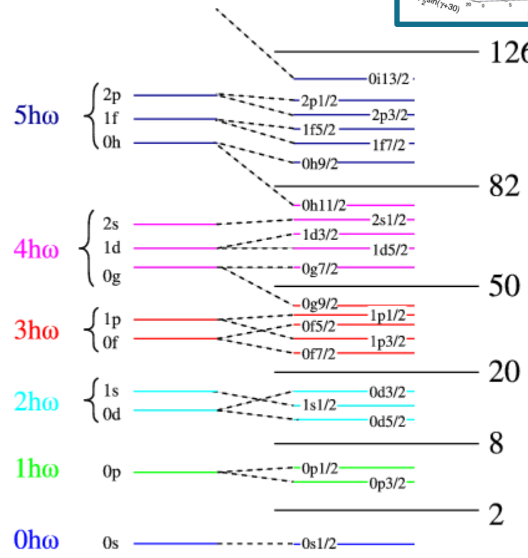

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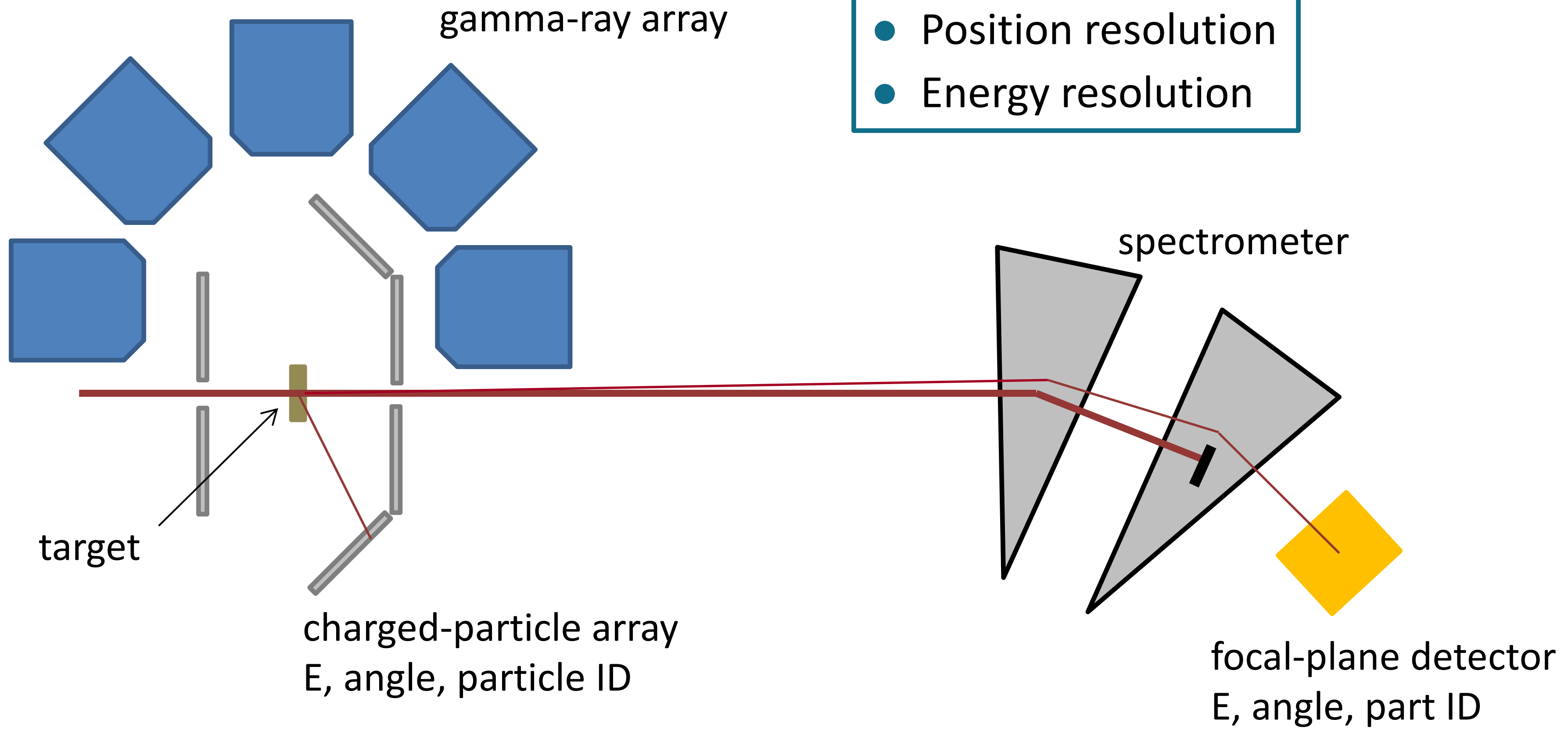
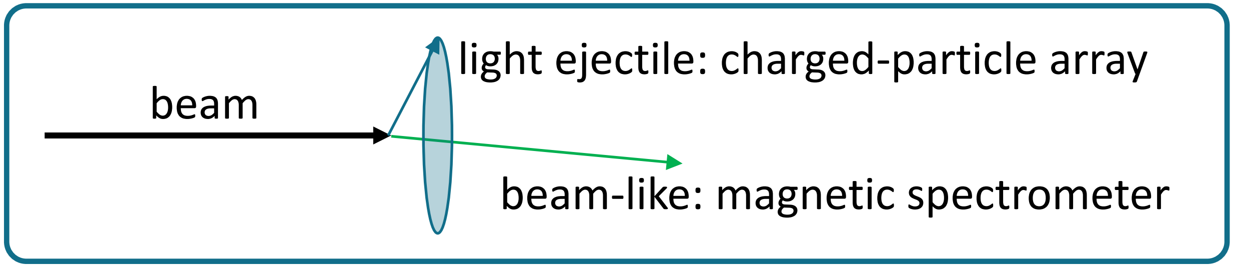
General setup

Keys:

- Efficiency
- Position resolution
- Energy resolution



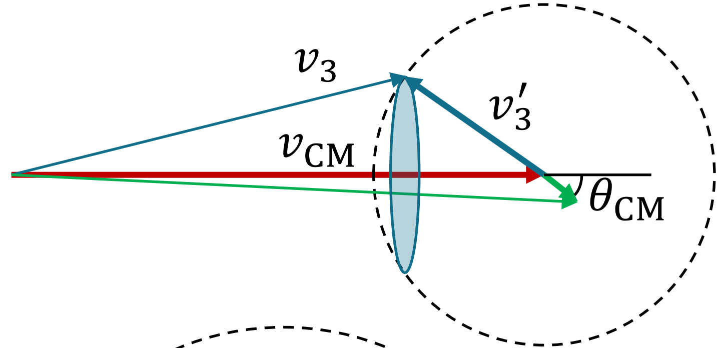
Inverse kinematics



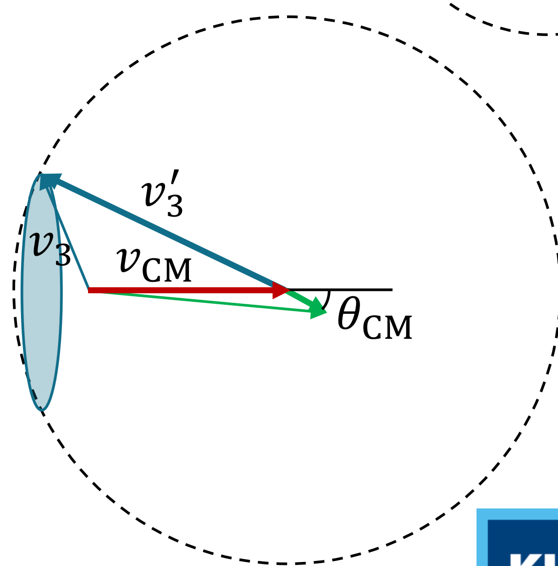
$$\frac{v_3'}{v_{\mathrm{CM}}} \xrightarrow{Q \ll E} \approx \sqrt{\frac{m_2 m_4}{m_1 m_3}} \approx \sqrt{\frac{m_2}{m_3}}$$

inverse kinematics

$m_2 < m_3$
pick-up (p,d)



$m_2 > m_3$
stripping (d,p)



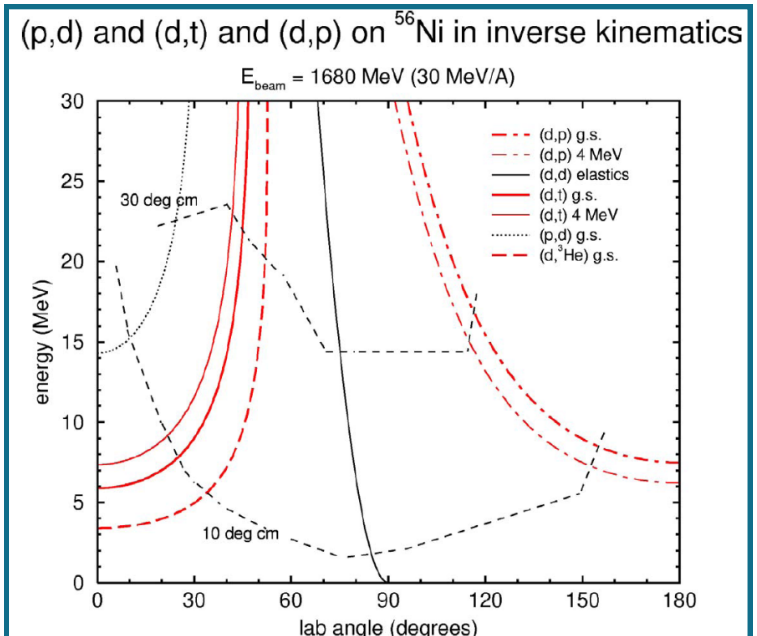
Exotic nuclei: inverse kinematics

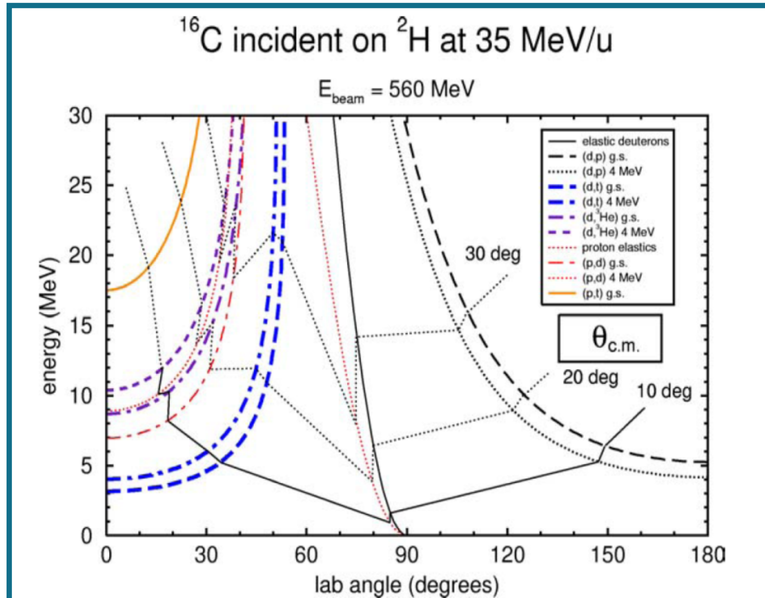
source: Wilton Catford

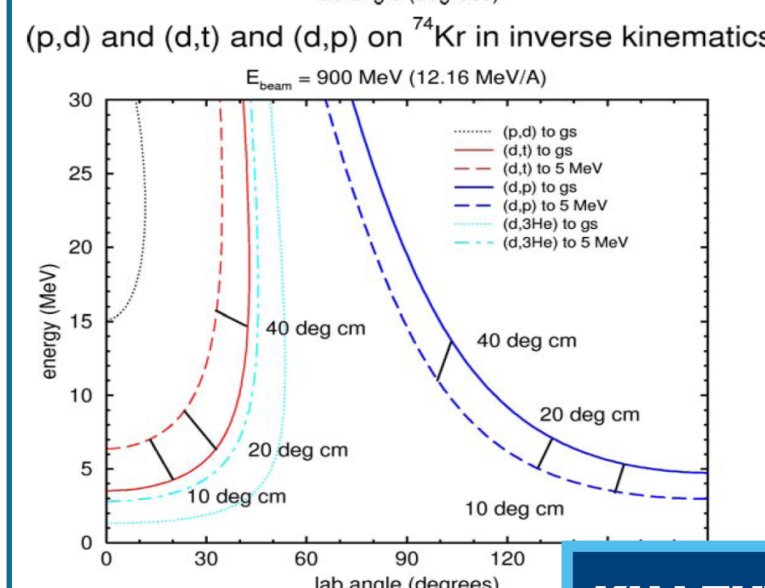
Light particles

Kinematics depends:

- mainly on the masses of the light particles
- not so much on beam mass or velocity







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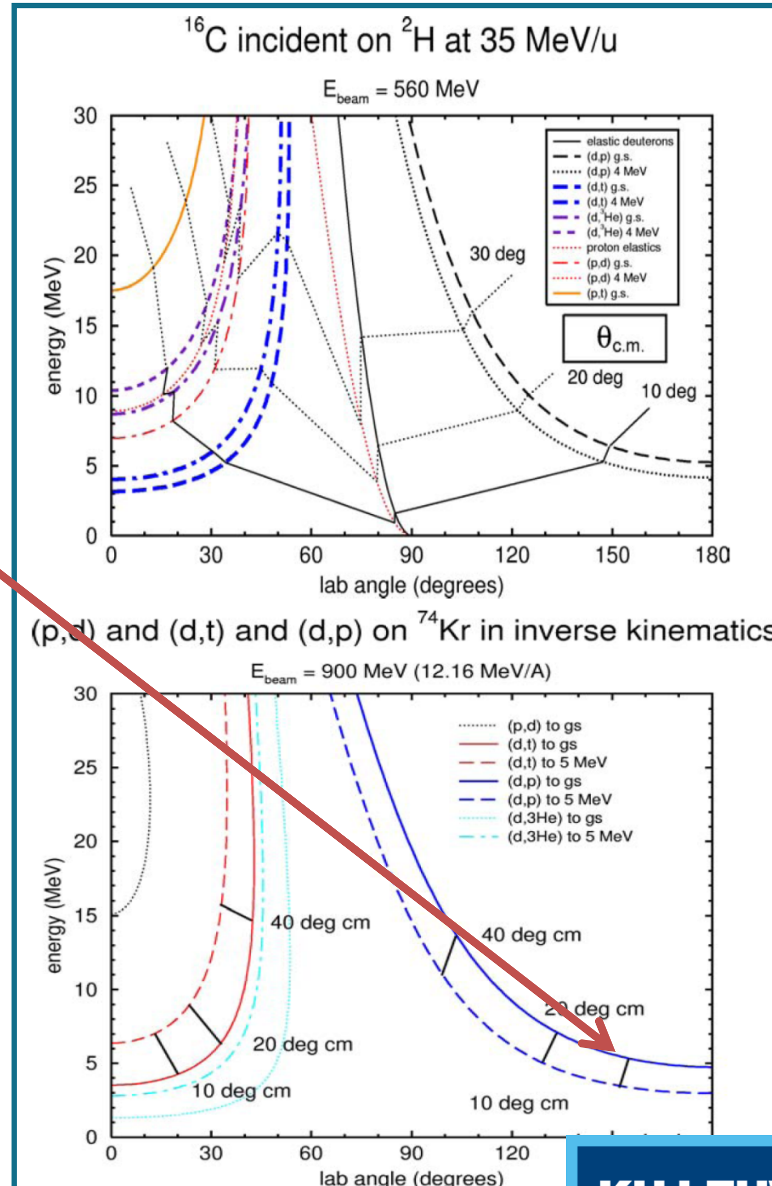
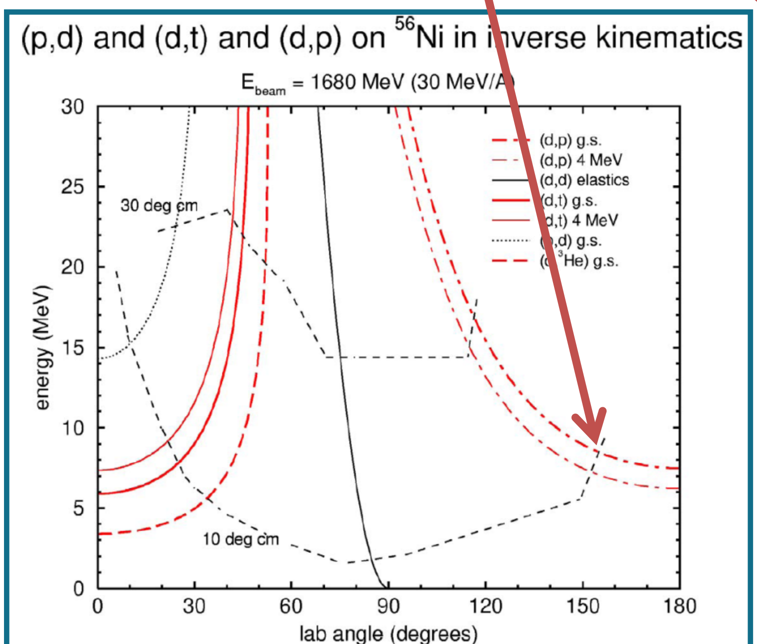
Exotic nuclei: inverse kinematics

source: Wilton Catford

- Most particles at 90 deg
  but maximum of cross sections
  at forward and backward angles
- Kinematic compression:
  very small differences
  in energy of the light particle
  for different *E**





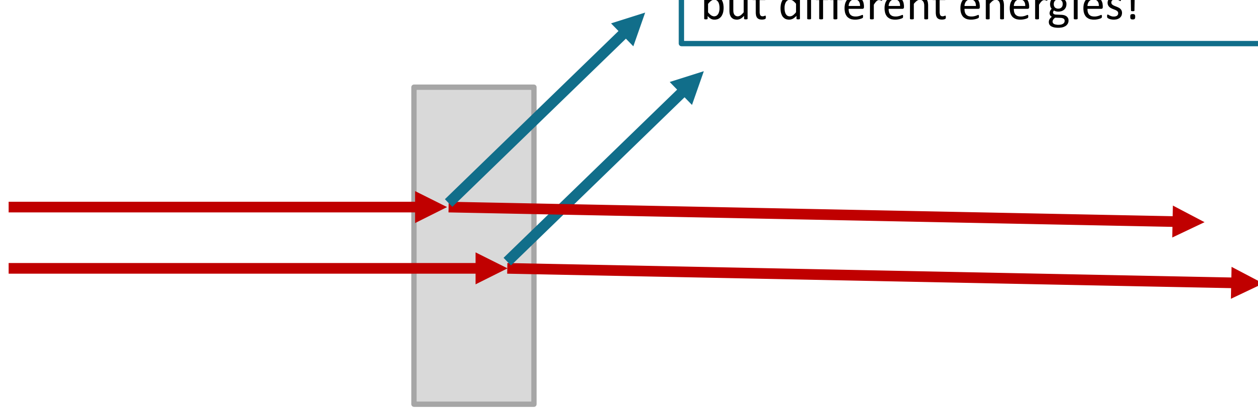
The luminosity dilemma

- We have weak beams
  → we could increase the target thickness

but

- We do not know the energy pf the beam at the interaction point

same angle
from same reaction (Q-value)
but different energies!



- Limit for (d,p):
  resolution in E*≈300 keV
  for ≈200 μg/cm^2 target
  (depends on many factors!!)

Limits in resolution

Resolution in *E**

- Light beam: better detect beam-like particle (limit on angular resolution)
- Heavier beam: better detect light recoil (limit on E resolution from energy loss in the target)
- In general: much worse than direct kinematics

152 J.S. Winfield et al. / Nucl. Instr. and Meth. in Phys. Res. A 396 (1997) 147–164

Table 2
Major contributions in keV to the resolution of the excitation energy spectra of single neutron stripping and pickup reactions in inverse kinematics, where the heavy ion is detected in a spectrometer. The detection angle corresponds to 10°_{cm}. The last column is an approximate estimate as a sum in quadrature of the net effect of five non-Gaussian contributions. Other symbols are explained in the text

Reaction	E_i/A (MeV)	θ_{lab}	Origin of contribution $\Delta\theta$	Δp	E_{stragg}	$\Theta_{1/2}$	dE/dx	Σ_{quad}
$p(^{12}Be,\,^{11}Be)d$	30	1.07°	172	147	101	74	23	259
$p(^{12}Be,\,^{11}Be)d$	15	1.06°	84	71	99	74	37	169
$p(^{77}Kr,\,^{76}Kr)d$	30	0.16°	1404	811	808	723	56	1952
$p(^{77}Kr,\,^{76}Kr)d$	10	0.10°	334	143	502	570	268	883
$d(^{76}Kr,\,^{77}Kr)p$	10	0.21°	1140	614	2177	1859	1321	3408

Table 3
Major contributions in keV to the resolution of the excitation energy spectra of single neutron pickup and stripping reactions in inverse kinematics, where the light particle is detected in a silicon detector. Symbols as described in text and Table 2

Reaction	E_i/A (MeV)	θ_{lab}	Origin of contribution $\Delta\theta$	ΔE_f	ΔE_i	$\Theta_{1/2}$	dE/dx	Σ_{quad}
$p(^{12}Be,d)^{11}Be$	30	19.0°	136	74	114	96	649	685
$p(^{12}Be,d)^{11}Be$	15	17.8°	66	72	55	89	984	995
$p(^{77}Kr,d)^{76}Kr$	30	15.0°	124	55	64	63	186	249
$p(^{77}Kr,d)^{76}Kr$	10	6.0°	26	24	23	19	775	777
$d(^{76}Kr,p)^{77}Kr$	10	155.3°	52	93	37	60	1309	1316

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Nucleon-Transfer Reactions with Radioactive Ion Beams

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International School of Physics "Enrico Fermi"

14-19 July 2017

Nuclear Physics with Stable and Radioactive Ion Beams

Lecture 2/3

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Contents

- Nuclear reactions
  - Types of reactions
  - Characteristics of direct reactions
- Why use transfer reactions
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  - Q-value, angular momentum, spectroscopic factors
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  - Motivations
  - Challenges: inverse kinematics
- **Case studies**
  - **Light nuclei, N=8**
  - The emergence of N=16
  - The spin-orbit term
  - Mg and Ni, the 0^+s
  - Ni region
  - ...

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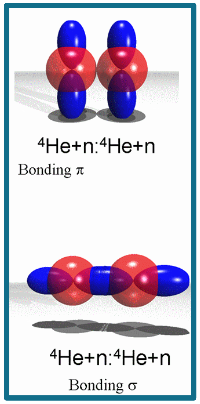
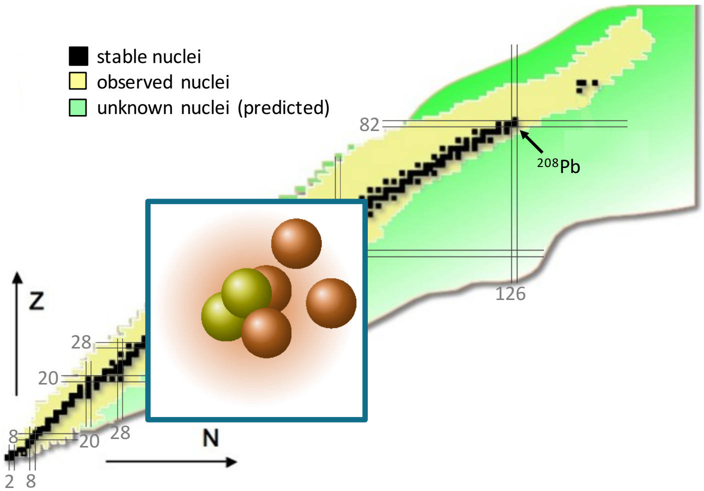
Light nuclei

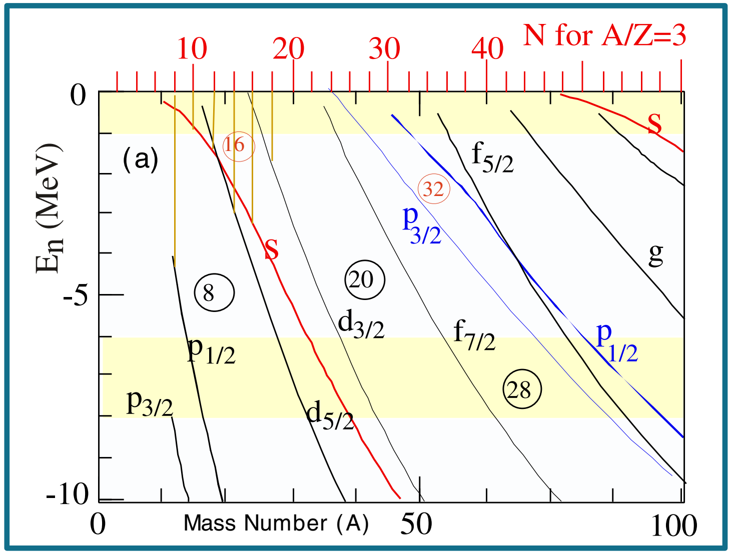
- Halo structures
- Clustering and deformation



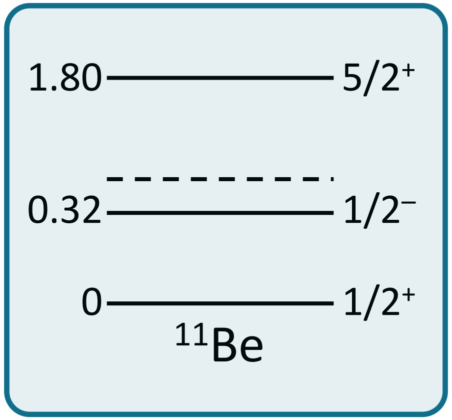


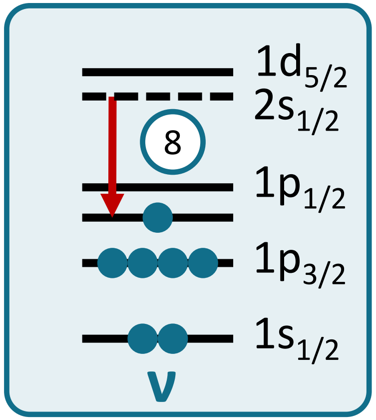
Disappearance of N=8

- Ground state in ^{15}C
  Inversion of levels in ^{11}Be
- Due to proton-neutron interaction and the removal of protons
  I. Talmi and I. Unna PRL 4 (1960) 469
- Cause of the halo in ^{11}Li, ^{11}Be, ^{14}Be



A Ozawa et al, PRL 84 (2000) 5493





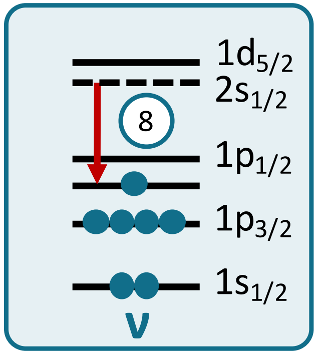
Light nuclei – I

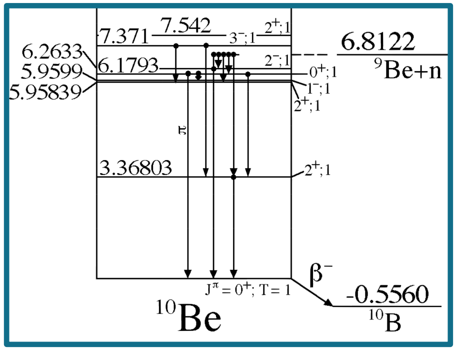
S Fortier et al, PLB 461 (1999) 22
J Winfield et al, NPA 683 (2001) 48

Ground state of ^{11}Be

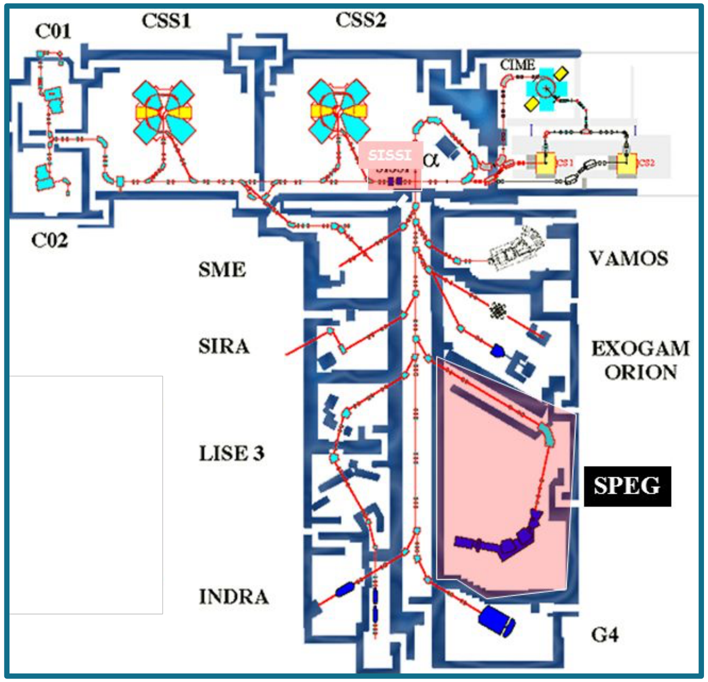
- $[0^+ \otimes 2s]_{1/2+}$ or $[2^+ \otimes 1d]_{1/2+}$?
  "^{10}Be core" configuration in ^{11}Be?
- 2^+ in ^{10}Be at 3.34 MeV

→ Probe overlap between ^{11}Be gs and ^{10}Be $0^+/2^+$ states





- **Experiment: ^{11}Be(p,d)^{10}Be**
  at GANIL
  - Primary beam ^{15}N 65 MeV/nucleon
  - In-flight fragment separation in SISSI/alpha
    → ^{11}Be at 35.3 MeV/nucleon
  - Detection in SPEG



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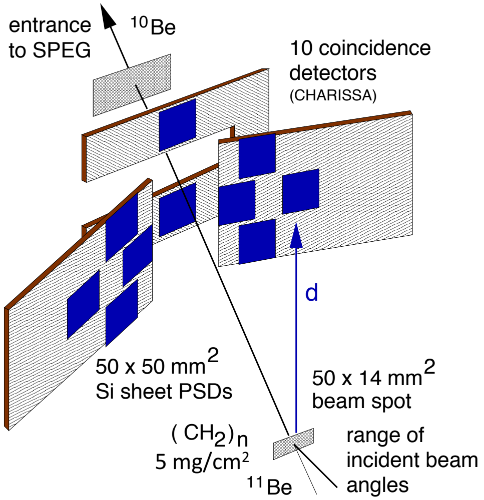
Light nuclei – I

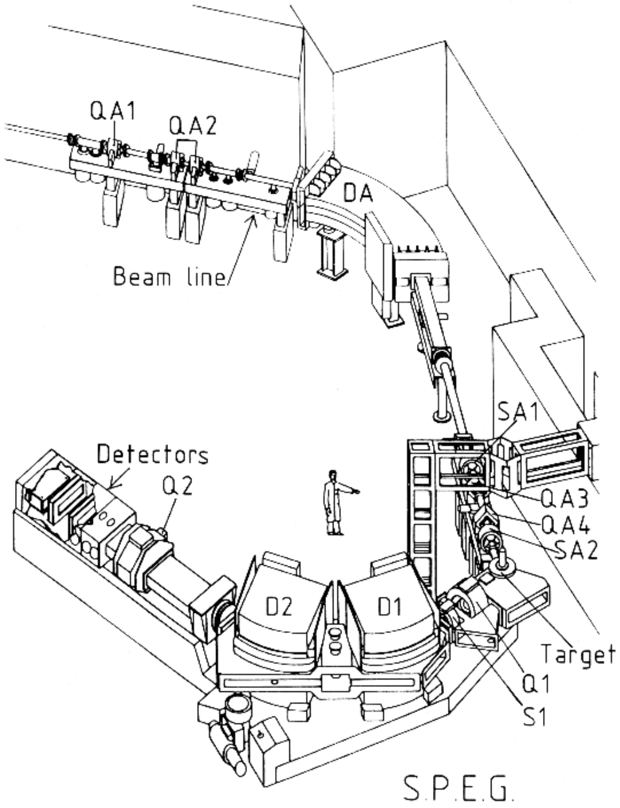
S Fortier et al, PLB 461 (1999) 22
J Winfield et al, NPA 683 (2001) 48

Ground state of ^{11}Be

Experiment: ^{11}Be(p,d)^{10}Be

- d in CHARISSA: particle detectors (resistive)
- ^{10}Be SPEG: (dispersion-matched) spectrometer





Light nuclei – I

S Fortier et al, PLB 461 (1999) 22
J Winfield et al, NPA 683 (2001) 48

Ground state of ^{11}Be

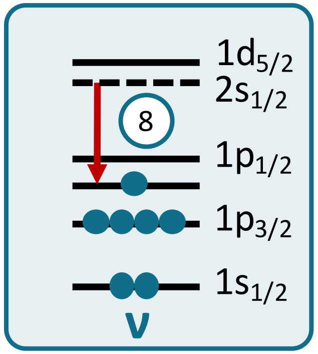
Experiment: ^{11}Be(p,d)^{10}Be

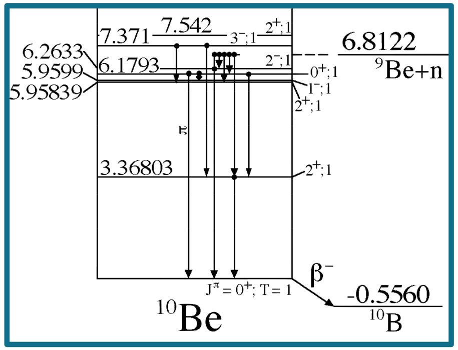
- 0^+ state in ^{10}Be populated by removal of the $2s_{1/2}$ neutron

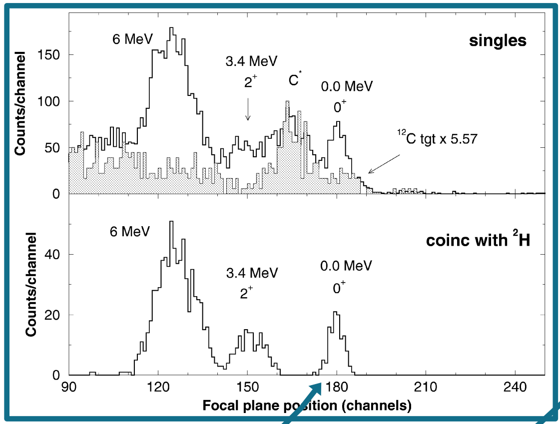
→ assume pure $[0^+ \otimes 2s]_{1/2+}$ configuration, calculate dσ/dΩ for 0^+ and normalize → SF for $[0^+ \otimes 2s]_{1/2+}$

- 2^+ state populated by removal of a $d_{5/2}$ neutron only possible if ^{11}Be gs contains the $[2^+ \otimes 1d]_{1/2+}$ configuration

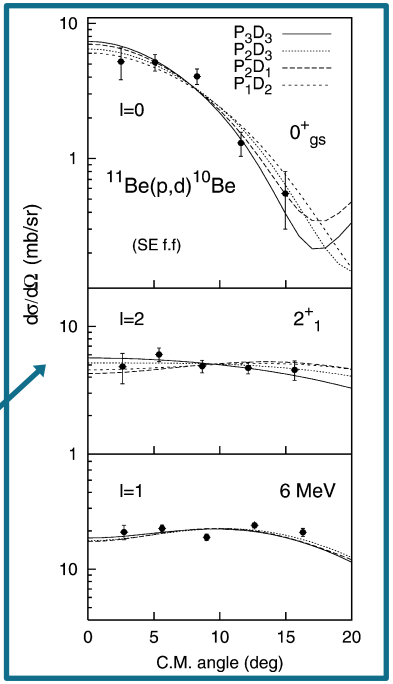
→ assume pure $[2^+ \otimes 1d]_{1/2+}$ configuration, calculate dσ/dΩ for 2^+ and normalize → SF for $[2^+ \otimes 1d]_{1/2+}$







resolution ≈700 keV



different optical model potentials

Light nuclei – I

S Fortier et al, PLB 461 (1999) 22
J Winfield et al, NPA 683 (2001) 48

Ground state of ^{11}Be

Experiment: ^{11}Be(p,d)^{10}Be

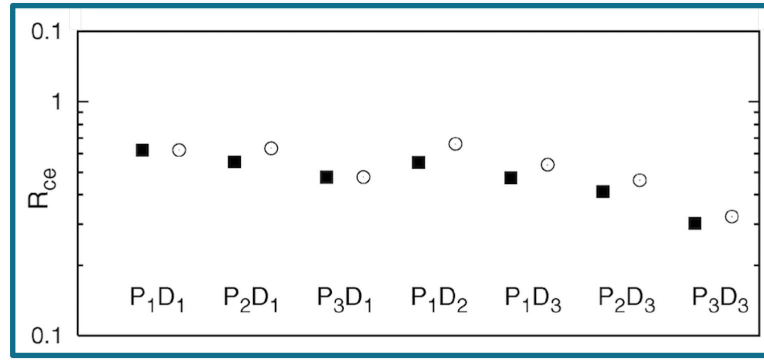
- Caution: how to build the $[0^+ \otimes 2s]_{1/2+}$ and $[2^+ \otimes 1d]_{1/2+}$ configurations?

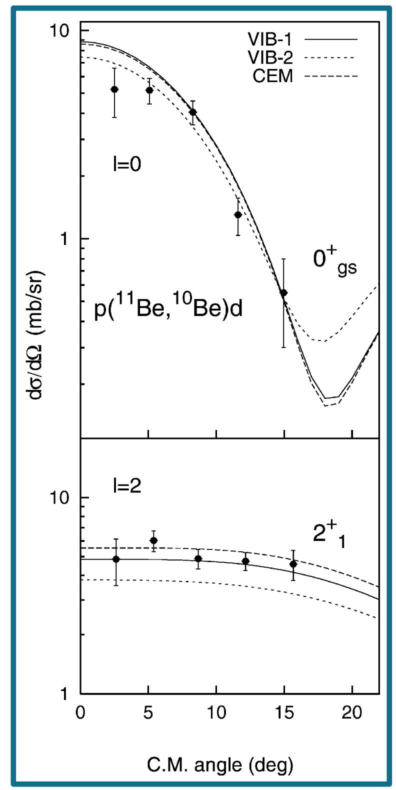
1. Assume ^{10}Be inert and bind the neutron with a Woods-Saxon potential

Result: SF(0^+) ≤ 70%, SF(2^+) ≥ 30%

2. Take into account the large deformation of ^{10}Be in the 2^+ state (solve coupled-channel problem)

Result: SF(0^+) = 84%, SF(2^+) = 16%





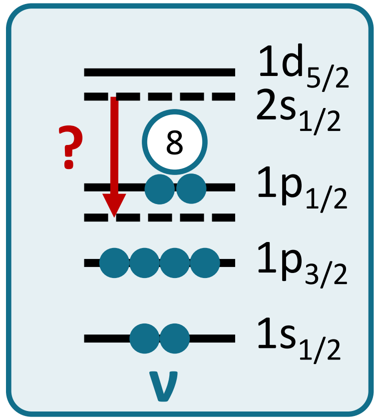
no normalisation

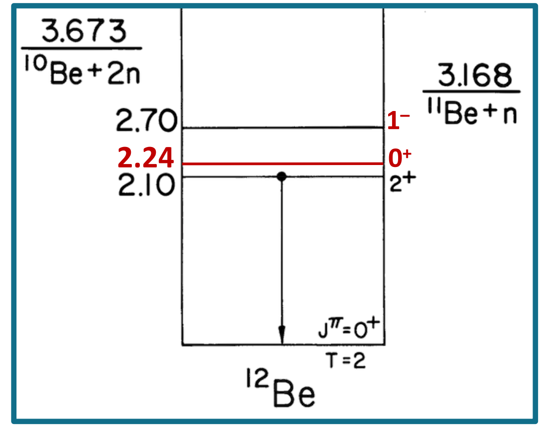
Light nuclei – II

R Kanungo et al, PLB 682 (2010) 391

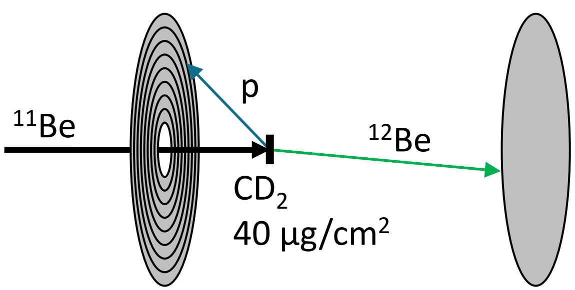
Structure of states in ^{12}Be

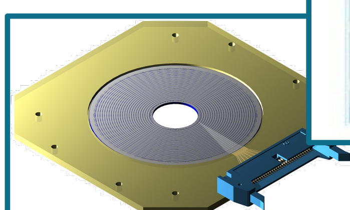
- What is the content of $\nu(s_{1/2})^2$ in the 0^+states of ^{12}Be?
- Also measured in knock-out reactions – but those cannot separate 0^+_1 and 0^+_2

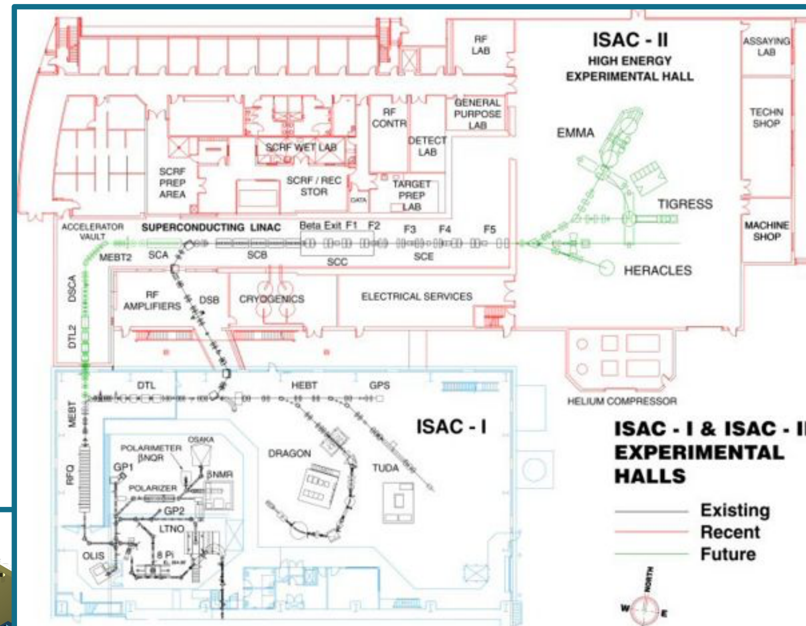




- **Experiment: ^{11}Be(d,p)^{12}Be** at TRIUMF
  - ISOL production
  - Post-acceleration to 5 MeV/nucleon







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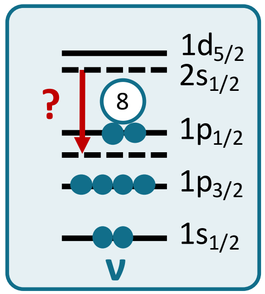
Light nuclei – II

R Kanungo et al, PLB 682 (2010) 391

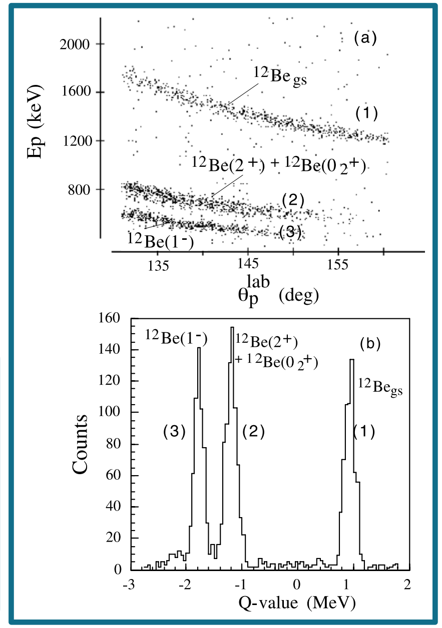
Structure of states in ^{12}Be

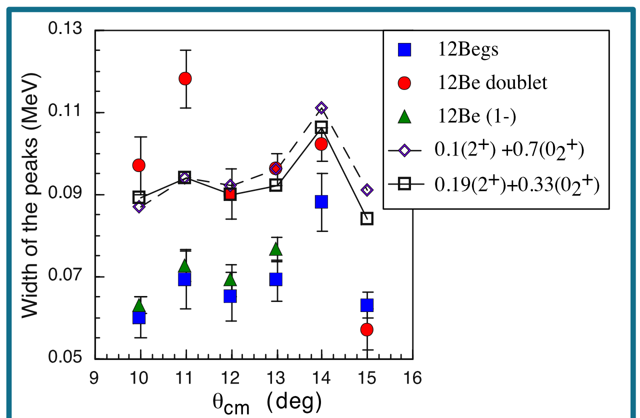
Experiment: ^{11}Be(d,p)^{12}Be

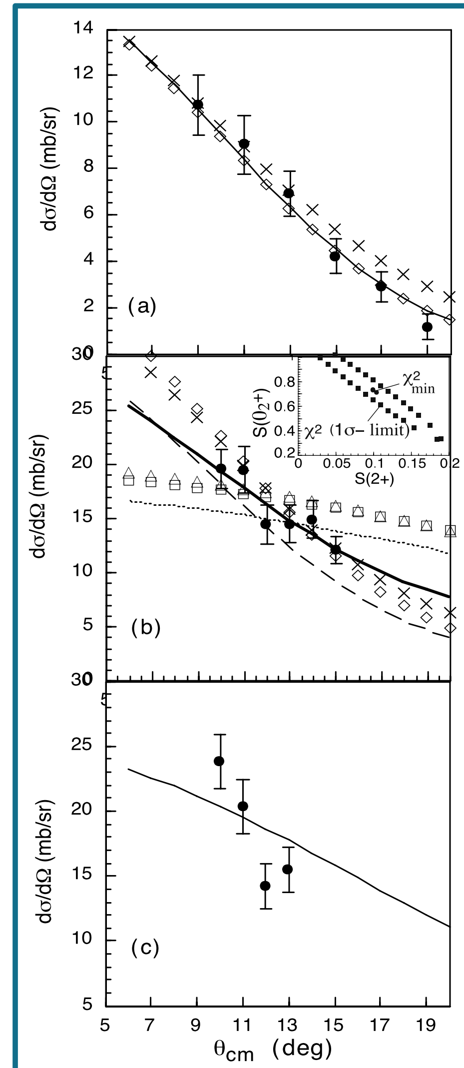
- Transfer to all bound states is observed
  0^+_1 and 0^+_2 → neutron to $2s_{1/2}$
  2^+ → neutron to $1d_{5/2}$
  1^- → neutron to $1p_{1/2}$
- Doublet fitted with a sum of the two configurations



Content of s-wave neutron:
0^+_1 : $0.28^{+0.03}_{-0.07}$
0^+_2 : $0.73^{+0.27}_{-0.40}$
The 0^+_2 is probably a halo state







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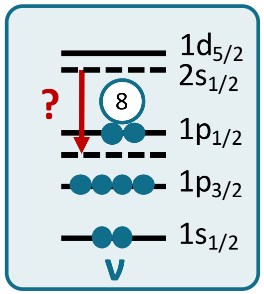

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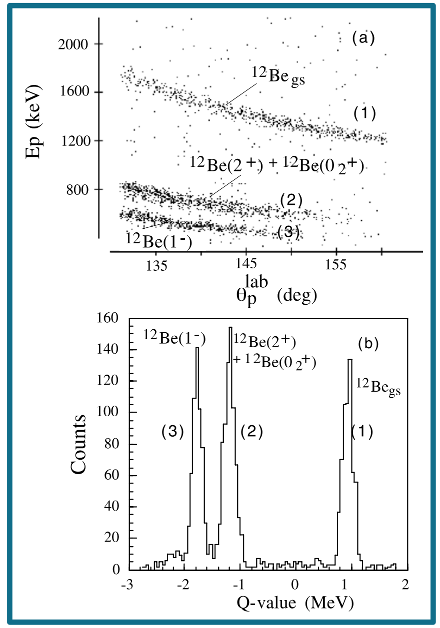

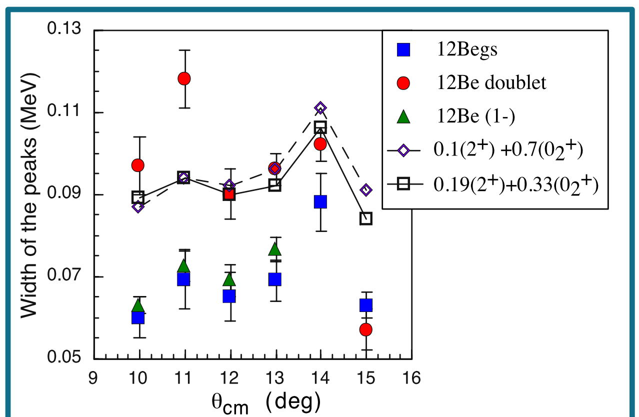

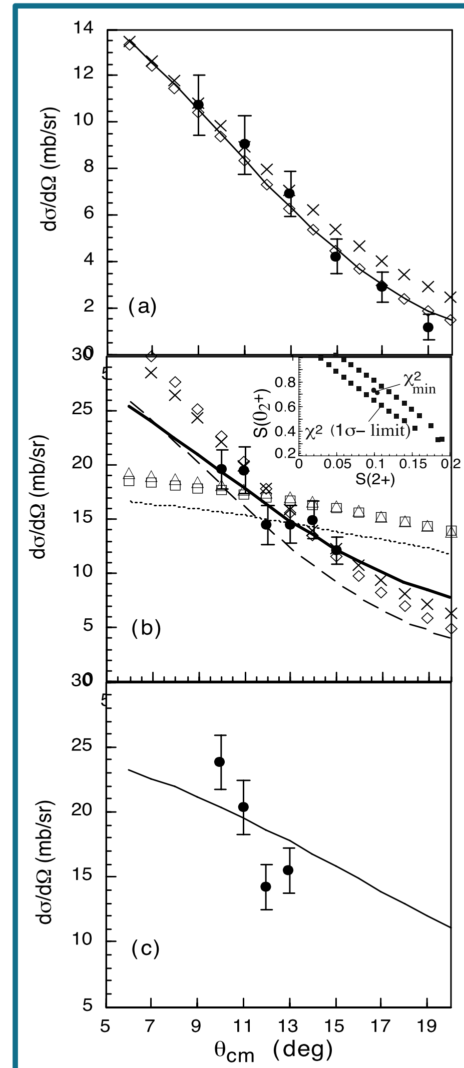

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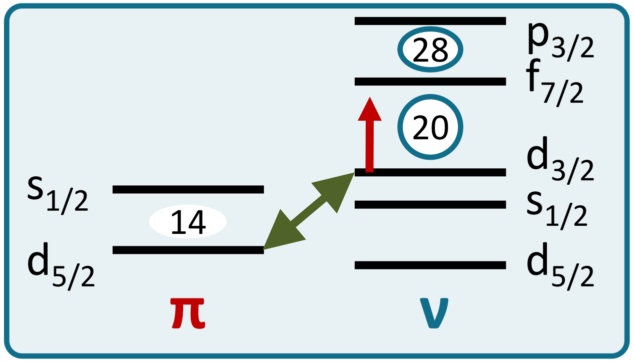
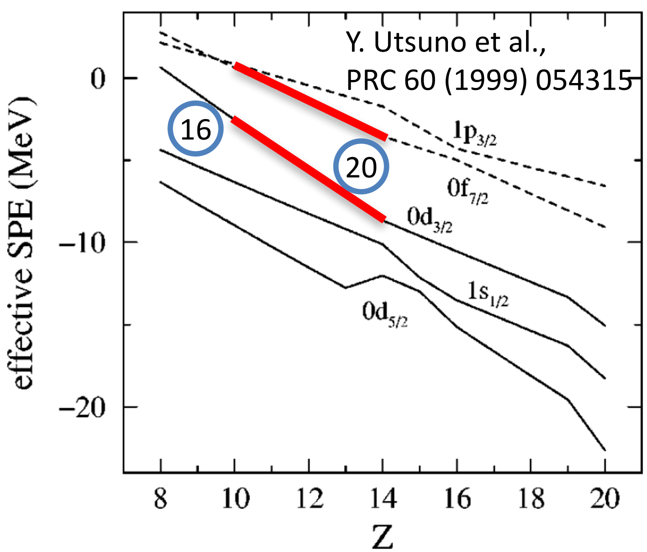
  - Motivations
  - Challenges: inverse kinematics
- **Case studies**
  - Light nuclei, N=8
  - **The emergence of N=16**
  - The spin-orbit term
  - Mg and Ni, the 0^+s
  - Ni region
  - ...

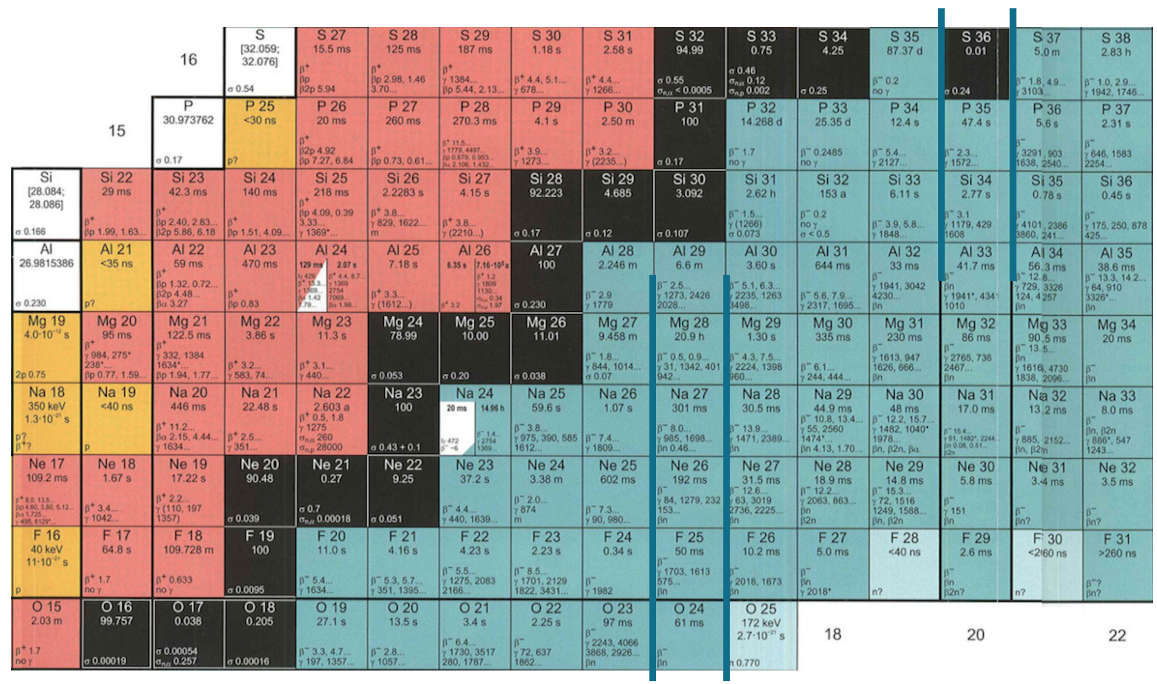
The emergence of N=16

…and the disappearance of N=20

- Historically this was the first identification of shell evolution far from stability (mid-’70)







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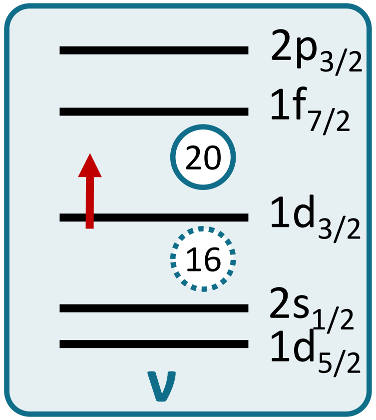
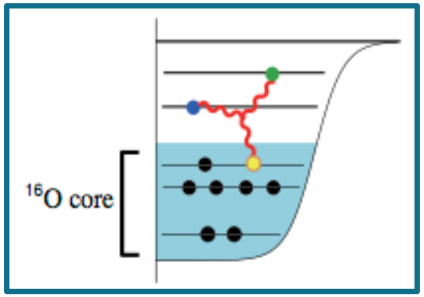
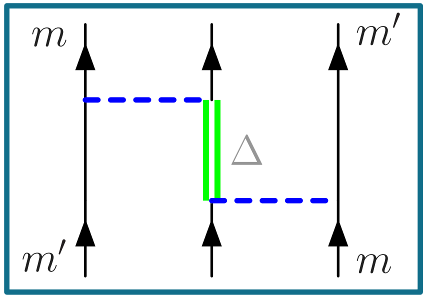
The emergence of N=16

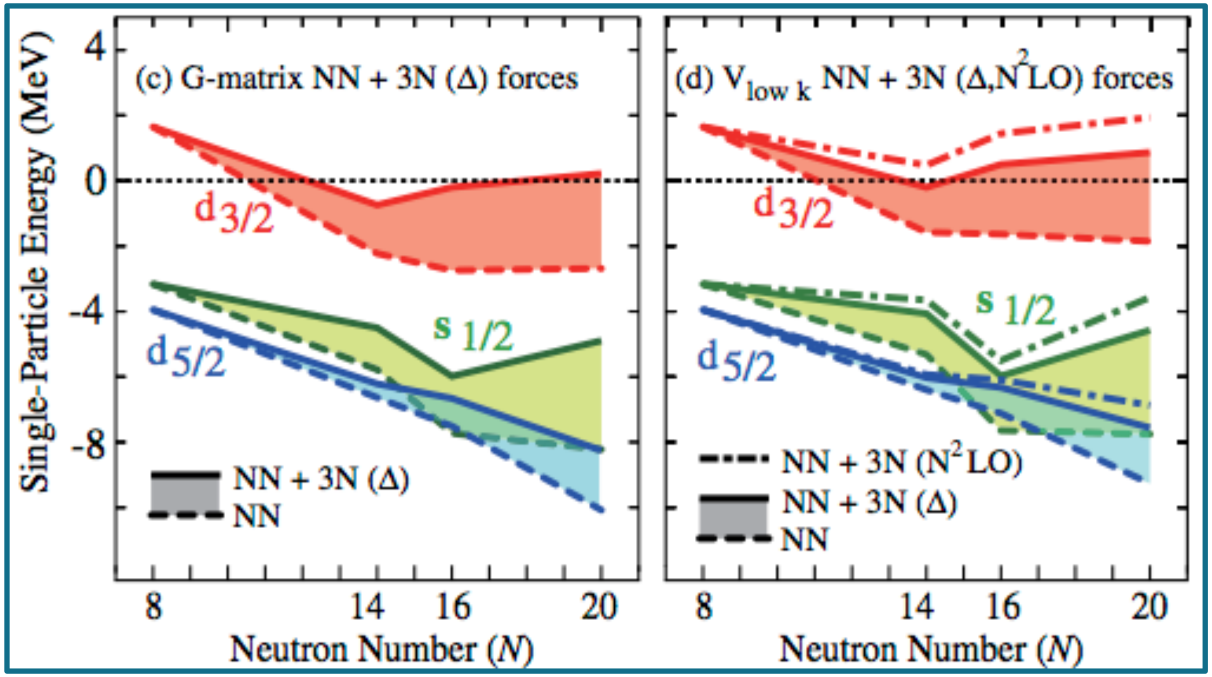
- 3-body forces in O isotopes

T Otsuka et al, PRL 105 (2010) 032501







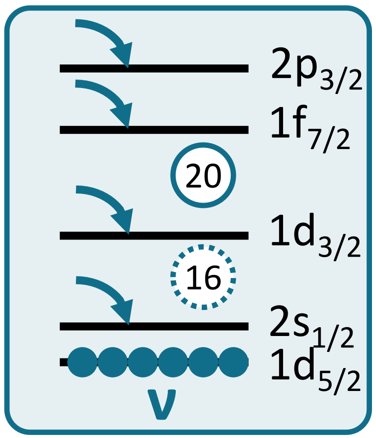


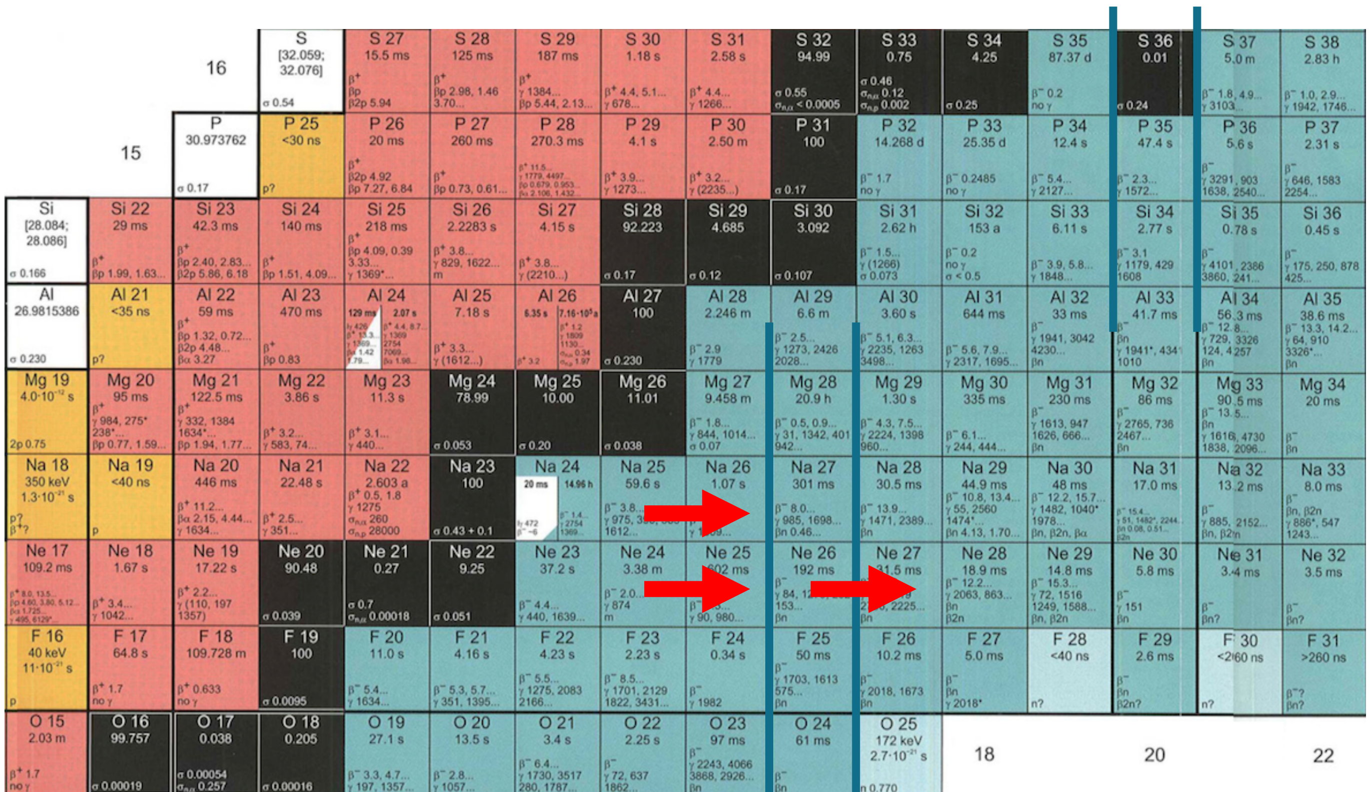
(d,p) on Ne and Na isotopes

W Catford et al, PRL 104 (2010) 192501
SM Brown et al, PRC 85 (2012) 011302(R)
GL Wilson et al, PLB 759 (2016) 417

Experiments at GANIL and TRIUMF

- ^{24}Ne(d,p)
- ^{26}Ne(d,p)
- ^{25}Na(d,p)





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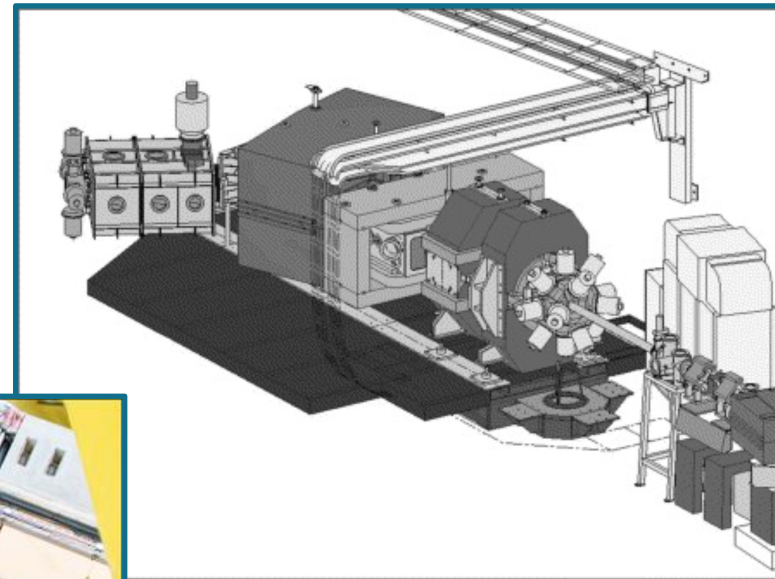
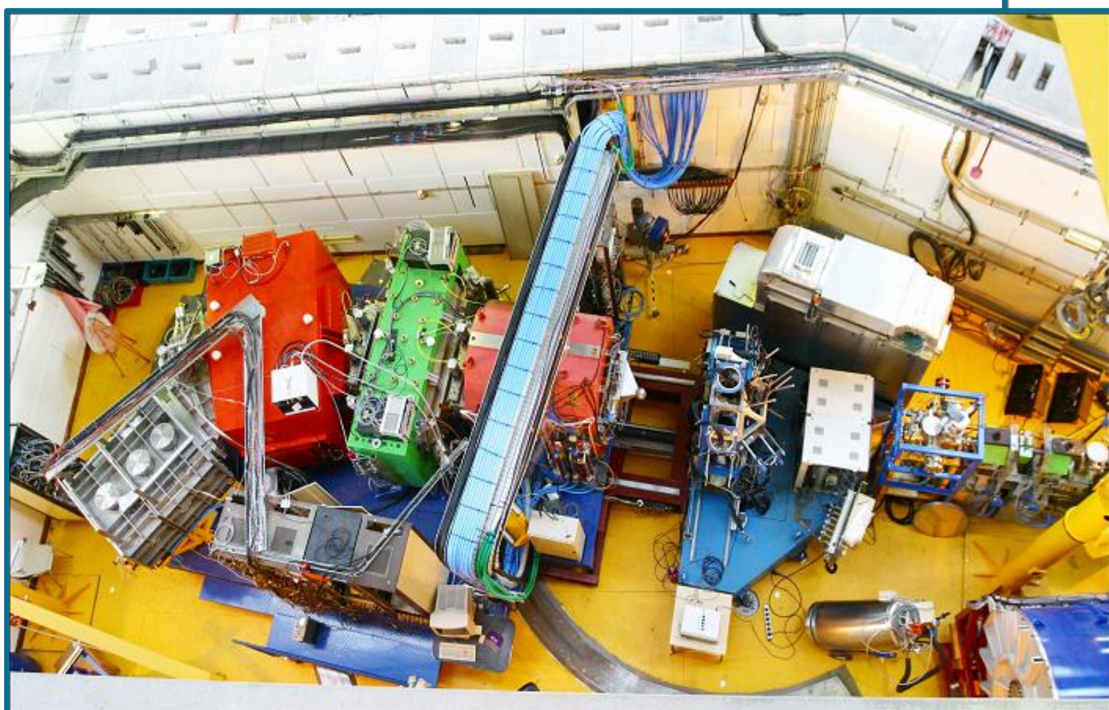
(d,p) on Ne and Na isotopes

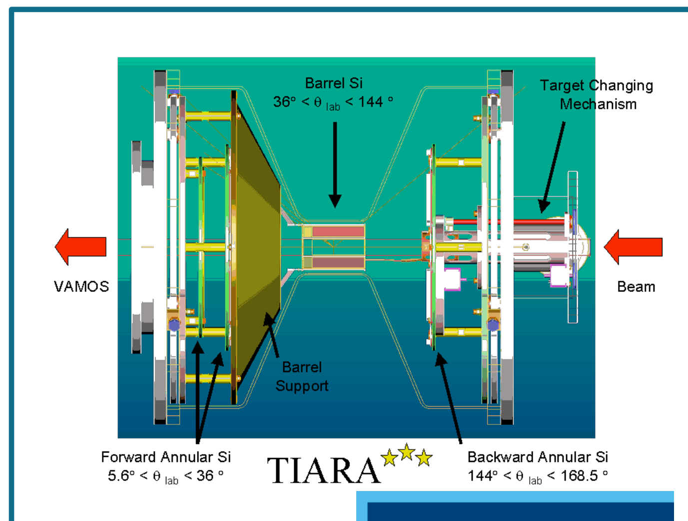
W Catford et al, PRL 104 (2010) 192501
SM Brown et al, PRC 85 (2012) 011302(R)

At GANIL (SPIRAL)

- TIARA charged-particle detectors
- EXOGAM γ-ray array
- VAMOS spectrometer







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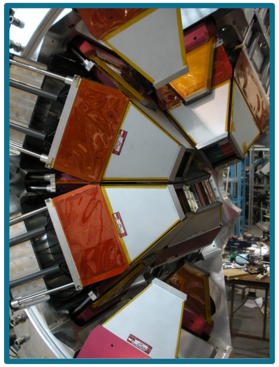
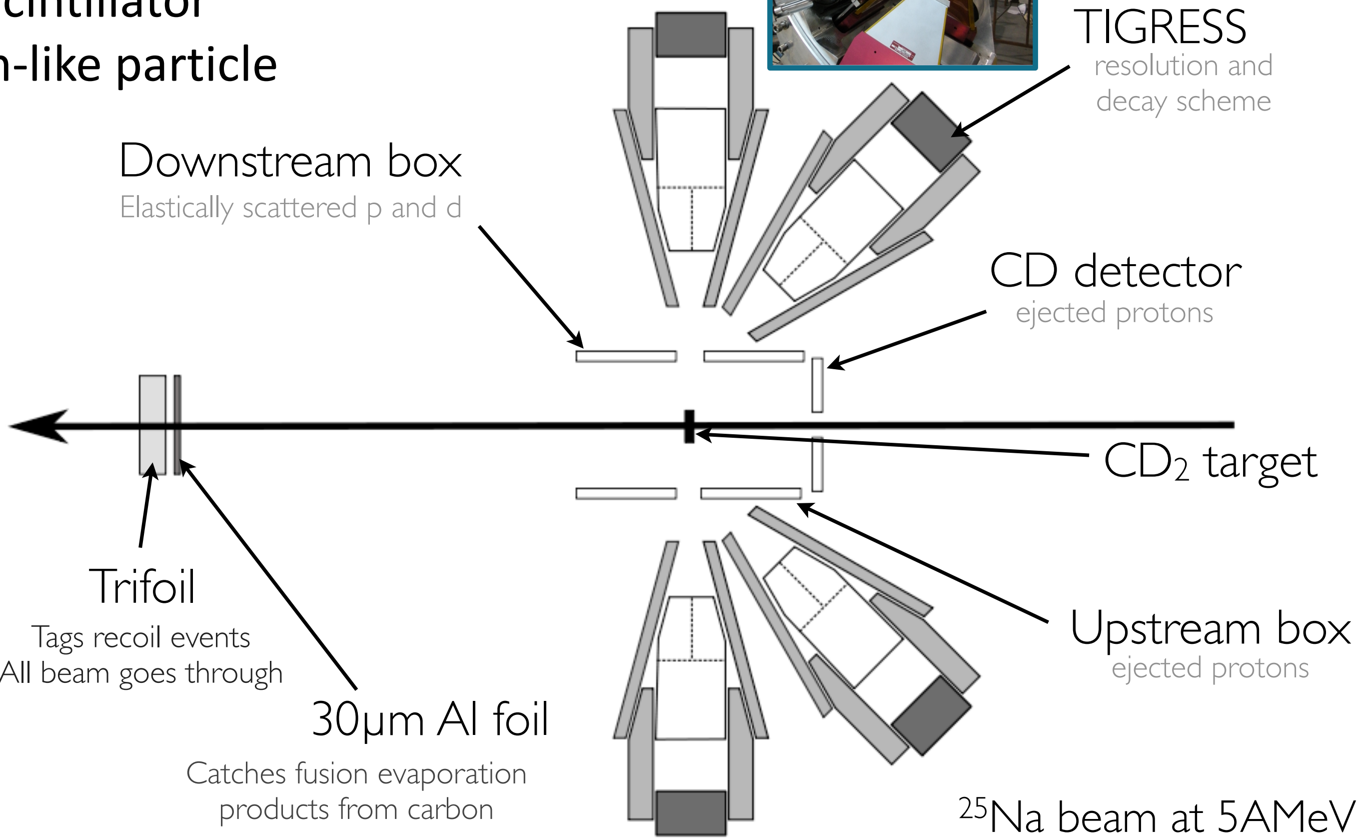
(d,p) on Ne and Na isotopes

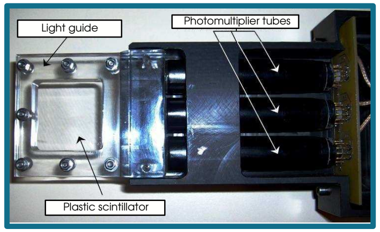
GL Wilson et al, PLB 759 (2016) 417

At TRIUMF (ISAC-II)

- SHARC charged-particle detectors
- TIGRESS γ-ray array
- TRIFOIL plastic scintillator
  to identify beam-like particle





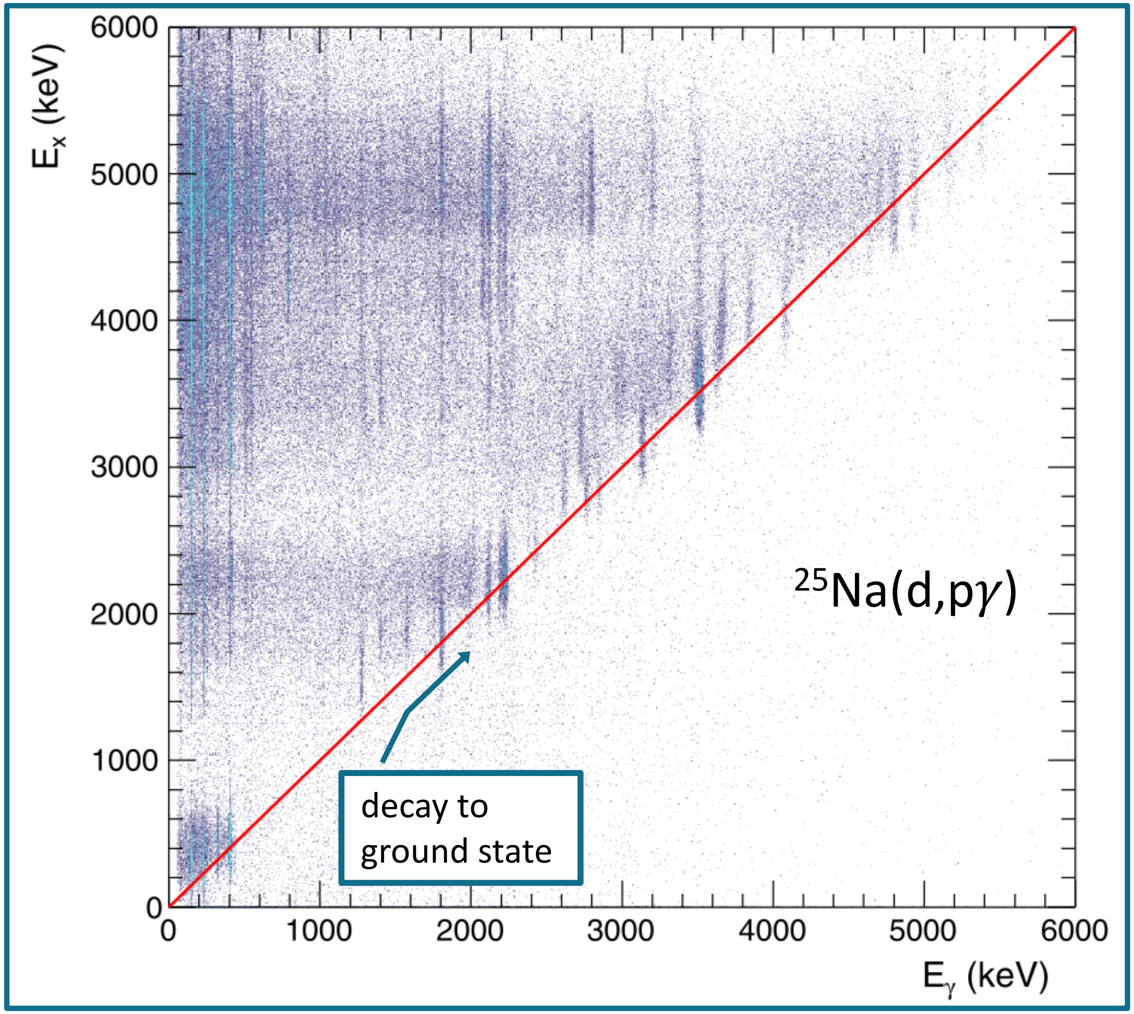


(d,p) on Ne and Na isotopes

GL Wilson et al, PLB 759 (2016) 417

Conditions

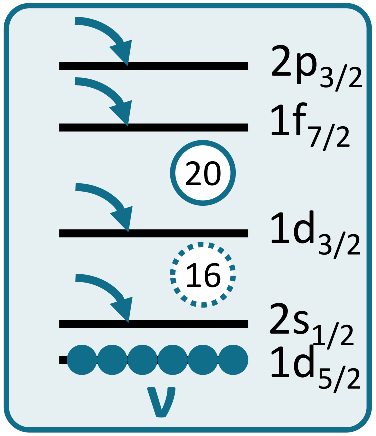
- Populated state decays promptly
- Angular resolution for Doppler correction

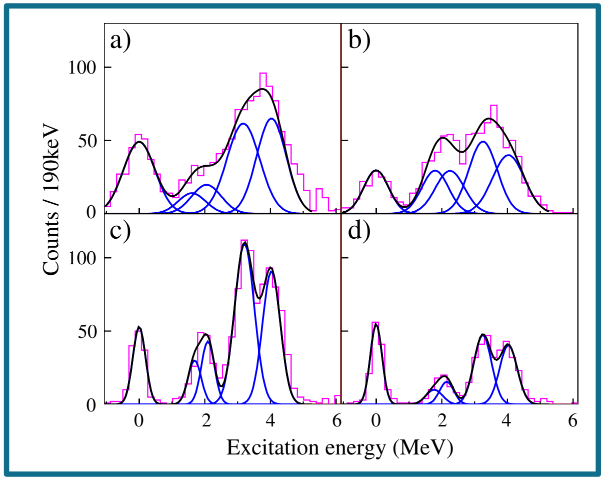


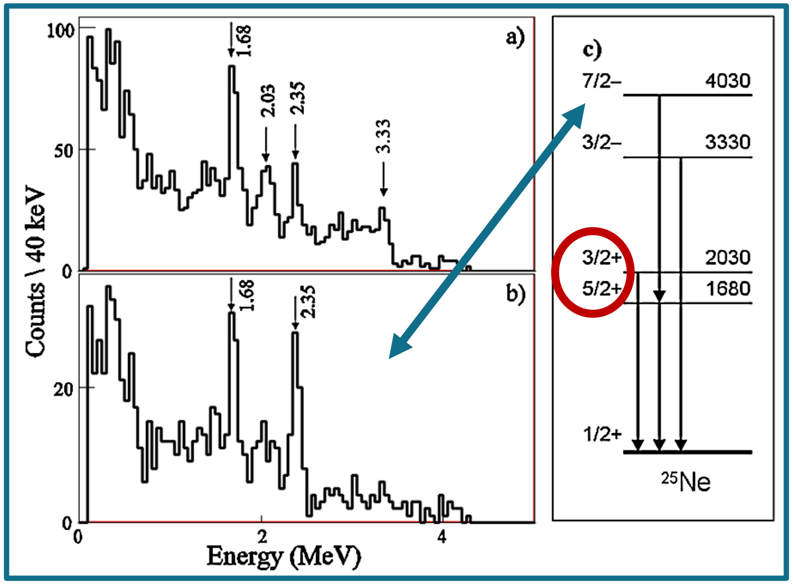
(d,p) on Ne and Na isotopes

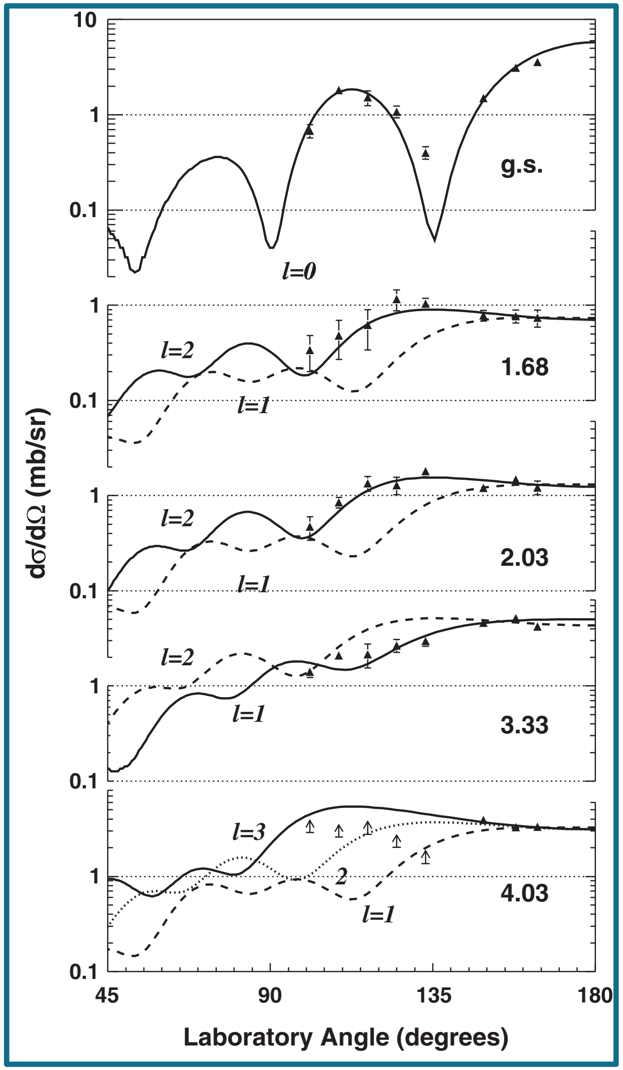
W Catford et al, PRL 104 (2010) 192501

$^{24}Ne(d,p)$





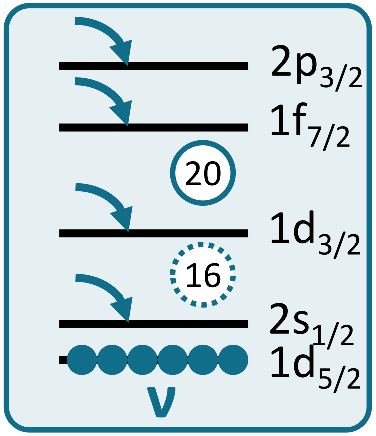




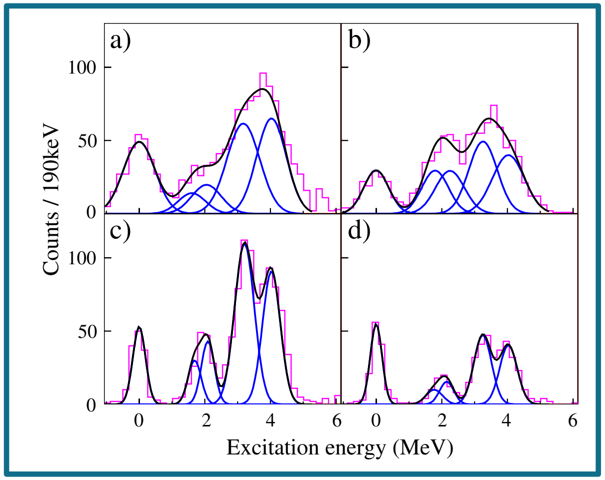
(d,p) on Ne and Na isotopes

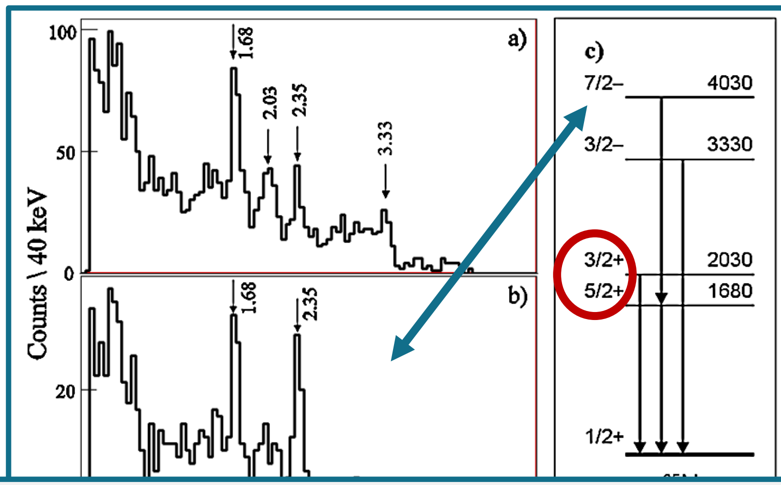
W Catford et al, PRL 104 (2010) 192501

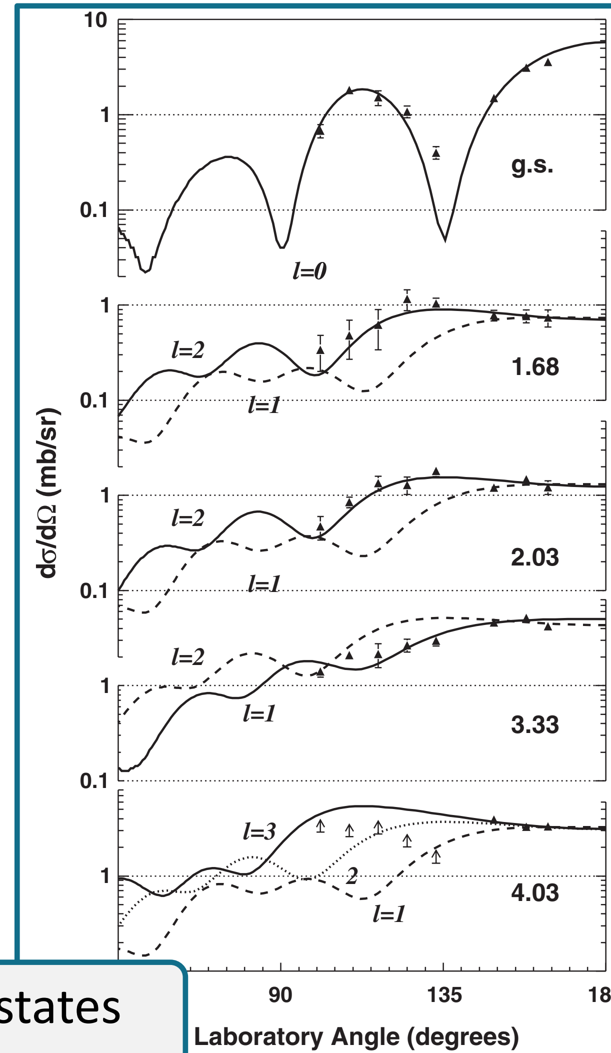
^{24}Ne(d,p)



SF(1/2$^+$) = 0.80
SF(5/2$^+$) = 0.15
SF(3/2$^+$) = 0.44
SF(3/2$^-$) = 0.75
SF(7/2$^-$) = 0.80







- Firm assignment of the spin of the first two excited states
- Raise of the 3/2$^+$ (≈1 MeV) with respect to the 5/2$^+$ compared to ^{27}Mg

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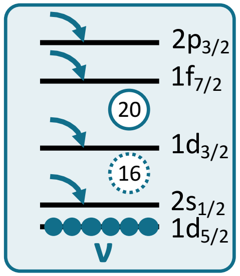
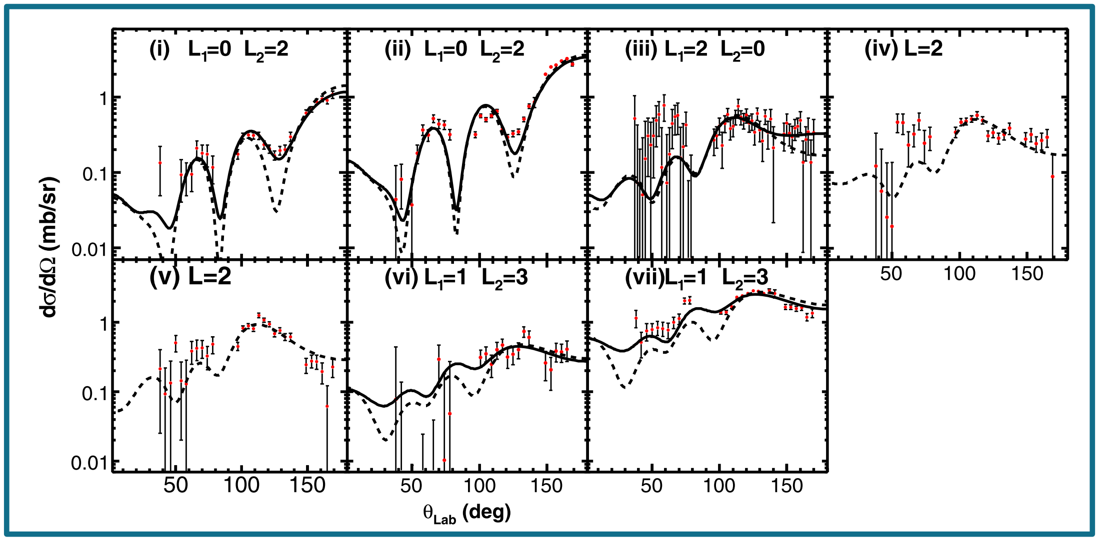
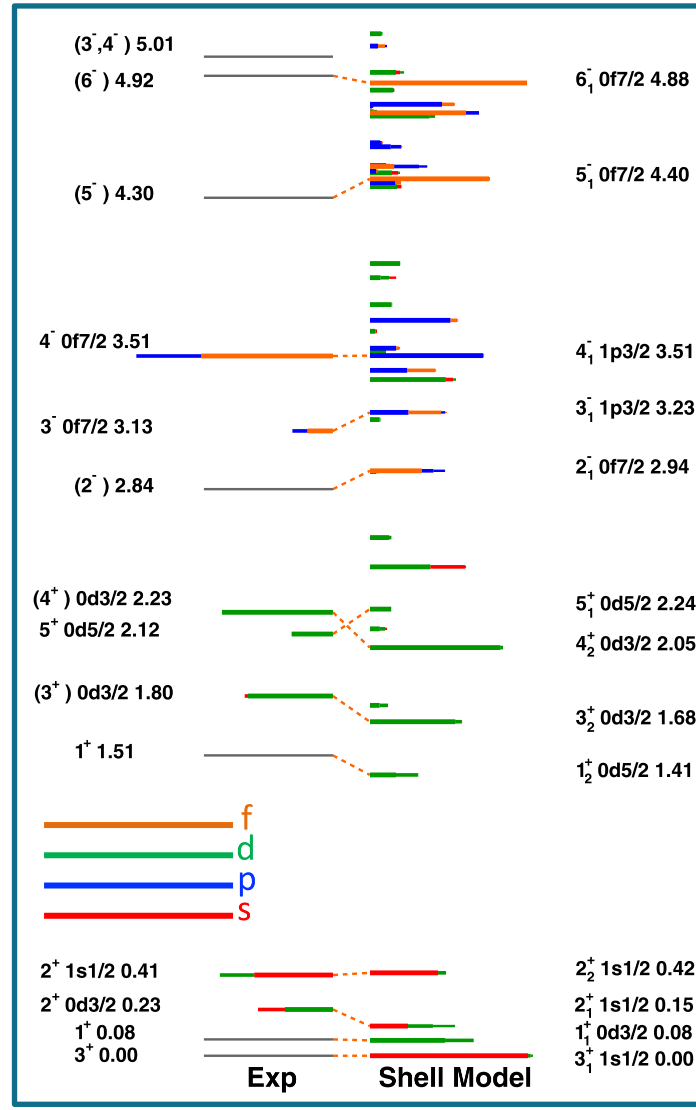
(d,p) on Ne and Na isotopes

GL Wilson et al, PLB 759 (2016) 417

^{25}Na(d,p)







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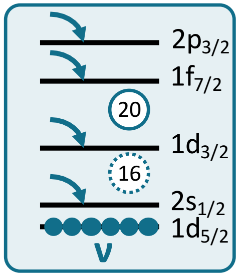
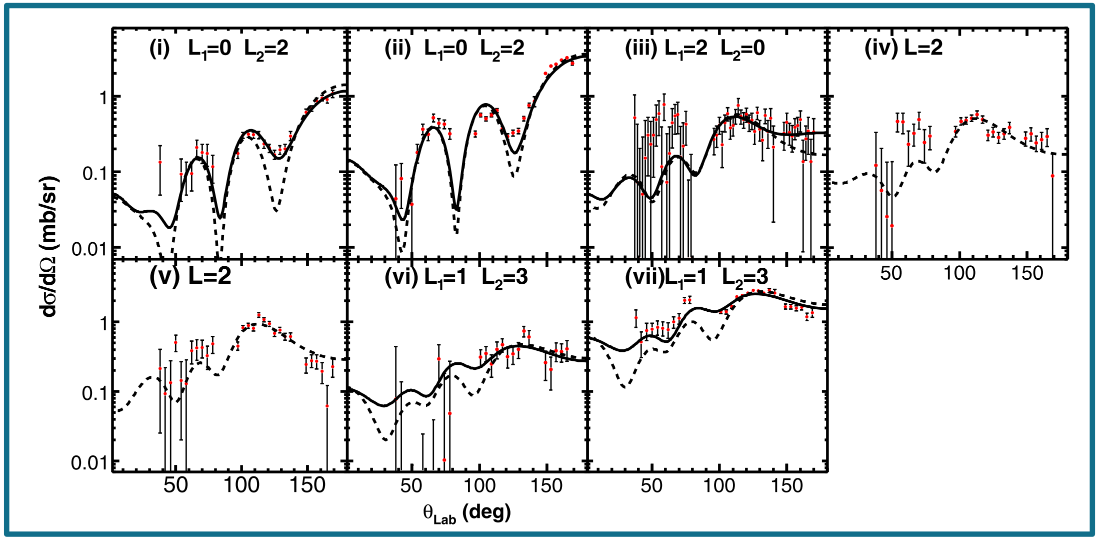
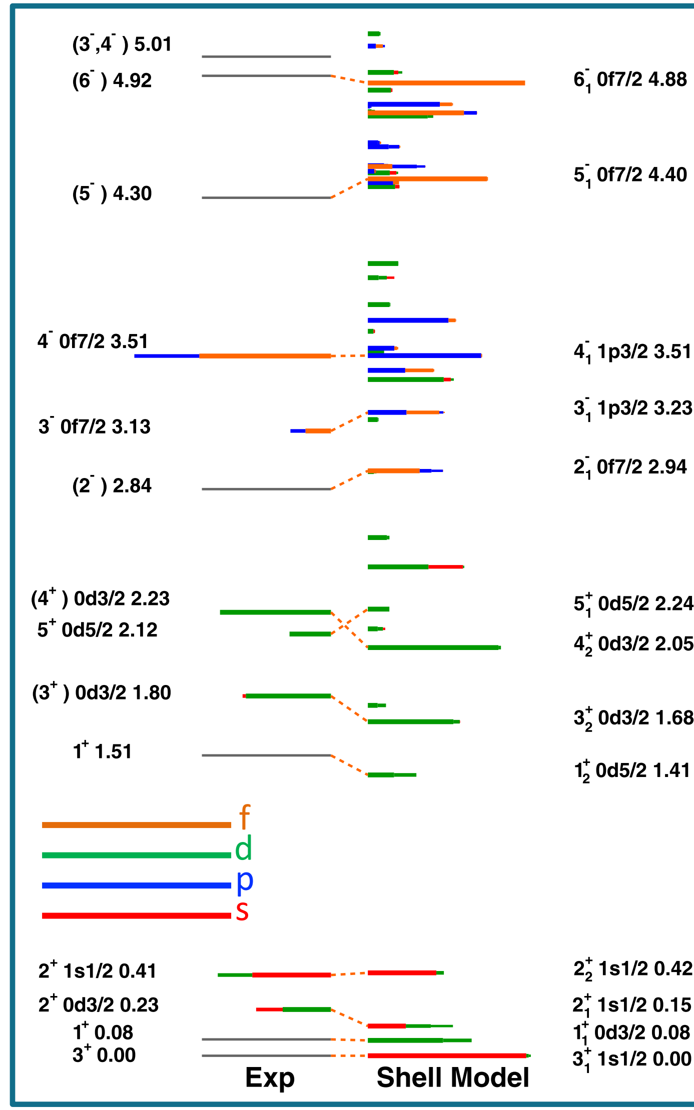
(d,p) on Ne and Na isotopes

GL Wilson et al, PLB 759 (2016) 417

^{25}Na(d,p)







- Important role of intruder configuration (negative parity states)
- Results reproduced by calculations with N=20 gap reduced by 700 keV

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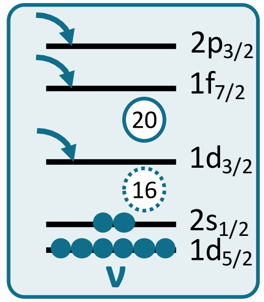
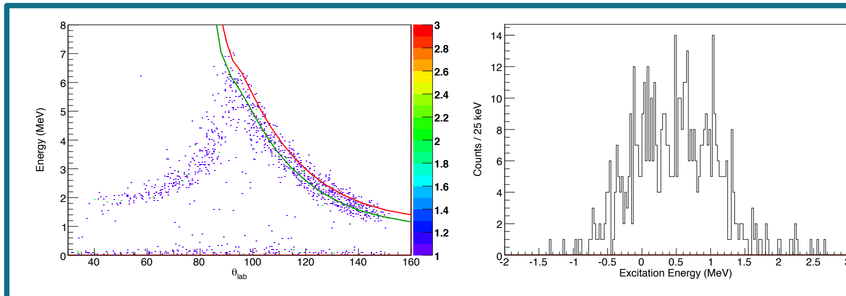
(d,p) on Ne and Na isotopes

M Brown et al, PRC 85 (2012) 011302(R)

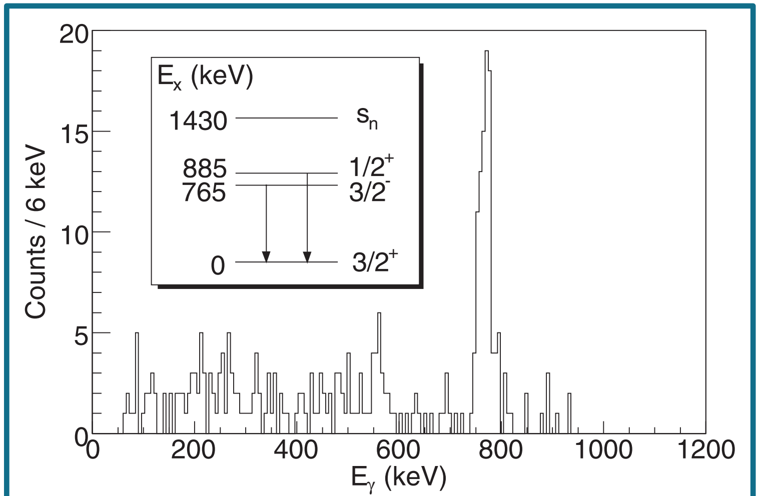
^{26}Ne(d,p)

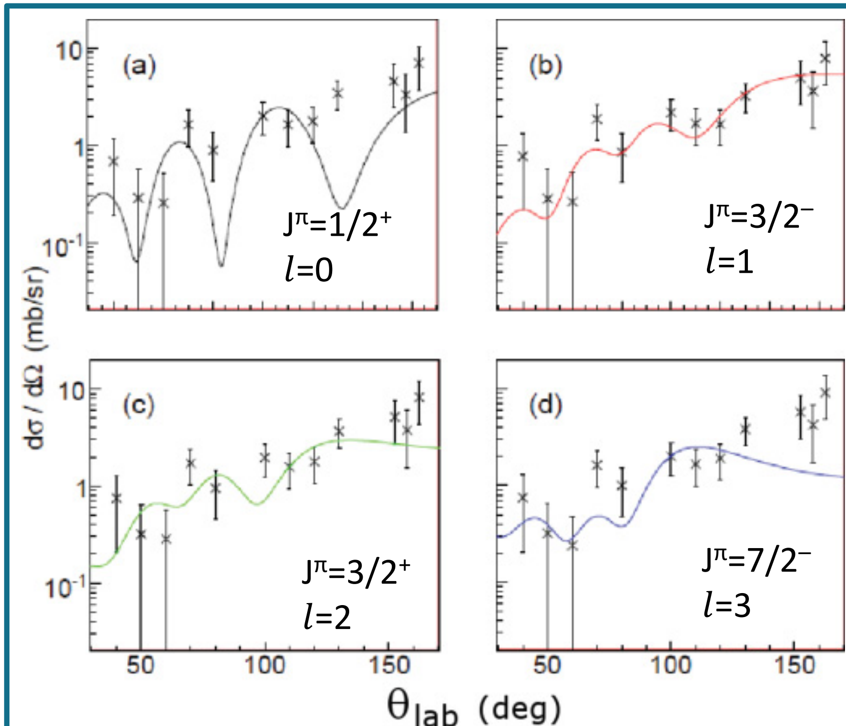


- Angular distributions: efficiency correction for coincidences as function of the spin
- Ground-state selection: E*<200 keV



(a) Measured proton kinematics.
(b) Excitation energy.





Very low 3/2⁻ intruder state

(d,p) on Ne and Na isotopes

M Brown et al, PRC 85 (2012) 011302(R)

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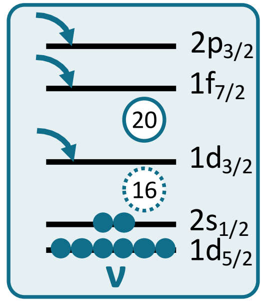

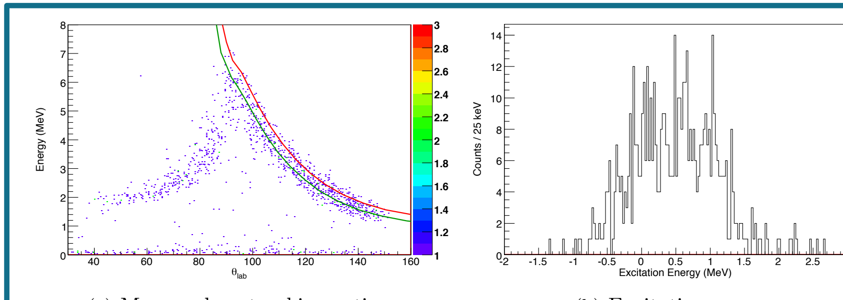

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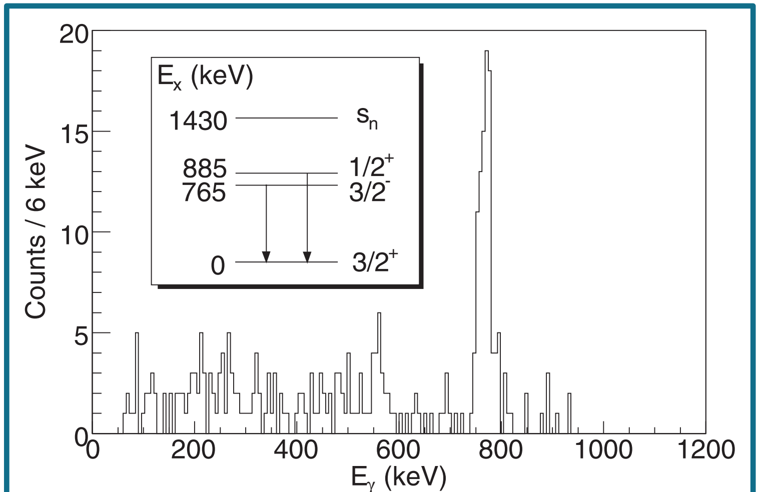

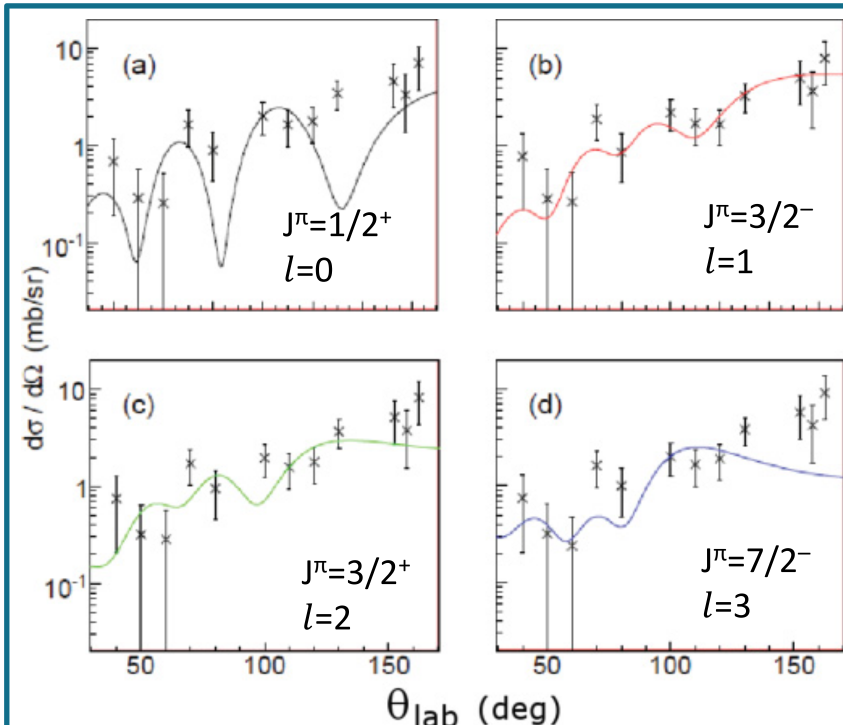

Very low 3/2⁻ intruder state

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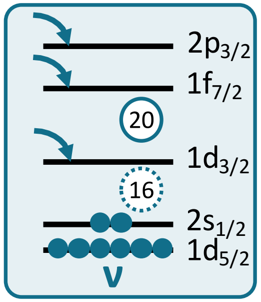
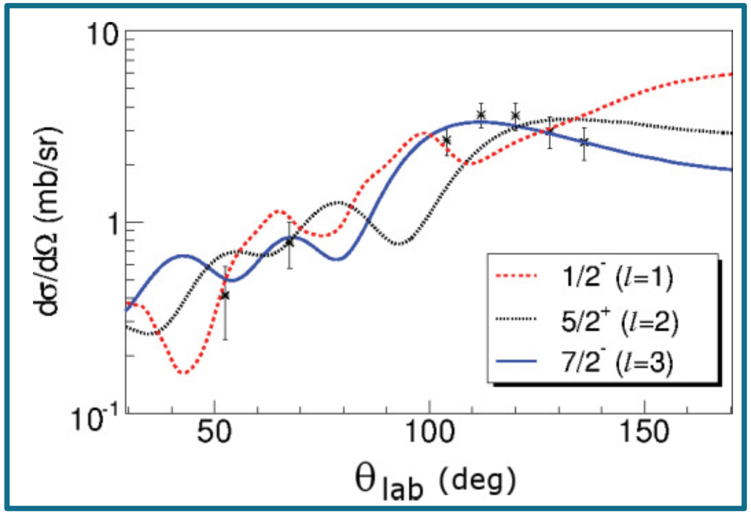
(d,p) on Ne and Na isotopes

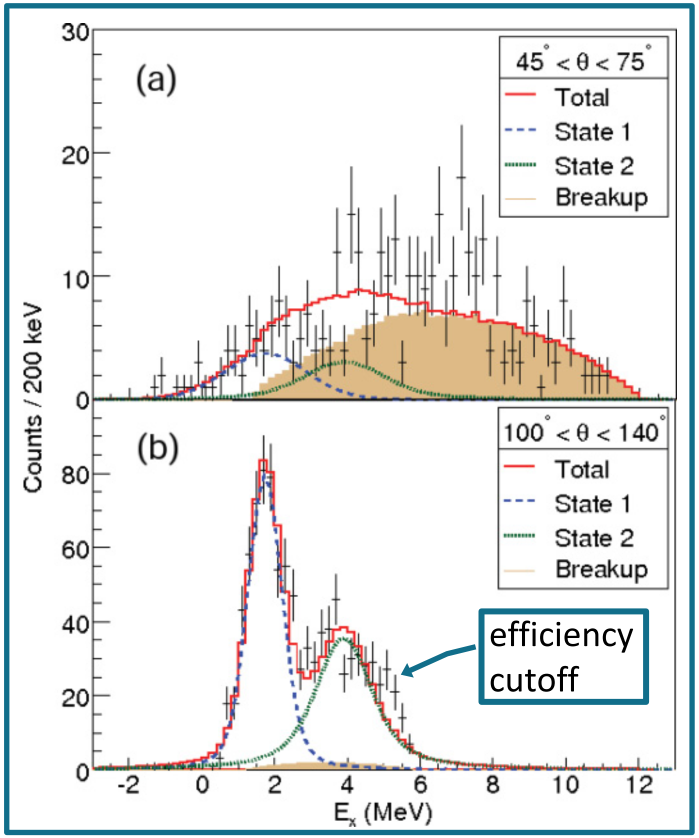
M Brown et al, PRC 85 (2012) 011302(R)

^{26}Ne(d,p)

- Proton coincidences with ^{26}Na: transfer to unbound states







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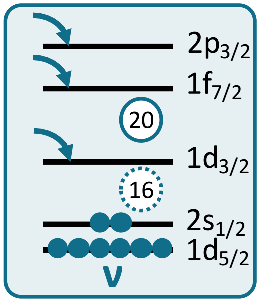

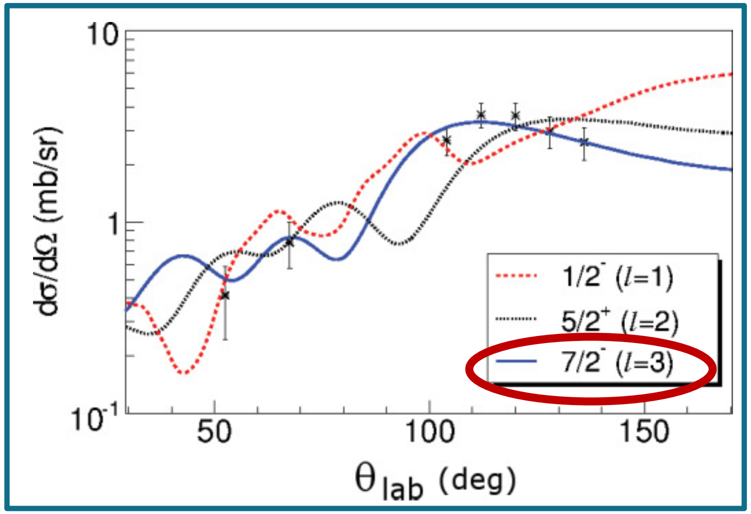

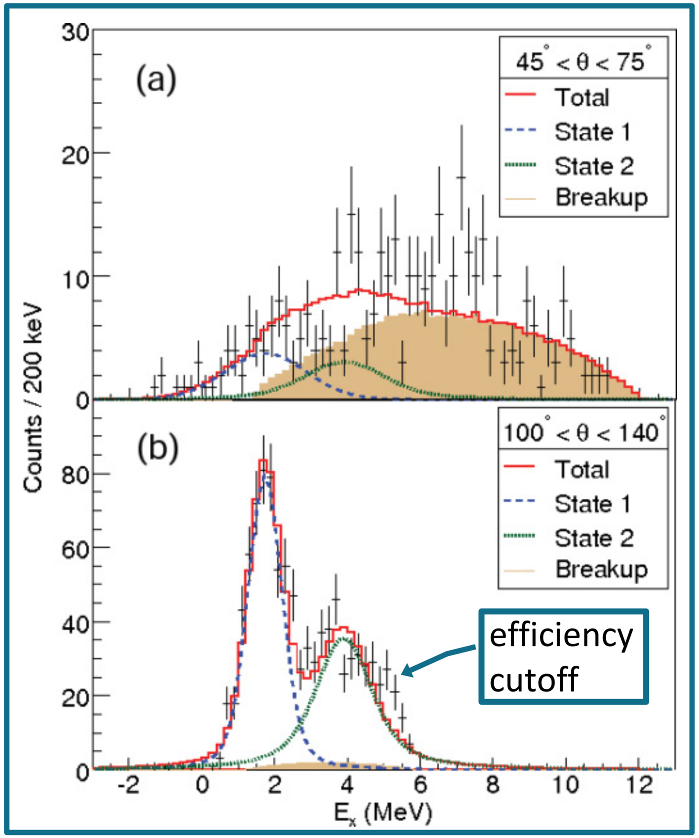

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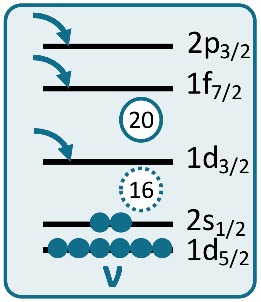

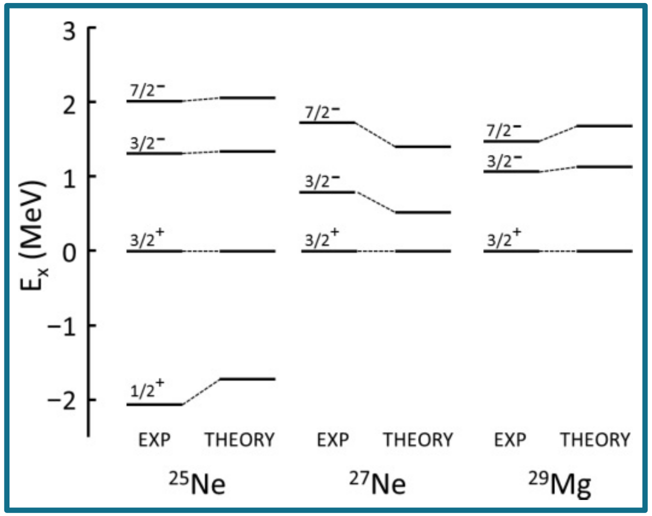

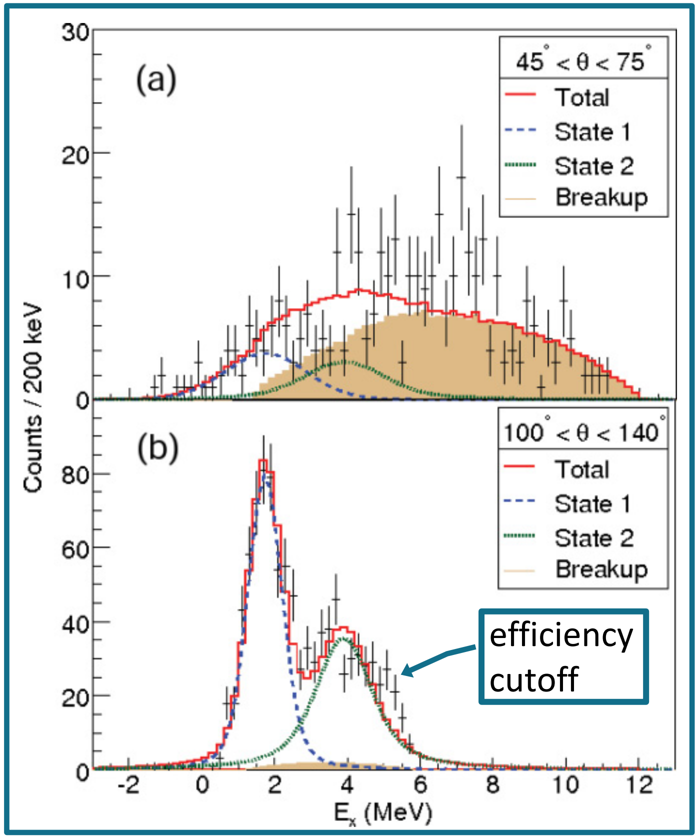

SF(3/2$^+$) = 0.42
SF(3/2$^-$) = 0.64
SF(1/2$^+$) = 0.17
SF(7/2$^-$) = 0.35

- Identification of intruder states 3/2$^-$, 7/2$^-$
- Results reproduced by calculations with N=20 gap reduced by 700 keV

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Nucleon-Transfer Reactions with Radioactive Ion Beams

Riccardo Raabe
KU Leuven, Instituut voor Kern- en Stralingsfysica

International School of Physics "Enrico Fermi”

14-19 July 2017

Nuclear Physics with Stable and Radioactive Ion Beams

Lecture 3/3

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Contents

- Nuclear reactions
  - Types of reactions
  - Characteristics of direct reactions
- Why use transfer reactions
  - Information from reactions
  - Q-value, angular momentum, spectroscopic factors
- Reactions and RIBs
  - Motivations
  - Challenges: inverse kinematics
- **Case studies**
  - Light nuclei, N=8
  - The emergence of N=16
  - **The spin-orbit term**
  - Mg and Ni, the 0^+s
  - ...

The spin-orbit term

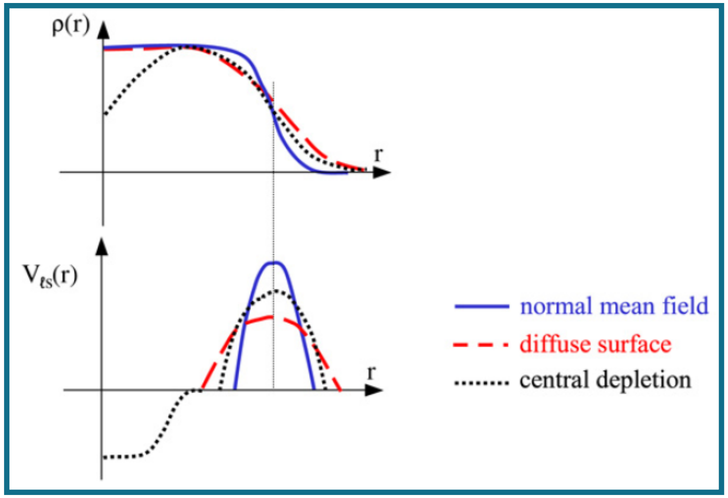
- One-body spin-orbit potential:

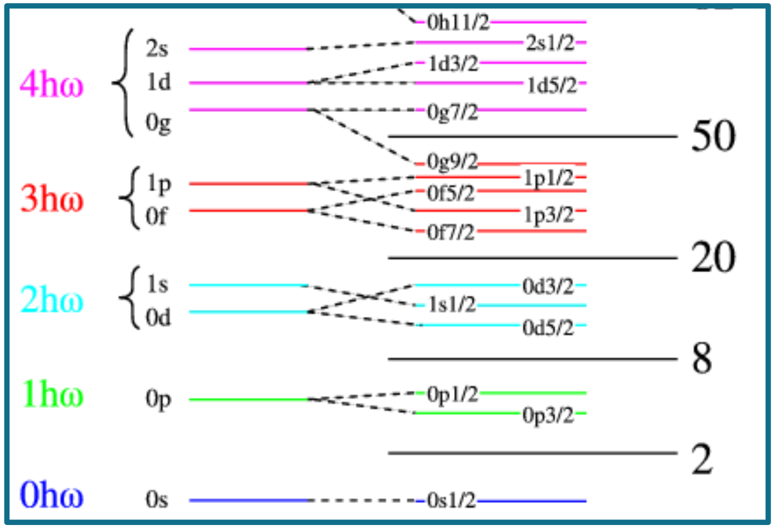
$$V_{\ell s}(r) = \frac{1}{r}\frac{d\rho}{dr}\,\vec{\ell}\cdot\vec{s}$$

→ a diffuse matter distribution should decrease the SO term

→ a depletion of density at the center should induce a decrease of SO for nucleons in the region

O. Sorlin, M.-G. Porquet, PPNP 61 (2008) 602





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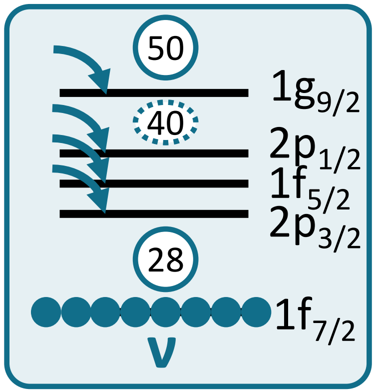
Spin orbit at the surface?

L Gaudefroy et al, PRL 97 (2006) 092501

"Reduction of the Spin-Orbit Splittings at the N=28 shell closure"

^{46}Ar(d,p)^{47}Ar at GANIL (SPIRAL)



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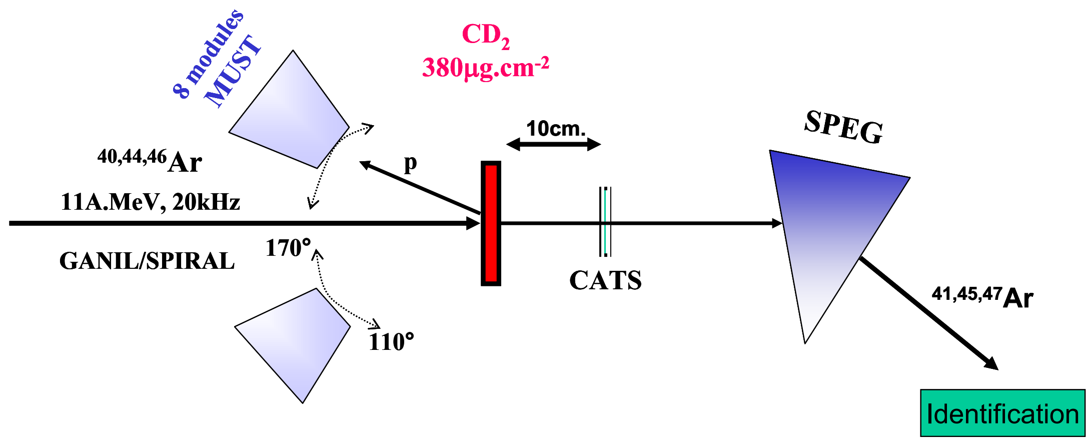
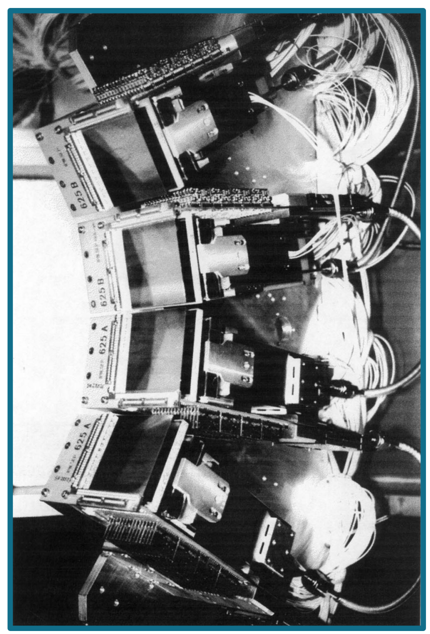
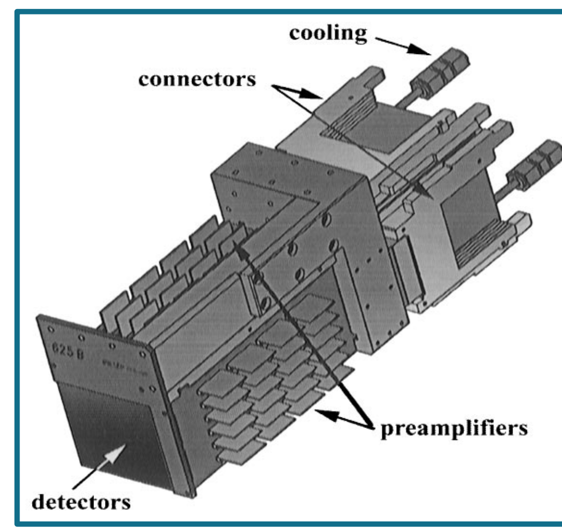


- SPEG for identification of ^{47}Ar
- MUST charged-particle telescope detectors Si-Si(Li)-CsI





Y. Blumenfeld et al
NIMA 421 (1999) 471

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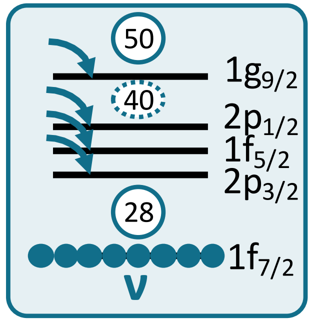
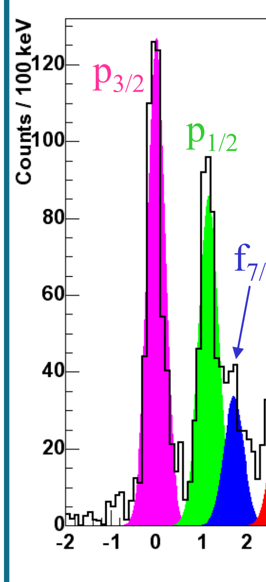
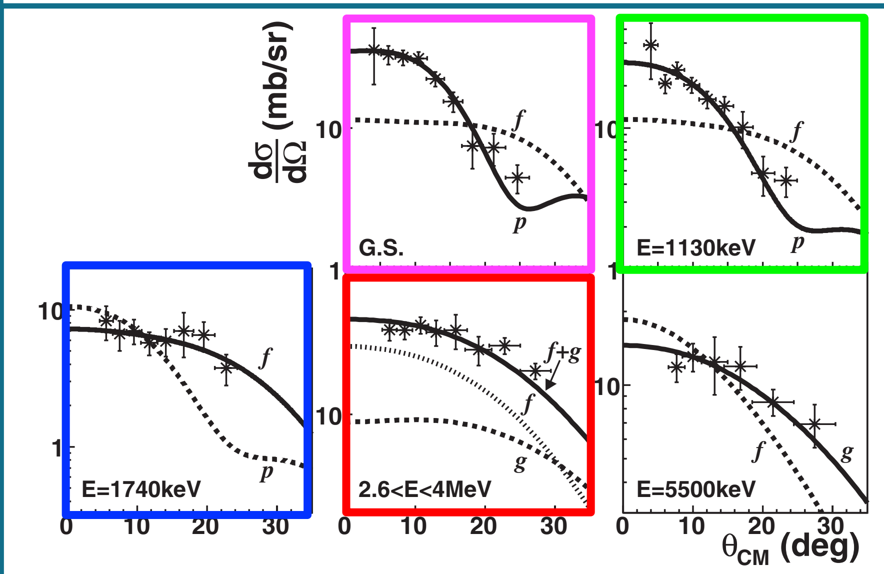
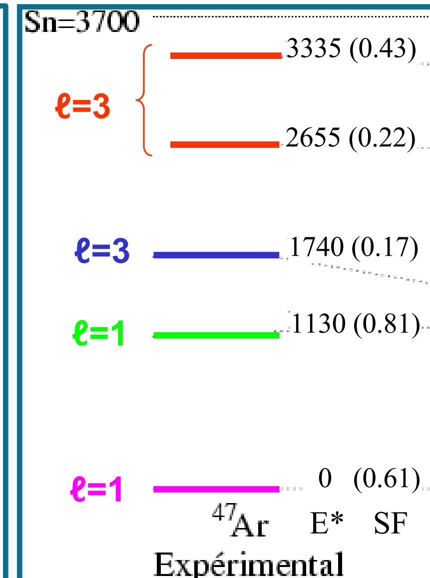


p strength almost complete
missing $f_{5/2}$ strength from calculations

spin deduced from comparison with calculations







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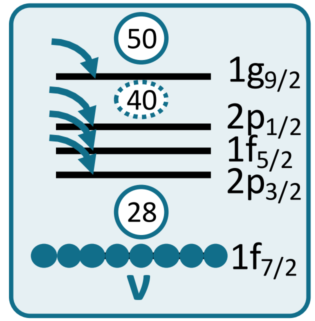
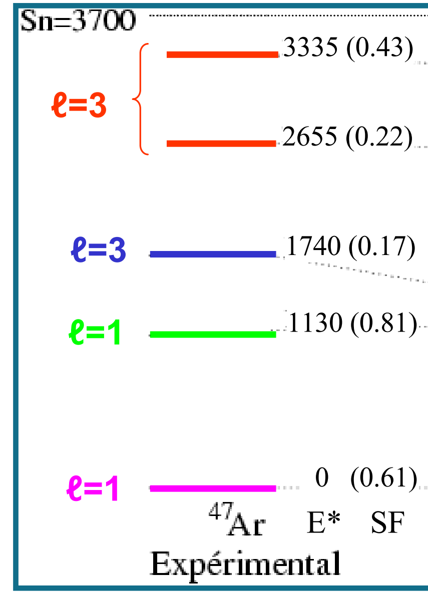
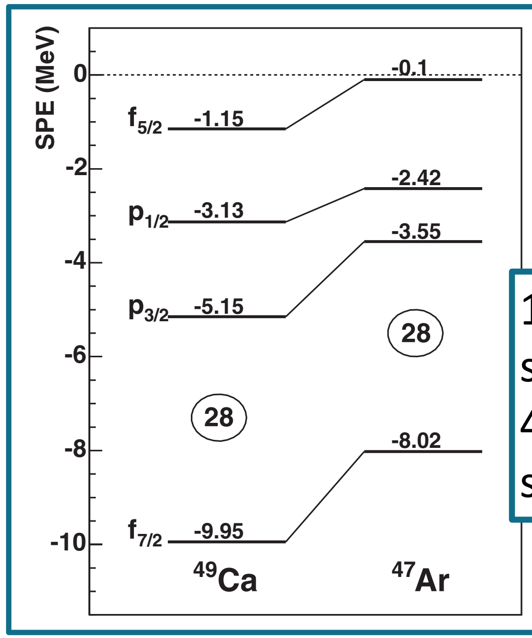
"Reduction of the Spin-Orbit Splittings at the N=28 shell closure"

^{46}Ar(d,p)^{47}Ar

- Mass excess of ground state from *Q*-value → N=28 gap deduced
  Reduction of 330 keV compared to ^{49}Ca
- Centroid of $f_{5/2}$ deduced from experiment and calculations; plotted with energy of the "p states"
- Differences with ^{49}Ca (N=28 gap) ascribed to the removal of protons from $d_{3/2}$ and $s_{1/2}$







10% reduction of splitting f orbitals;
45% reduction of splitting p orbitals

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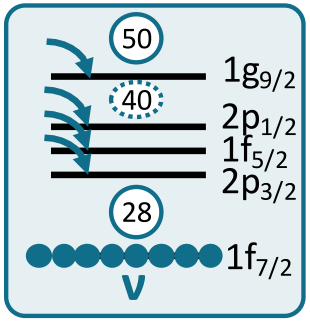

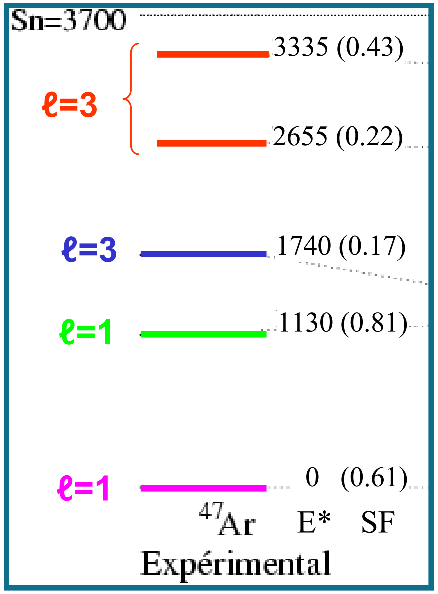

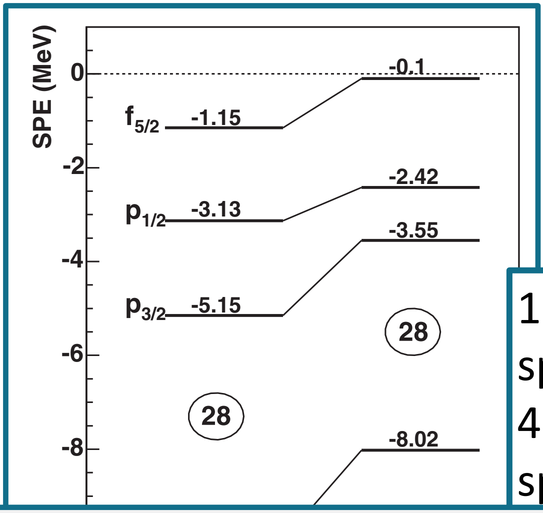

10% reduction of splitting f orbitals; 45% reduction of splitting p orbitals

- Tensor force sufficient to explain reduction of splitting of f orbitals
- Reduction of splitting p orbitals can be due to removal of $s_{1/2}$ proton

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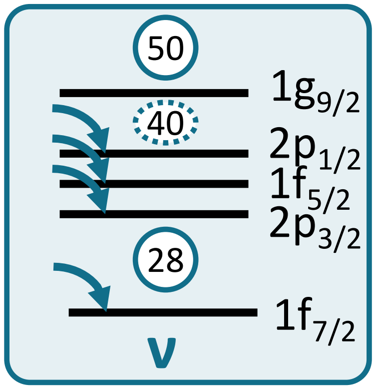
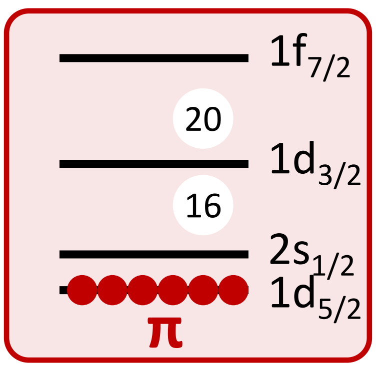
Bubble in nucleus?

G Burgunder et al, PRL 112 (2014) 042502

"Experimental Study of the Two-Body Spin-Orbit Force in Nuclei"

^{34}Si(d,p)^{35}Si at GANIL (LISE)





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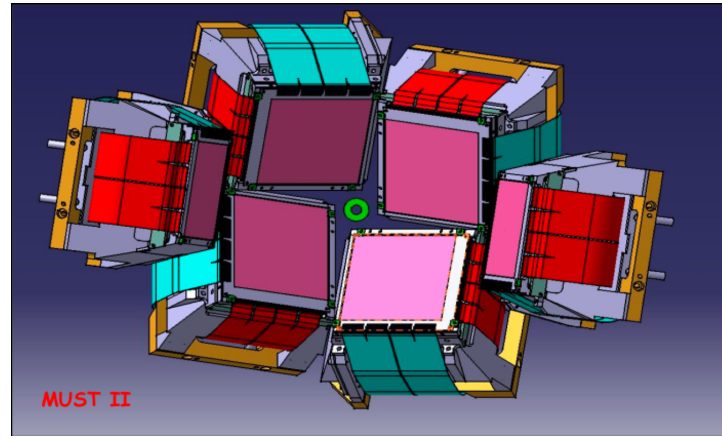
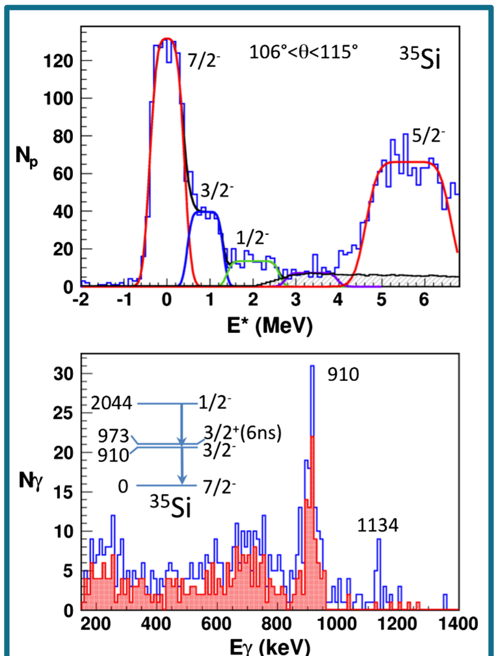
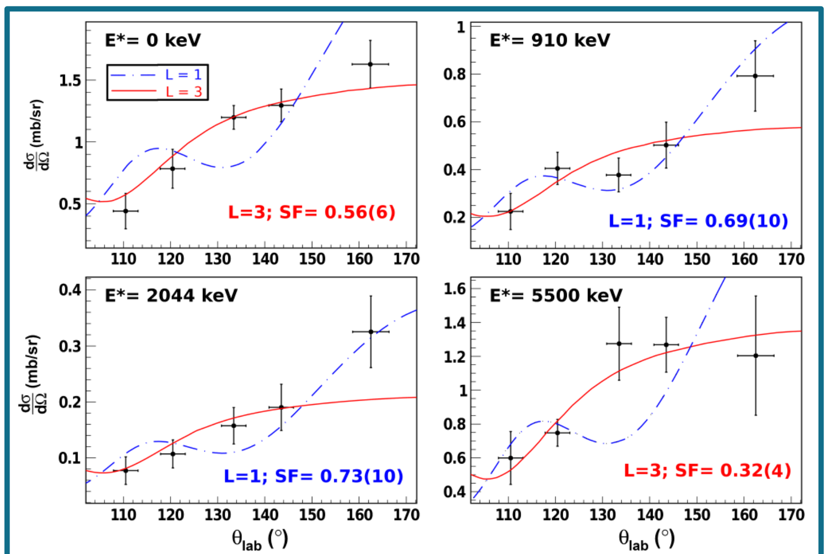
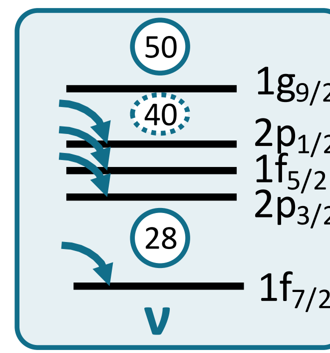
- MUST2 charged-particle detector
- Ionisation chamber + plastic detector for identification of the beam-like particle
- EXOGAM γ-ray array









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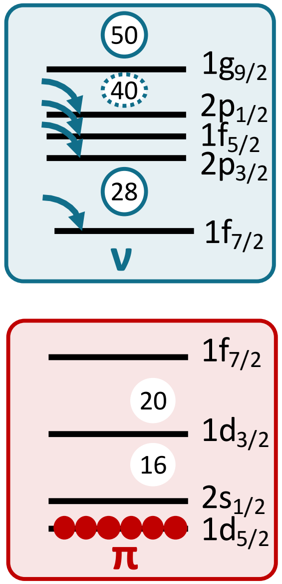

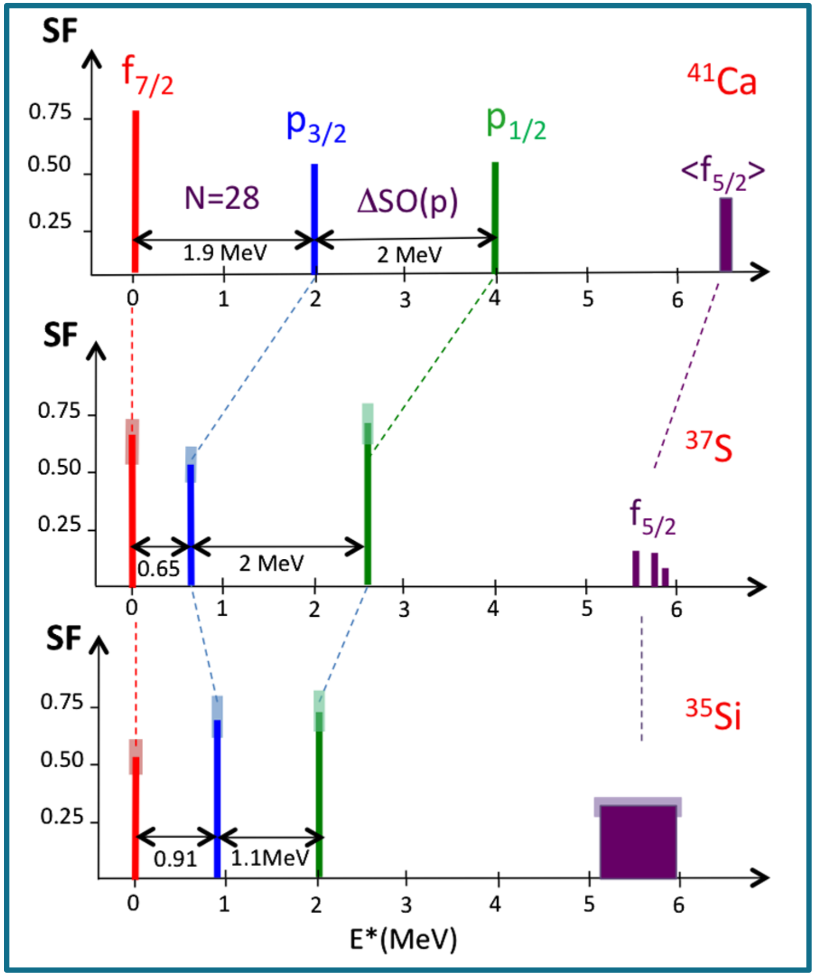

The Two-Body SO-force is constrained by the experimental values

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G Burgunder et al, PRL 112 (2014) 042502

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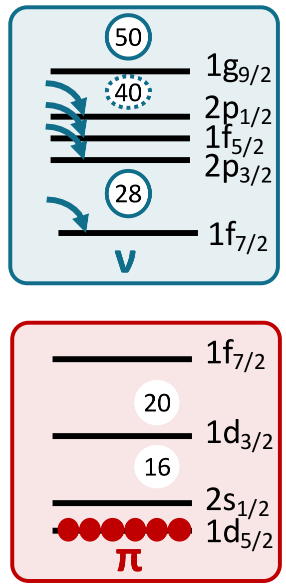
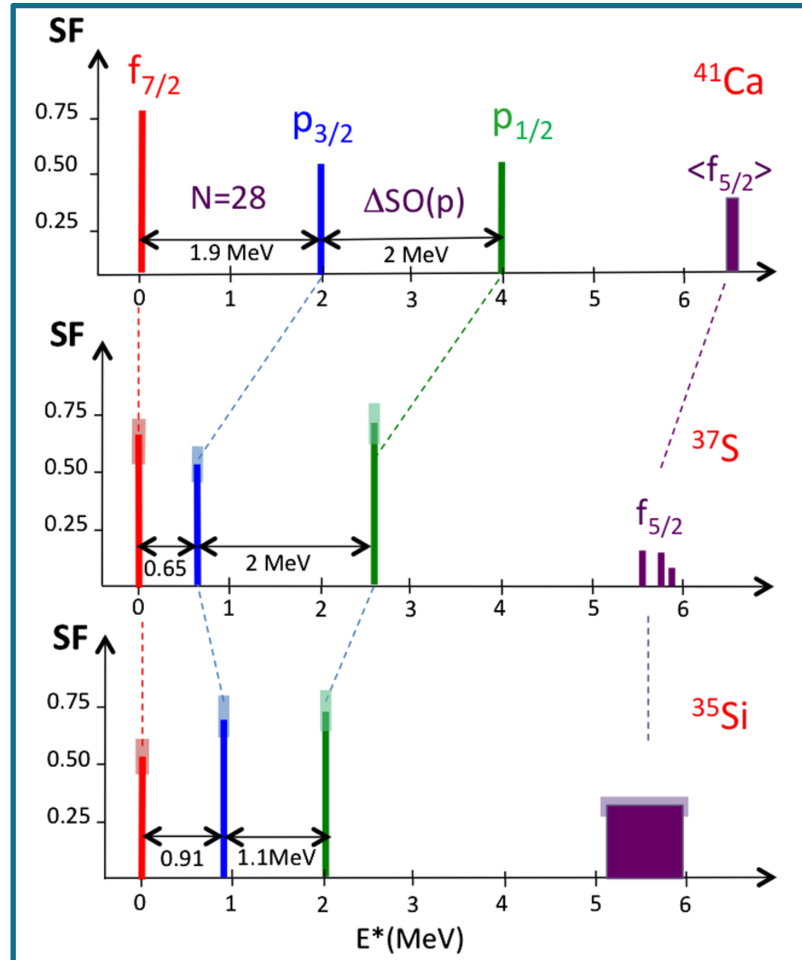




The Two-Body SO-force is constrained by the experimental values

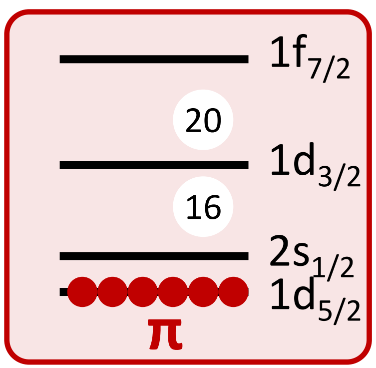
Bubble in nucleus?

A Mutschler et al, Nat Phys 13 (2017) 152

Occupation of $s_{1/2}$ in ^{34}Si

^{34}Si proton removal

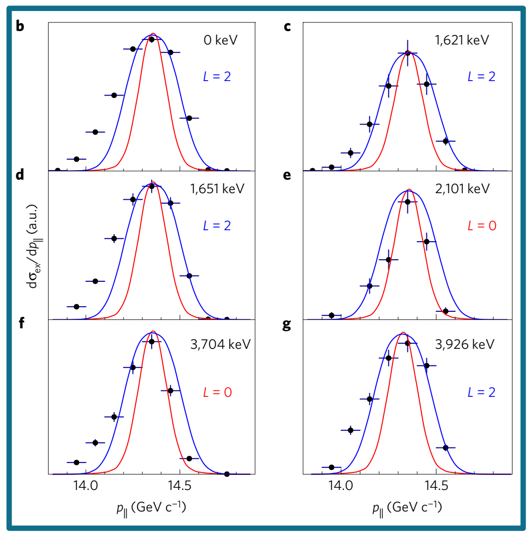
- Experiment at MSU
- ^{34}Si on ^{9}Be target proton and γ detection
- l from momentum distribution of protons
- Deduced spin and SFs of states in ^{33}Al

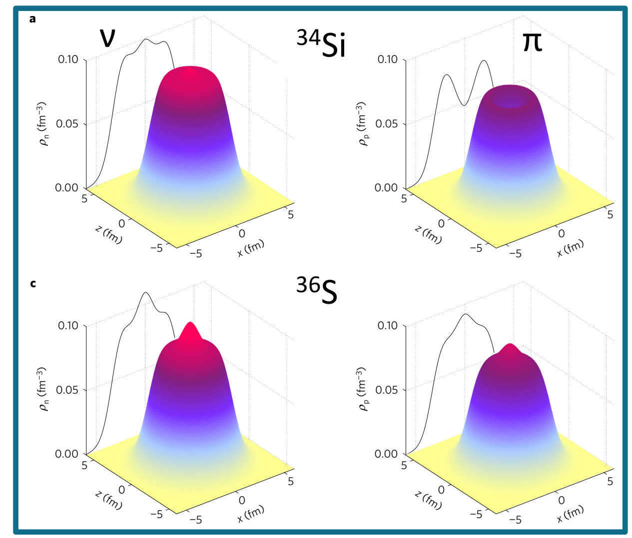


ARTICLES
PUBLISHED ONLINE: 24 OCTOBER 2016 | DOI: 10.1038/NPHYS3916
nature physics

A proton density bubble in the doubly magic ^{34}Si nucleus

A. Mutschler[1,2], A. Lemasson[2,3], O. Sorlin[2*], D. Bazin[4], C. Borcea[5], R. Borcea[5], Z. Dombrádi[6], J.-P. Ebran[7], A. Gade[4], H. Iwasaki[4], E. Khan[1], A. Lepailleur[2], F. Recchia[3], T. Roger[2], F. Rotaru[5], D. Sohler[6], M. Stanoiu[5], S. R. Stroberg[4,8], J. A. Tostevin[9], M. Vandebrouck[1], D. Weisshaar[3] and K. Wimmer[3,10,11]





Occupation of $s_{1/2}$ in ^{34}Si is only 17%
Density is depleted inside the nucleus

KU LEUVEN

Bubble in nucleus?

A Mutschler et al, Nat Phys 13 (2017) 152

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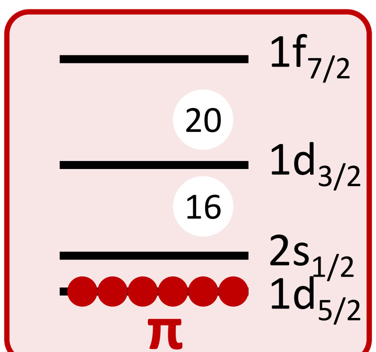

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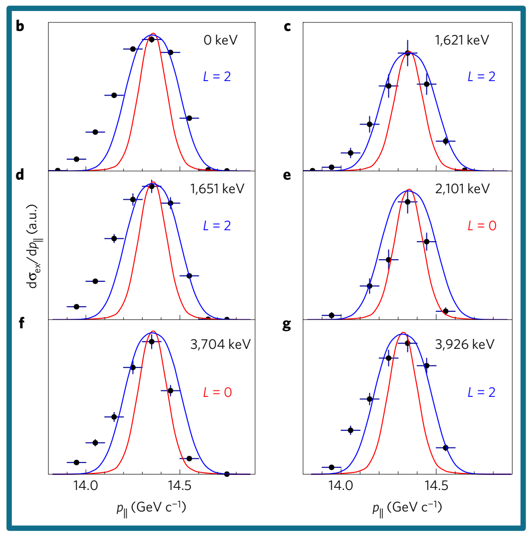
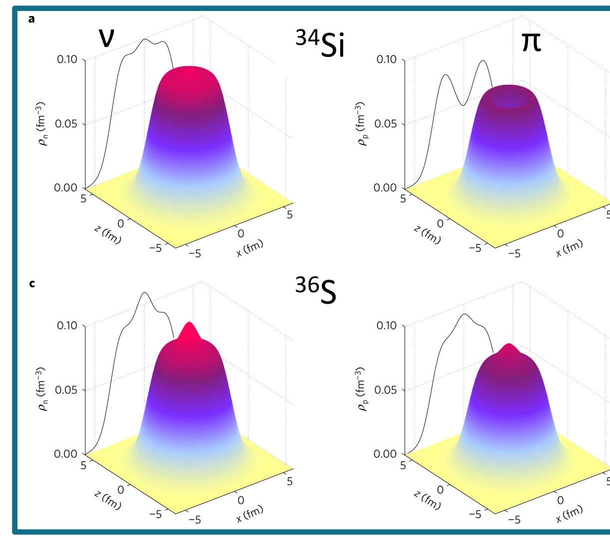
nature physics

A proton density bubble in the doubly magic ^{34}Si nucleus

A. Mutschler[1,2], A. Lemasson[2,3], O. Sorlin[2*], D. Bazin[4], C. Borcea[5], R. Borcea[5], Z. Dombrádi[6], J.-P. Ebran[7], A. Gade[4], H. Iwasaki[4], E. Khan[1], A. Lepailleur[2], F. Recchia[3], T. Roger[2], F. Rotaru[5], D. Sohler[6], M. Stanoiu[5], S. R. Stroberg[4,8], J. A. Tostevin[9], M. Vandebrouck[1], D. Weisshaar[3] and K. Wimmer[3,10,11]





Occupation of $s_{1/2}$ in ^{34}Si is only 17%
Density is depleted <u>inside</u> the nucleus

Contents

- Nuclear reactions
  - Types of reactions
  - Characteristics of direct reactions
- Why use transfer reactions
  - Information from reactions
  - Q-value, angular momentum, spectroscopic factors
- Reactions and RIBs
  - Motivations
  - Challenges: inverse kinematics
- **Case studies**
  - Light nuclei, N=8
  - The emergence of N=16
  - The spin-orbit term
  - **Mg and Ni, the 0^+s**
  - ...

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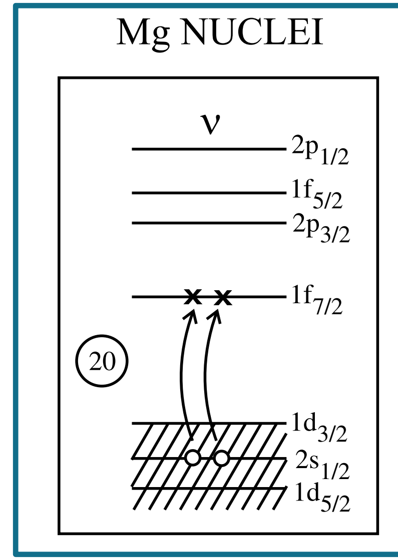
The structure of 0^+ states

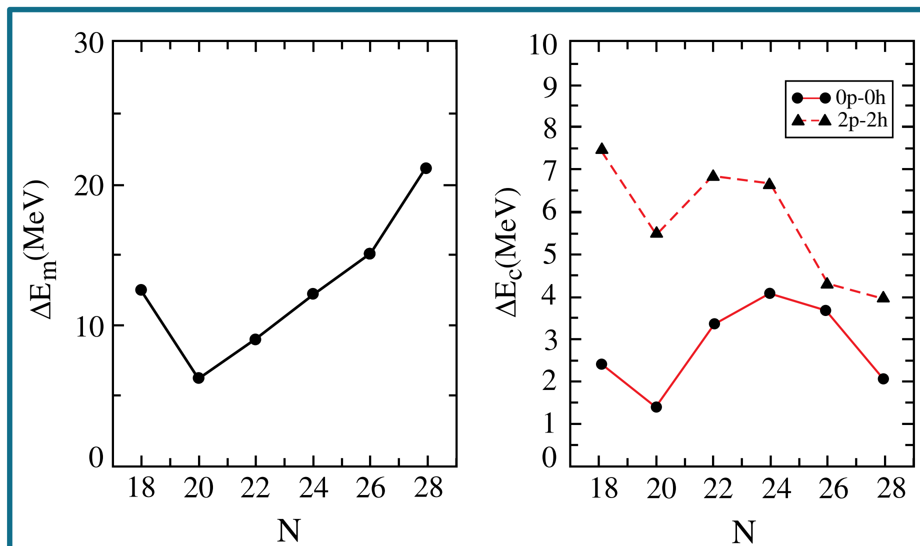
- When the monopole gap is of the same size as the correlation energy:

  2p-2h configurations appear at low energy
  0^+ states with different shapes

- "Shape transitions" and "islands of inversion":
  How can we probe the s.p. content of the wave function?



K Heyde and JL Wood,
Rev Mod Phys 83 (2011) 1467



E Caurier et al, PRC 58 (1998) 2033

Use two-neutron transfer to connect 0^+ states with similar configurations

Caution

- The initial state should be known
- Reaction process: two neutrons as a cluster?

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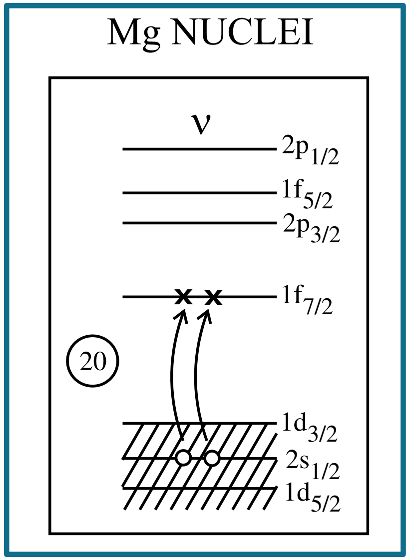

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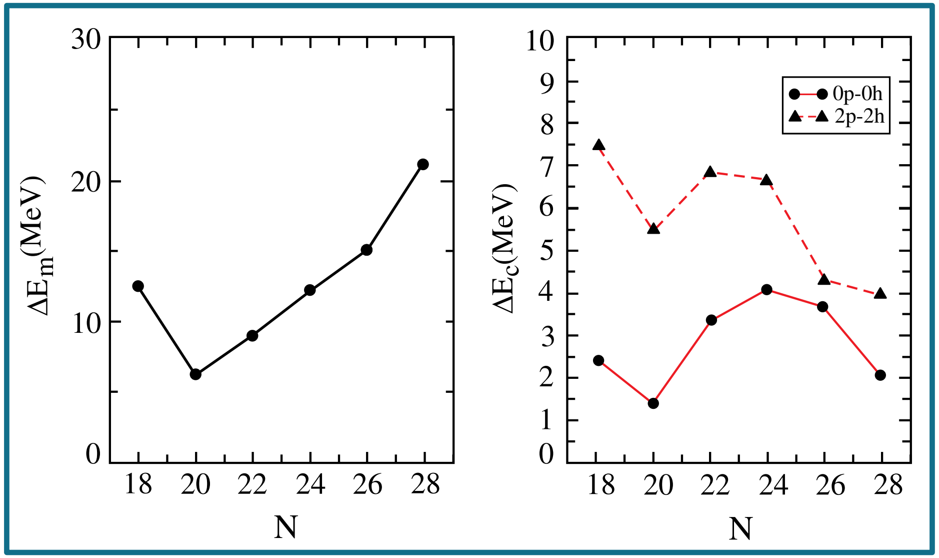

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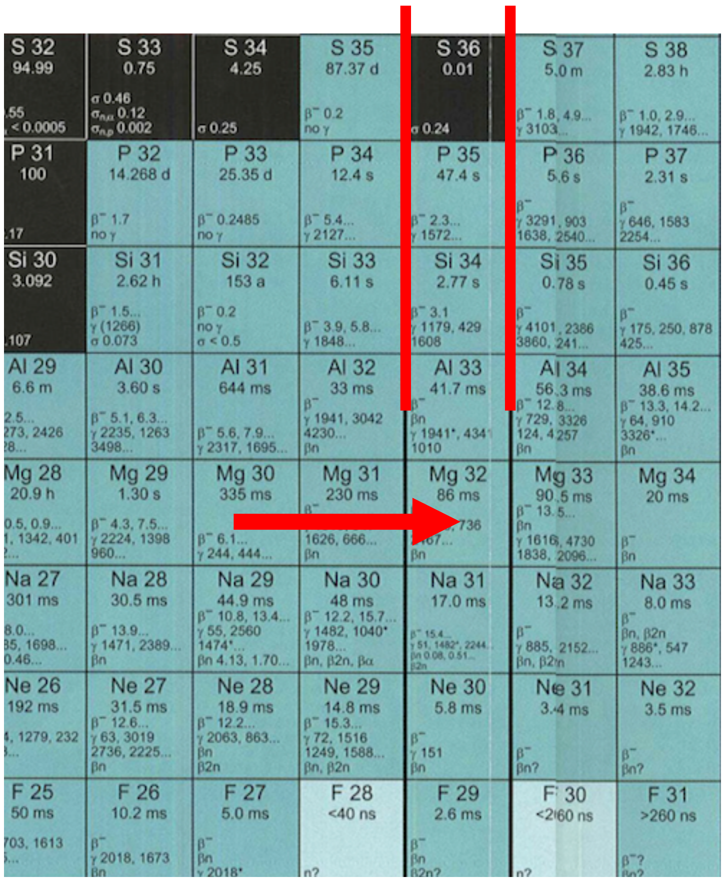
The 0^+ states in ^{32}Mg

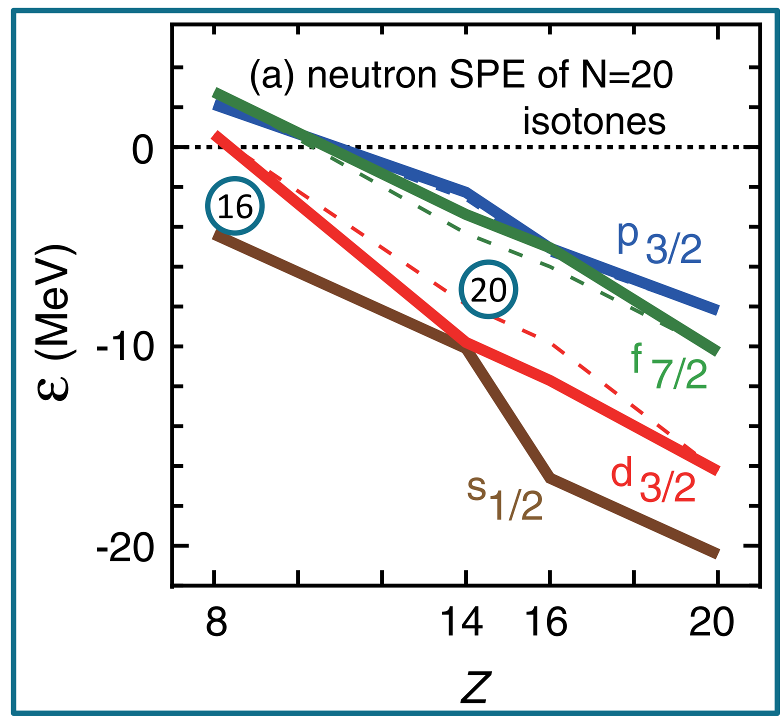
K Wimmer et al., PRL 105 (2010) 252501

Looking for the second, spherical 0^+ in ^{32}Mg

$^{30}Mg(t,p)^{32}Mg$



T Otsuka et al, PRL 104 (2010) 012501



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The 0^+ states in ^{32}Mg

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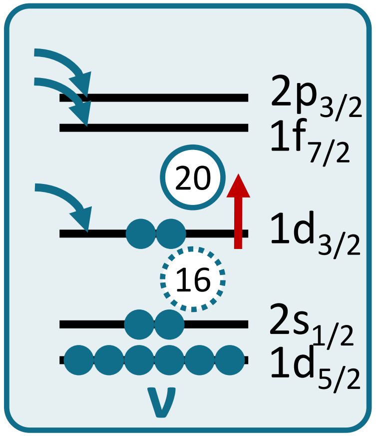
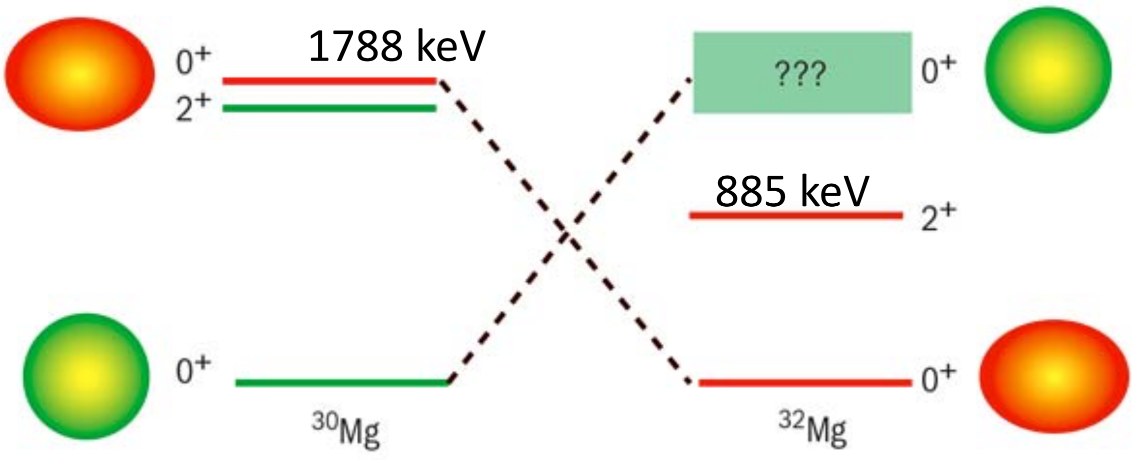
Looking for the second, spherical 0^+ in ^{32}Mg

$^{30}Mg(t,p)^{32}Mg$

- ^{30}Mg: spherical ground state, deformed (intruder) excited state; small mixing
- ^{32}Mg: only ground state 0^+ known, deformed Predictions for 0^+_2 between 1.4 MeV and 3 MeV
- Two-neutron transfer to
  – find the second 0^+
  – determine the overlap





Two-neutron transfer to ^{32}Mg

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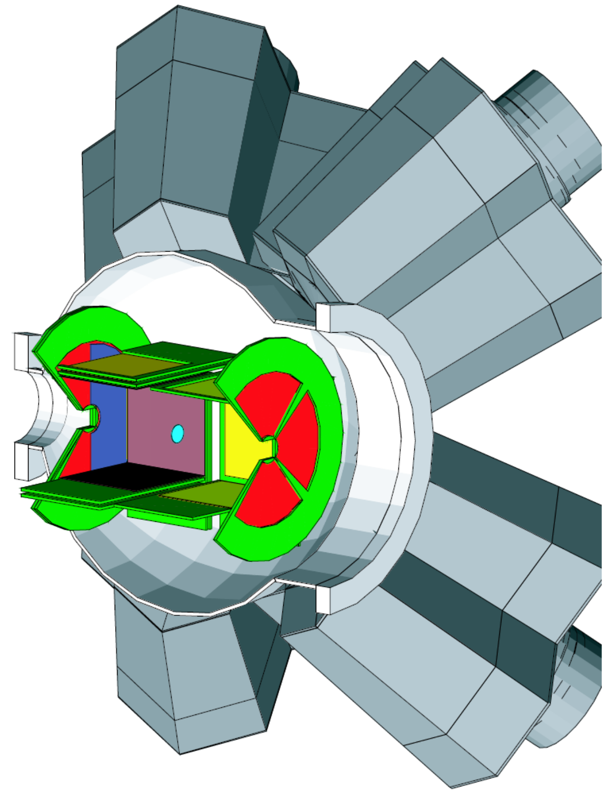
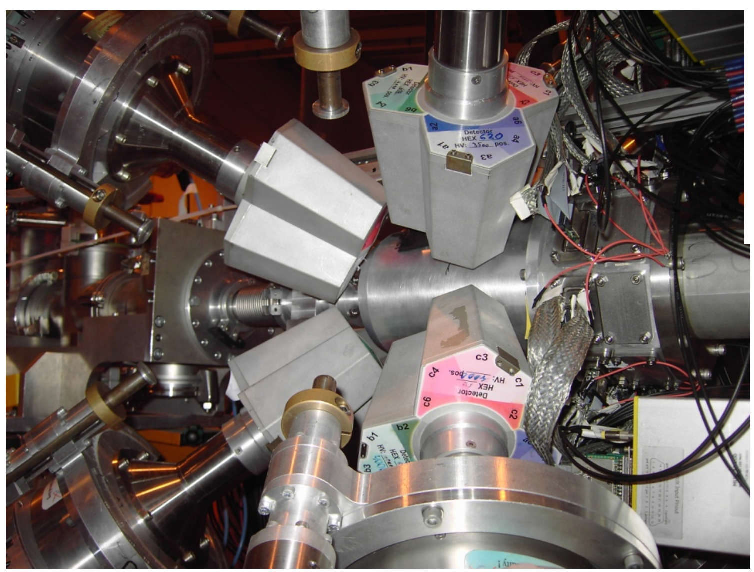
Looking for the second, spherical 0^+ in ^{32}Mg

^{30}Mg(t,p)^{32}Mg

- ^{30}Mg beam at REX-ISOLDE, 1.8 MeV/nucleon (below fusion barrier for Ti)
- Tritium-implanted Ti foil (t: 40 μg/cm^2)
- T-REX charged-particle detector
- Miniball γ-ray array





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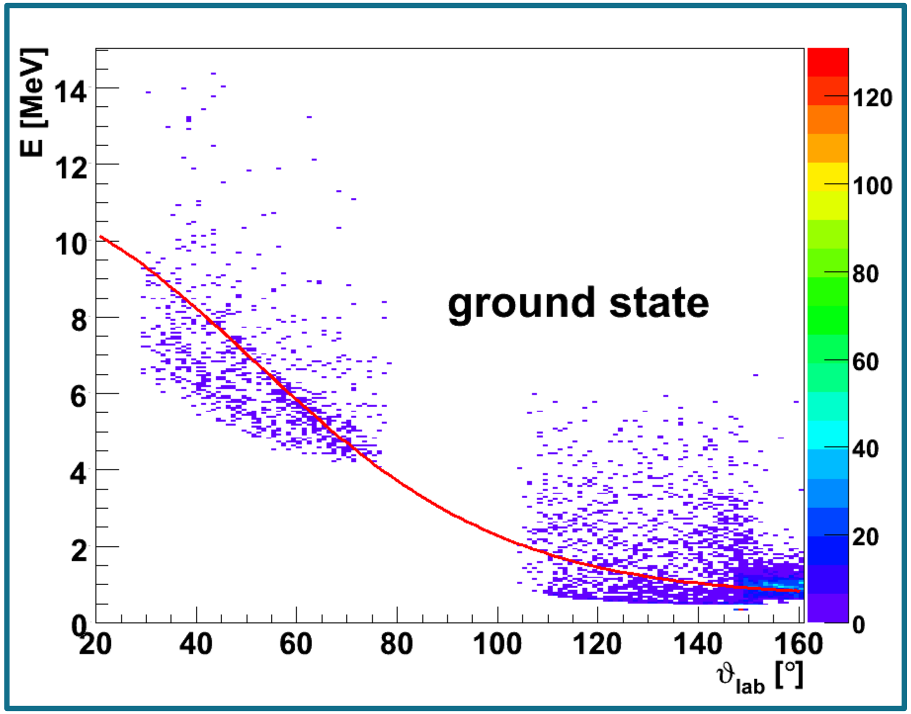

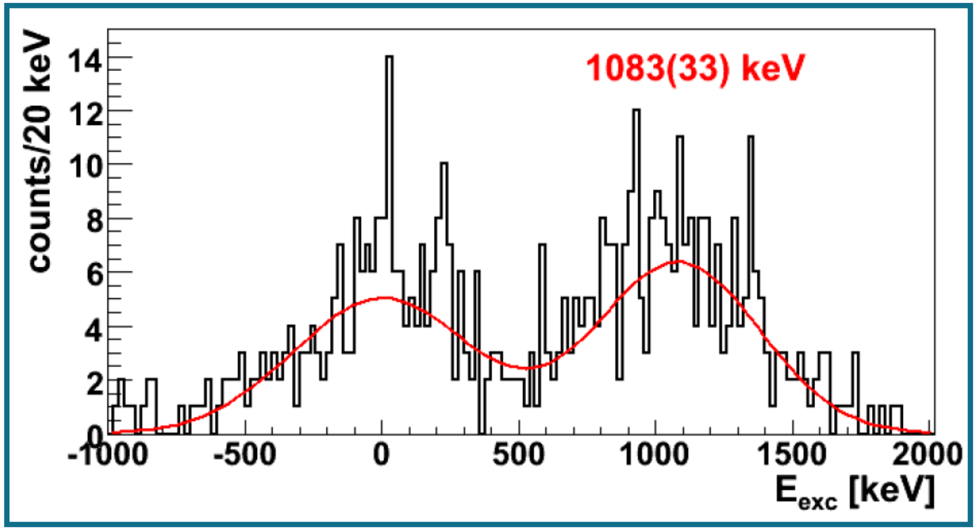

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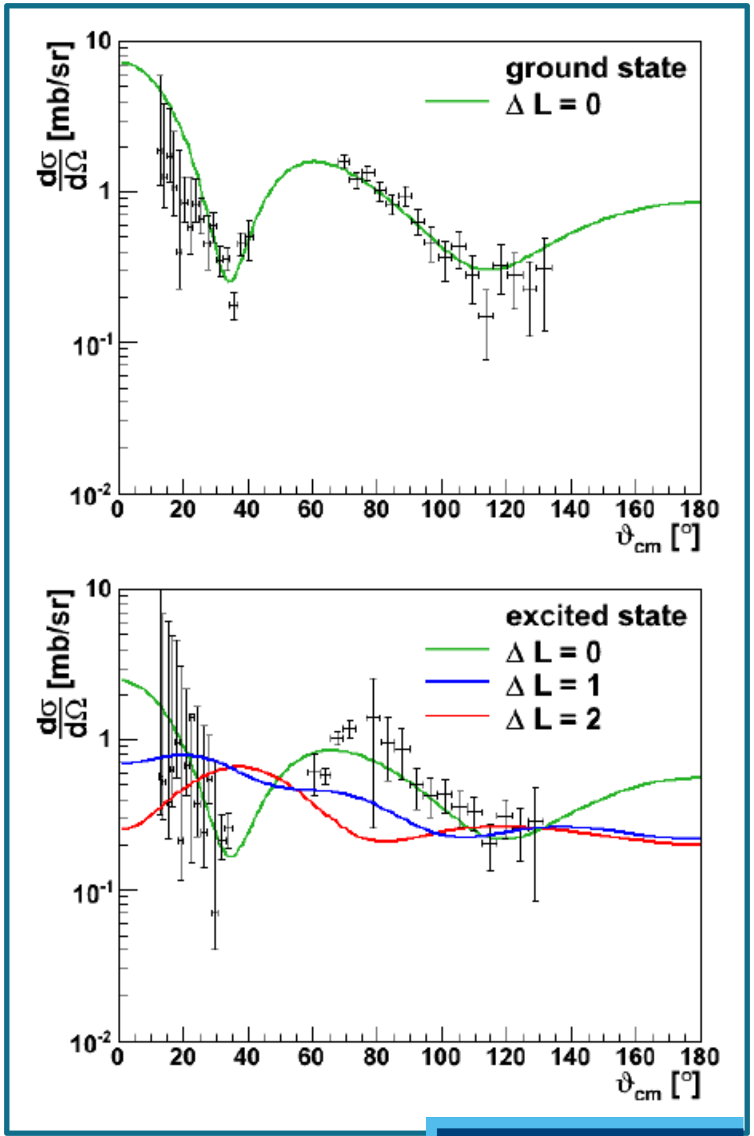
- γ-ray coincidences with excited state: no 2^+ (18 cts expected from 2^+ at 886 keV)



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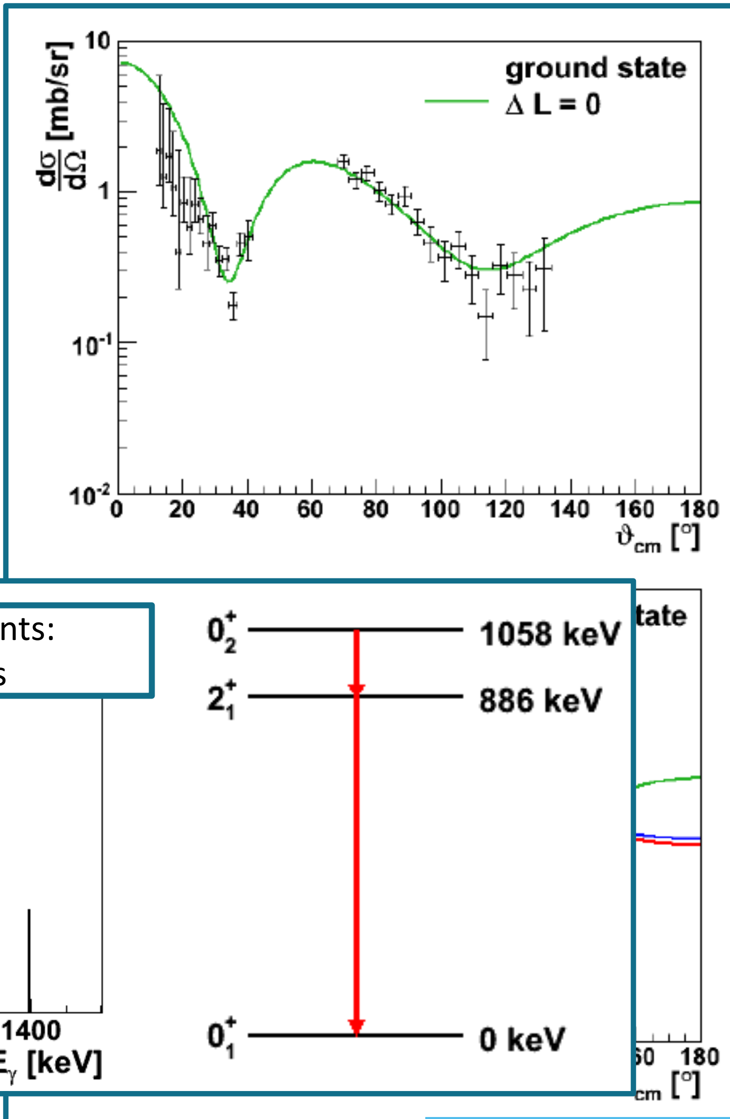

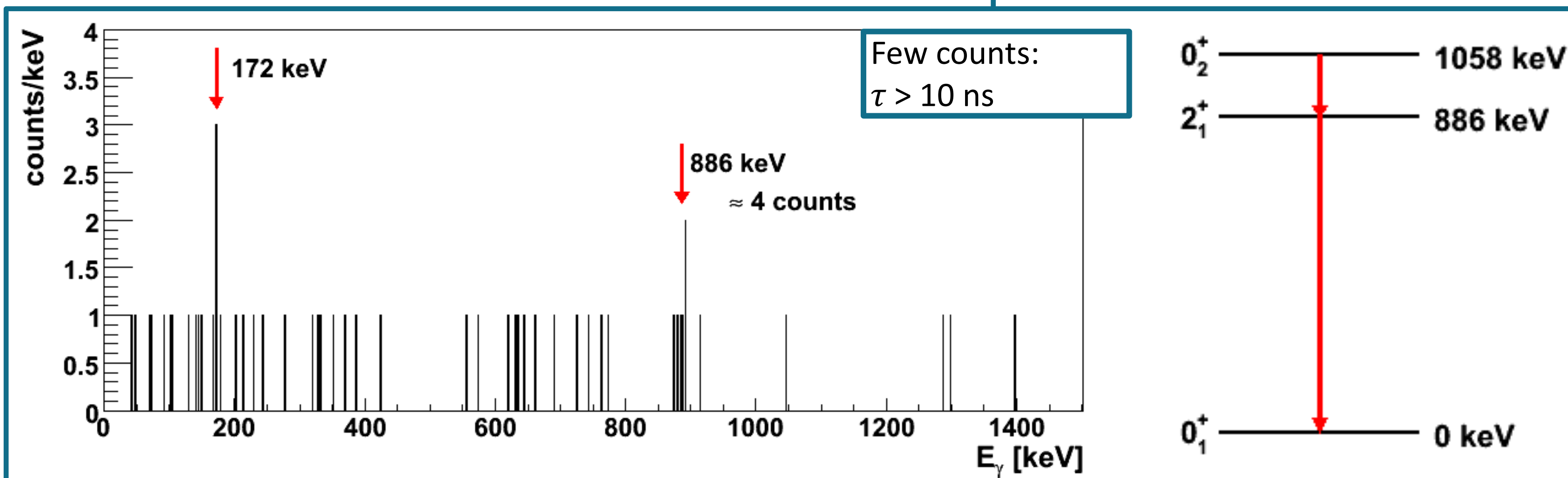

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Looking for the second, spherical 0^+ in ^{32}Mg

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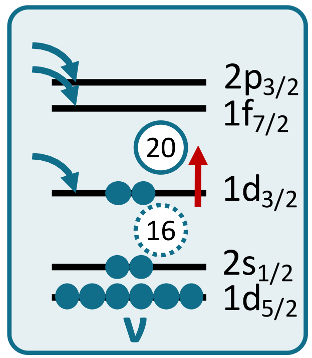
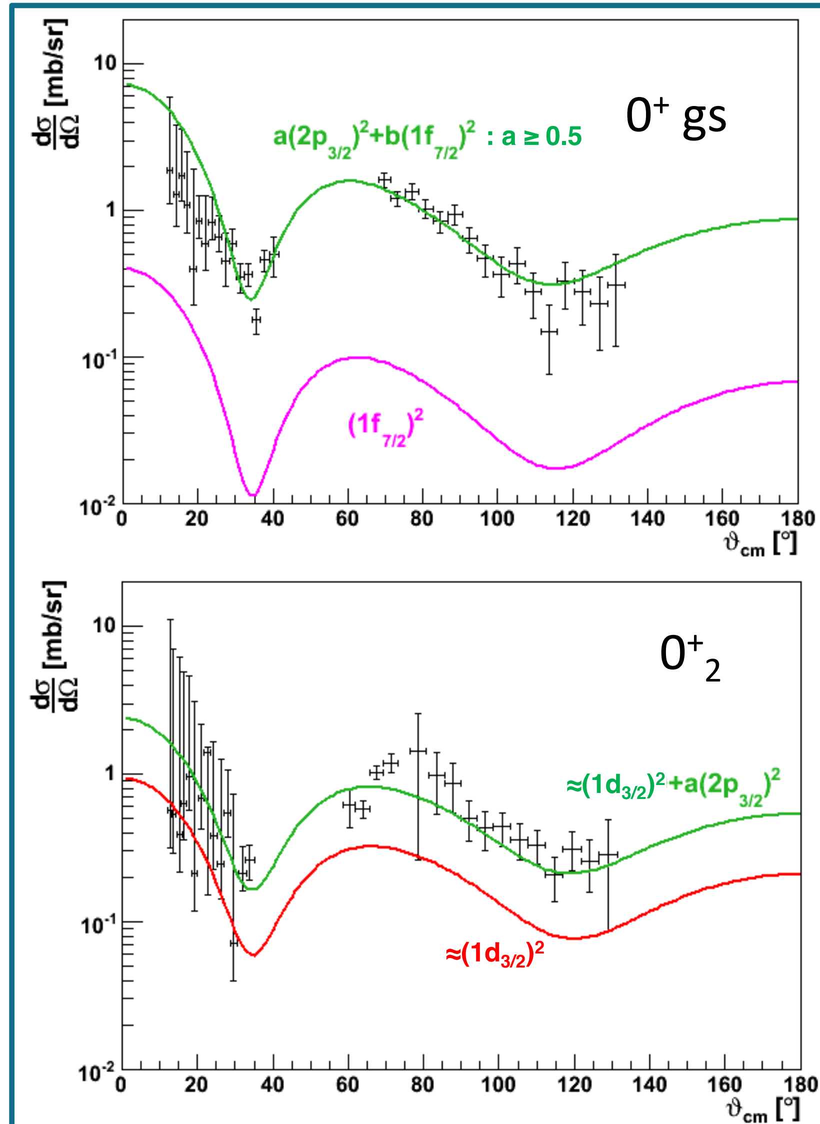
- Two-step transfer?
  ^{30}Mg(t,d) large negative *Q*-value

- 0^+_2 lower than predicted
- Long lifetime
- Similar cross sections



- $(p_{3/2})^2$ component, strong in the g.s.
- Mixing between the 0^+s?

→ Measure monopole strength for 0^+_2



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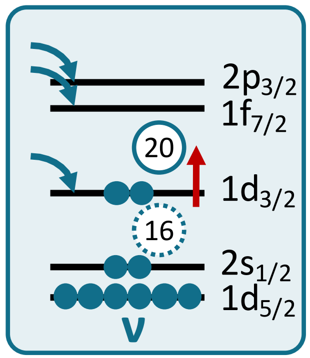
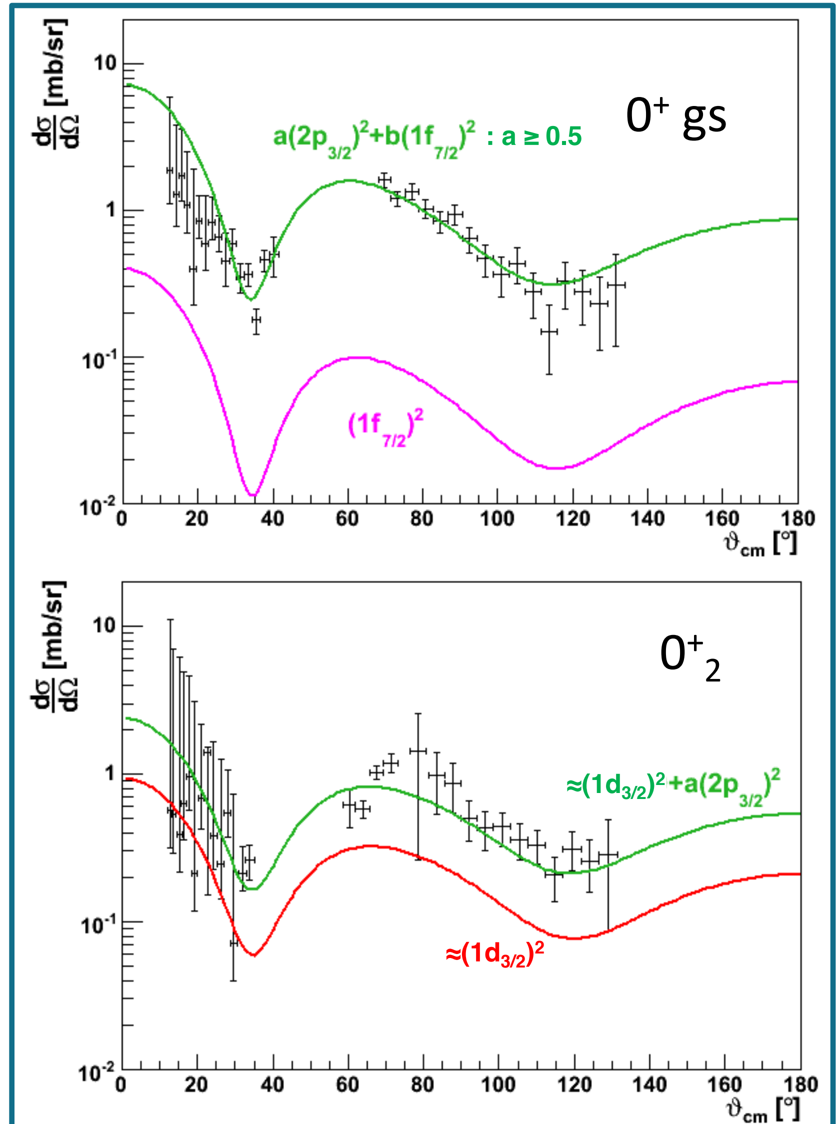




- $(p_{3/2})^2$ component, strong in the g.s.
- Mixing between the 0^+s?

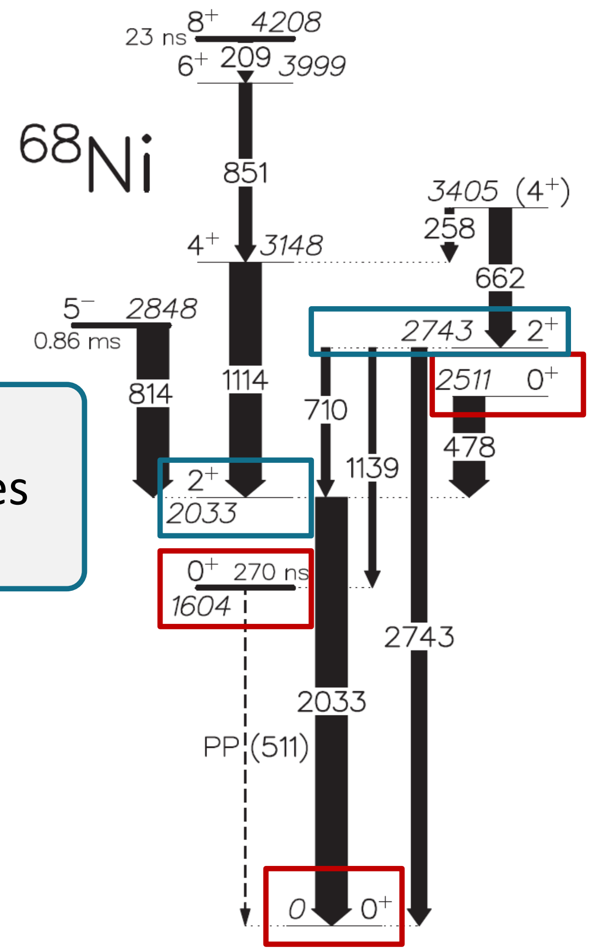
→ Measure monopole strength for 0^+_2

The 0^+ states in ^{68}Ni

Recent experimental work

- F. Flavigny et al., PRC 91 (2015) 034310
- S. Suchyta et al., PRC 89 (2013) 021301R
- F. Recchia et al., PRC 88 (2013) 041302R
- R. Broda et al., PRC 86 (2012) 064312
- C. J. Chiara et al., PRC 86 (2012) 041304R
- A. Dijon et al., PRC 85 (2012) 031301R

Three 0^+ states and two 2^+ states below 2.8 MeV



Level scheme from F. Recchia et al.
PRC 88 (2013) 041302R

Crucial information

- Precise measurement of 0^+_2 energy
  Since 1982: 1770(30) keV from ^{70}Zn(^{14}C,^{16}O)^{68}Ni
  Now: 1603.5(3) keV
- Two transitions feeding 0^+_2 (1139 and 2420 keV)
- Firm assignment of several spin/parities

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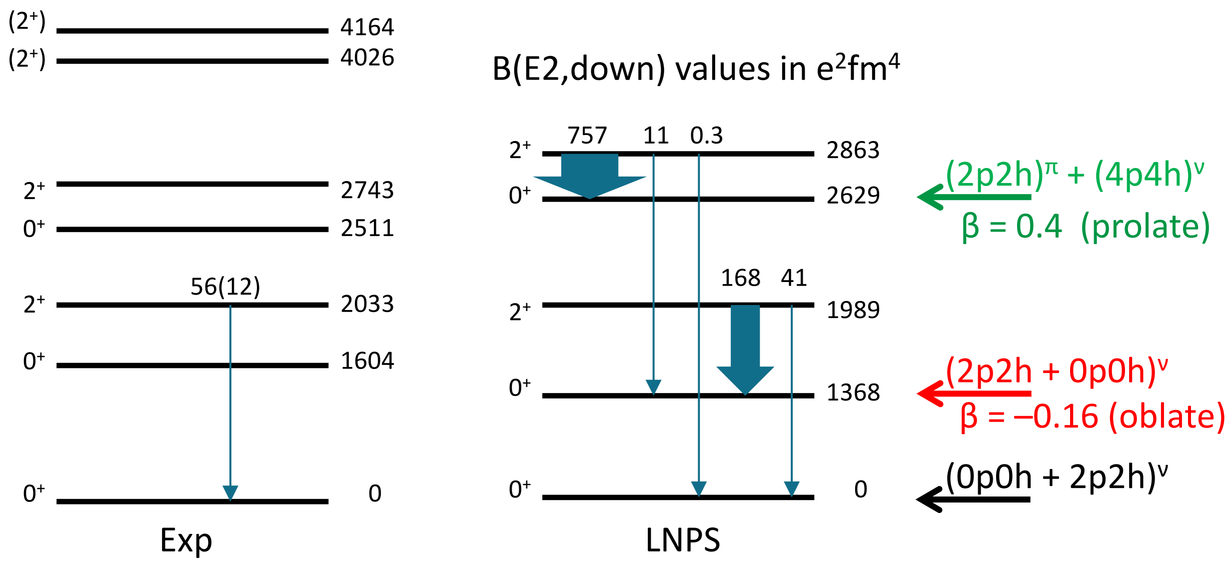
The 0^+ states in ^{68}Ni

Large-scale Shell Model with LNPS interaction

S Lenzi et al, PRC 82 (2010) 054301

- ^{48}Ca core, π pf – ν pf$g_{9/2}d_{5/2}$ to describe Fe and Cr



^{68}Ni

"dominant proton configuration has exactly two f7/2 protons less than the ground state"

"The 0^+_1 and 0^+_2 states "are characterized by "similar proton occupancies with leading 0p-0h (neutron) configuration for the 0^+_1 ground state and 2p-2h (neutron) configurations for the 0^+_2."

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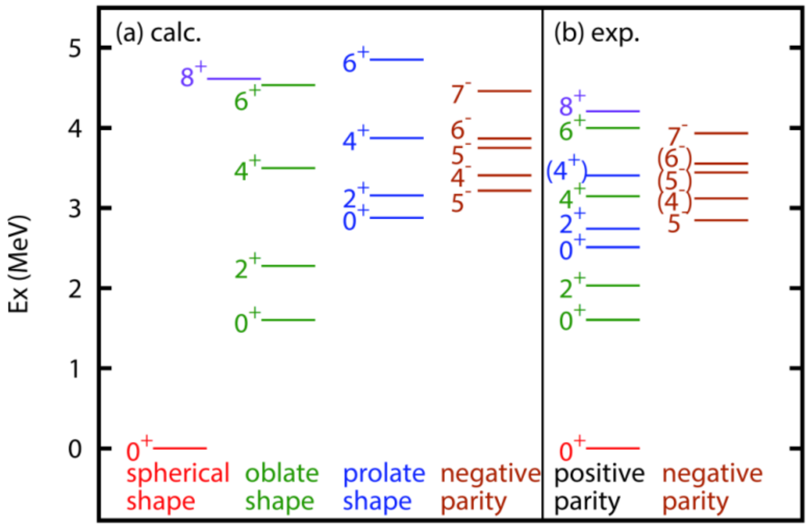
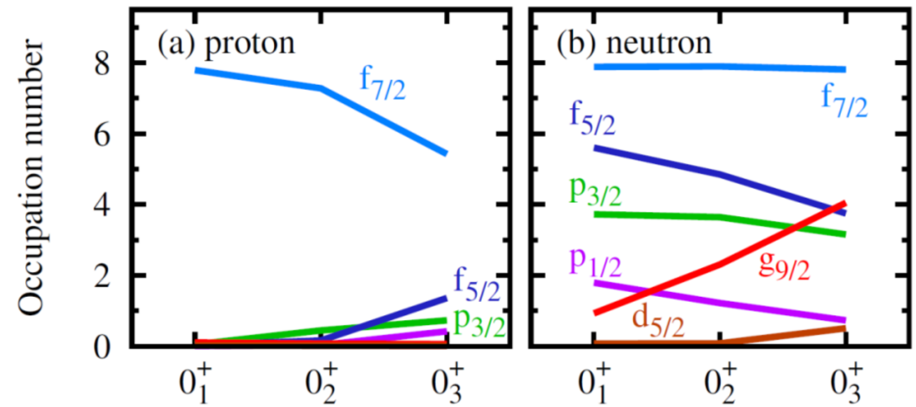
The 0^+ states in ^{68}Ni

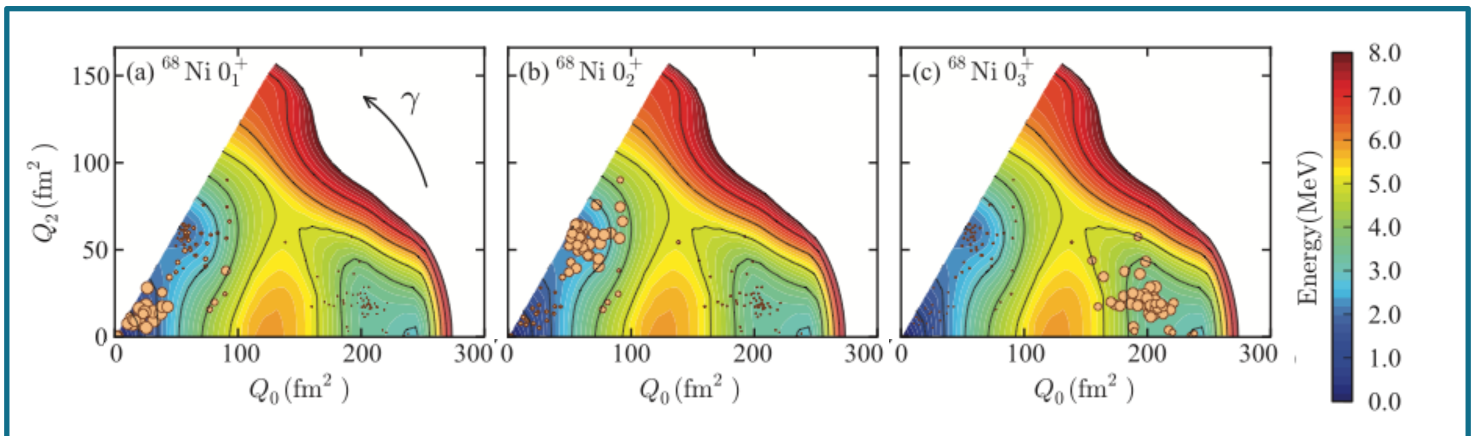
Monte-Carlo Shell-Model

Y. Tsunoda et al., PRC 89 (2014) 031301R

- Full pf + $g_{9/2}$ + $d_{5/2}$ for both neutrons and protons







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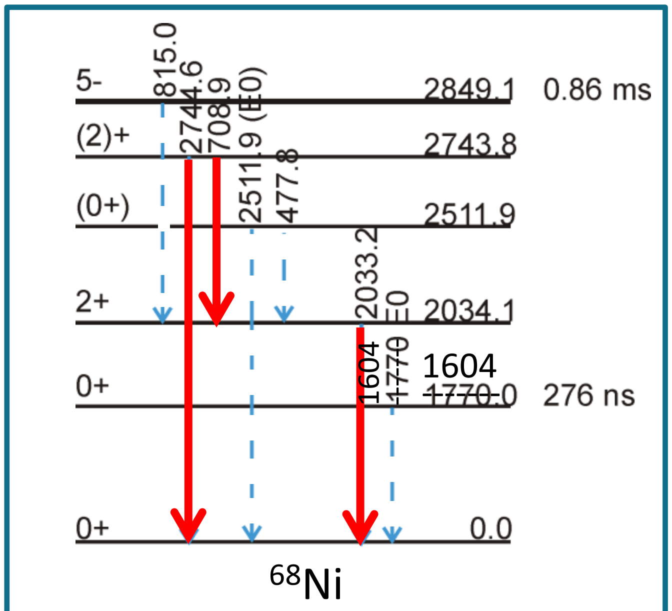
Two-neutron transfer to ^{68}Ni

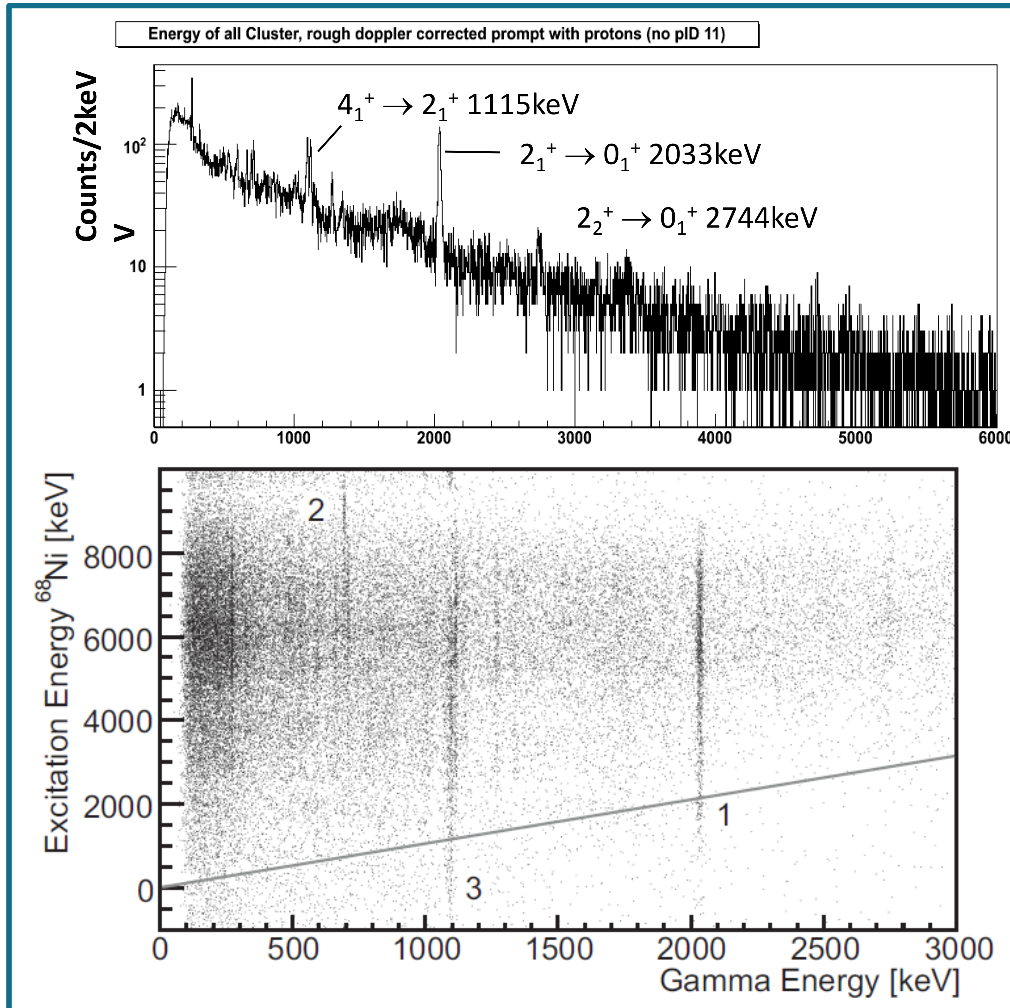
J Elseviers, PhD thesis, KU Leuven

Probing the structure of 0^+ and 2^+ states in ^{68}Ni

^{66}Ni(t,p)^{68}Ni at 2.6 MeV/nucleon

- Few γ's to ground state
- No p-γ-γ coincidences





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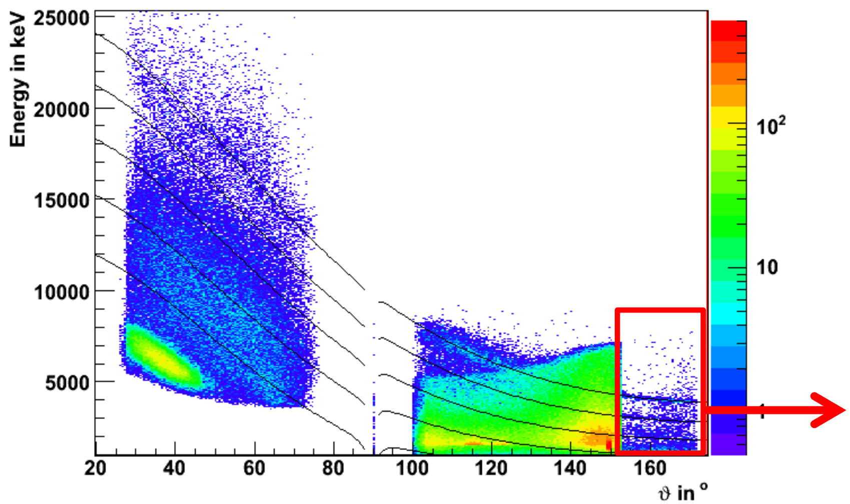

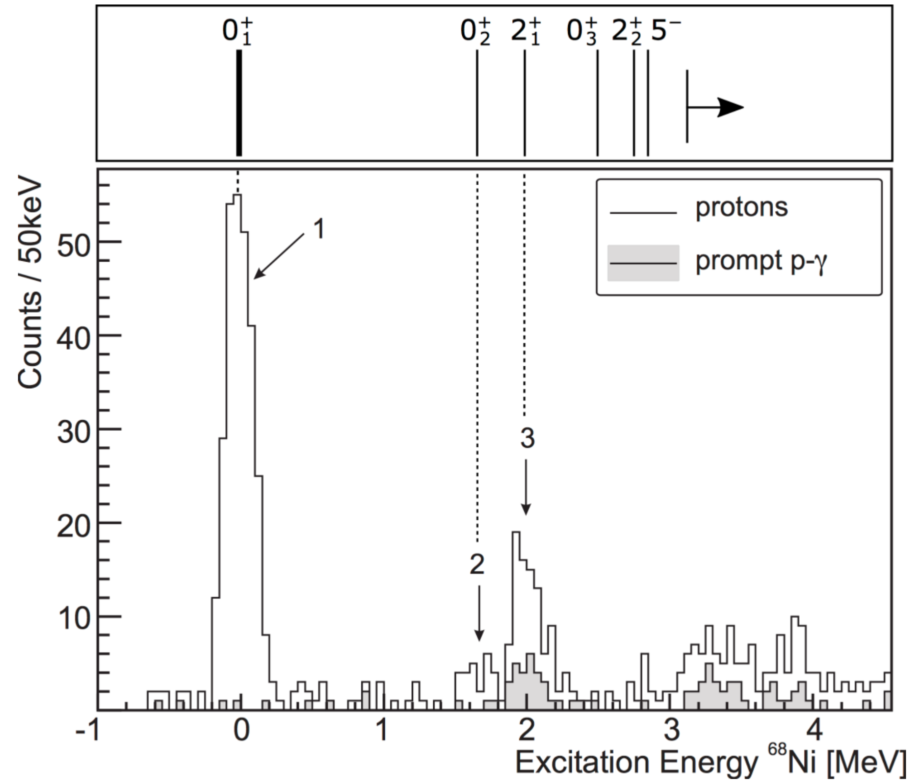

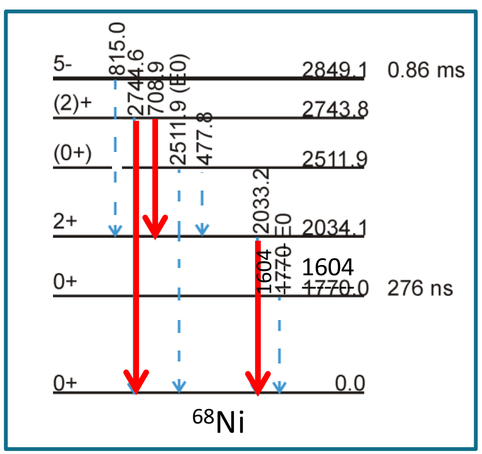

- Population of 0^+_2 : 5.4(11)% of g.s.
- Upper limits (<4%) on population of 0^+_3 and 2^+_2

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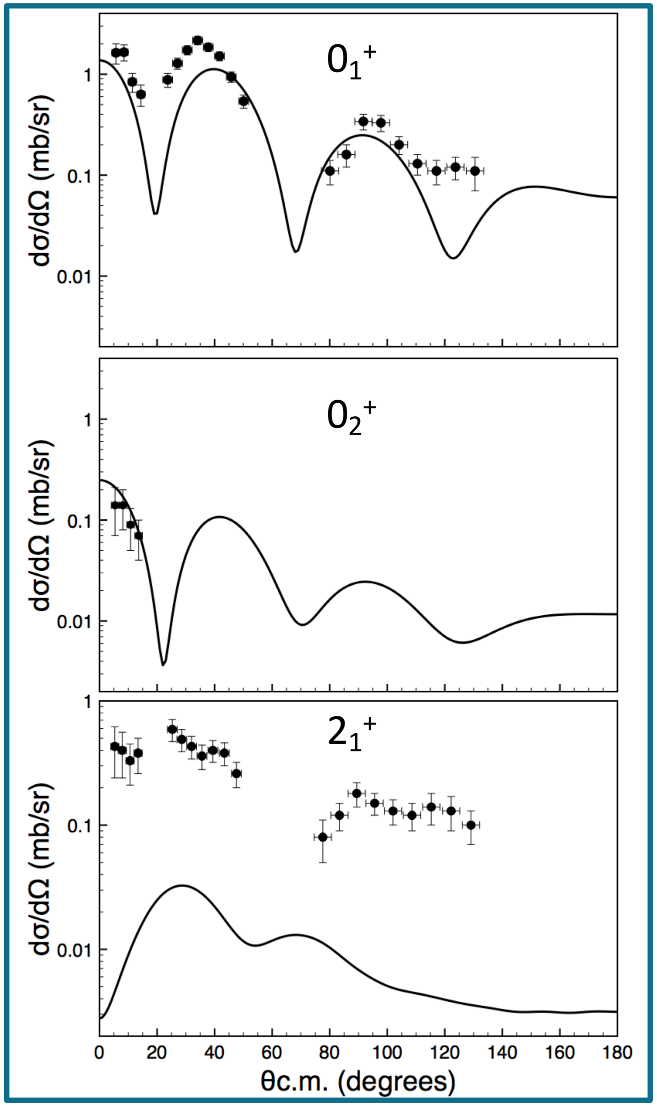
Probing the structure of 0^+ and 2^+ states in ^{68}Ni

^{66}Ni(t,p)^{68}Ni at 2.6 MeV/nucleon

- Two-neutron overlap amplitudes from MCSM (T. Otsuka) pf+$g_{9/2}$+$d_{5/2}$ both protons and neutrons
- Works well for the 0^+s does not reproduce the 2^+_1



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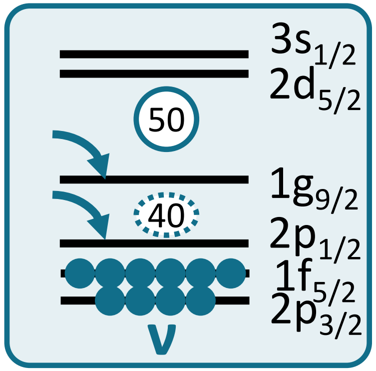

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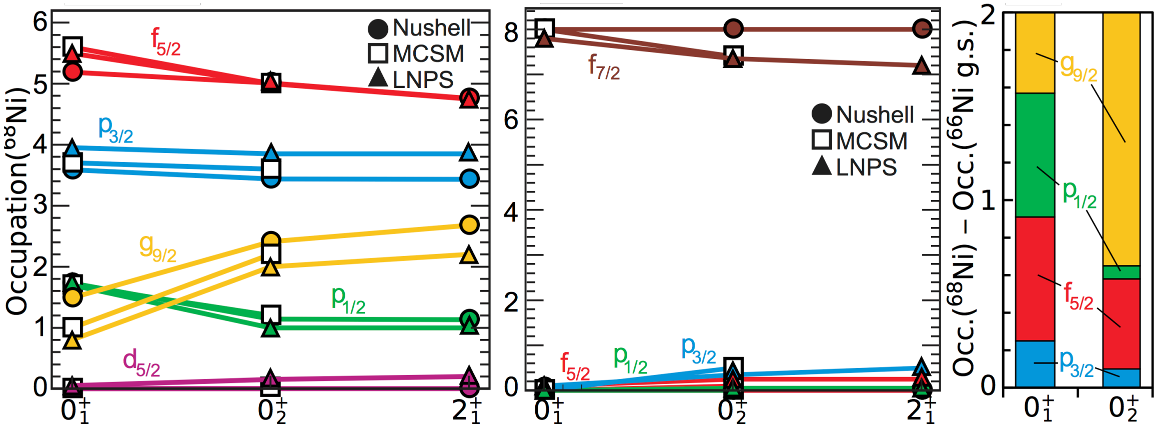
neutron - **occupation numbers** - protons



	$f_{5/2}$		$p_{3/2}$		$p_{1/2}$		$g_{9/2}$	
^{66}Ni gs	4.53		3.34		1.07		1.06	
^{68}Ni gs	5.19	**+0.66**	3.59	+0.25	1.73	**+0.66**	1.49	+0.43
^{68}Ni 0^+_2	5.01	+0.48	3.44	+0.10	1.14	+0.07	2.41	**+1.35**

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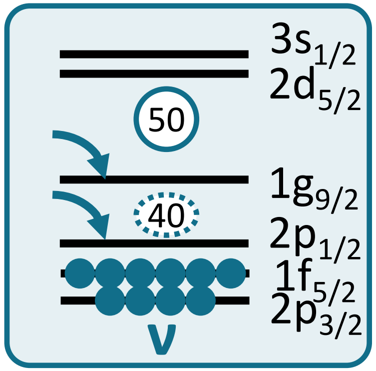

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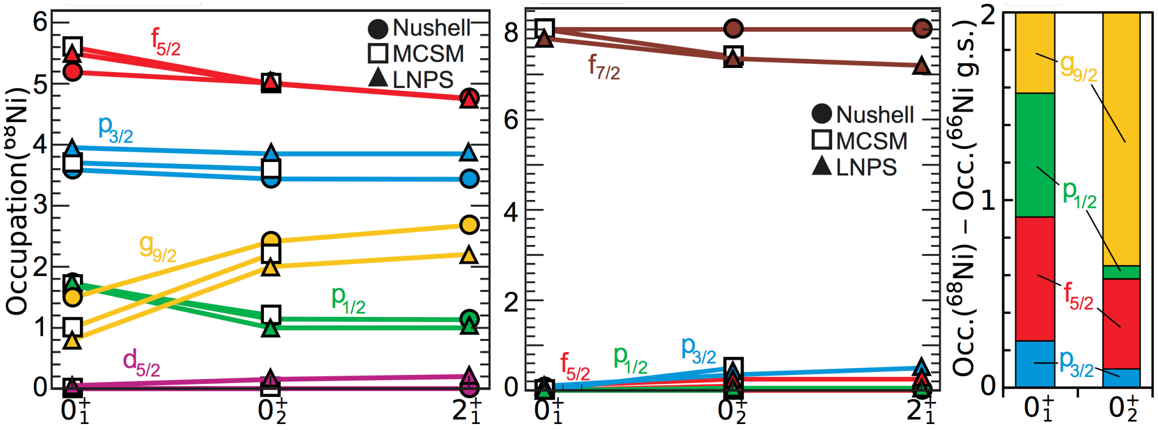


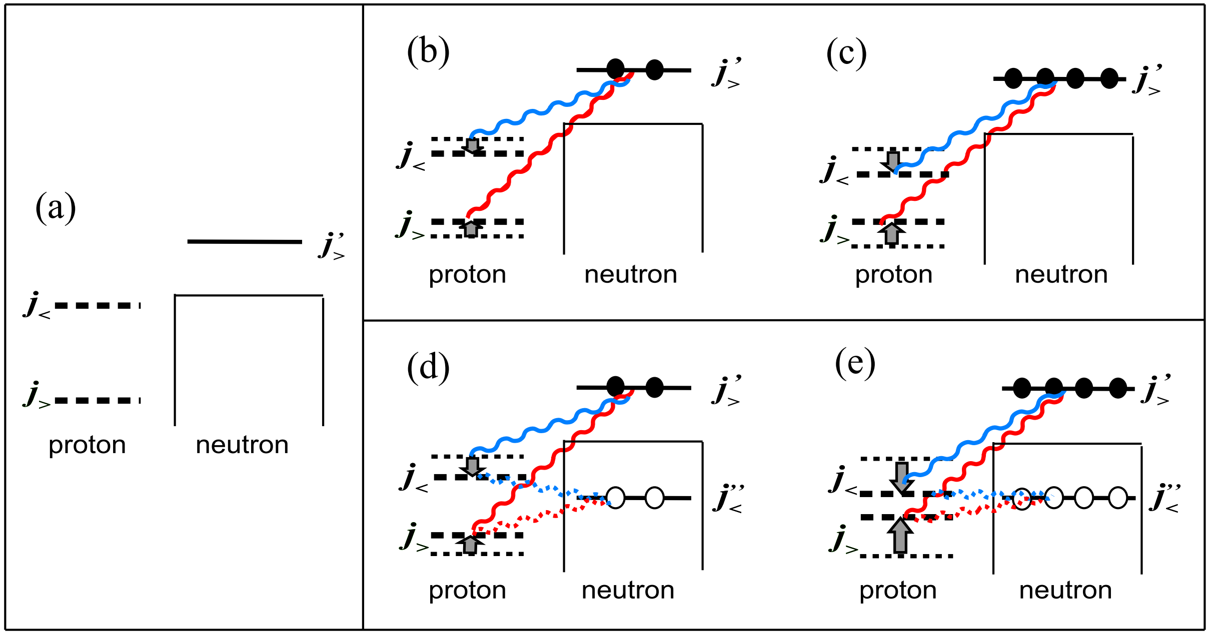
Agreement for $0^+_{1,2}$ states
0^+_1 state populated by transfer filling N=40
0^+_2 state populated by transfer across N=40

0^+s in Pb: same mechanism?

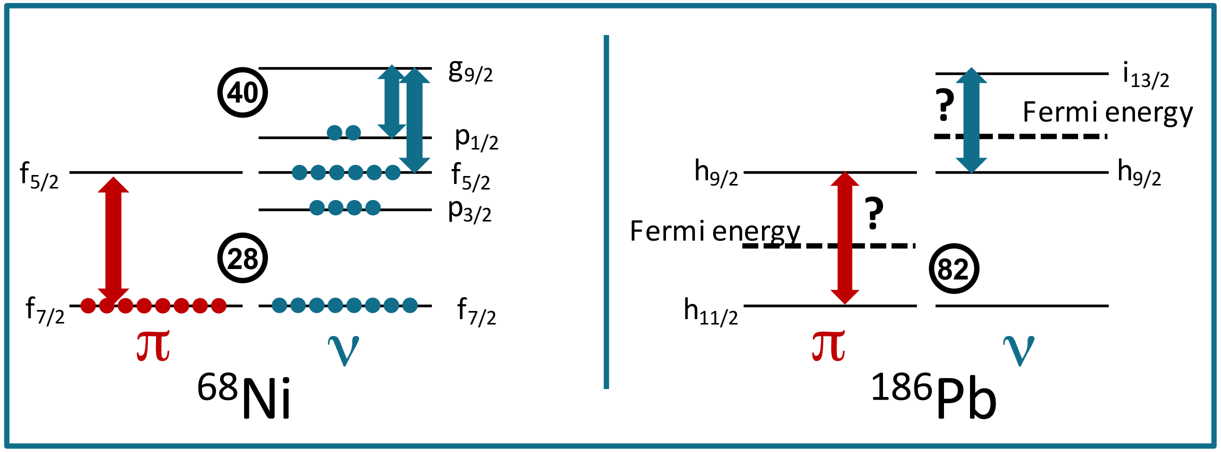
T Otsuka and Y Tsunoda, JPG 43 (2016) 024009

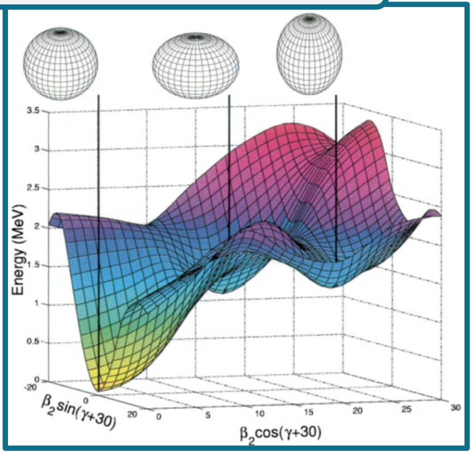
T Otsuka and Y Tsunoda
JPG 43 (2016) 024009

- Type-I shell evolution: number of nucleons in different isotopes
- Type-II shell evolution: occupancies within the same nucleus



From Ni to n-deficient Pb region





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  - **TRIUMF, GANIL, ISOLDE, Oak Ridge, Argonne…**

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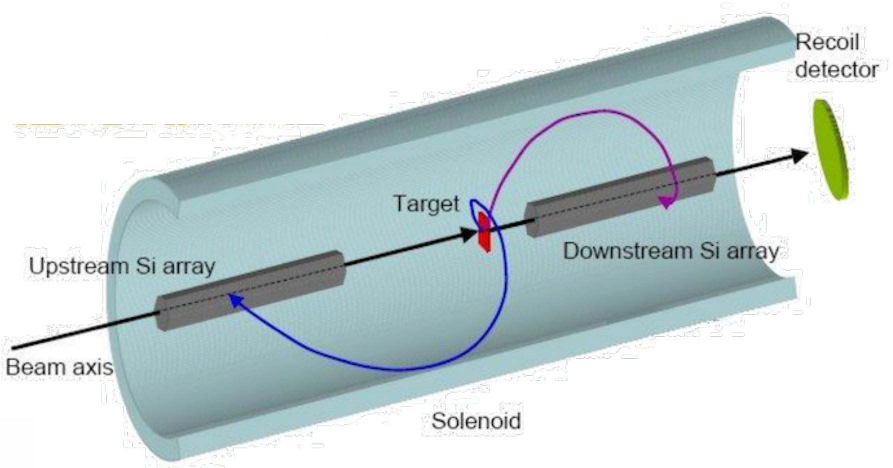
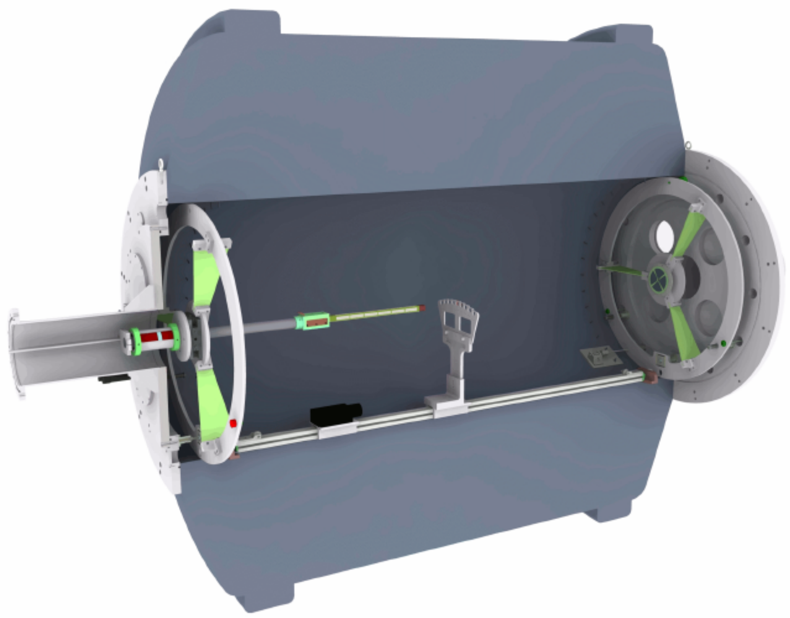
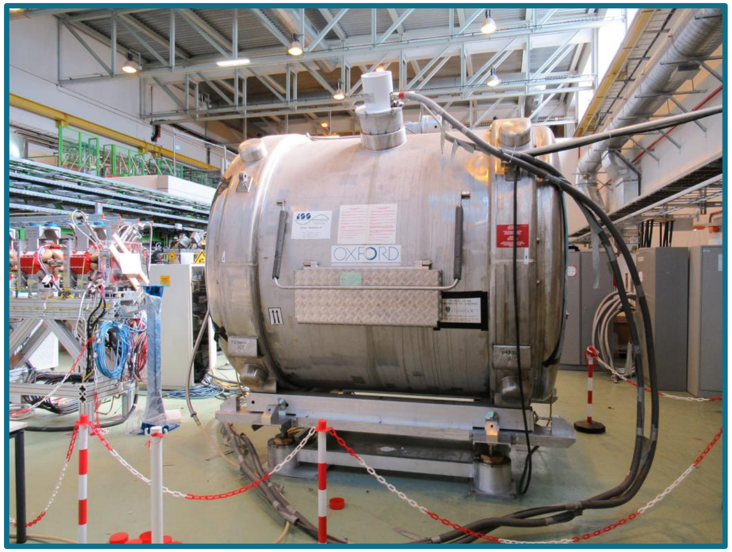
Improvements – Experimental side

Kinematic compression

- Solved by the HELIOS approach
  $E_{\mathrm{lab}} = E_{\mathrm{cm}} - A + Bz$
- At Argonne and soon at ISOLDE



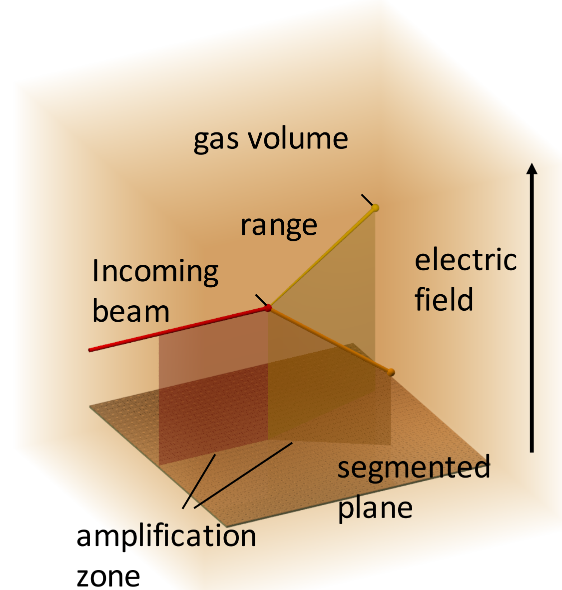


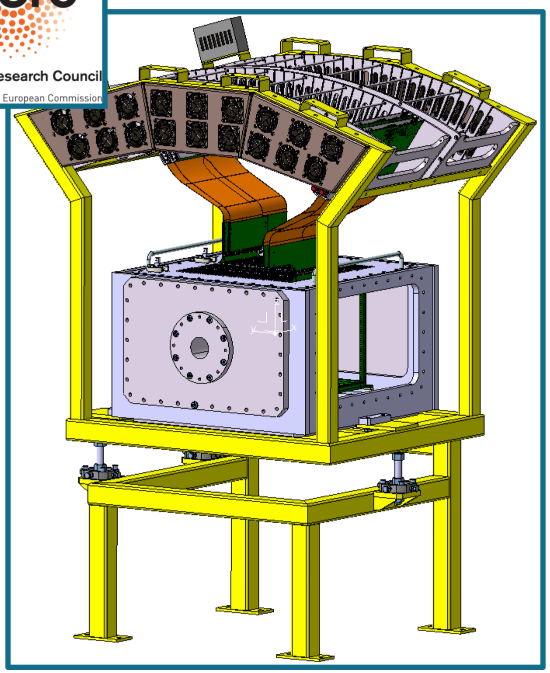


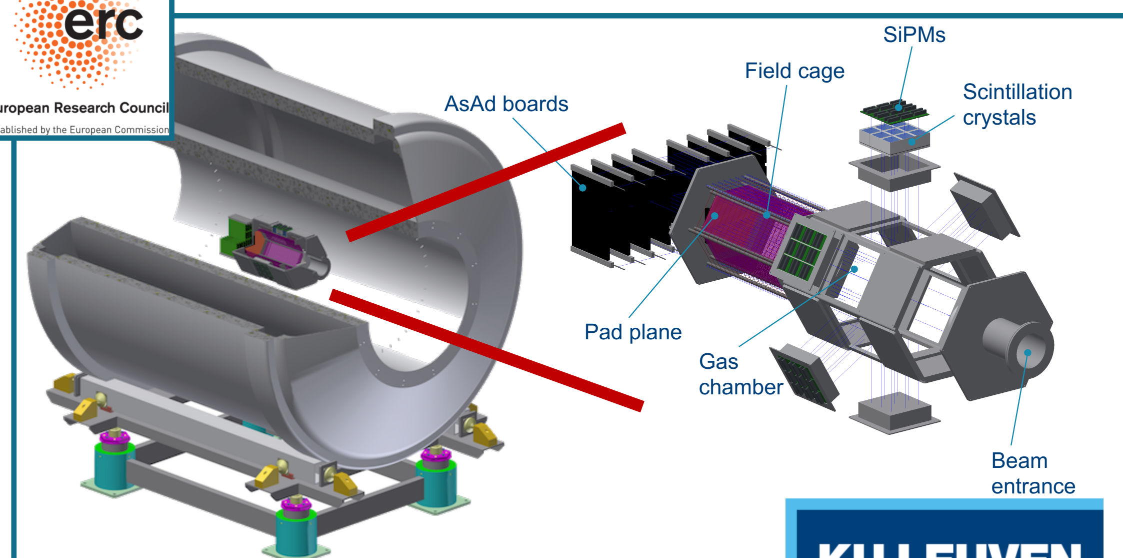
Improvements – Experimental side

Target thickness vs resolution

- Solved by the Active Target approach
  Large thickness but detection of the vertex
- ACTAR TPC, SpecMAT





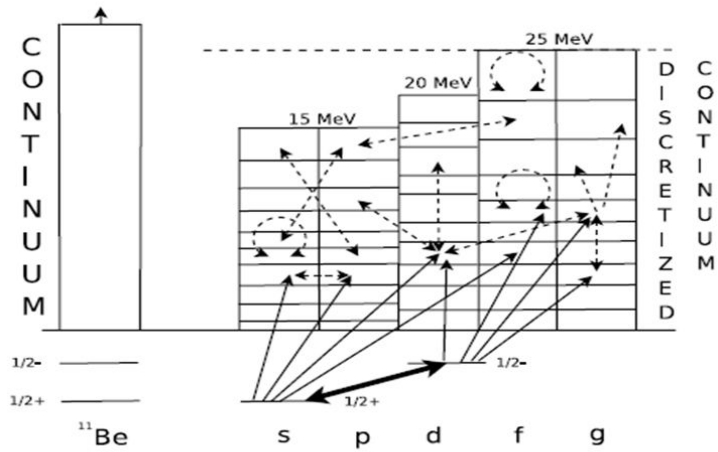


Improvements – Theoretical side

Reaction mechanism

- Weakly bound nuclei
  - – Effects of extended matter distributions
  - – Effects of continuum
- Transfer to the continuum
  - – Spectroscopic factors?
- Multi-step processes
  - – Importance at low energies
  - – Include in calculations

Schematic representation of bound and continuum states and their couplings in CDCC calculations



Full lines: Hagino 2000.

Dashed lines: additional couplings by Diaz-Torres and Thompson 2002

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…thank you for your attention!

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