# **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 1/3

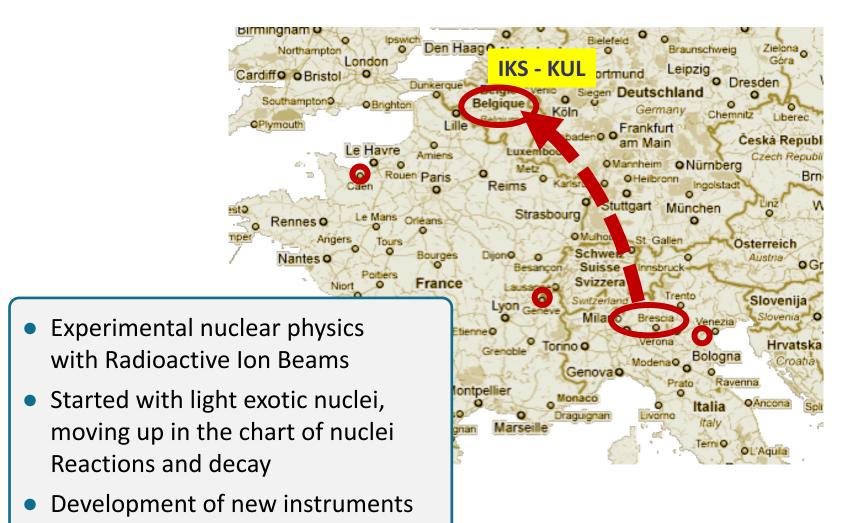


# **About myself**





# **About myself**



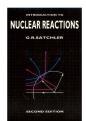


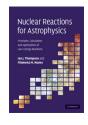
### **Contents**

- 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**

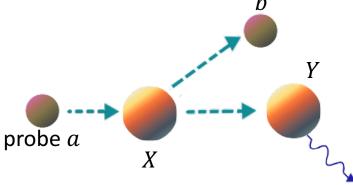
A nucleus X collides with a probe a (particle, γ-ray).
 In the collision they exchange energy, momentum and possibly mass
 As a result we obtain a product nucleus Y and some outgoing radiation b (particle, γ-ray)

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

Alternative notation:

Puts the accent on the process (a, b)

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





# Types of reactions (list not exhaustive)

<u>Elastic</u> scattering: X(a, a)X
 Always present!

 $^{12}C(p,p)^{12}C$   $^{208}Pb(n,n)^{208}Pb$ 

• Inelastic scattering:  $X(a, a')X^*$ 

- $^{12}\text{C}(p,p')^{12}\text{C}^*$   $^{40}\text{Ca}(\alpha,\alpha')^{40}\text{Ca}^*$
- Rearrangement reactions: (ex)change of mass
  - <u>Transfer</u> reactions:
    - stripping X((a+c),a)(X+c)
    - pick-up (X + c)(a, (a + c))X <sup>12</sup>C(p,d)<sup>11</sup>C
  - Knock-out reactions: X(a,ac)Y
- $^{12}C(p,2p)^{11}B$

 $^{12}C(d,p)^{13}C$ 

• Photo-disintegration:  $X(\gamma, a)Y$ 

 $^{16}O(\gamma,\alpha)^{12}C$ 

• Capture reactions:  $X(a, \gamma)Y$ 

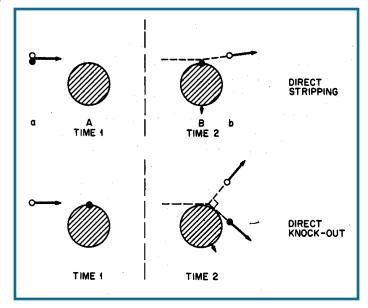
 $^{14}N(\alpha,\gamma)^{18}F$ 

- 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**

- <u>Direct</u> 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 <u>selective</u>
   Provide information about the similarity between initial and final states





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# 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:

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

$$Q\text{-value for the } (i,f) \text{ channel}$$

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

$$Q = E_{k,f} - E_{k,i}$$

→ we can measure Q and thus identify the channel

Example: 
$${}^{40}\text{Ca}(d,p){}^{41}\text{Ca}$$
:  
 $\Delta({}^{40}\text{Ca}) = -34846 \text{ keV}$   
 $\Delta({}^{41}\text{Ca}) = -35138 \text{ keV}$   
 $\Delta(d) = 13136 \text{ keV}$   
 $\Delta(p) = 7289 \text{ keV}$   
 $\Rightarrow Q = 6139 \text{ keV} = 6.139 \text{ MeV}$ 



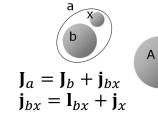
# **Conservation of angular momentum (and parity)**

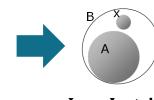
- $\mathbf{J}_a + \mathbf{J}_A + \overrightarrow{\ell_\alpha} = \mathbf{J}_b + \mathbf{J}_B + \overrightarrow{\ell_B}$ The <u>transferred angular momentum</u> in  $a + A \rightarrow b + B$ is defined as  $\mathbf{l} = \overrightarrow{\ell_{\alpha}} - \overrightarrow{\ell_{\beta}}$
- Transfer reactions:  $(b+x)+A \rightarrow b+(A+x)$  with b+x=a, A+x=B

$$\mathbf{l} = (\mathbf{J}_B - \mathbf{J}_A) + (\mathbf{J}_b - \mathbf{J}_a)$$

$$\mathbf{l} = \mathbf{j}_{Ax} - \mathbf{j}_{bx}$$

$$\rightarrow \mathbf{l} = \mathbf{l}_{Ax} - \mathbf{l}_{bx}$$







 $\mathbf{j}_{Ax} = \mathbf{l}_{Ax} + \mathbf{j}_{x}$ 

- $\rightarrow l$  is constrained by the binding angular momenta
- $\rightarrow$  only few l participate for a given channel 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:  ${\bf l}={\bf q}\times{\bf R}$  where  ${\bf q}={\bf k}_{\alpha}-{\bf k}_{\beta}$  is the transferred momentum
- $\bullet$  For a given populated state q is fixed in magnitude For a given observation angle  $k_{\beta}$  is fixed in direction
  - $\rightarrow l/q$  is fixed (angle  $\beta$  between q and R is fixed)
  - $\rightarrow$  events originate on two rings with radius l/q
- Conditions on the observation angle  $\theta$ 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  $\bar{k} = \sqrt{k_{\alpha}k_{\beta}}$  )

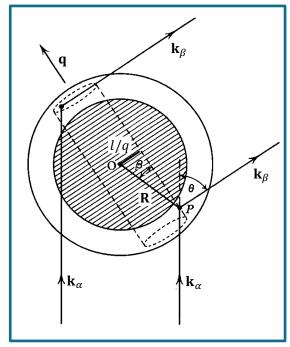
-  $l/q \le R$  (reaction on the surface)

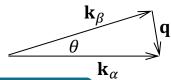
we find

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

Relation between the transferred angular momentum and the scattering angle

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

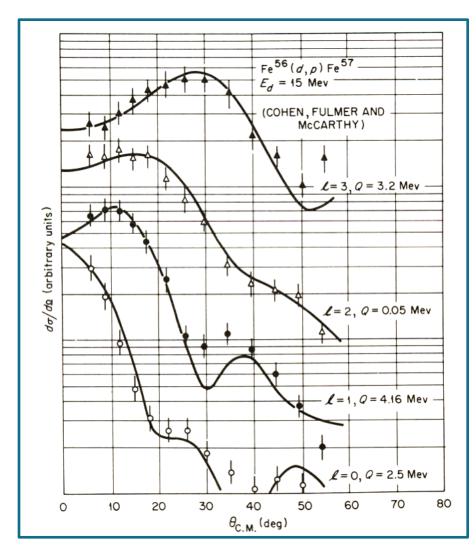






# How to measure the transferred angular momentum

- 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:

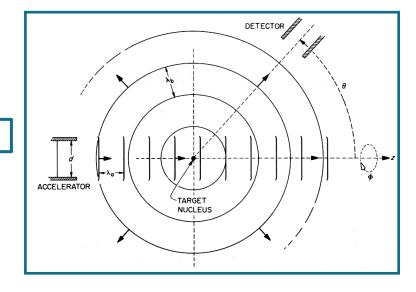
$$(\nabla^2 + k^2)\psi(\mathbf{r}) = U(\mathbf{r})\psi(\mathbf{r})$$

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)



$$U \approx \int \phi_a^* \phi_A^* V \phi_b \phi_B d\tau$$



# **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  $\phi_A$  and  $\phi_B$  which is expressed by the <u>spectroscopic factor</u> (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:

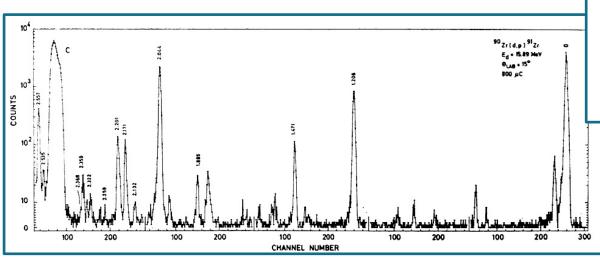
$$\left(\frac{d\sigma}{d\Omega}\right)_{\exp} = S_{(l_{Ax}j_{Ax})_{J_B}} \left(\frac{d\sigma}{d\Omega}\right)_{\text{cal}}$$

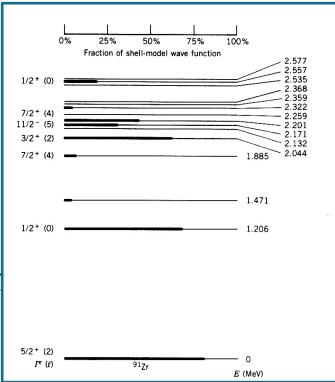
The spectroscopic factor is a measure of how much the populated state contains the "pure" cluster (single-particle) configuration



# **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



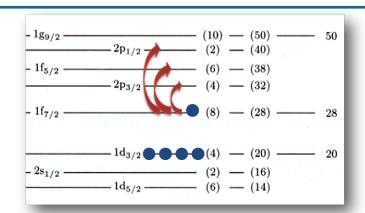
# **Spectroscopic factors - caution**

- 1. Absolute spectroscopic factors depend upon
  - the approximation used for the calculation (DWBA, ADWA, CRC...)
  - the potentials (interaction and binding)
- → usually, <u>relative</u> spectroscopic factors are used to derive structure information
- For pure "single-particle" states the spectroscopic factors satisfy <u>sum rules</u>
   However, a given configuration could be present
   in several excited states (<u>fragmentation</u>)
   and it is usually difficult to measure all the strength

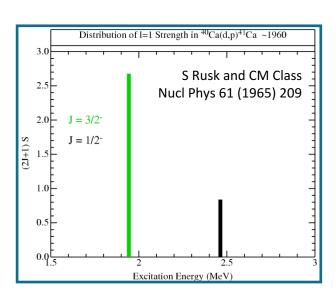


# **Strength fragmentation**

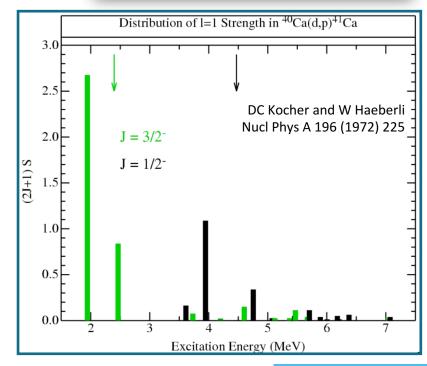
- If the strength is fragmented: the single-particle energy is taken to be the centroid (mean energy, weighted by the spectroscopic factor)
- Need to detect as much strength as possible!



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







Example: p<sub>3/2</sub>-p<sub>1/2</sub> spin-orbit splitting in <sup>41</sup>Ca



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# New physics far from stability

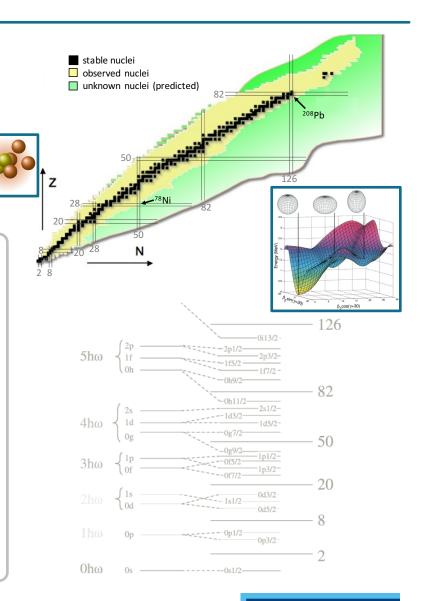
- Halos, cluster structures
- Shape transitions and coexistence (macroscopic picture)
- Changes in the shell structure

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

• ..





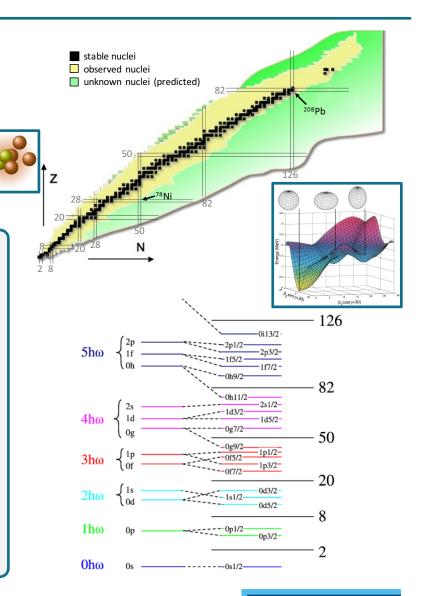
# New physics far from stability

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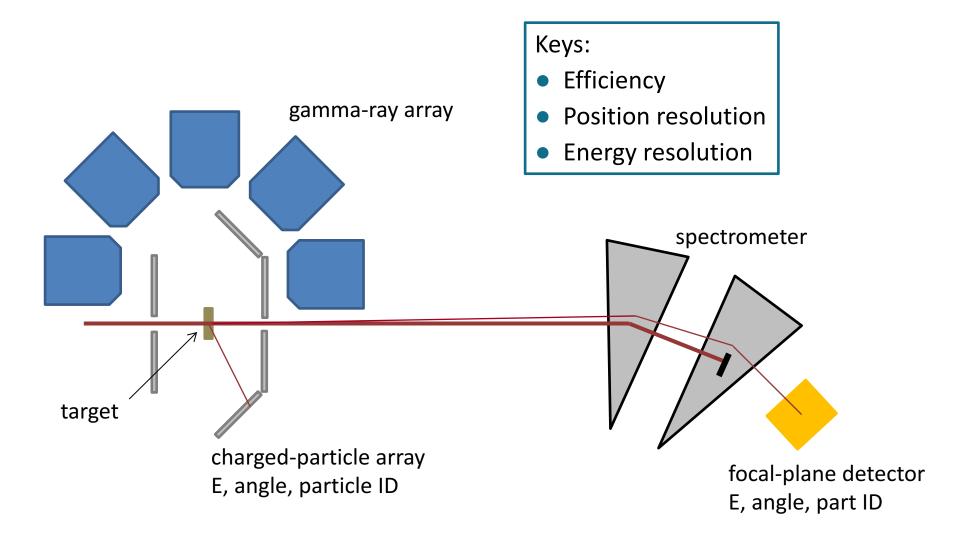
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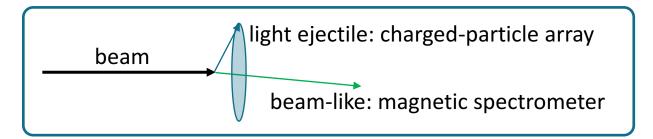
# **General setup**

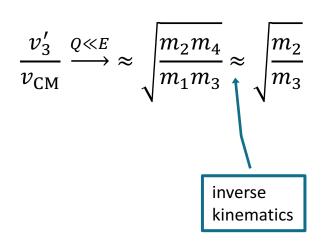


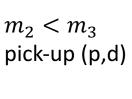


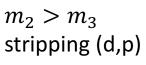
 $v_3'$ 

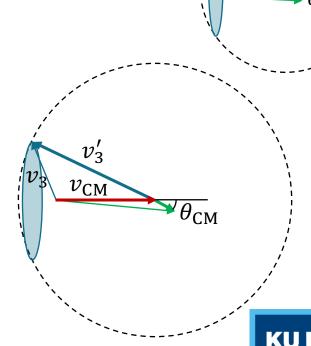
## **Inverse kinematics**











 $v_3$ 

 $v_{\mathsf{CM}}$ 

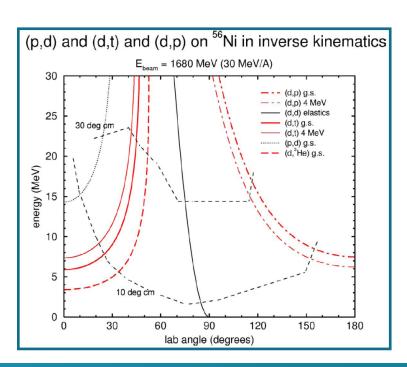
## **Exotic nuclei: inverse kinematics**

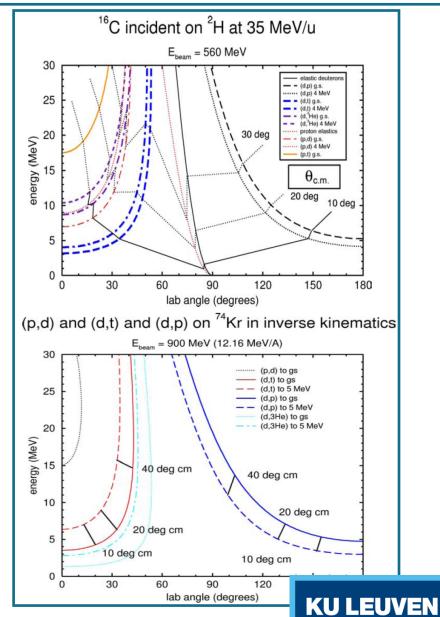
source: Wilton Catford

#### **Light particles**

Kinematics depends:

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

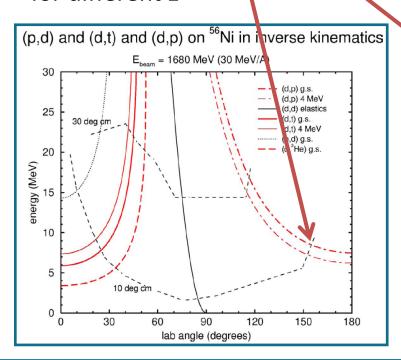


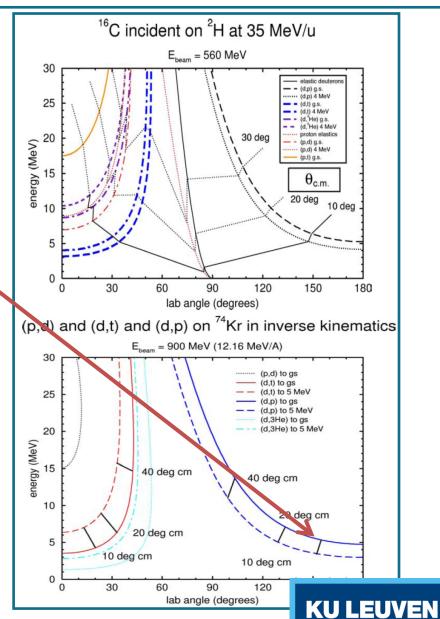


## **Exotic nuclei: inverse kinematics**

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 same angle at the interaction point from same reaction (Q-value) but different energies! Limit for (d,p): resolution in E\*≈300 keV for ≈200 µg/cm<sup>2</sup> 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°<sub>cm</sub>. 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

$E_{\rm i}/A$ (MeV)	$\theta_{ m lab}$	Origin of contribution					$\Sigma_{ m quad}$
		$\Delta \theta$	$\Delta p$	$E_{ m stragg}$	$\Theta_{1/2}$	dE/dx	
30	1.07°	172	147	101	74	23	259
15	1.06°	84	71	99	74	37	169
30	0.16°	1404	811	808	723	56	1952
10	0.10°	334	143	502	570	268	883
10	0.21°	1140	614	2177	1859	1321	3408
	30 15 30 10	(MeV)  30 1.07° 15 1.06° 30 0.16° 10 0.10°	30     1.07°     172       15     1.06°     84       30     0.16°     1404       10     0.10°     334	$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	$ \Delta\theta \qquad \Delta p \qquad E_{\rm stragg} \qquad \Theta_{1/2} $ 30	$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$

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	$E_{\rm i}/A$ (MeV)	$ heta_{lab}$	Origin of contribution					$\Sigma_{ m quad}$
			$\Delta \theta$	$\Delta E_f$	$\Delta E_i$	$\Theta_{1/2}$	dE/dx	
p(12Be, d)11Be	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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  - 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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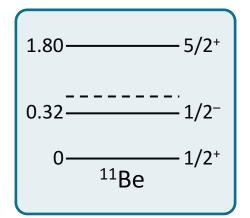


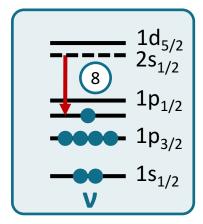
# Light nuclei

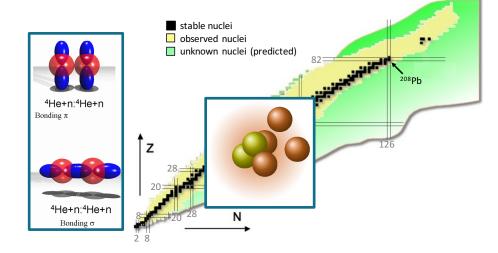
- Halo structures
- Clustering and deformation

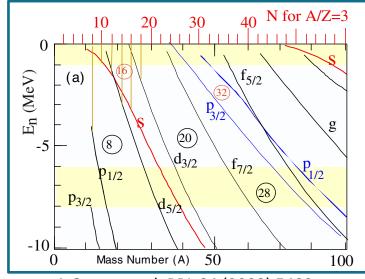
#### **Disappearance of N=8**

- Ground state in <sup>15</sup>C
   Inversion of levels in <sup>11</sup>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 <sup>11</sup>Li, <sup>11</sup>Be, <sup>14</sup>Be









A Ozawa et al, PRL 84 (2000) 5493

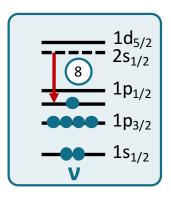


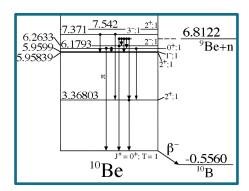
#### S Fortier et al, PLB 461 (1999) 22 J Winfield et al, NPA 683 (2001) 48

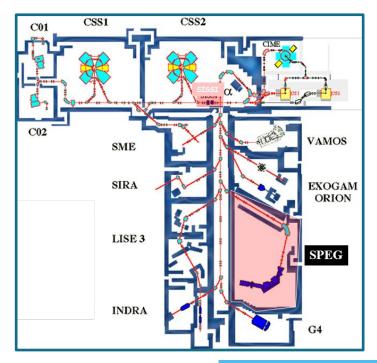
# Light nuclei – I

#### **Ground state of <sup>11</sup>Be**

- $[0^+ \otimes 2s]_{1/2+}$  or  $[2^+ \otimes 1d]_{1/2+}$ ? "10Be core" configuration in <sup>11</sup>Be?
- 2<sup>+</sup> in <sup>10</sup>Be at 3.34 MeV
- → Probe overlap between <sup>11</sup>Be gs and <sup>10</sup>Be 0+/2+ states
- Experiment: <sup>11</sup>Be(p,d)<sup>10</sup>Be
   at GANIL
  - Primary beam <sup>15</sup>N 65 MeV/nucleon
  - In-flight fragment separation in SISSI/alpha
     → <sup>11</sup>Be at 35.3 MeV/nucleon
  - Detection in SPEG









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

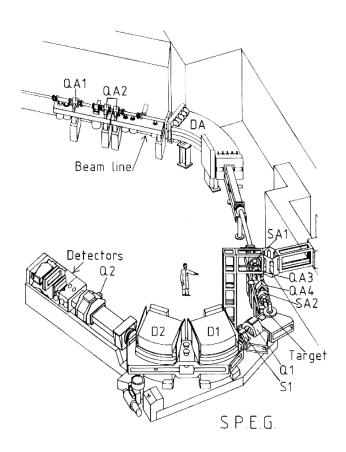
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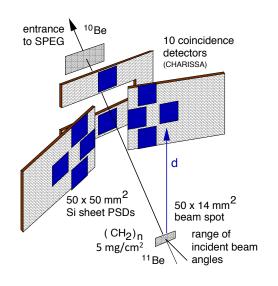
#### Ground state of <sup>11</sup>Be

Experiment: <sup>11</sup>Be(p,d)<sup>10</sup>Be

d in CHARISSA: particle detectors (resistive)

<sup>10</sup>Be SPEG: (dispersion-matched) spectrometer







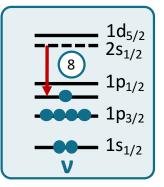


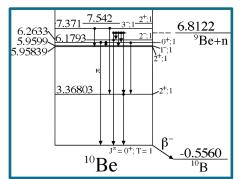
# Light nuclei – I

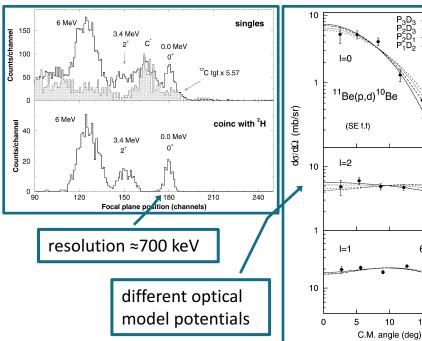
#### **Ground state of <sup>11</sup>Be**

### Experiment: <sup>11</sup>Be(p,d)<sup>10</sup>Be

- 0<sup>+</sup> state in <sup>10</sup>Be populated by removal of the 2s<sub>1/2</sub> neutron
- $\rightarrow$  assume pure  $[0^+ \otimes 2s]_{1/2+}$ configuration, calculate  $d\sigma/d\Omega$  for  $0^+$ and normalize  $\rightarrow$  SF for  $[0^+ \otimes 2s]_{1/2+}$
- 2<sup>+</sup> state populated by removal of a d<sub>5/2</sub> neutron only possible if <sup>11</sup>Be gs contains the [2<sup>+</sup> ⊗ 1d]<sub>1/2+</sub> configuration
- $\rightarrow$  assume pure  $[2^+ \otimes 1d]_{1/2+}$ configuration, calculate  $d\sigma/d\Omega$  for  $2^+$ and normalize  $\rightarrow$  SF for  $[2^+ \otimes 1d]_{1/2+}$









6 MeV

15

# Light nuclei – I

#### **Ground state of <sup>11</sup>Be**

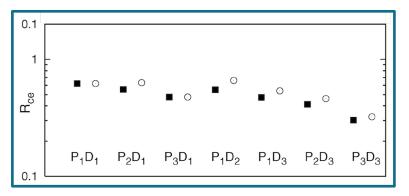
## Experiment: <sup>11</sup>Be(p,d)<sup>10</sup>Be

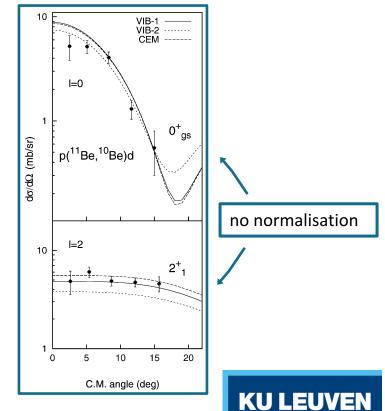
- Caution: how to build the [0<sup>+</sup> ⊗ 2s]<sub>1/2+</sub>
   and [2<sup>+</sup> ⊗ 1d]<sub>1/2+</sub> configurations?
- 1. Assume <sup>10</sup>Be inert and bind the neutron with a Woods-Saxon potential

Result: 
$$SF(0^+) \le 70\%$$
,  $SF(2^+) \ge 30\%$ 

2. Take into account the large deformation of <sup>10</sup>Be in the 2<sup>+</sup> state (solve coupled-channel problem)

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



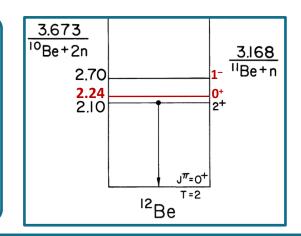


## Light nuclei - II

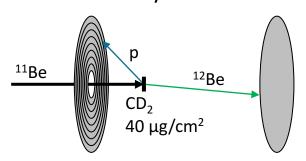
#### R Kanungo et al, PLB 682 (2010) 391

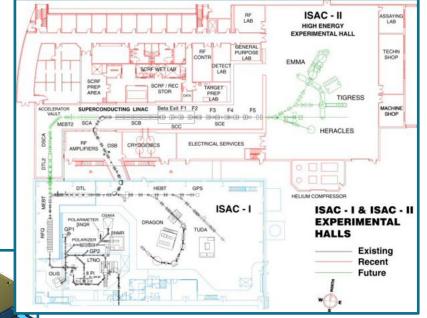
#### Structure of states in <sup>12</sup>Be

- What is the content of  $v(s_{1/2})^2$  in the 0+states of  $^{12}$ Be?
- Also measured in knock-out reactions – but those cannot separate 0<sup>+</sup><sub>1</sub> and 0<sup>+</sup><sub>2</sub>



- Experiment: <sup>11</sup>Be(d,p)<sup>12</sup>Be at TRIUMF
  - ISOL production
  - Post-acceleration to 5 MeV/nucleon





## Light nuclei - II

#### R Kanungo et al, PLB 682 (2010) 391

#### Structure of states in <sup>12</sup>Be

## Experiment: <sup>11</sup>Be(d,p)<sup>12</sup>Be

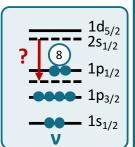
Transfer to all bound states is observed

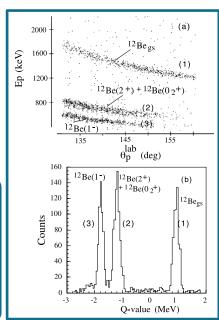
 $0^+_1$  and  $0^+_2 \rightarrow$  neutron to  $2s_{1/2}$ 

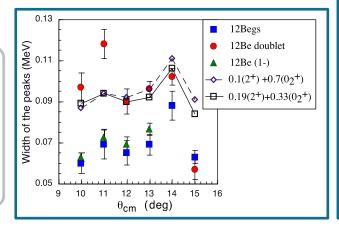
 $2^+ \rightarrow \text{neutron to } 1d_{5/2}$ 

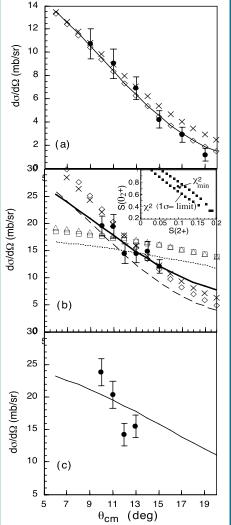
 $1^- \rightarrow \text{neutron to } 1p_{1/2}$ 

 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<sup>+</sup><sub>2</sub> is probably a halo state



## Light nuclei - II

R Kanungo et al, PLB 682 (2010) 391

#### Structure of states in <sup>12</sup>Be

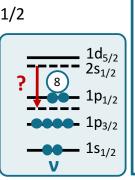
## Experiment: <sup>11</sup>Be(d,p)<sup>12</sup>Be

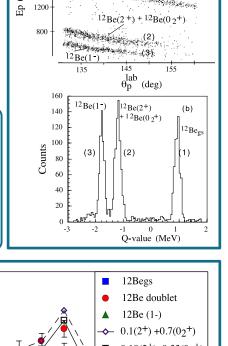
Transfer to all bound states
 is observed

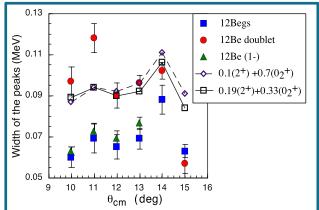
 $0^+_1$  and  $0^+_2 \rightarrow$  neutron to  $2s_{1/2}$  $2^+ \rightarrow$  neutron to  $1d_{5/2}$ 

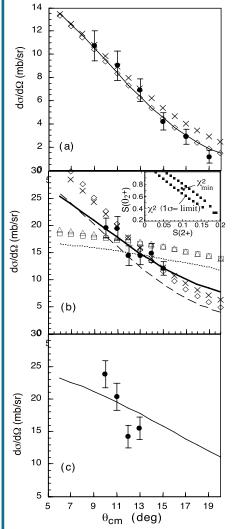
 $1^- \rightarrow \text{neutron to } 1p_{1/2}$ 

 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<sup>+</sup><sub>2</sub> is probably a halo state



## **Contents**

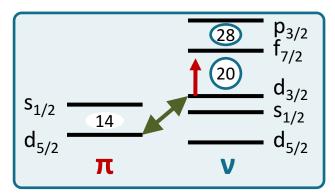
- Nuclear reactions
  - Types of reactions
  - Characteristics of direct reactions
- Why use transfer reactions
  - Information from reactions
  - Q-value, angular momentum, spectroscopic factors
- Reactions and RIBs
  - Motivations
  - Challenges: inverse kinematics
- Case studies
  - Light nuclei,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

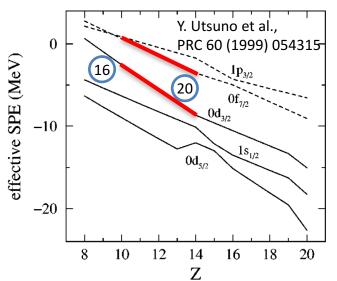


# The emergence of N=16

## ...and the disappearance of N=20

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





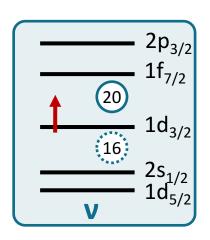
16   32.069    15.5 ms   125 ms   125 ms   127 ms   1.18 s   2.58 s   94.99   0.75   4.25   87.37 d   0.01   5.0 m   2.83   2.83   2.5 ms	Si Si 22	P 30.973762	[32.059; 32.076] \$\sigma 0.54\$ \$\text{P 25}\$	15.5 ms BP BP 5.94 P 26	125 ms β <sup>+</sup> βρ 2.98, 1.46 3.70	187 ms β <sup>+</sup> γ 1384 βρ 5.44, 2.13	1.18 s β* 4.4, 5.1	2.58 s	94.99	0.75					S 38 2.83 h
15	Si Si 22	P 30.973762	σ 0.54 β β P 25	P 26	3.70	βр 5.44, 2.13	β <sup>+</sup> 4.4, 5.1	8+44	1800	σ 0.46	987 11 1 13			200000000000000000000000000000000000000	
15 P 26 P 27 P 28 P 29 P 30 P 31 P 32 P 33 P 34 P 35 P 36 P 37 P 37	Si Si 22	30.973762			P 27				σ 0.55 σ <sub>ea</sub> < 0.0005	σ <sub>n,α</sub> 0.12 σ <sub>n</sub> 0.002	σ 0.25		0.24	3 <sup>-</sup> 1.8, 4.9	β <sup>-</sup> 1.0, 2.9 y 1942, 1746
15  a 0.17 p?	Si Si 22	5	<30 ns	20 ms					P 31	P 32	P 33	P 34	P 35	P 36	P 37
Si   Si   Si   Si   Si   Si   Si   Si		σ 0.17		*	260 ms		4.1 s	2.50 m	100	14.268 d	25.35 d	12.4 s	47.4 s	5.6 s	2.31 s
[28.084; 29 ms 42.3 ms 140 ms 218 ms 2.2283 4.15 s 92.223 4.685 3.092 2.62 h 153 a 6.11 s 2.77 s 0.78 s 0.45 28.086] b   0.400, 0.39   0.39   0.39   0.400, 0.39   0.39   0.400, 0.39   0.39   0.400   0.39   0.39   0.400   0.39			p? B	3p 7.27, 6.84	A CONTRACTOR OF THE PARTY OF TH	y 1779, 4497_ 50 0.679, 0.953		β <sup>+</sup> 3.2 γ (2235)	σ 0.17			β <sup>-</sup> 5.4 γ 2127	β <sup>-</sup> 2.3 γ 1572	3291, 903 1638, 2540	γ 646, 1583 2254
6* B2.40, 2.63 8* B3.40 P3.622 8*3.8 B*3.5 B*0.2 B*3.5															Si 36 0.45 s
	β*		B* 3		y 829, 1622		-017	-0.12	-0.107	y (1266)	noy	β 3.9, 5.8	1179, 429	3 <sup>-</sup> 74101, 2386	β" γ 175, 250, 878
Al Al 21 Al 22 Al 23 Al 24 Al 25 Al 26 Al 27 Al 28 Al 29 Al 30 Al 31 Al 32 Al 33 Al 34 Al 3	Al Al 21	21 Al 22	Al 23	Al 24	Al 25	Al 26	Al 27	Al 28	Al 29	Al 30	Al 31			Al 34	Al 35
β 12 8 β 13.3 1 β 13	26.9815386 <35 ns	β+	b.	426 8* 4.4. 8.7	7.18 s	8*12	100	2.246 m	THE RESERVE THE PARTY OF THE PA	William Co.	644 ms	β"	β-	B" 12.8	38.6 ms β 13.3, 14.2
0 230 p?	0.230 p?	B2p 4.48	B+ 1.1	1369 2754 4 1.42 7069 79 5a 1.98		1130	σ 0.230		y 1273, 2426	2235, 1263		4230	y 1941', 434'	124, 4257	3326*
														Mg 33	Mg 34
794, 275 7332, 1384 0 148, 0 0 5, 0 9, 0 143, 75, 1613, 947 7766, 736 736, 736, 736, 736, 736, 736	β <sup>+</sup> 7 984, 275*	β <sup>+</sup> γ 332, 1384				10.00		β 1.8	β <sup>-</sup> 0.5, 0.9	8" 4.3, 7.5		β" γ 1613, 947	β <sup>-</sup> γ 2765, 736	β <sup>-</sup> 13.5 βn	20 ms
2e 75   1534   1	р 0.75 βр 0.77, 1.59	1.59 βp 1.94, 1.77	у 583, 74 у	440					y 31, 1342, 401 942		β 6.1 γ 244, 444			γ 1616, 4730 1838, 2096	
350 keV <40 ns 446 ms 22.48 s 2.603 a 100 20 ms 14.96 h 59.6 s 1.07 s 301 ms 30.5 ms 44.9 ms 48 ms 17.0 ms 13.2 ms 8.0 m	350 keV <40 ns		22.48 s	2.603 a											Na 33 8.0 ms
13:10 <sup>21</sup> s   \$\begin{array}{cccccccccccccccccccccccccccccccccccc	1.3·10 <sup>-21</sup> s		Y.	1275				0=74	β- 8.0	8 <sup></sup> 13.9	y 55, 2560	y 1482, 1040°	07154	8-	β <sup>-</sup> βn, β2n
p 7 634 y 351 y 351 y 351 y 1809 in 0.48 in jn 4.13, 170 jn, j2n, pa 104 in jn 4.13, 170 jn, j2n, pa 104 in jn 4.13, 170 jn jn jn 4.13, 170 jn jn jn 4.13, 170 jn	P	γ 1634	γ 351 σ	σ <sub>n.p</sub> 28000		β -6 1369	1612	y 1809	βn 0.46	βn	βn 4.13, 1.70	βη, β2η, βα	ßn 0.08, 0.51 ß2n	βn, β2m	Maddan Market
109.2 ms 1.67 s 17.22 s 90.48 0.27 9.25 37.2 s 3.38 m 602 ms 192 ms 31.5 ms 18.9 ms 14.8 ms 5.8 ms 3.4 ms 3.5 m										31.5 ms	18.9 ms	14.8 ms			Ne 32 3.5 ms
9*48.135. 16:48.386.512. 18.41.1279.232 (63.3019) 17.12. 18.41.1279.232 (63.3019) 17.12. 18.41.1279.232 (63.3019) 17.12. 18.41.1279.232 (63.3019) 17.12. 17.12. 18.41.1279.232 (63.3019) 17.12. 18.41.1279.232 (63.3019) 17.12. 17.12. 17.12. 17.12. 17.12. 17.12. 17.12. 17.12. 17.12. 17.12. 17.12. 17.13. 17.12. 17.12. 17.12. 17.12. 17.12. 17.12. 17.12. 17.13. 17.12. 17.12. 17.12. 17.12. 17.12. 17.12. 17.12. 17.13. 17.12. 17.12. 17.12. 17.12. 17.12. 17.12. 17.12. 17.13. 17.12. 17.12. 17.12. 17.12. 17.12. 17.12. 17.12. 17.13. 17.12. 17.12. 17.13. 17.1	p 4.60, 3.80, 5.12 B <sup>+</sup> 3.4	β <sup>+</sup> 2.2 γ(110, 197		0.7		8-44		8-73	β- γ 84, 1279, 232	63, 3019	7 2063, 863	772, 1516	β-	0-	0-
1042	495, 6129°	1357)	σ 0.039 σ	7 <sub>0,62</sub> 0.00018		y 440, 1639	m	y 90, 980	βη	βn	β2n	βη, β2η	βn	A STATE OF THE PARTY OF THE PAR	βn?
120 120 120 120 120 120 120 120 120 120	40 keV 64.8 s														F 31 >260 ns
β*1.7 β*0.833 β*5.4. β*5.5.5. β*5.8. β*5.8. γ 1770, 2129 β*575 γ 2018, 1673 β*6 β*6. Γ 17703, 1613 β*7 β*6 β*7	β* 1.7	β <sup>+</sup> 0.633	σ 0.0095 B			y 1275, 2083	y 1701, 2129		575	2018, 1673	β <sup>-</sup> βn y 2018*	n?	β <sup>-</sup> βn β2n?	n?	β=? Bo2
015 016 017 018 019 020 021 022 023 024 025							O 22	O 23	O 24				1		Jan.
		5/ 0.038	0.205	27.1 s	13.5 s		2.25 s	β-	61 ms		18		20		22
p+1.7						7 1730, 3517		3868, 2926	β <sup>+</sup> βn	n 0.770					

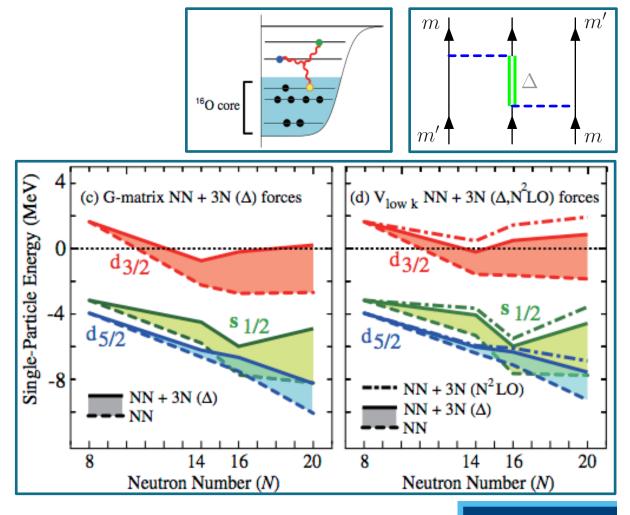


# The emergence of N=16

3-body forces in O isotopes

T Otsuka et al, PRL 105 (2010) 032501





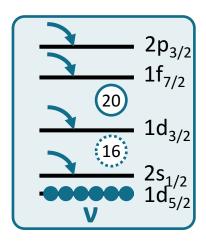


W Catford et al, PRL 104 (2010) 192501 SM Brown et al, PRC 85 (2012) 011302(R)

GL Wilson et al, PLB 759 (2016) 417

## **Experiments at GANIL and TRIUMF**

- <sup>24</sup>Ne(d,p)
- <sup>26</sup>Ne(d,p)
- <sup>25</sup>Na(d,p)



		16	S [32.059; 32.076]	S 27 15.5 ms	S 28 125 ms	S 29 187 ms	S 30 1.18 s	S 31 2.58 s	S 32 94.99	S 33 0.75	S 34 4.25	S 35 87.37 d	S 36 0.01	S 37 5.0 m	S 38 2.83 h
			σ 0.54	βρ β2p 5.94	βp 2.98, 1.46 3.70	γ 1384 βρ 5.44, 2.13	β <sup>+</sup> 4.4, 5.1 γ 678	β <sup>+</sup> 4.4 γ 1266	σ 0.55 σ <sub>0,α</sub> < 0.0005	σ 0.46 σ <sub>n,α</sub> 0.12 σ <sub>n,p</sub> 0.002	σ 0.25	β= 0.2 no γ	σ 0.24	β <sup>-</sup> 1.8, 4.9 γ 3103	β <sup>-</sup> 1.0, 2.9 γ 1942, 1746
		P 30.973762	P 25 <30 ns	P 26 20 ms	P 27 260 ms	P 28 270.3 ms	P 29 4.1 s	P 30 2.50 m	P 31	P 32 14,268 d	P 33 25.35 d	P 34 12.4 s	P 35 47.4 s	P 36 5.6 s	P 37
	15			β <sup>+</sup> β2p 4.92	6+	8 <sup>+</sup> 11.5 y 1779, 4497	B <sup>+</sup> 3.9	β <sup>+</sup> 3.2		β <sup>-</sup> 1.7	β- 0.2485	8-5.4	β- 2.3	B-	8-
		σ 0.17	p?	βр 7.27, 6.84	Вр 0.73, 0.61	\$0 0.679, 0.953 \$4 2.106, 1.432	γ 1273	y (2235)	σ 0.17	no y	no γ	у 2127	y 1572	γ 3291, 903 1638, 2540	γ 646, 1583 2254
Si [28.084;	Si 22 29 ms	Si 23 42.3 ms	Si 24 140 ms	Si 25 218 ms	Si 26 2.2283 s	Si 27 4.15 s	Si 28 92.223	Si 29 4.685	Si 30 3.092	Si 31 2.62 h	Si 32 153 a	Si 33 6.11 s	Si 34 2.77 s	Si 35 0.78 s	Si 36 0.45 s
28.086]	β*	β <sup>+</sup> βp 2.40, 2.83	β*	βp 4.09, 0.39 3.33	β <sup>+</sup> 3.8 γ 829, 1622	β+ 3.8				β <sup>-</sup> 1.5 γ (1266)	β <sup>-</sup> 0.2	β 3.9, 5.8	β <sup>-</sup> 3.1 7 1179, 429	β <sup>-</sup> γ 4101, 2386	β <sup>-</sup> y 175, 250, 878
σ 0.166	βp 1.99, 1.63 Al 21	β2p 5.86, 6.18	βp 1.51, 4.09	γ 1369*	M	γ (2210)	σ 0.17	a 0.12	σ 0.107	σ 0.073	σ < 0.5	ү 1848	1608	3860, 241	425
AI 26.9815386	<35 ns	Al 22 59 ms	Al 23 470 ms	Al 24	Al 25	Al 26 6.35 s  7.16-105a	Al 27	Al 28 2.246 m	Al 29 6.6 m	Al 30 3.60 s	Al 31 644 ms	Al 32 33 ms	Al 33 41.7 ms	Al 34 56,3 ms	Al 35 38.6 ms
		β <sup>+</sup> βp 1.32, 0.72		8* 13.3. y 1369		β* 1.2 γ 1809			β- 2.5	β 5.1, 6.3		β <sup>-</sup> y 1941, 3042	β <sup>-</sup>	β <sup>-</sup> 12.8 γ 729. 3326	β 13.3, 14.2 γ 64, 910
σ 0.230	p?	β2ρ 4.48 βα 3.27	β <sup>+</sup> βρ 0.83	β* 13.3 y 1369 y 1369 2754 βα 1.42 7069 f.79 βα 1.98	β <sup>+</sup> 3.3 γ (1612)	β <sup>4</sup> 3.2 σ <sub>0.0</sub> 0.34 σ <sub>0.0</sub> 1.97	σ 0.230	β <sup>-</sup> 2.9 γ 1779	y 1273, 2426 2028	y 2235, 1263 3498	β <sup>-</sup> 5.6, 7.9 γ 2317, 1695	4230 βn	y 1941*, 4341 1010	124, 4.257 Bn	3326*
Mg 19	Mg 20	Mg 21	Mg 22	Mg 23	Mg 24	Mg 25	Mg 26	Mg 27	Mg 28	Mg 29	Mg 30	Mg 31	Mg 32	Mg 33	Mg 34
4.0·10 <sup>-12</sup> s	95 ms	122.5 ms	3.86 s	11.3 s	78.99	10.00	11.01	9.458 m	20.9 h	1.30 s	335 ms	230 ms	86 ms	90.5 ms β 13.5	20 ms
· 医数拟悬	γ 984, 275* 238*	7 332, 1384 1634*	β+ 3.2	β+ 3.1	1000			β <sup>-</sup> 1.8 y 844, 1014	β" 0.5, 0.9 y 31, 1342, 401	β <sup>-</sup> 4.3, 7.5 γ 2224, 1398	β <sup>-</sup> 6.1	γ 1613, 947 1626, 666	y 2765, 736 2467	βn y 1616, 4730	87
2p 0.75	βp 0.77, 1.59	βρ 1.94, 1.77	y 583, 74	y 440	σ 0.053	σ 0.20	σ 0.038	σ 0.07	942	960	7 244, 444	βn	βn	1838, 2096	βn
Na 18 350 keV	Na 19 <40 ns	Na 20 446 ms	Na 21 22.48 s	Na 22 2.603 a	Na 23	Na 24 20 ms 14.96 h	Na 25 59.6 s	Na 26	Na 27 301 ms	Na 28 30.5 ms	Na 29 44.9 ms	Na 30 48 ms	Na 31 17.0 ms	Na 32 13.2 ms	Na 33 8.0 ms
1.3·10 <sup>-21</sup> s		B <sup>+</sup> 11.2	10.000	β <sup>+</sup> 0.5, 1.8 γ 1275			β- 3.8		β <sup>-</sup> 8.0	6 <sup></sup> 13.9	β 10.8, 13.4 y 55, 2560	β 12.2, 15.7 y 1482, 1040*	87.154	n=	β <sup>-</sup> βn, β2n
ρ? β <sup>+</sup> ?	P	βα 2.15, 4.44 γ 1634	β <sup>+</sup> 2.5 γ 351	σ <sub>n,α</sub> 260 σ <sub>n,p</sub> 28000	σ 0.43 + 0.1	β 1.4. β -6 1369.	γ 975, 3 1612	1 VI	γ 985, 1698 βn 0.46	γ 1471, 2389 βn	1474' βn 4.13, 1.70	1978 βn, β2n, βα	y 51, 1482*, 2244. pn 0.08, 0.51	γ 885, 2152 βn, β2tn	γ 886*, 547 1243
Ne 17	Ne 18	Ne 19	Ne 20	Ne 21	Ne 22	Ne 23	Ne 24	Ne 25	Ne 26	Ne 27	Ne 28	Ne 29	Ne 30	Ne 31	Ne 32
109.2 ms	1.67 s	17.22 s	90.48	0.27	9.25	37.2 s	3.38 m	602 ms	192 ms	31,5 ms	18.9 ms	14.8 ms	5.8 ms	3.44 ms	3.5 ms
β* 8.0, 13.5 βρ 4.60, 3.80, 5.12 βει 1.725	β+ 3.4	β <sup>+</sup> 2.2 γ (110, 197		σ 0.7		β- 4.4	β 2.0 γ 874	10	y 84, 12 153	2 0, 2225	7 2063, 863 Bn	γ 72, 1516 1249, 1588	β <sup>-</sup> γ 151	8-	8-
F 16	y 1042 F 17	1357) F 18	σ 0.039 F 19	σ <sub>n,ε</sub> 0.00018	σ 0.051	7 440, 1639	m = 00	y 90, 980	βn	βn	β2n	βn, β2n	βn	βn?	ßn?
40 keV	64.8 s	109.728 m	100	F 20	F 21 4.16 s	F 22 4.23 s	F 23	F 24 0.34 s	F 25 50 ms	F 26	F 27	F 28 <40 ns	F 29	F: 30 <260 ns	F 31 >260 ns
11·10 <sup>-21</sup> s		College State	THE PROPERTY			β- 5.5	β 8.5		β <sup>-</sup> y 1703, 1613	8-	8-		8-	-2.00115	-200113
р	β <sup>+</sup> 1.7 no γ	β <sup>+</sup> 0.633 no γ	σ 0.0095	β¯ 5.4 γ 1634	β <sup>-</sup> 5.3, 5.7 γ 351, 1395	y 1275, 2083 2166	y 1701, 2129 1822, 3431	β <sup></sup> γ 1982	575 βn	γ 2018, 1673 βn	βn γ 2018*	n?	βn β2n?	n?	β <sup>-</sup> ? βn?
O 15	O 16	0 17	0 18	0 19	0 20	0 21	0 22	0 23	0 24	O 25					
2.03 m	99.757	0.038	0.205	27.1 s	13.5 s	3.4 s	2.25 s	97 ms β	61 ms	172 keV 2.7·10 <sup>-21</sup> s	18		20		22
β+ 1.7	σ 0.00019	σ 0.00054	-0.00016	β 3.3, 4.7	β 2.8	β 6.4 γ 1730, 3517	β <sup>-</sup> γ 72, 637	y 2243, 4066 3868, 2926	β-						
noγ	σ 0.00019	σ <sub>n,α</sub> 0.257	σ 0.00016	ү 197, 1357	γ 1057	280, 1787	1862	βn	βn	n 0.770					



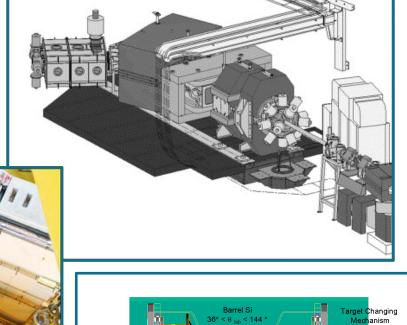
## W Catford et al, PRL 104 (2010) 192501 SM Brown et al, PRC 85 (2012) 011302(R)

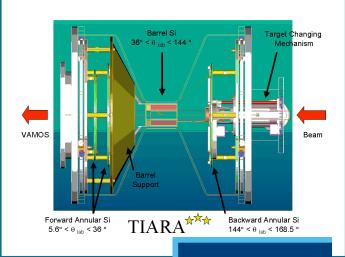
# (d,p) on Ne and Na isotopes

## At GANIL (SPIRAL)

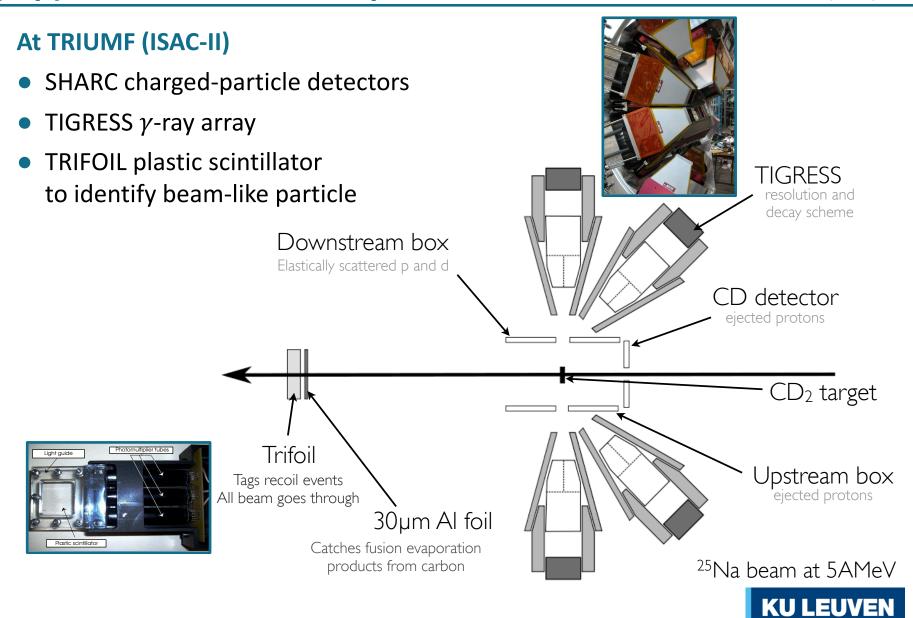
- TIARA charged-particle detectors
- EXOGAM  $\gamma$ -ray array
- VAMOS spectrometer





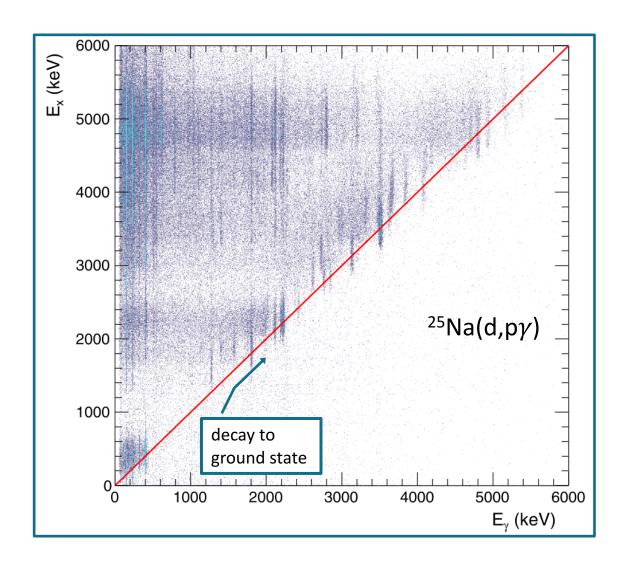


GL Wilson et al, PLB 759 (2016) 417



#### **Conditions**

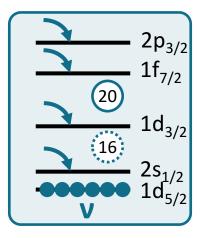
- Populated state decays promptly
- Angular resolution for Doppler correction

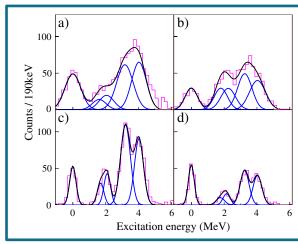


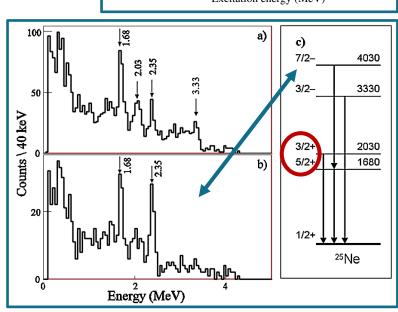


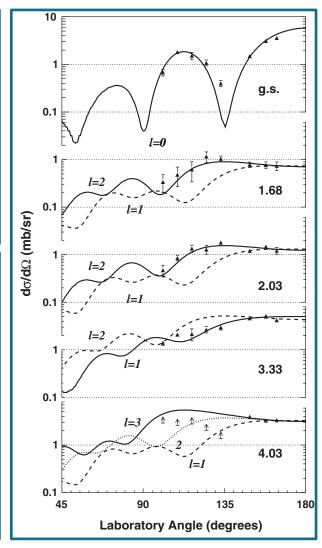
#### W Catford et al, PRL 104 (2010) 192501

# <sup>24</sup>Ne(d,p)





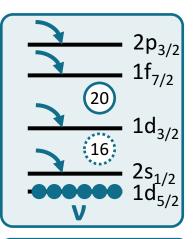






#### W Catford et al, PRL 104 (2010) 192501

# <sup>24</sup>Ne(d,p)



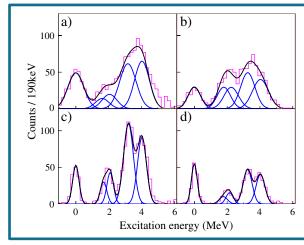
$$SF(1/2^+) = 0.80$$

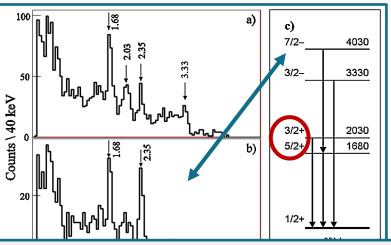
$$SF(5/2^+) = 0.15$$

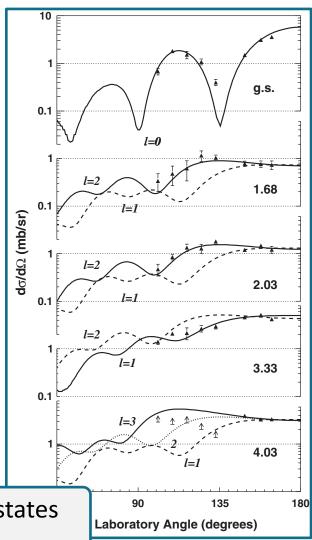
$$SF(3/2^+) = 0.44$$

$$SF(3/2^{-}) = 0.75$$

$$SF(7/2^{-}) = 0.80$$





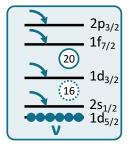


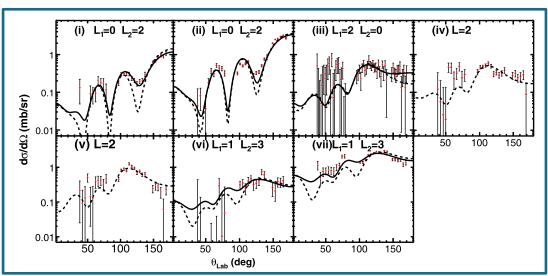
- Firm assignment of the spin of the first two excited states
- Raise of the  $3/2^+$  ( $\approx 1$  MeV) with respect to the  $5/2^+$  compared to  $^{27}$ Mg

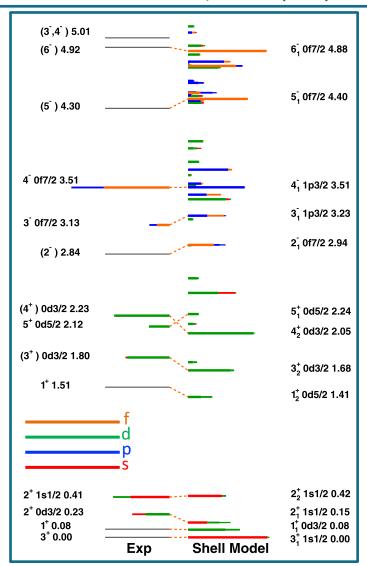


#### GL Wilson et al, PLB 759 (2016) 417

<sup>25</sup>Na(d,p)



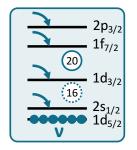


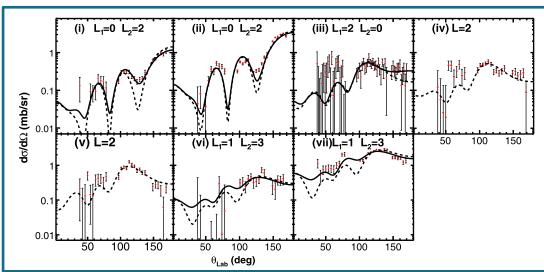




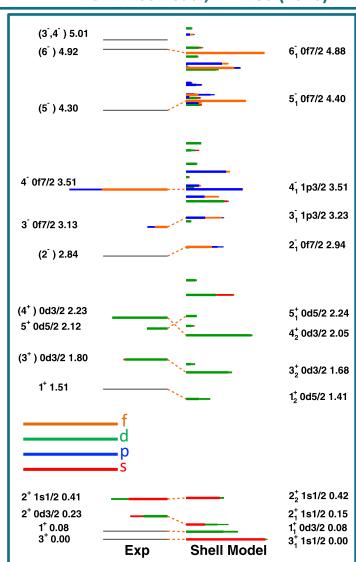
#### GL Wilson et al, PLB 759 (2016) 417

<sup>25</sup>Na(d,p)





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

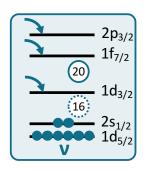




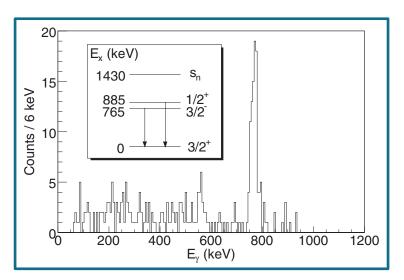
M Brown et al, PRC 85 (2012) 011302(R)

# <sup>26</sup>Ne(d,p)

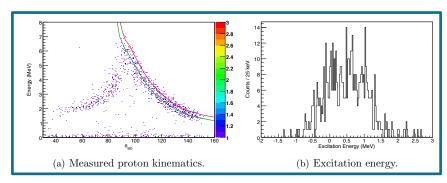
 Angular distributions: efficiency correction for coincidences as function of the spin

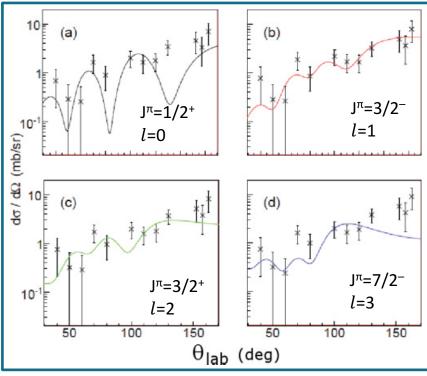


Ground-state selection: E\*<200 keV</li>



Very low 3/2<sup>-</sup> intruder state



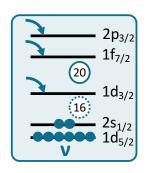




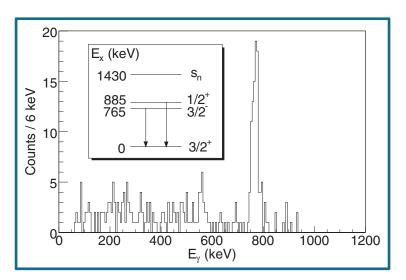
M Brown et al, PRC 85 (2012) 011302(R)

## <sup>26</sup>Ne(d,p)

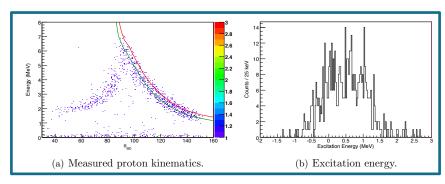
 Angular distributions: efficiency correction for coincidences as function of the spin

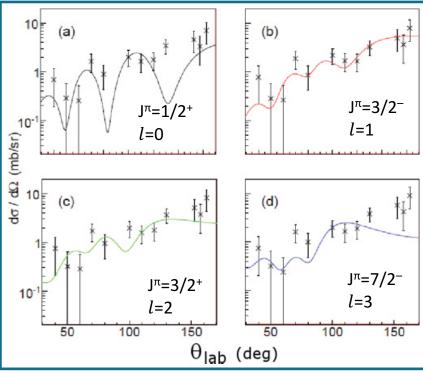


Ground-state selection: E\*<200 keV</li>



Very low 3/2<sup>-</sup> intruder state



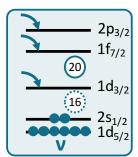


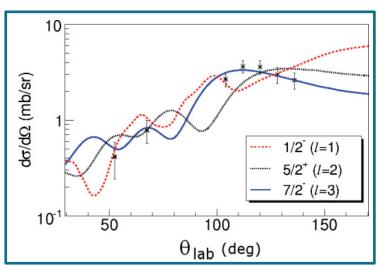


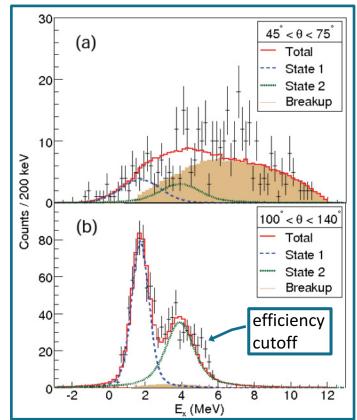
#### M Brown et al, PRC 85 (2012) 011302(R)

# <sup>26</sup>Ne(d,p)

 Proton coincidences with <sup>26</sup>Na: transfer to unbound states





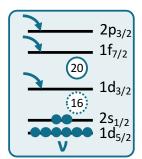


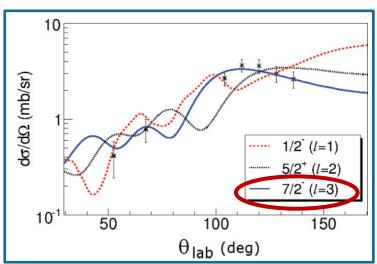


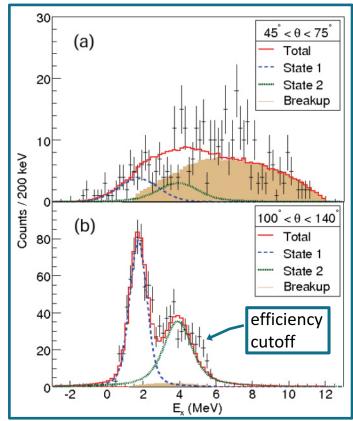
#### M Brown et al, PRC 85 (2012) 011302(R)

## <sup>26</sup>Ne(d,p)

 Proton coincidences with <sup>26</sup>Na: transfer to unbound states





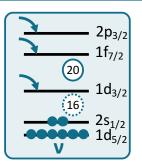




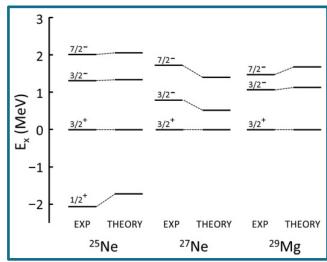
#### M Brown et al, PRC 85 (2012) 011302(R)

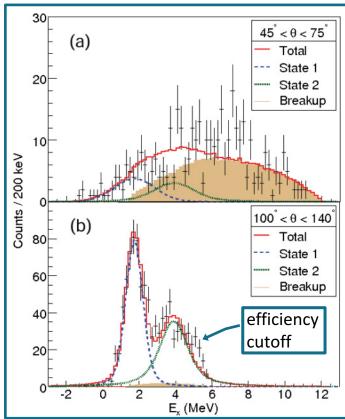
# <sup>26</sup>Ne(d,p)

 Proton coincidences with <sup>26</sup>Na: transfer to unbound states



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





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



# **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



## **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
  - ...



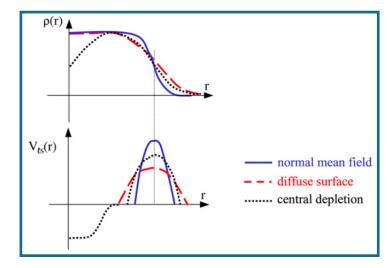
# The spin-orbit term

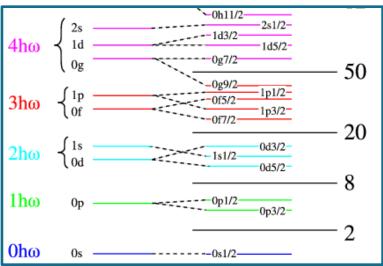
One-body spin-orbit potential:

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

- → 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



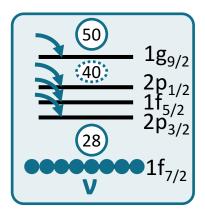




L Gaudefroy et al, PRL 97 (2006) 092501

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

<sup>46</sup>Ar(d,p)<sup>47</sup>Ar at GANIL (SPIRAL)



z	43Ti	44Ti	45Ti	46Ti	47Ti	48Ti	49Ti	50Ti	51Ti	52Ti	53Ti	54Ti	55Ti	56Ti	57Ti	58Ti	59Ti
	42Sc	43Sc	44Sc	45Sc	46Sc	47Sc	48Sc	49Sc	50 Sc	51 Sc	52Sc	53Sc	548c	55Sc	56Sc	57Sc	58Sc
20	41Ca	42Ca	43Ca	44Ca	45Ca	46Ca	47Ca	48Ca	49Ca	50Ca	51Ca	52Ca	53Ca	54Ca	55Ca	56Ca	57⊂a
	40K	41K	42K	43K	44K	45K	46K	47K	48K	49K	50K	51K	52 <b>K</b>	53K	54K	55K	56K
18	39Ar	40Ar	41Ar	42Ar	43Ar	44Ar	45Ar	46Ar	47Ar	48Ar	49A1	50Ar	51Ar	52Ar	53Ar		
	38CI	39Cl	40CI	41Cl	42CI	43Cl	44Cl	45Cl	46CI	47Cl	48CI	49Cl	50CI	51Cl			
16	37 S	385	395	405	415	425	435	445	458	46S	475	485	495				
	36P	37P	38P	39P	40P	41P	42P	43P	44P	45P	46P						
14	35Si	36Si	37Si	38Si	39 Si	40Si	41Si	42Si	43Si	44Si							
	21		23		25		27		29		31		33		35		N

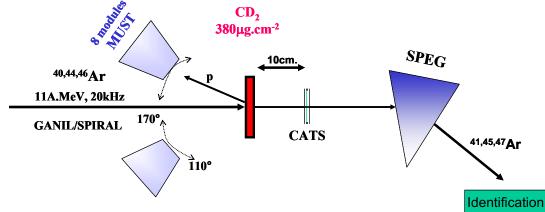


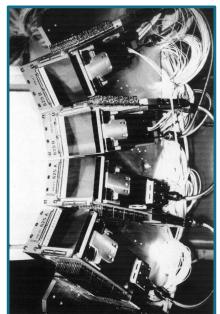
L Gaudefroy et al, PRL 97 (2006) 092501

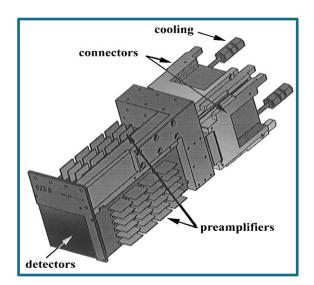
"Reduction of the Spin-Orbit Splittings at the N=28 shell closure"

<sup>46</sup>Ar(d,p)<sup>47</sup>Ar at GANIL (SPIRAL)

- SPEG for identification of <sup>47</sup>Ar
- MUST charged-particle telescope detectors Si-Si(Li)-CsI







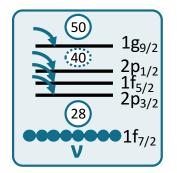
Y. Blumenfeld et al NIMA 421 (1999) 471



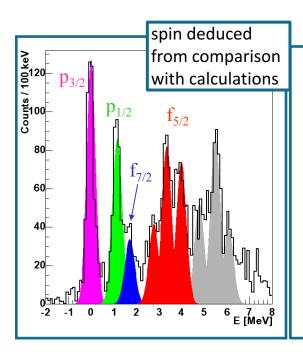
L Gaudefroy et al, PRL 97 (2006) 092501

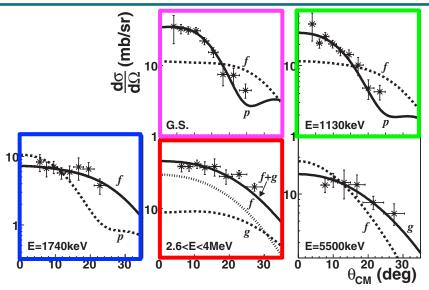
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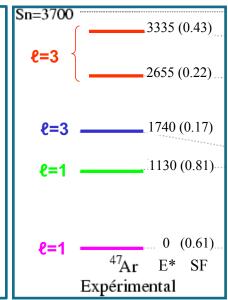
<sup>46</sup>Ar(d,p)<sup>47</sup>Ar



p strength almost complete missing f<sub>5/2</sub> strength from calculations







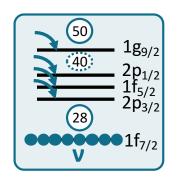


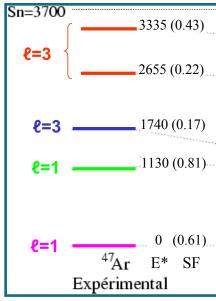
L Gaudefroy et al, PRL 97 (2006) 092501

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

## <sup>46</sup>Ar(d,p)<sup>47</sup>Ar

- Mass excess of ground state from Q-value
   → N=28 gap deduced
   Reduction of 330 keV compared to <sup>49</sup>Ca
- Centroid of f<sub>5/2</sub> 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  $s_{1/2}$





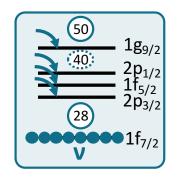
KU LEUVEN

L Gaudefroy et al, PRL 97 (2006) 092501

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

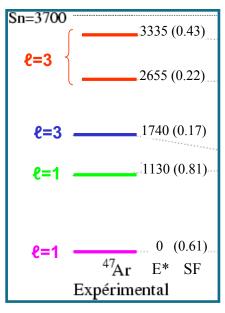
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- Centroid of f<sub>5/2</sub> deduced from experiment and calculations; plotted with energy of the "p states"
- Differences with  $^{49}$ Ca (N=28 gap) ascribed to the removal of protons from  $d_{3/2}$  and  $s_{1/2}$



-2.42

-3.55



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

SPE (MeV)

**KU LEUVEN** 

p<sub>1/2</sub> -3.13

p<sub>3/2</sub> -5.15

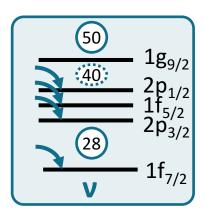
(28)

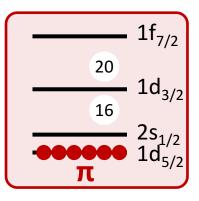
## **Bubble in nucleus?**

G Burgunder et al, PRL 112 (2014) 042502

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

<sup>34</sup>Si(d,p)<sup>35</sup>Si at GANIL (LISE)





z	38Ca	39Ca	40Ca	41Ca	42Ca	43Ca	44Ca	45Ca	46Ca	47Ca	48Ca	49Ca	50Ca	51Ca	52Ca	53Ca	54Ca
	37K	38K	39K	40K	41K	42K	43K	44K	45K	46K	47K	48K	49K	50K	51K	52K	53K
18	36Ar	37Ar	38Ar	39Ar	40Ar	41Ar	42Ar	43Ar	44AI	45Ar	46Ar	47Aı	48Ar	49Ar	50Ar	51Ar	52Ar
	35CI	36CI	37Cl	38CI	39Cl	40CI	41Cl	42CI	43CI	44CI	45Cl	46CI	47CI	48CI	49CI	50CI	51CI
16	345	358	36S	37 S	385	395	40S	415	425	435	445	458	46S	475	485	495	
	33P	34P	35P	36P	37P	38P	39P	40P	41P	42P	43P	44P	45P	46P			
14	32Si	33Si	34Si	35Si	36Si	37Si	38Si	39 Si	40Si	41Si	42Si	43Si	44Si				
	31 A.I	32AI	33Al	34AL	35Al	36Al	37AI	38AI	39AI	40Al	41Al	42Al	43Al				
12	30 <b>M</b> g	31Mg	32 <b>M</b> g	33 <b>M</b> g	34Mg	35Mg	36Mg	37Mg	38 <b>M</b> g	39Mg	40 <b>M</b> g						
	18		20		22		24		26		28		30		32		N



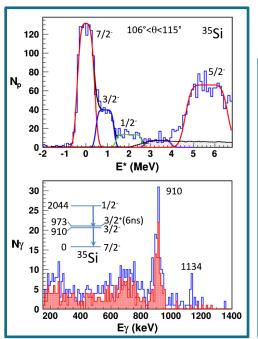
## **Bubble in nucleus?**

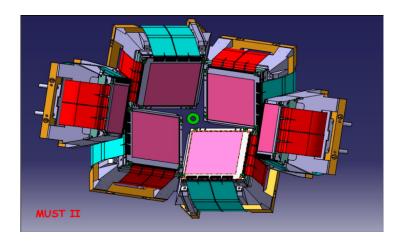
G Burgunder et al, PRL 112 (2014) 042502

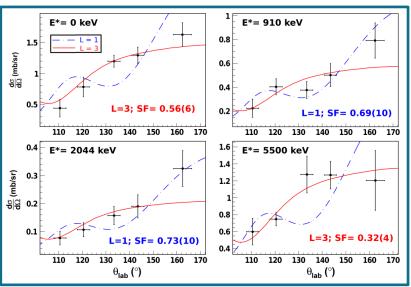
## "Experimental Study of the Two-Body Spin-Orbit Force in Nuclei"

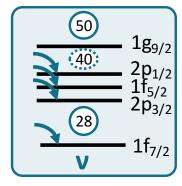
## <sup>34</sup>Si(d,p)<sup>35</sup>Si at GANIL (LISE)

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







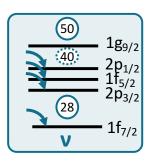


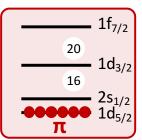


## "Experimental Study of the Two-Body Spin-Orbit Force in Nuclei"

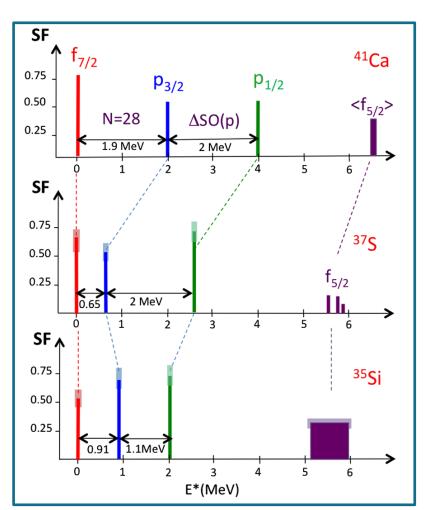
## <sup>34</sup>Si(d,p)<sup>35</sup>Si at GANIL (LISE)

- Comparison between "doubly magic nuclei"
- Difference only due to density-dependent terms in the SO-splitting





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

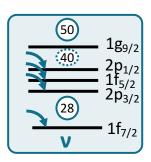


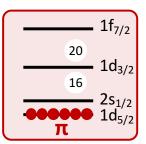


## "Experimental Study of the Two-Body Spin-Orbit Force in Nuclei"

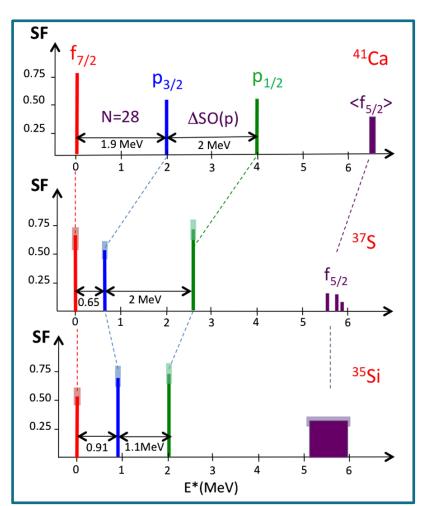
## <sup>34</sup>Si(d,p)<sup>35</sup>Si at GANIL (LISE)

- Comparison between "doubly magic nuclei"
- Difference only due to density-dependent terms in the SO-splitting





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





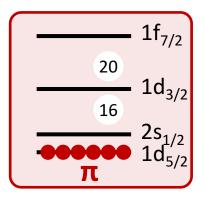
## **Bubble in nucleus?**

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

## Occupation of $s_{1/2}$ in <sup>34</sup>Si

## <sup>34</sup>Si proton removal

- Experiment at MSU
- $^{34}$ Si on  $^{9}$ Be target proton and  $\gamma$  detection
- *l* from momentum distribution of protons
- Deduced spin and SFs of states in <sup>33</sup>Al



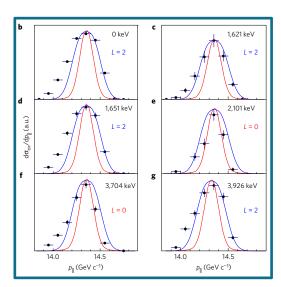
#### ARTICLES

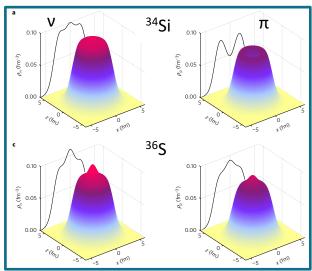
PUBLISHED ONLINE: 24 OCTOBER 2016 | DOI: 10.1038/NPHYS3916



# A proton density bubble in the doubly magic <sup>34</sup>Si nucleus

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





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



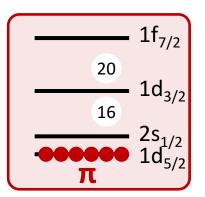
## **Bubble in nucleus?**

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

## Occupation of $s_{1/2}$ in <sup>34</sup>Si

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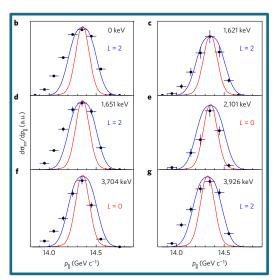
#### ARTICLES

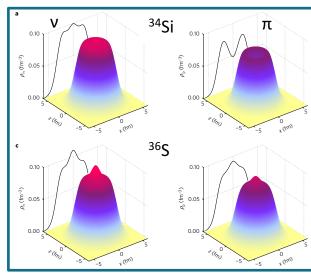
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## **Contents**

- 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 structure of 0<sup>+</sup> states

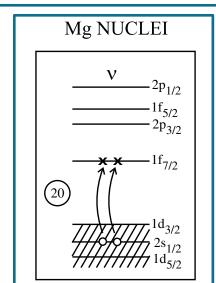
- When the monopole gap is of the same size as the correlation energy:
  - 2p-2h configurations appear at low energy **0**+ **states with different shapes**
- "Shape transitions" and "islands of inversion": How can we probe the s.p. content of the wave function?

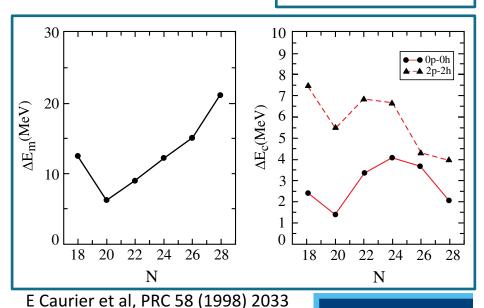
Use two-neutron transfer to connect 0<sup>+</sup> states with similar configurations

#### Caution

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

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





## The structure of 0<sup>+</sup> states

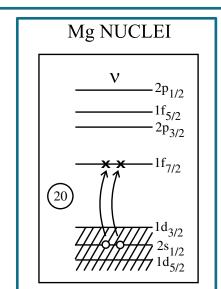
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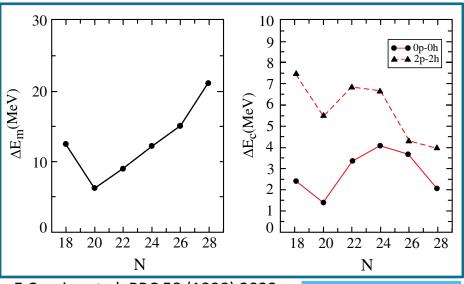
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K Heyde and JL Wood, Rev Mod Phys 83 (2011) 1467



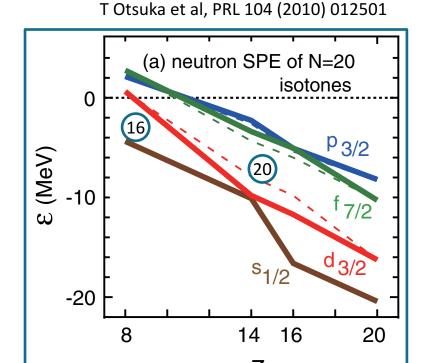


E Caurier et al, PRC 58 (1998) 2033



# Looking for the second, spherical 0<sup>+</sup> in <sup>32</sup>Mg <sup>30</sup>Mg(t,p)<sup>32</sup>Mg

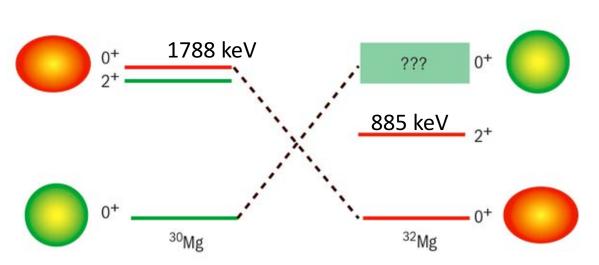
S 32 94.99	S 33 0.75	S 34 4.25	S 35 87.37 d	S 36	S 37	S 38
94.99	σ 0.46	4.25	87.37 0	0.01	5.0 m	2.83 h
.55 < 0.0005	σ <sub>n,α</sub> 0.12 σ <sub>n,ρ</sub> 0.002	σ 0.25	β <sup>-</sup> 0.2 no γ	σ 0.24	β <sup>-</sup> 1.8, 4.9 y 3103	β <sup>-</sup> 1.0, 2.9 y 1942, 1746
P 31	P 32 14.268 d	P 33 25.35 d	P 34 12.4 s	P 35 47.4 s	P 36 5.6 s	P 37 2.31 s
.17	β <sup>-</sup> 1.7 no γ	β <sup>-</sup> 0.2485 no γ	β <sup>-</sup> 5.4 γ 2127	β <sup>-</sup> 2.3 γ 1572	β <sup>-</sup> γ 3291, 903 1638, 2540	β <sup>-</sup> γ 646, 1583 2254
Si 30 3.092	Si 31 2.62 h	Si 32 153 a	Si 33 6.11 s	Si 34 2.77 s	Si 35 0.78 s	Si 36 0.45 s
.107	β <sup>-</sup> 1.5 γ (1266) σ 0.073	β <sup>-</sup> 0.2 no γ σ < 0.5	β <sup>-</sup> 3.9, 5.8 γ 1848	β <sup>-</sup> 3.1 γ 1179, 429 1608	β <sup>-</sup> γ 4101, 2386 3860, 241	β <sup>-</sup> γ 175, 250, 878 425
Al 29 6.6 m	Al 30 3.60 s	AI 31 644 ms	Al 32 33 ms	Al 33 41.7 ms	AI 34 56.3 ms	Al 35 38.6 ms
2.5 273, 2426 28	β <sup>-</sup> 5.1, 6.3 γ 2235, 1263 3498	β <sup>-</sup> 5.6, 7.9 γ 2317, 1695	β <sup>-</sup> γ 1941, 3042 4230 βn	βη γ 1941*, 4341 1010	β <sup>-</sup> 12.8 γ 729, 3326 124, 4257 βn	β <sup>-</sup> 13.3, 14.2 γ 64, 910 3326* βn
Mg 28 20.9 h	Mg 29 1.30 s	Mg 30 335 ms	Mg 31 230 ms	Mg 32 86 ms	Mg 33 90.5 ms β- 13.5	Mg 34 20 ms
0.5, 0.9 1, 1342, 401	β <sup>-</sup> 4.3, 7.5 γ 2224, 1398 960	β <sup>-</sup> 6.1 γ 244, 444	1626, 666 βn	,736 67 βn	βη γ 1616, 4730 1838, 2096	β <sup>-</sup> βn
Na 27 301 ms	Na 28 30.5 ms	Na 29 44.9 ms	Na 30	Na 31	Na 32 13.2 ms	Na 33 8.0 ms
8.0 35, 1698 0.46	β <sup>-</sup> 13.9 γ 1471, 2389 βn	β <sup>-</sup> 10.8, 13.4 γ 55, 2560 1474* βn 4.13, 1.70	β <sup>-</sup> 12.2, 15.7 γ 1482, 1040* 1978 βn, β2n, βα	р <sup>-</sup> 15.4 у 51, 1482°, 2244 рл 0.08, 0.51 §2n	β <sup>-</sup> γ 885, 2152 βn, β2m	β <sup>-</sup> βn, β2n γ 886*, 547 1243
Ne 26	Ne 27 31.5 ms	Ne 28 18.9 ms	Ne 29	Ne 30 5.8 ms	N⊕ 31 3.44 ms	Ne 32 3.5 ms
4, 1279, 232	β <sup>-</sup> 12.6 γ 63, 3019 2736, 2225 βn	β <sup>-</sup> 12.2 γ 2063, 863 βn β2n	β <sup>-</sup> 15.3 γ 72, 1516 1249, 1588 βn, β2n	β <sup>-</sup> γ 151 βn	β <sup>-</sup> βn?	β- βn?
F 25 50 ms	F 26 10.2 ms	F 27 5.0 ms	F 28 <40 ns	F 29 2.6 ms	F: 30 <2/60 ns	F 31 >260 ns
703, 1613 5	β <sup>-</sup> γ 2018, 1673 β0	β <sup>-</sup> βn γ 2018*	n?	β <sup>-</sup> βn β2n?	n?	β-?

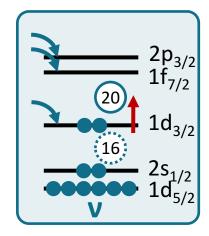


#### Looking for the second, spherical 0<sup>+</sup> in <sup>32</sup>Mg

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

- <sup>30</sup>Mg: spherical ground state, deformed (intruder) excited state; small mixing
- <sup>32</sup>Mg: only ground state 0<sup>+</sup> known, deformed
   Predictions for 0<sup>+</sup><sub>2</sub> between 1.4 MeV and 3 MeV
- Two-neutron transfer to
  - find the second 0<sup>+</sup>
  - determine the overlap



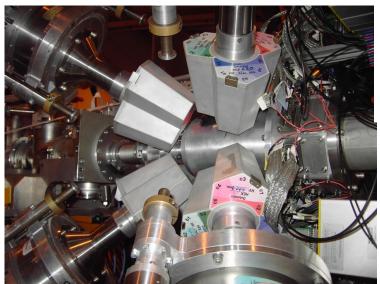


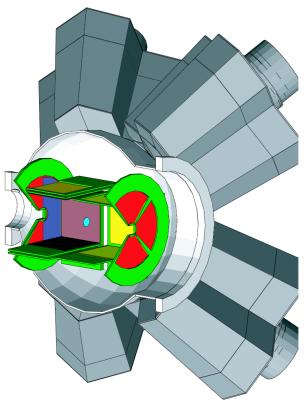


K Wimmer et al., PRL 105 (2010) 252501

# Looking for the second, spherical 0<sup>+</sup> in <sup>32</sup>Mg <sup>30</sup>Mg(t,p)<sup>32</sup>Mg

- <sup>30</sup>Mg beam at REX-ISOLDE, 1.8 MeV/nucleon (below fusion barrier for Ti)
- Tritium-implanted Ti foil (t: 40 μg/cm²)
- T-REX charged-particle detector
- Miniball  $\gamma$ -ray array



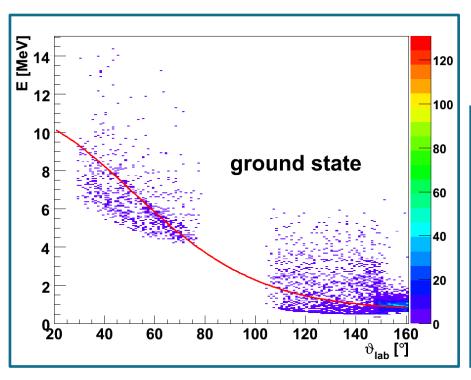


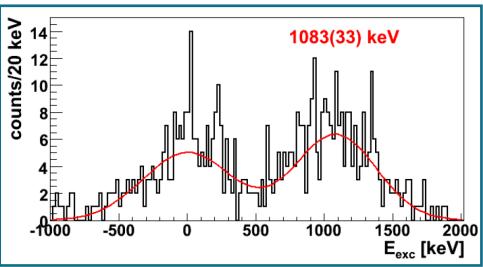


#### Looking for the second, spherical 0<sup>+</sup> in <sup>32</sup>Mg

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

 Two states identified, well separated



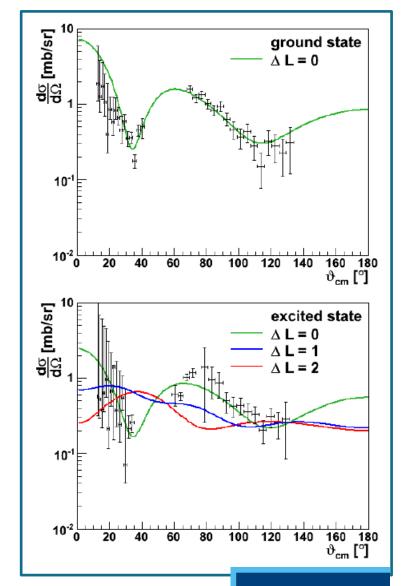




K Wimmer et al., PRL 105 (2010) 252501

# Looking for the second, spherical 0<sup>+</sup> in <sup>32</sup>Mg <sup>30</sup>Mg(t,p)<sup>32</sup>Mg

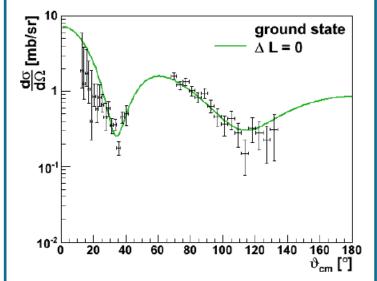
- Two states identified, well separated
- Angular distributions: l=0
- γ-ray coincidences with excited state:
   no 2+ (18 cts expected from 2+ at 886 keV)

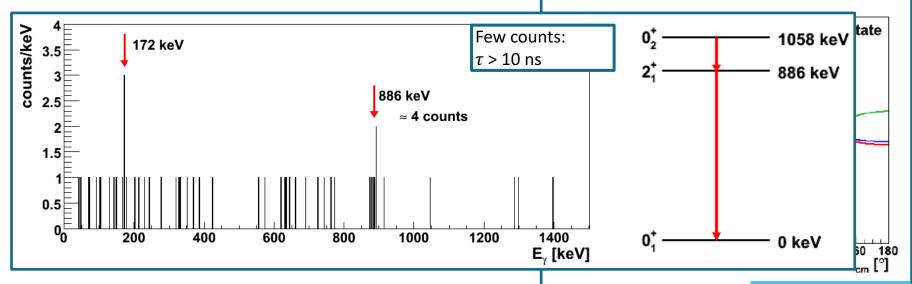


K Wimmer et al., PRL 105 (2010) 252501

# Looking for the second, spherical 0<sup>+</sup> in <sup>32</sup>Mg <sup>30</sup>Mg(t,p)<sup>32</sup>Mg

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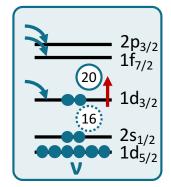




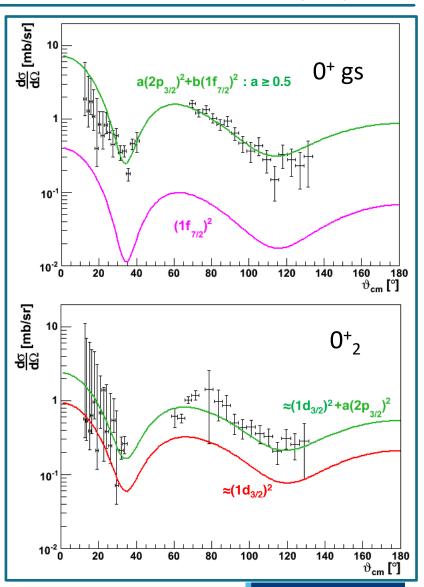
K Wimmer et al., PRL 105 (2010) 252501

# Looking for the second, spherical 0<sup>+</sup> in <sup>32</sup>Mg <sup>30</sup>Mg(t,p)<sup>32</sup>Mg

- Two-step transfer?
   30Mg(t,d) large negative Q-value
- 0<sup>+</sup><sub>2</sub> lower than predicted
- Long lifetime
- Similar cross sections



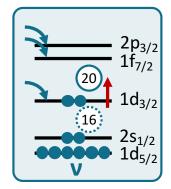
- $(p_{3/2})^2$  component, strong in the g.s.
- Mixing between the 0+s?
- → Measure monopole strength for 0<sup>+</sup><sub>2</sub>



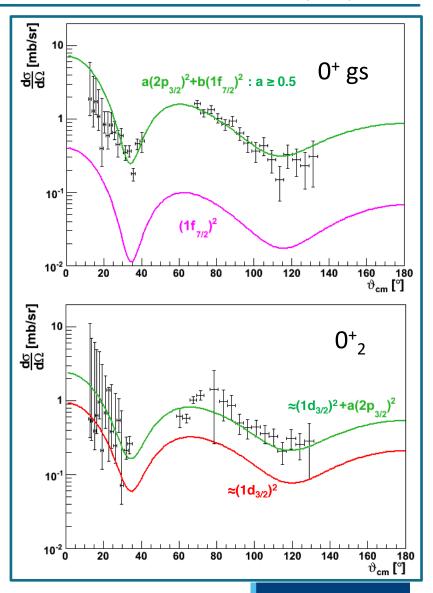
K Wimmer et al., PRL 105 (2010) 252501

# Looking for the second, spherical 0<sup>+</sup> in <sup>32</sup>Mg $^{30}$ Mg(t,p) $^{32}$ Mg

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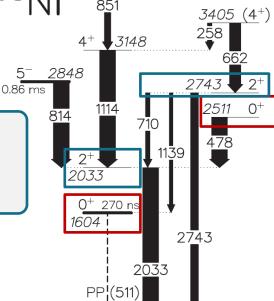


### The O<sup>+</sup> states in <sup>68</sup>Ni

### 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<sup>+</sup> states and two 2<sup>+</sup> states below 2.8 MeV



#### **Crucial information**

- Precise measurement of 0<sup>+</sup><sub>2</sub> energy
   Since 1982: 1770(30) keV from <sup>70</sup>Zn(<sup>14</sup>C,<sup>16</sup>O)<sup>68</sup>Ni
   Now: 1603.5(3) keV
- Two transitions feeding 0<sup>+</sup><sub>2</sub> (1139 and 2420 keV)
- Firm assignment of several spin/parities

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

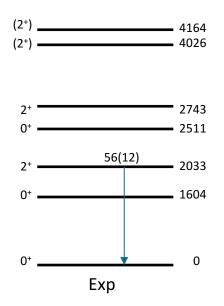


### The 0<sup>+</sup> states in <sup>68</sup>Ni

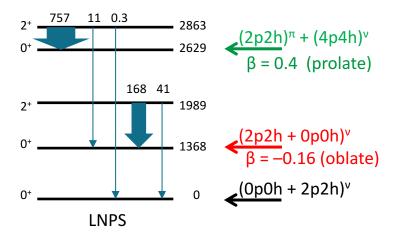
#### **Large-scale Shell Model with LNPS interaction**

S Lenzi et al, PRC 82 (2010) 054301

•  $^{48}$ Ca core,  $\pi$  pf –  $\nu$  pfg<sub>9/2</sub>d<sub>5/2</sub> to describe Fe and Cr



B(E2,down) values in e<sup>2</sup>fm<sup>4</sup>



"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."

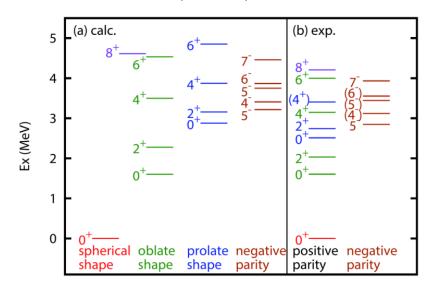
<sup>68</sup>N

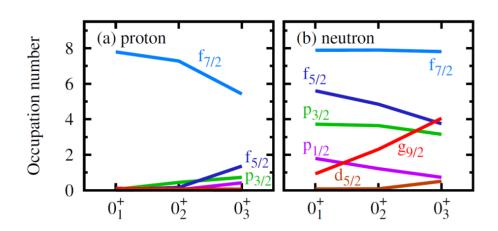


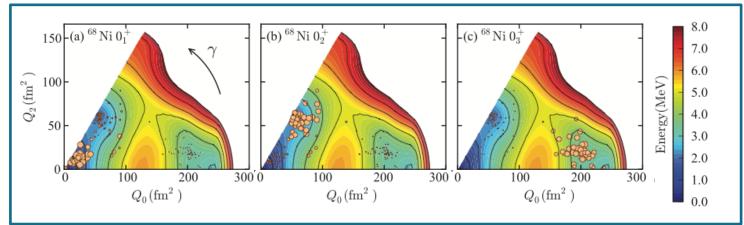
## The O<sup>+</sup> states in <sup>68</sup>Ni

#### 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





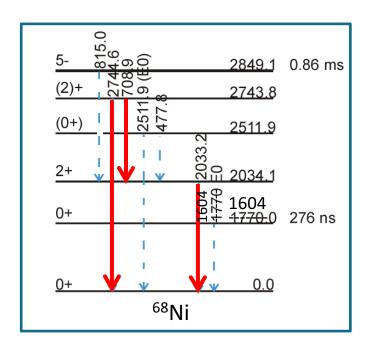


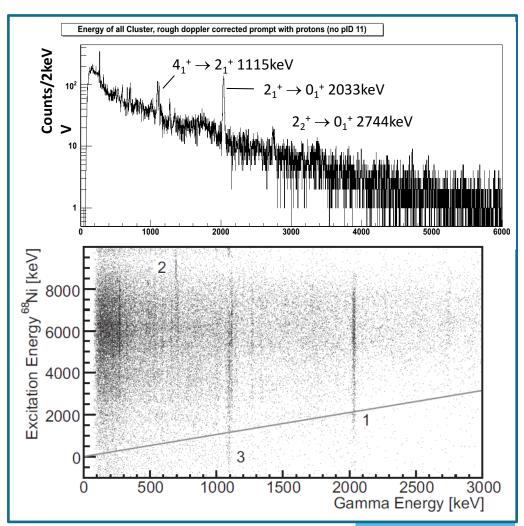


#### Probing the structure of 0<sup>+</sup> and 2<sup>+</sup> states in <sup>68</sup>Ni

#### <sup>66</sup>Ni(t,p)<sup>68</sup>Ni at 2.6 MeV/nucleon

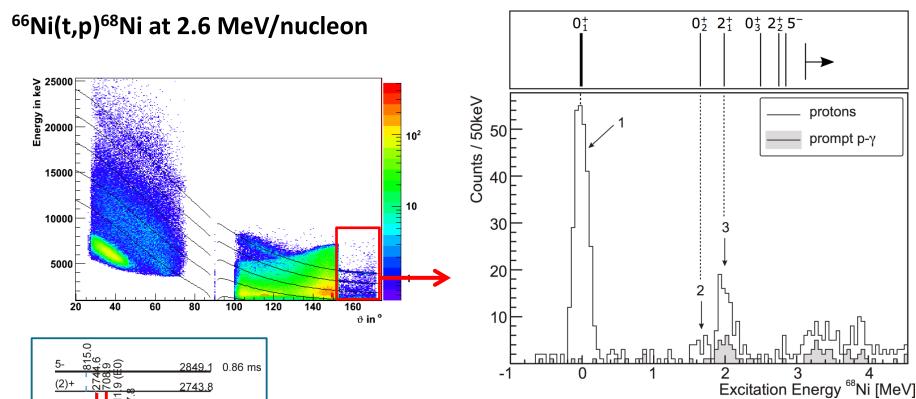
- Few γ's to ground state
- No p-γ-γ coincidences

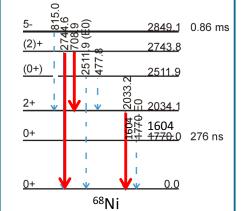




J Elseviers, PhD thesis, KU Leuven

#### Probing the structure of 0<sup>+</sup> and 2<sup>+</sup> states in <sup>68</sup>Ni





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

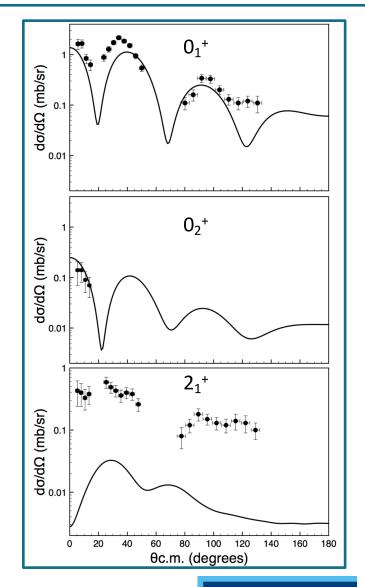


J Elseviers, PhD thesis, KU Leuven

# Probing the structure of 0<sup>+</sup> and 2<sup>+</sup> states in <sup>68</sup>Ni

### <sup>66</sup>Ni(t,p)<sup>68</sup>Ni at 2.6 MeV/nucleon

- Two-neutron overlap amplitudes from MCSM (T. Otsuka) pf+g<sub>9/2</sub>+d<sub>5/2</sub> both protons and neutrons
- Works well for the 0<sup>+</sup>s
   does not reproduce the 2<sup>+</sup><sub>1</sub>



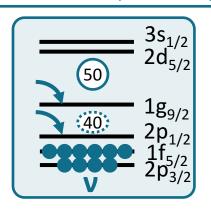


J Elseviers, PhD thesis, KU Leuven

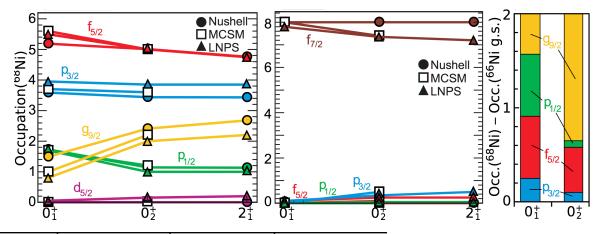
#### Probing the structure of 0<sup>+</sup> and 2<sup>+</sup> states in <sup>68</sup>Ni

#### <sup>66</sup>Ni(t,p)<sup>68</sup>Ni at 2.6 MeV/nucleon

 Two-neutron overlap amplitudes from MCSM (T. Otsuka) pf+g<sub>9/2</sub>+d<sub>5/2</sub> both protons and neutrons



#### neutron - **occupation numbers** - protons



	f <sub>5/2</sub>		p <sub>3/2</sub>		p <sub>1/2</sub>		<b>g</b> <sub>9/2</sub>	
<sup>66</sup> Ni gs	4.53		3.34		1.07		1.06	
<sup>68</sup> Ni gs	5.19	+0.66	3.59	+0.25	1.73	+0.66	1.49	+0.43
<sup>68</sup> Ni 0 <sup>+</sup> <sub>2</sub>	5.01	+0.48	3.44	+0.10	1.14	+0.07	2.41	+1.35

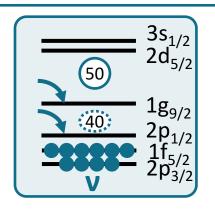


J Elseviers, PhD thesis, KU Leuven

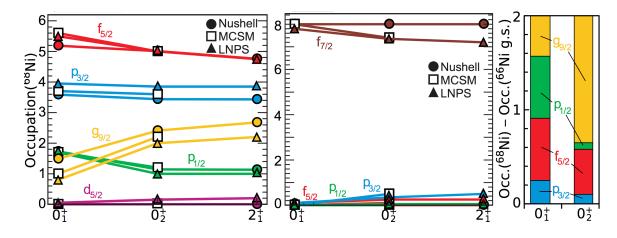
#### Probing the structure of 0<sup>+</sup> and 2<sup>+</sup> states in <sup>68</sup>Ni

#### <sup>66</sup>Ni(t,p)<sup>68</sup>Ni at 2.6 MeV/nucleon

 Two-neutron overlap amplitudes from MCSM (T. Otsuka) pf+g<sub>9/2</sub>+d<sub>5/2</sub> both protons and neutrons



#### neutron - occupation numbers - protons



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



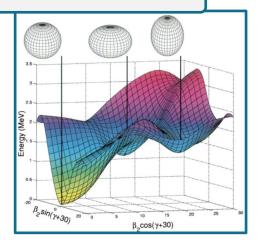
## 0<sup>+</sup>s in Pb: same mechanism?

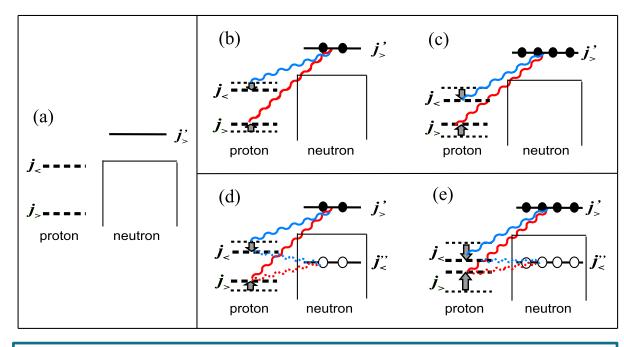
#### T Otsuka and Y Tsunoda, JPG 43 (2016) 024009

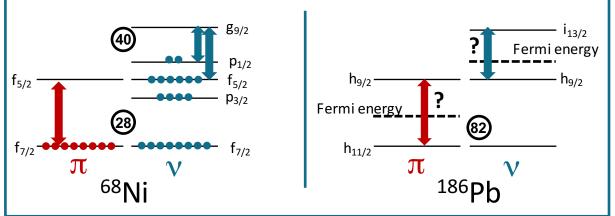
T Otsuka and Y Tsunoda JPG 43 (2016) 024009

- 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









#### **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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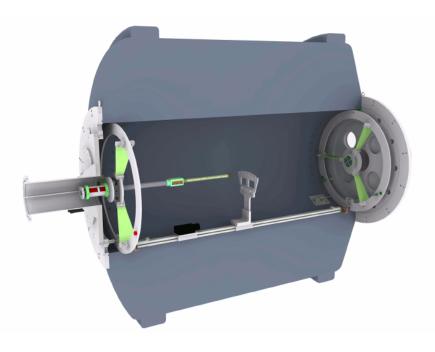
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  - Mg and Ni, the 0+s
  - TRIUMF, GANIL, ISOLDE, Oak Ridge, Argonne...

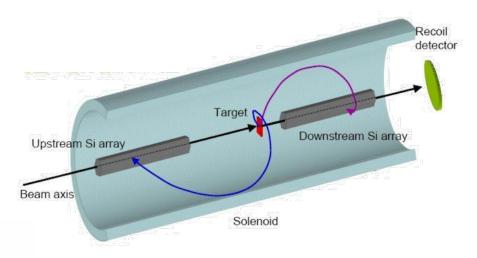


# Improvements – Experimental side

#### **Kinematic compression**

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





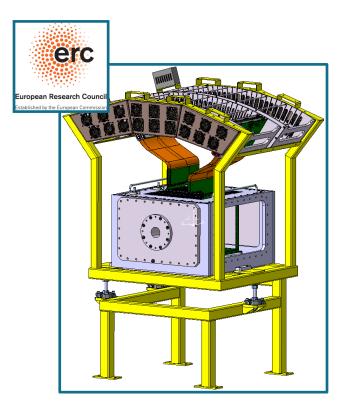


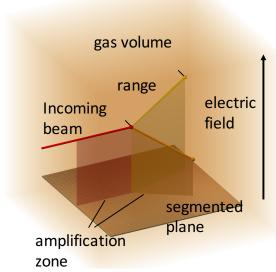


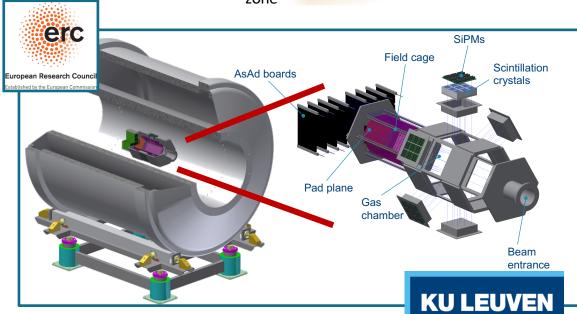
# Improvements – Experimental side

#### **Target thickness vs resolution**

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



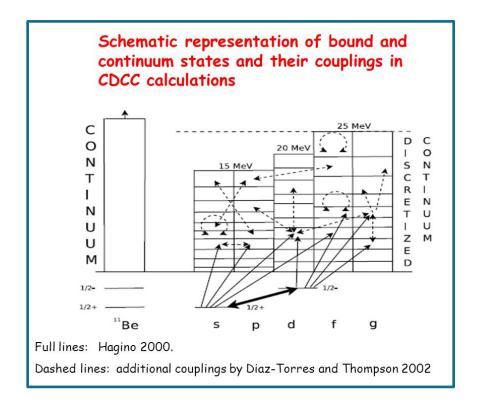




# Improvements – Theoretical side

#### **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





# ...thank you for your attention!

