Measuring the strength of the $\pi d_{5/2}$-$\nu d_{3/2}$ interaction: transfer reactions on neutron-rich oxygen and neon

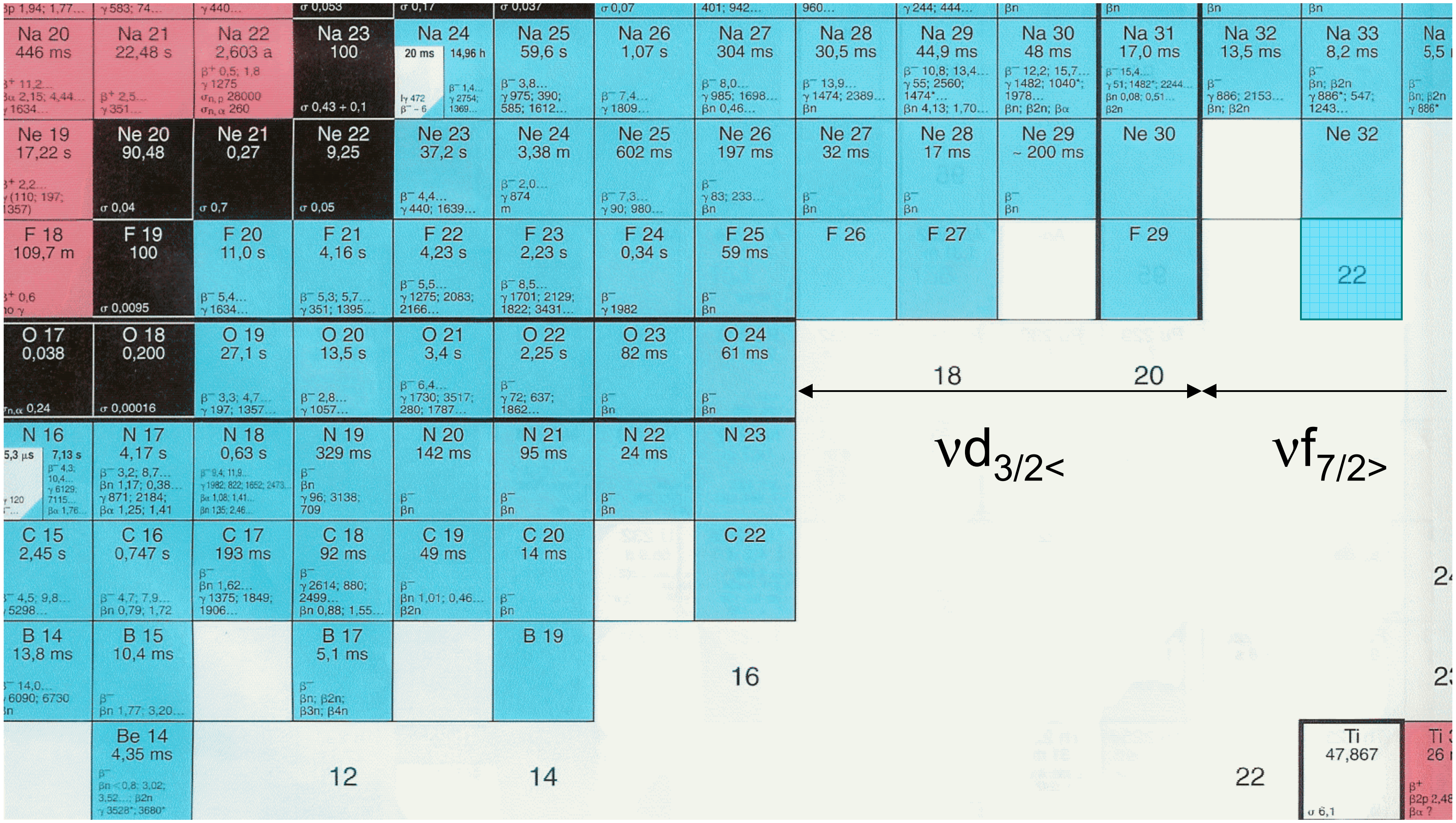
S. Franchoo, F. Azaiez, D. Beaumel,
Y. Blumenfeld, O. Sorlin ...

CNRS/ IN2P3 ...

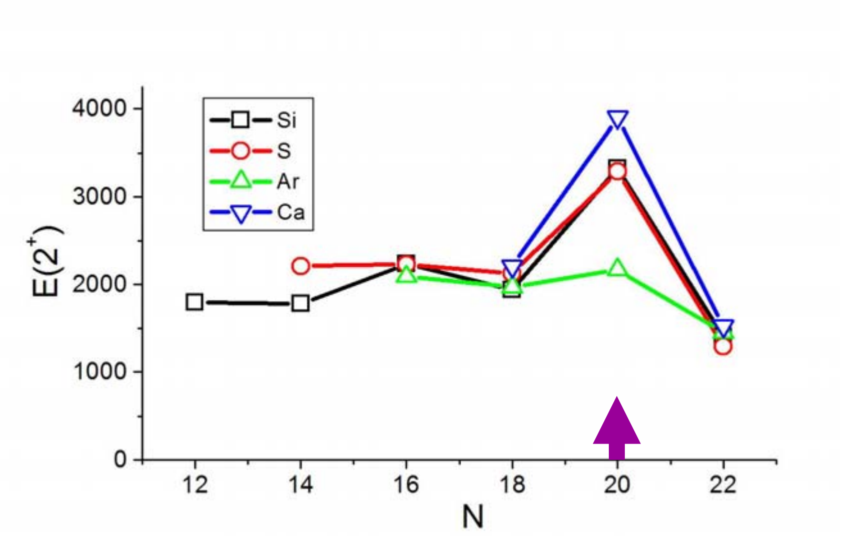
$\nu d_{3/2}$ unbound in O

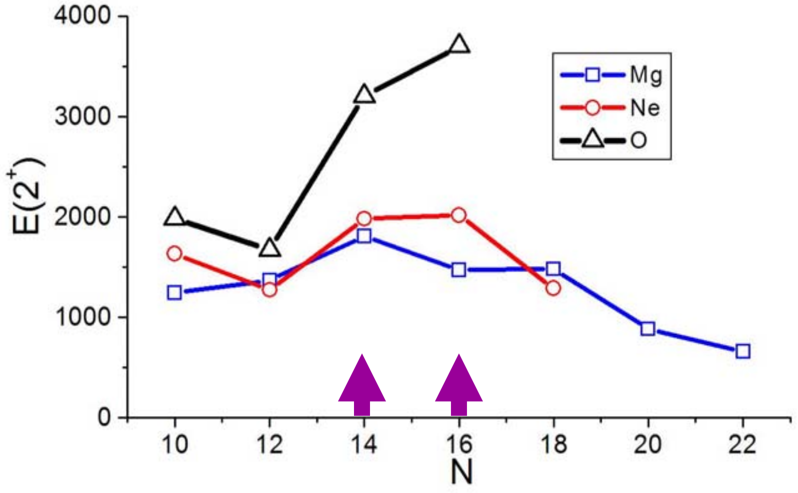
adding $\pi d_{5/2} \Rightarrow \nu d_{3/2}$ and $\nu f_{7/2}$ bound in F
Sakurai et al, PLB 448 (1999) 180

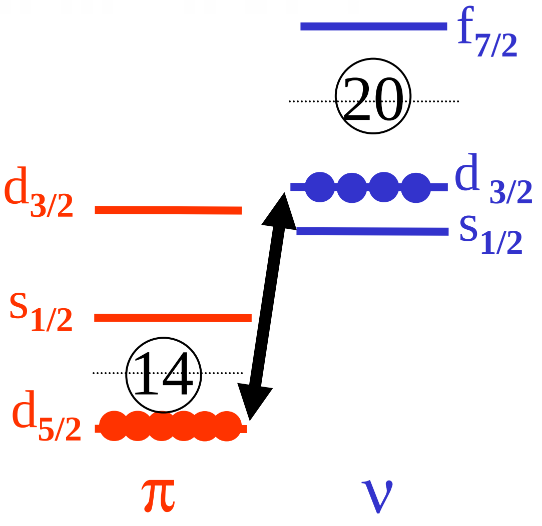
$\pi d_{5/2>} \leftrightarrow \nu d_{3/2<}$ attraction
before island of inversion



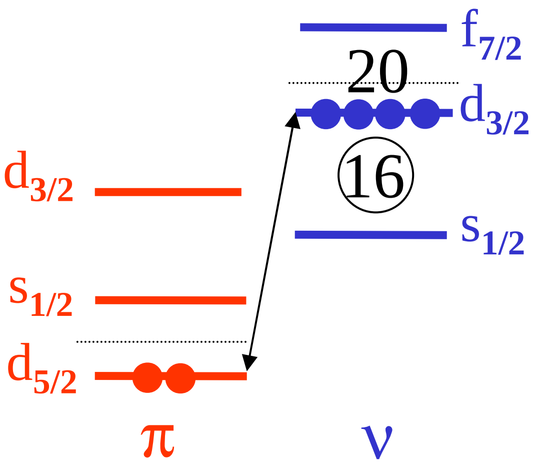
M. Belleguic et al, NPA 682 (2001)
M. Stanoiu et al, PRC (accepted)





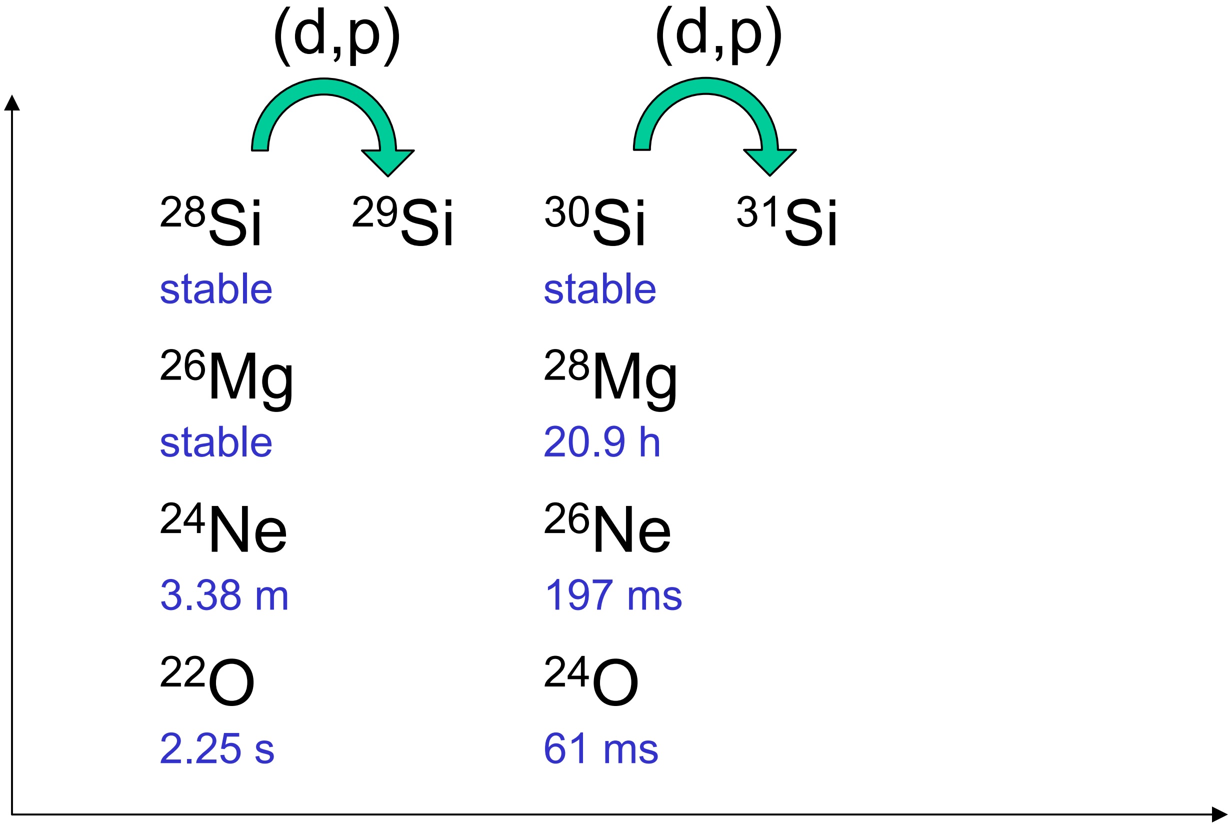


$^{34}Si_{20}$



$^{30}Ne_{20}$

need spectroscopic factors to determine centroids...



(d,p) (d,p)

^{28}Si ^{29}Si ^{30}Si ^{31}Si

Z=14 $\pi d_{5/2}^{6}$

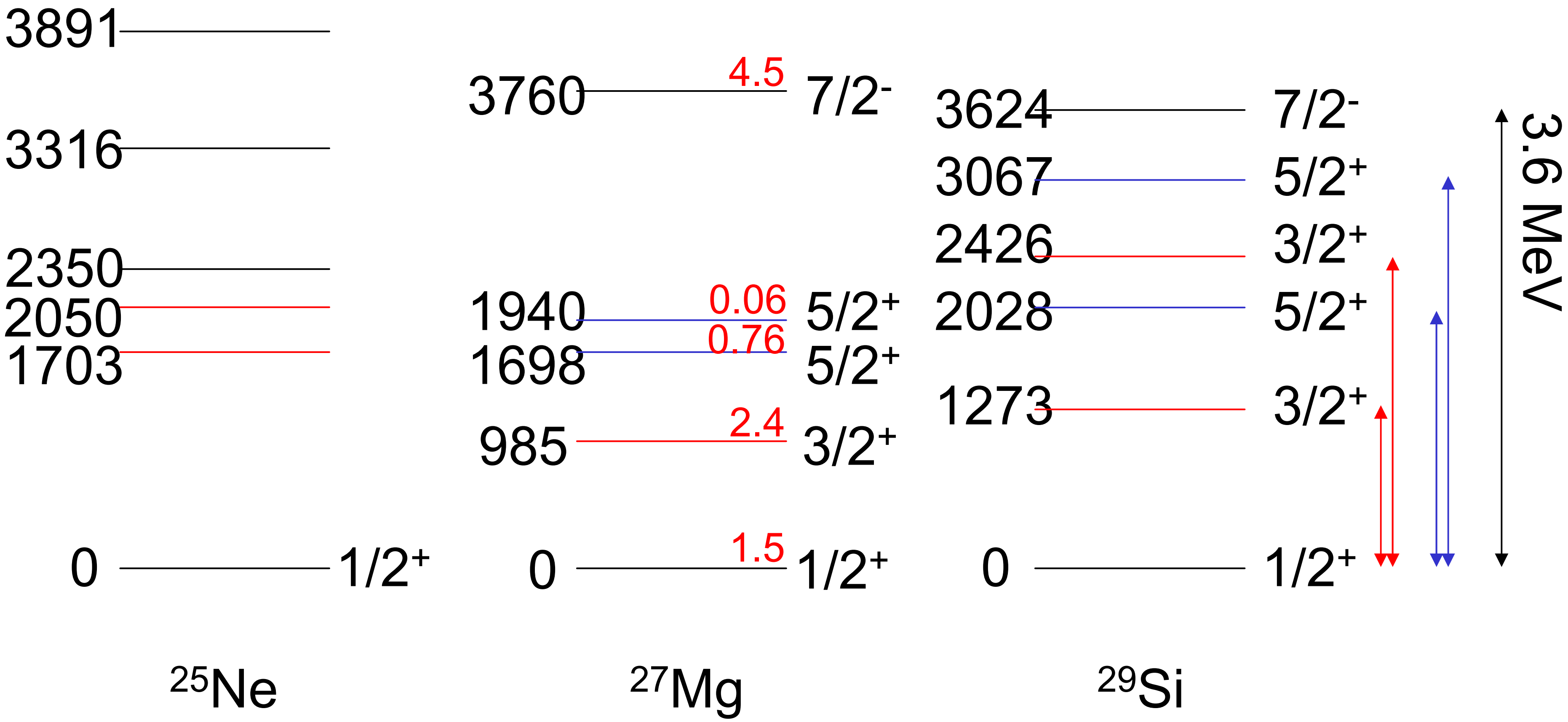
	N=14	N=16
Z=14 $\pi d_{5/2}^{6}$	^{28}Si stable	^{30}Si stable
Z=12 $\pi d_{5/2}^{4}$	^{26}Mg stable	^{28}Mg 20.9 h
Z=10 $\pi d_{5/2}^{2}$	^{24}Ne 3.38 m	^{26}Ne 197 ms
Z=8 $\pi d_{5/2}^{0}$	^{22}O 2.25 s	^{24}O 61 ms

N=14 $\nu d_{5/2}^{6}$

N=16 $\nu d_{5/2}^{6} s_{1/2}^{2} d_{3/2}^{0} f_{7/2}^{0}$

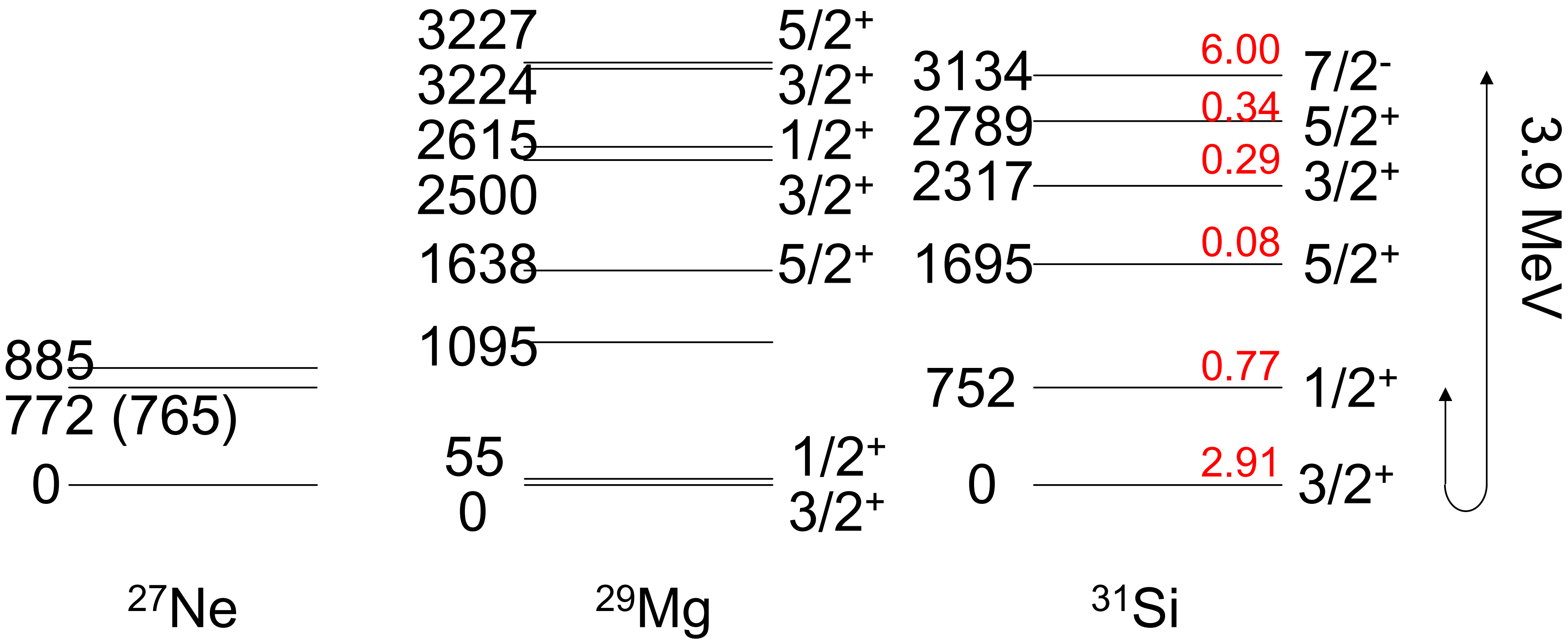
$\pi d_{5/2} \leftrightarrow \nu d_{3/2}$

Selected levels in ^{27}Mg and ^{29}Si
^{25}Ne from Reed et al, PRC 60 (1999) 024311
and Catford et al, JPG 31 (2005) S1655

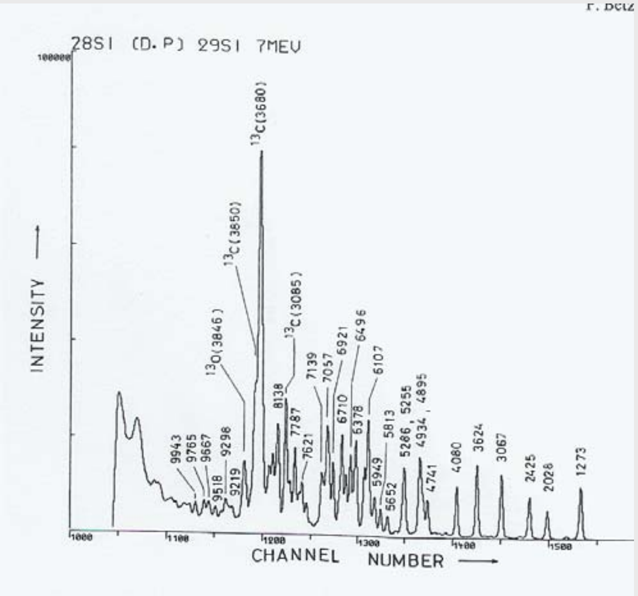


^{29}Mg from Baumann et al, PRC 36 (1987) 765

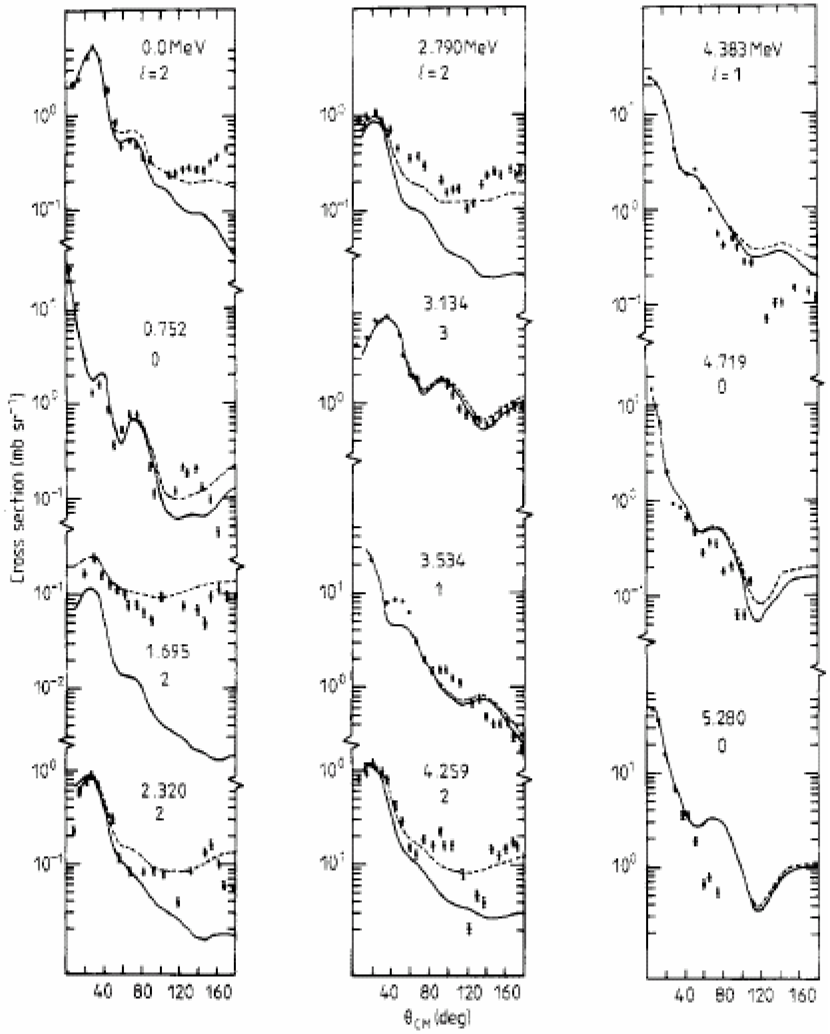
^{27}Ne from Belleguic et al, PRC 72 (2005) 054316
and Obertelli et al, submitted to PLB



$^{28}Si(d,p)^{29}Si$:
Betz et al, ZPA 309 (1982) 163
no SF deduced from spectra



$^{30}Si(d,p)^{31}Si$:
Watson & Slater, JPG 9 (1983) 1417

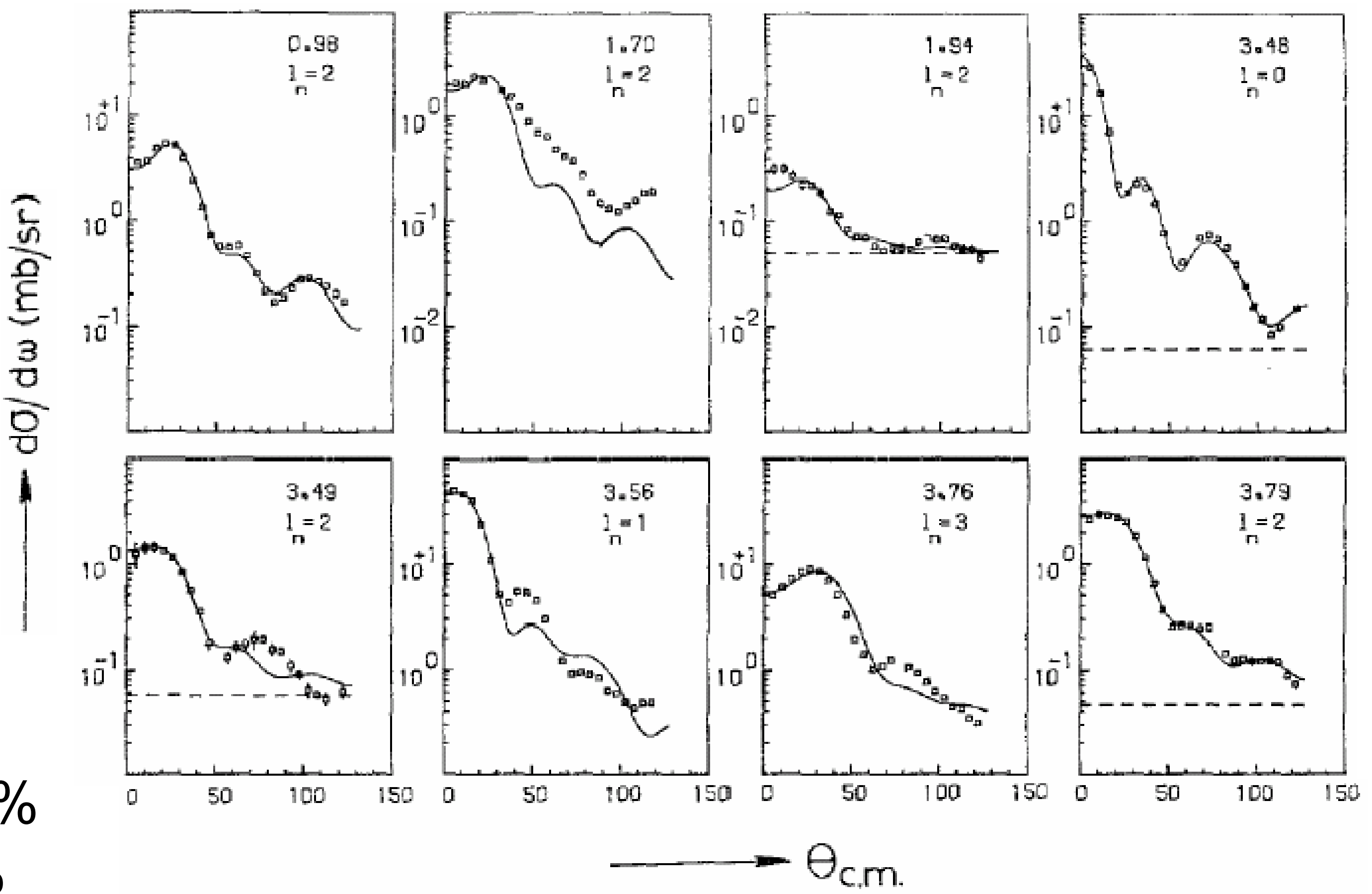


$d_{5/2}$	6.5%
$s_{1/2}$	61.5%
$d_{3/2}$	79.2%
$f_{7/2}$	75%

E_d = 10 MeV

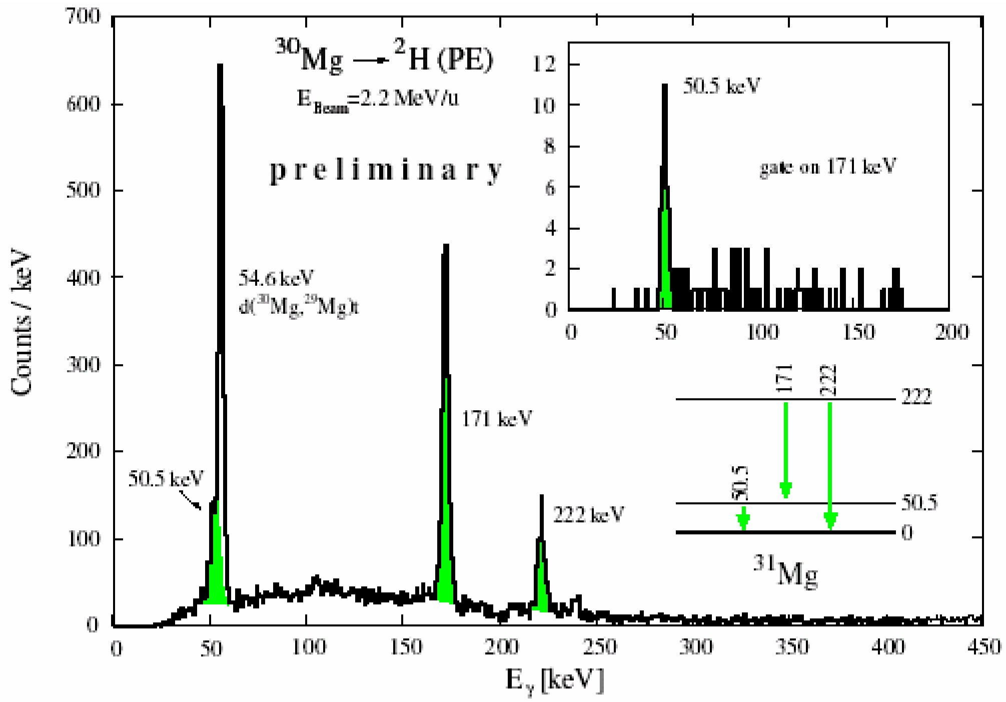
^{26}Mg(d,p)^{27}Mg: Meurders & van der Steld, NPA 230 (1974) 317

E_d = 12 MeV



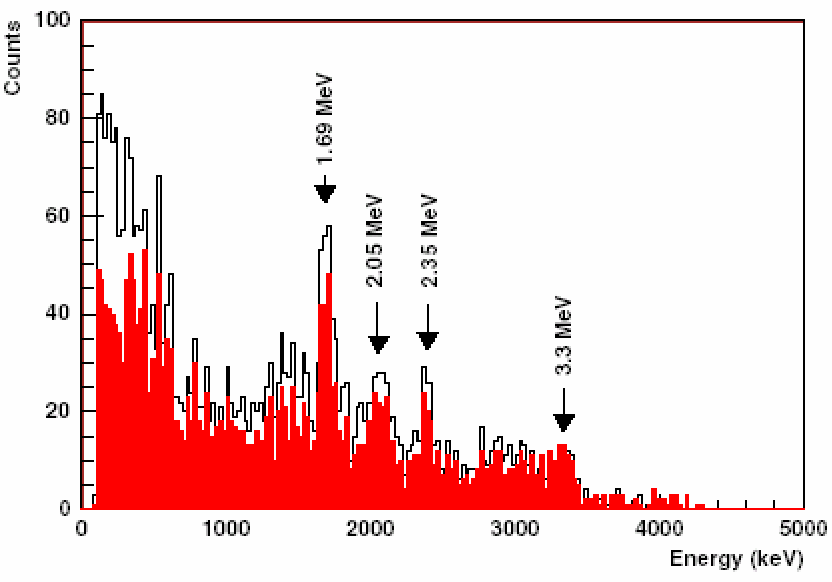
$s_{1/2}$	100%
$d_{3/2}$	88%
$f_{7/2}$	56%

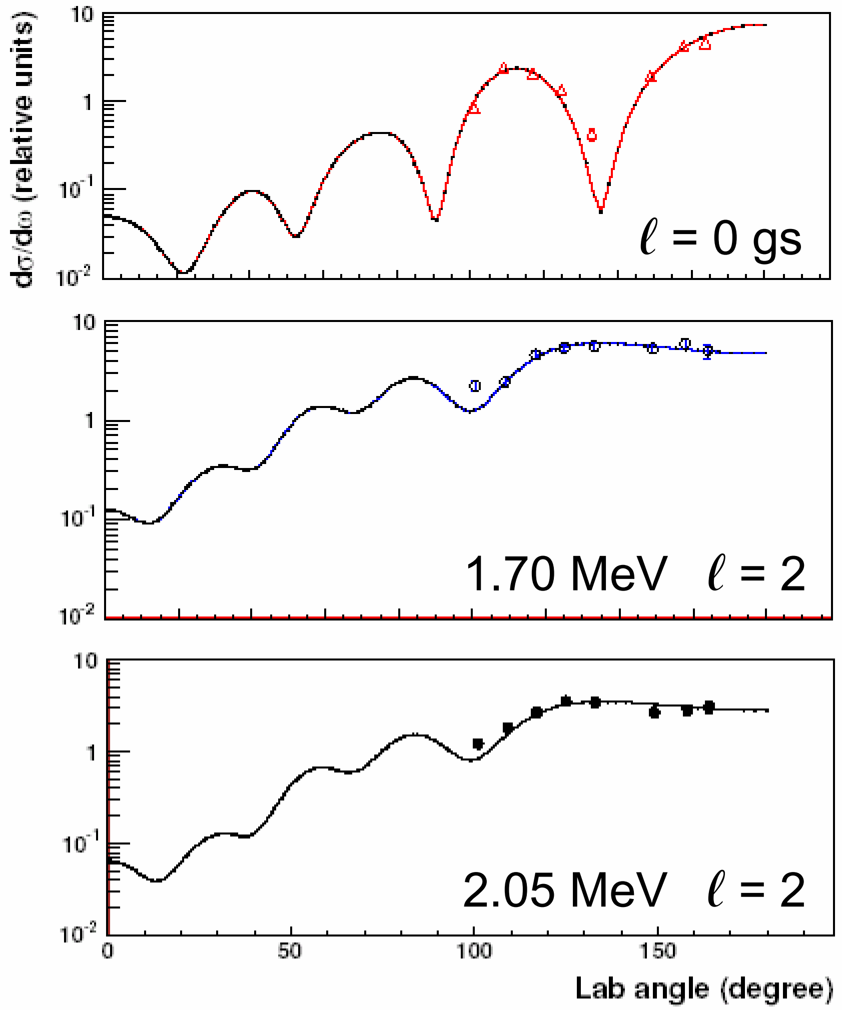
^{30}Mg(d,p)^{31}Mg at 2.2 MeV/u
H Scheit et al, NPA 746 (2004) 96c & EPJA 25 s01 (2005) 397



^{28}Mg(d,p)^{29}Mg at Rex-Isolde
determine position of 7/2$^-$
at SC: 2 10^6 /μC x 5% = 2 10^5 /2μC ($t_{1/2}$ = 20.9 h)

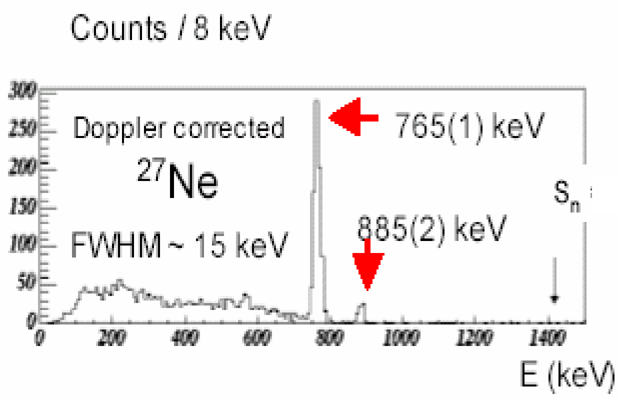
^{24}Ne(d,p)^{25}Ne at 10 MeV/u
Catford et al, JPG 31 (2005) S1655





8 π mm mrad
no beam tracking!

^{26}Ne(d,p)^{27}Ne at 10 MeV/u
Obertelli et al, submitted to PLB



no SF determined

^{36}S fragmentation
Belleguic et al,
PRC 72 (2005) 054316

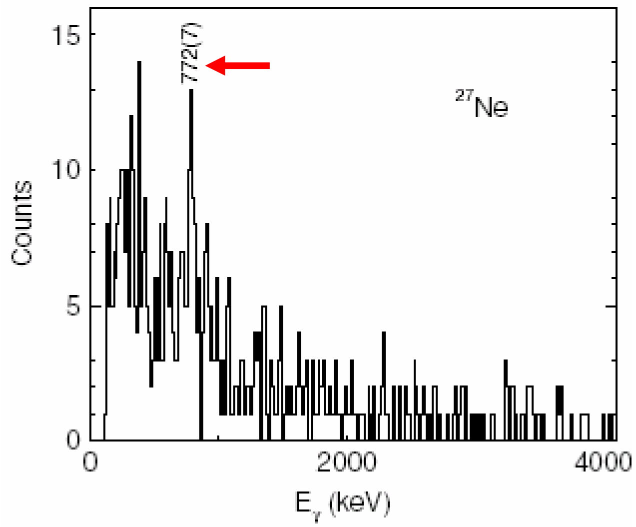


FIG. 4. Ge γ-ray spectrum of ^{27}Ne.

^{24,26}Ne(d,p)^{25,27}Ne at Rex-Isolde:
Good beam quality for post-accelerated beam
Same intensity Rex - Spiral

^{24}Ne: 1 10^6 /µC x 5% = 1 10^5 /2µC Ganil: 2 10^5 /s
^{26}Ne: 4 10^4 /µC x 5% = 4 10^3 /2µC Ganil: 3 10^3 /s
U Bergmann et al, NIMB 204 (2003) 22

$^{22}O(d,p)^{23}O$ at Rex-Isolde

beam development:
U Köster et al, EPJA 25 s01 (2005) 729

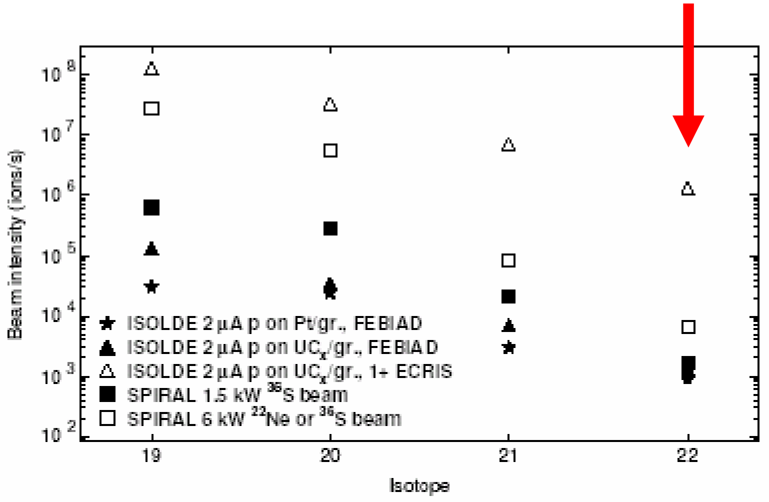
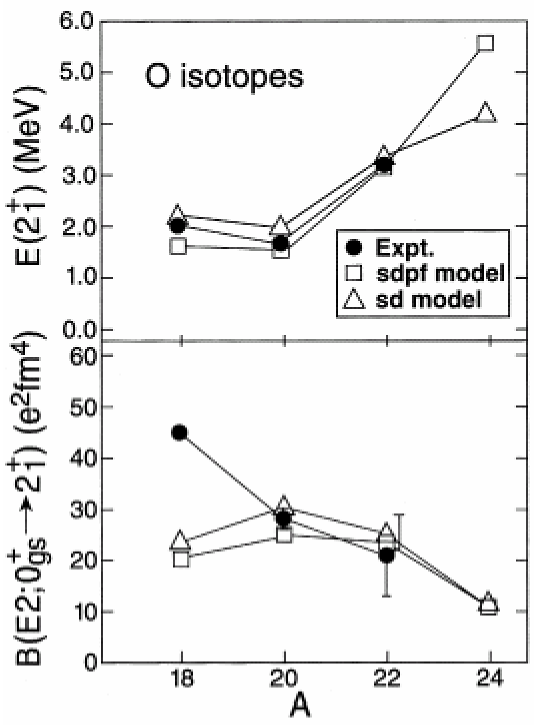


Fig. 2. Measured (full symbols) and extrapolated (open symbols) beam intensities for neutron-rich oxygen isotopes.

^{22}O: 10^6 /s !
At Ganil, 100 /s expected

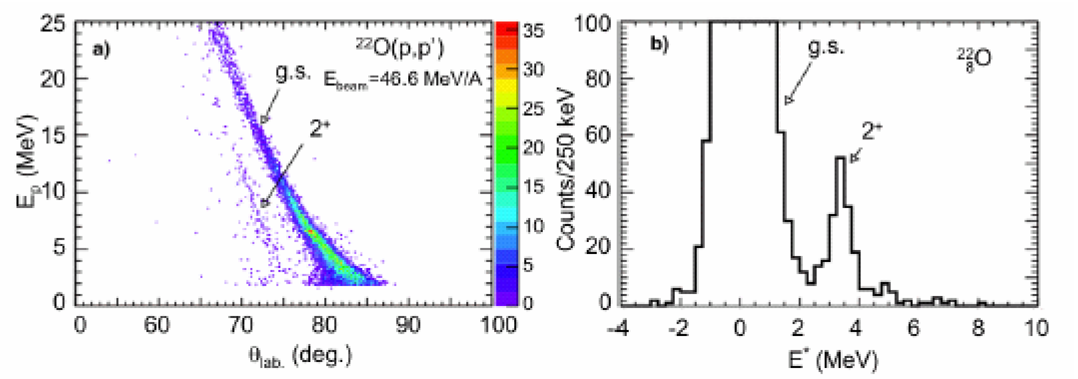
$^{24}O(d,p)^{25}O$?

B(E2) ^{22}O:
P. Thirolf et al, PLB 485 (2000) 16



^{22}O(p,p'):
E. Becheva et al, PRL 96 (2006) 012501

$\frac{M_\nu/M_\pi}{N/Z}$ $(^{20}\mathrm{O}) = 2.2(5)$ $\frac{M_\nu/M_\pi}{N/Z}$ $(^{22}\mathrm{O}) = 1.4(5)$



B(E2) ^{24}O ?!

L Gaudefroy et al, JPG 31 (2005)

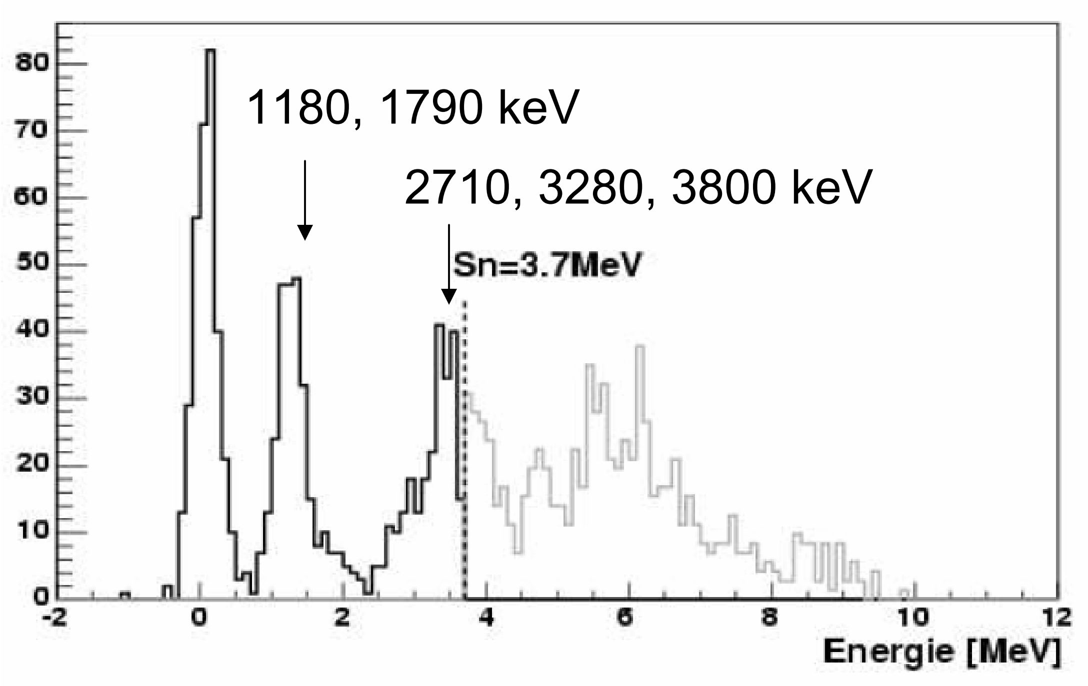
^{44,46}Ar(d,p)^{45,47}Ar at 10 MeV/u

Must + Cats + Speg at Ganil

^{45}Ar: 100% $f_{7/2}$, 50% $p_{1/2,3/2}$

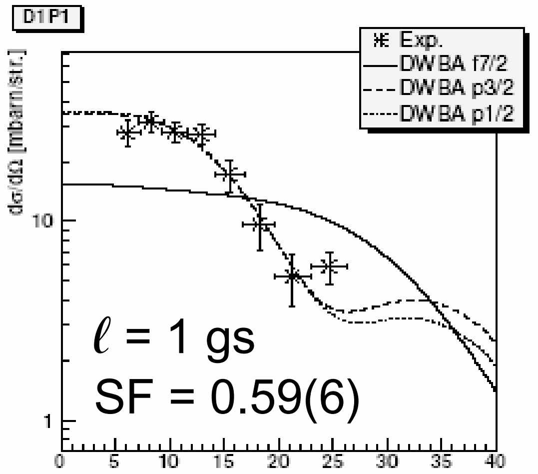
^{47}Ar: 100% $p_{1/2,3/2}$, 60% $f_{5/2}$

⇒ N=28 remains



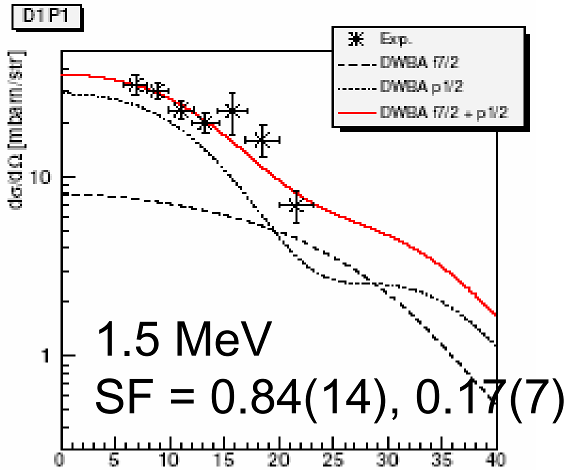
1180, 1790 keV

2710, 3280, 3800 keV



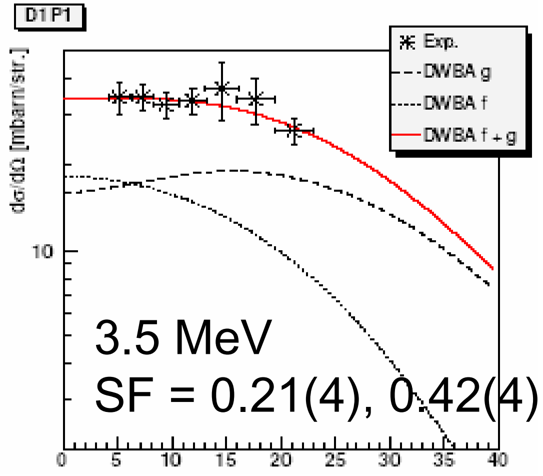
ℓ = 1 gs

SF = 0.59(6)



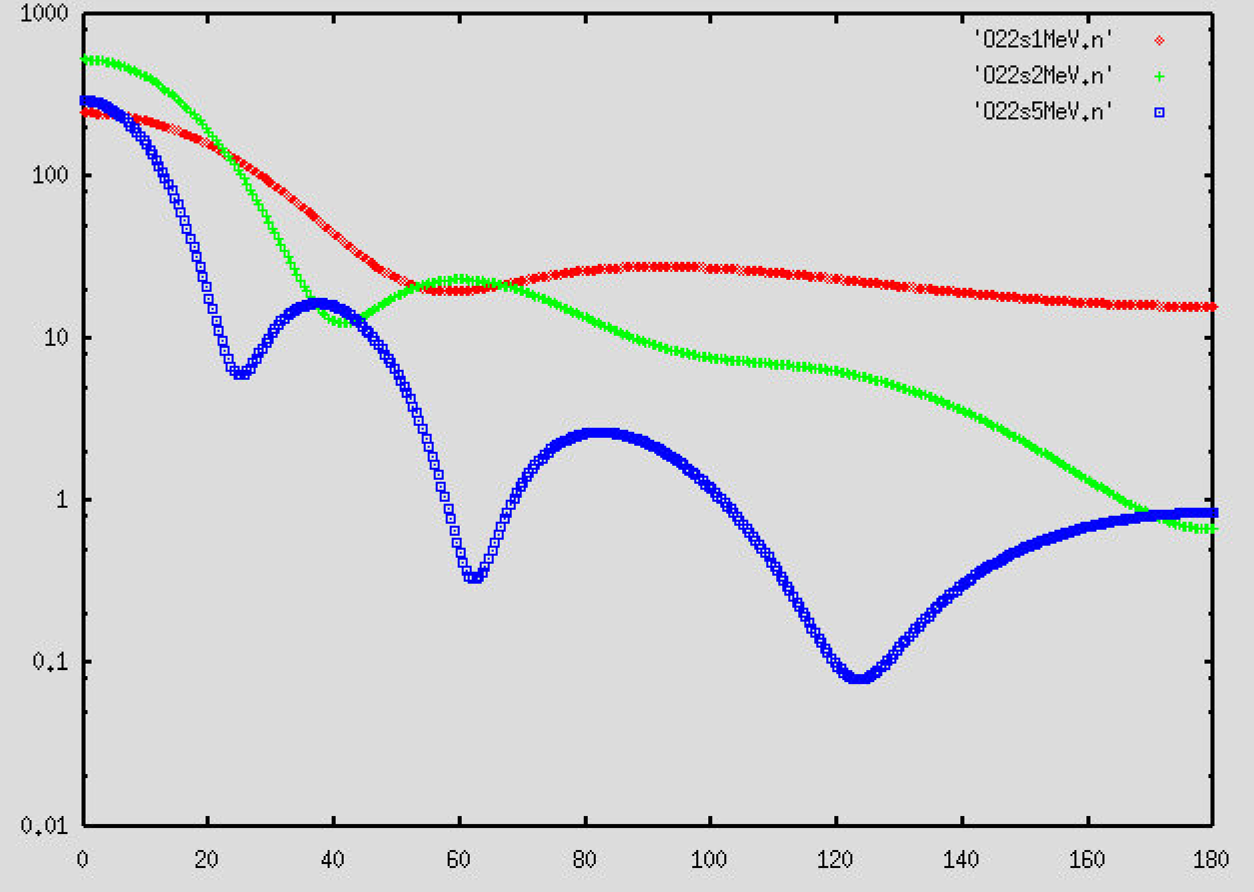
1.5 MeV

SF = 0.84(14), 0.17(7)



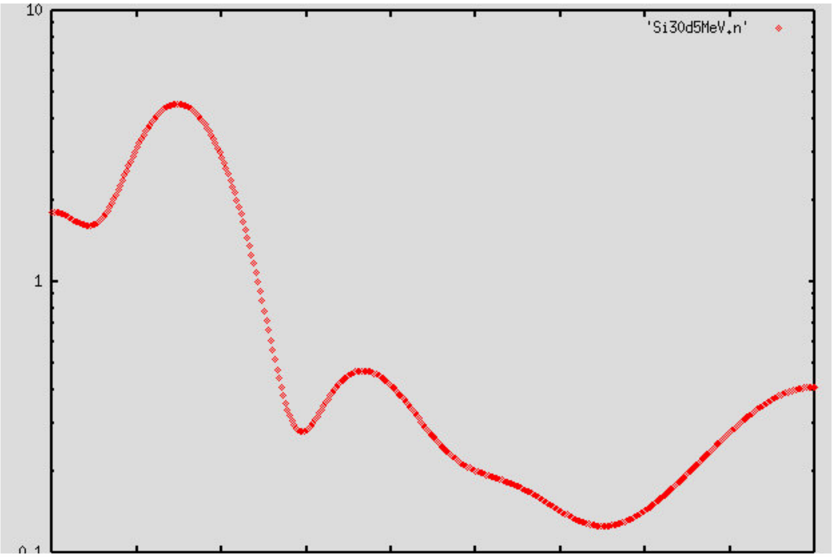
3.5 MeV

SF = 0.21(4), 0.42(4)

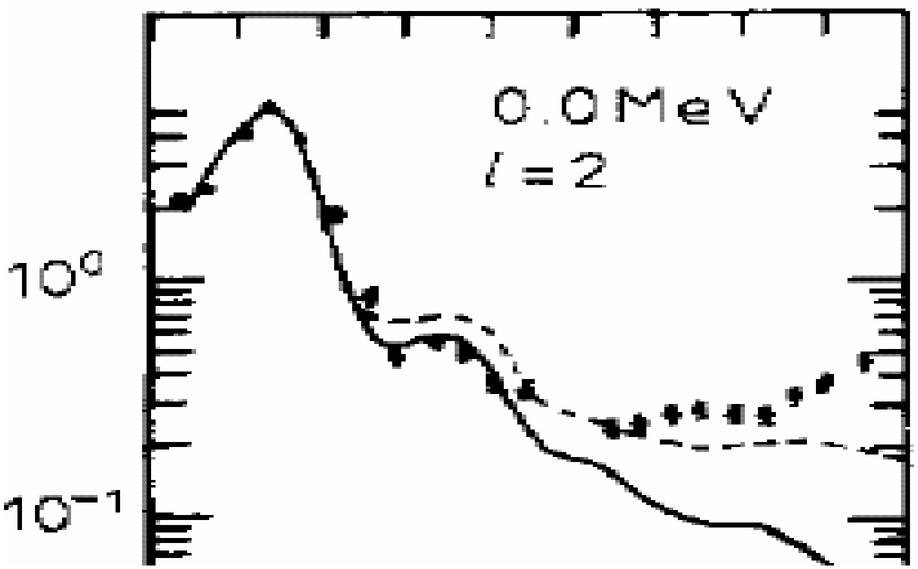


Rex-Isolde energy upgrade ≳ 5 MeV/u

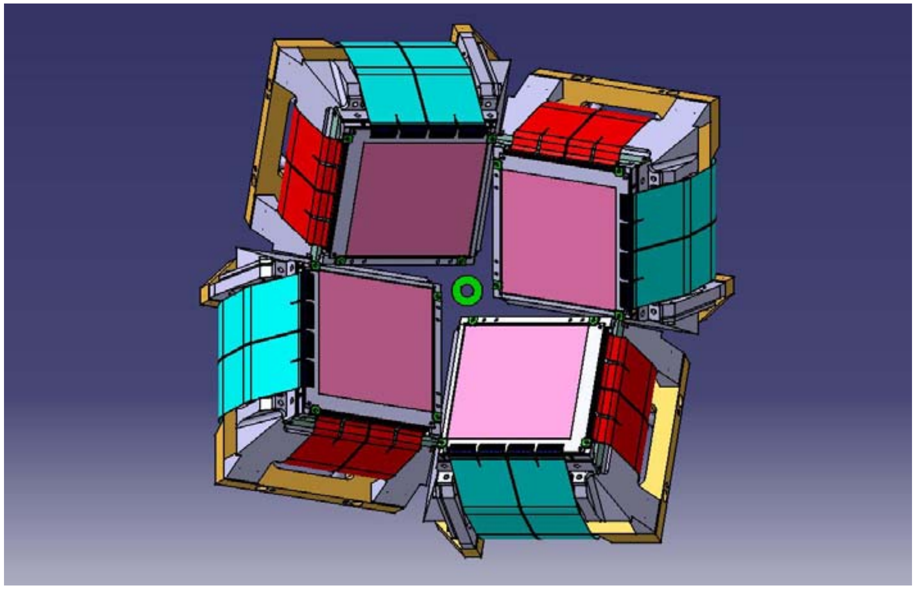
low $S_n \Rightarrow$ high σ



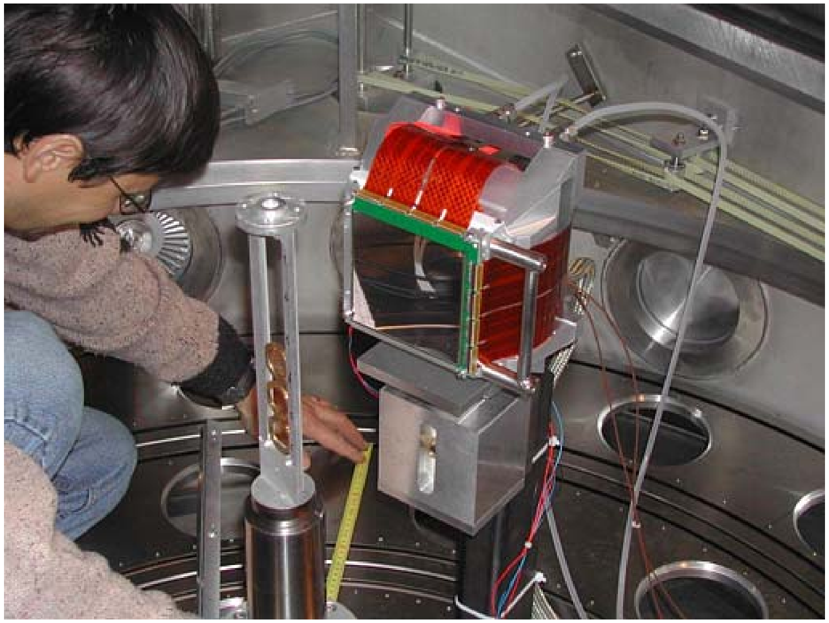
Dwuck4 + Ch89
Wales & Johnson,
NPA 274 (1976) 168
R. Varner, Phys.
Rep. 201 (1991) 57



^{30}Si(d,p)^{31}Si:
Watson & Slater,
JPG 9 (1983) 1417



MUST2



IPN Orsay, Saclay, Ganil

Must-1: Y Blumenfeld et al,
NIMA 366 (1999) 298

Spectrometer?

Measuring the strength of the $\pi d_{5/2}$-$\nu d_{3/2}$ interaction: transfer reactions on neutron-rich oxygen and neon

measure spectroscopic factors to determine centroids...

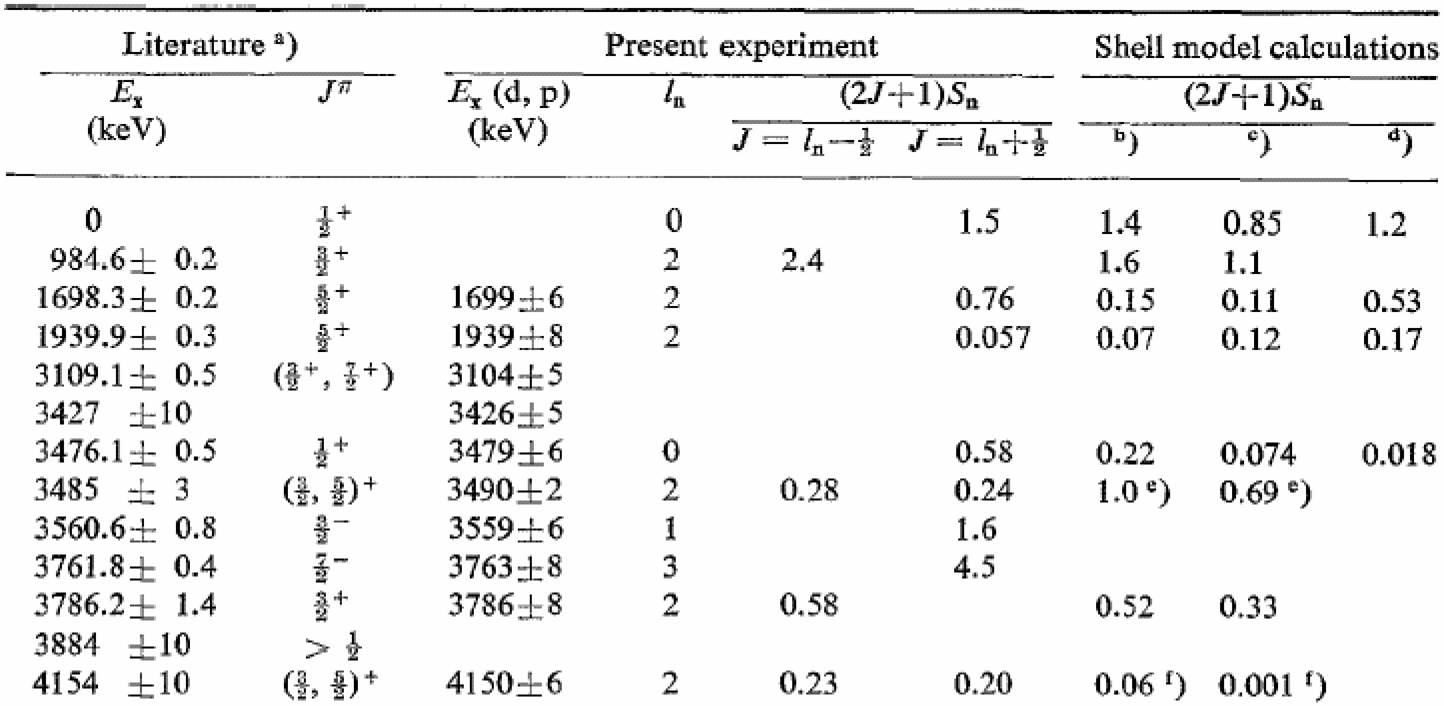
rather large cross sections...

development of oxygen beams

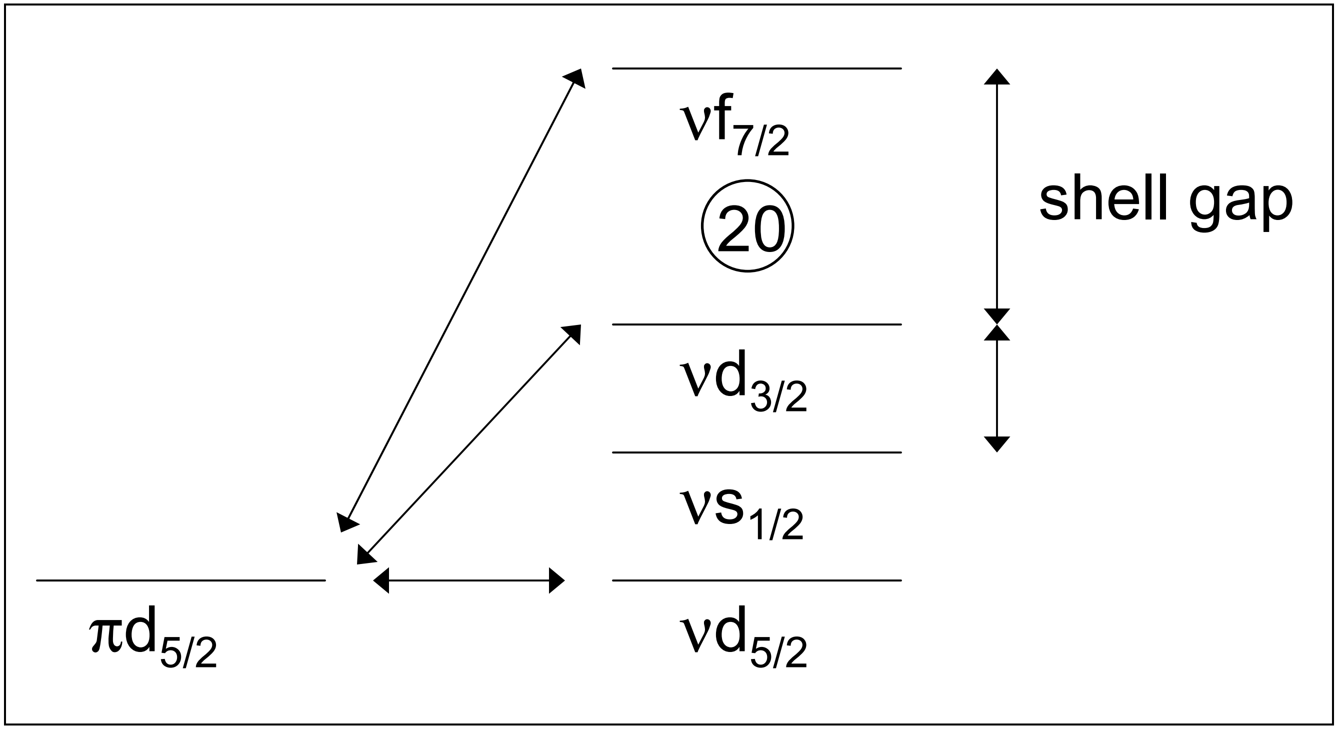
wait for energy upgrade

collaborators welcome !

^{26}Mg(d,p)^{27}Mg: Meurders & van der Steld, NPA 230 (1974) 317



Literature a)		Present experiment				Shell model calculations		
E_x (keV)	J^π	E_x (d, p) (keV)	l_n	$(2J+1)S_n$		$(2J+1)S_n$		
				$J = l_n - \frac{1}{2}$	$J = l_n + \frac{1}{2}$	b)	c)	d)
0	$\frac{1}{2}^+$		0		1.5	1.4	0.85	1.2
984.6 ± 0.2	$\frac{3}{2}^+$		2	2.4		1.6	1.1	
1698.3 ± 0.2	$\frac{5}{2}^+$	1699 ± 6	2		0.76	0.15	0.11	0.53
1939.9 ± 0.3	$\frac{5}{2}^+$	1939 ± 8	2		0.057	0.07	0.12	0.17
3109.1 ± 0.5	$(\frac{3}{2}^+, \frac{7}{2}^+)$	3104 ± 5						
3427 ± 10		3426 ± 5						
3476.1 ± 0.5	$\frac{1}{2}^+$	3479 ± 6	0		0.58	0.22	0.074	0.018
3485 ± 3	$(\frac{3}{2}, \frac{5}{2})^+$	3490 ± 2	2	0.28	0.24	1.0 e)	0.69 e)	
3560.6 ± 0.8	$\frac{3}{2}^-$	3559 ± 6	1		1.6			
3761.8 ± 0.4	$\frac{7}{2}^-$	3763 ± 8	3		4.5			
3786.2 ± 1.4	$\frac{3}{2}^+$	3786 ± 8	2	0.58		0.52	0.33	
3884 ± 10	$> \frac{1}{2}$							
4154 ± 10	$(\frac{3}{2}, \frac{5}{2})^+$	4150 ± 6	2	0.23	0.20	0.06 f)	0.001 f)	



$\nu f_{7/2}$

⑳

shell gap

$\nu d_{3/2}$

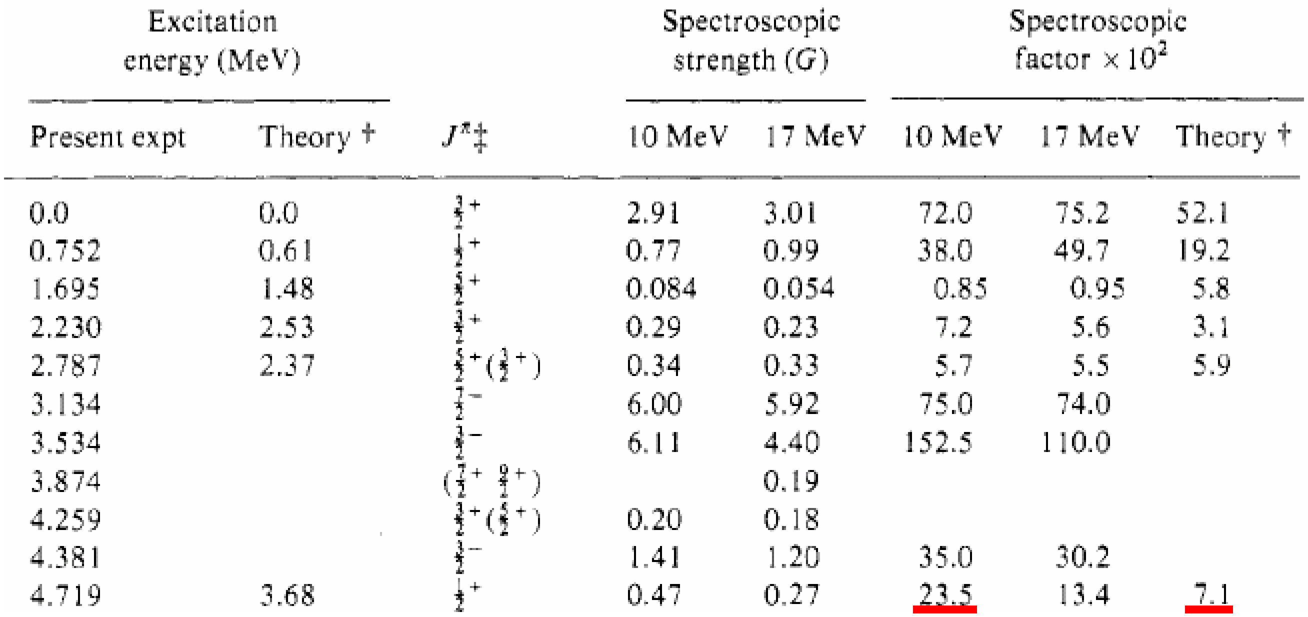
$\nu s_{1/2}$

$\pi d_{5/2}$

$\nu d_{5/2}$

need SF to determine centroids correctly!

^{30}Si(d,p)^{31}Si:
Watson & Slater, JPG 9 (1983) 1417



Excitation energy (MeV)			Spectroscopic strength (G)		Spectroscopic factor × 10^2		
Present expt	Theory †	J^{π}‡	10 MeV	17 MeV	10 MeV	17 MeV	Theory †
0.0	0.0	$\frac{3}{2}^+$	2.91	3.01	72.0	75.2	52.1
0.752	0.61	$\frac{1}{2}^+$	0.77	0.99	38.0	49.7	19.2
1.695	1.48	$\frac{5}{2}^+$	0.084	0.054	0.85	0.95	5.8
2.230	2.53	$\frac{3}{2}^+$	0.29	0.23	7.2	5.6	3.1
2.787	2.37	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.34	0.33	5.7	5.5	5.9
3.134		$\frac{7}{2}^-$	6.00	5.92	75.0	74.0	
3.534		$\frac{3}{2}^-$	6.11	4.40	152.5	110.0	
3.874		$(\frac{7}{2}^+\ \frac{9}{2}^+)$		0.19			
4.259		$\frac{3}{2}^+(\frac{5}{2}^+)$	0.20	0.18			
4.381		$\frac{3}{2}^-$	1.41	1.20	35.0	30.2	
4.719	3.68	$\frac{1}{2}^+$	0.47	0.27	23.5	13.4	7.1

B(E2) of neutron-rich carbon isotopes

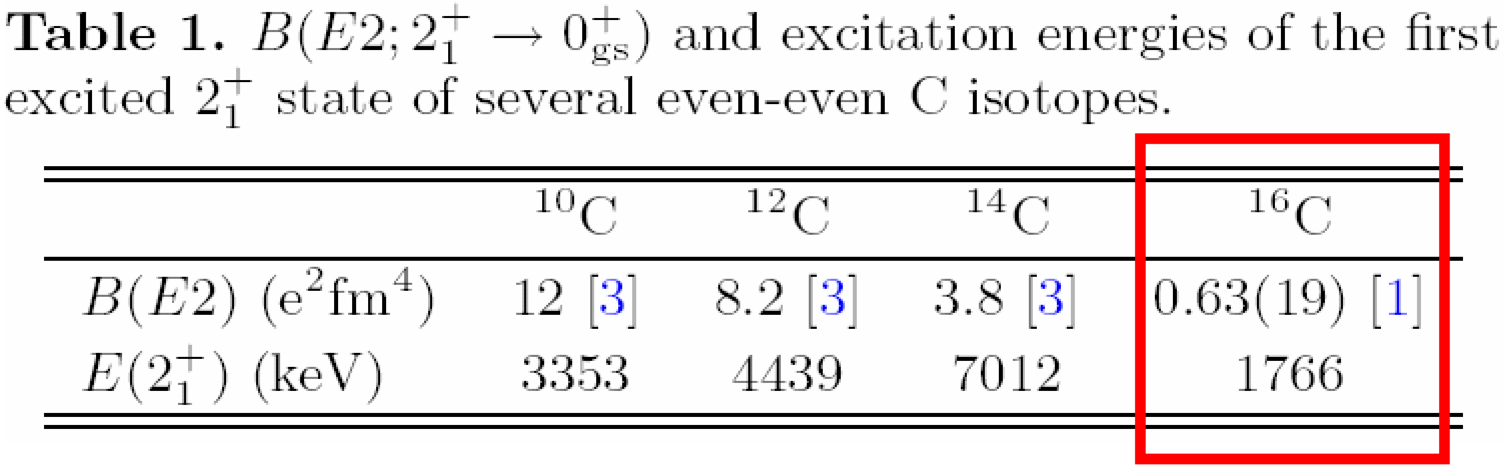


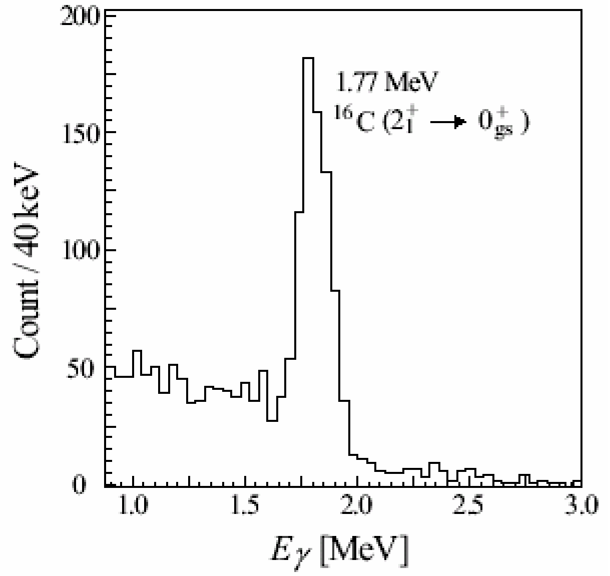
Table 1. $B(E2; 2_1^+ \rightarrow 0_{gs}^+)$ and excitation energies of the first excited 2_1^+ state of several even-even C isotopes.

	^{10}C	^{12}C	^{14}C	^{16}C
$B(E2)$ (e^2fm^4)	12 [3]	8.2 [3]	3.8 [3]	0.63(19) [1]
$E(2_1^+)$ (keV)	3353	4439	7012	1766

RSM: Imai et al, PRL 92 (2004) 062501
only protons affected by EM

(p,p'): Ong et al, EPJA 25 s01 (2005) 347
both π and ν undergo NN interaction

protons and neutrons decoupled!
effect of $\nu s_{1/2}$ on SO



Coulomb excitation of ^{18}C ($t_{1/2}$ = 92 ms) at Rex-Isolde
E(2^+) = 1620 keV

^{16}C: $\pi p_{3/2}{}^4\ p_{1/2}{}^0\ \nu s_{1/2}{}^2$
^{18}C: $\pi p_{3/2}{}^4\ p_{1/2}{}^0\ \nu s_{1/2}{}^2 d_{5/2}{}^2$

<u>too low cross section:</u> 5 e^2fm^4 = 8.8 mb
^{18}C + ^{208}Pb at 3.25 MeV/u ie below barrier

<u>too low yield:</u>
^{16}CO 5 10^3 μC^{-1}
^{18}CO 160 μC^{-1}
18 g/cm2 HfO_2 fiber target + Ecris

Todd-Rutel et al, PRC69 (2004) 021301(R)
mirror effect of $\nu s_{1/2}$ on SO $\pi p_{1/2}, p_{3/2}$

^{14,16}C(d,^{3}He)^{13,15}B: feasible!? $p_{3/2}$ too deeply bound

^{22,24}O(d,^{3}He)^{21,23}N: ^{24}O intensity insufficient?

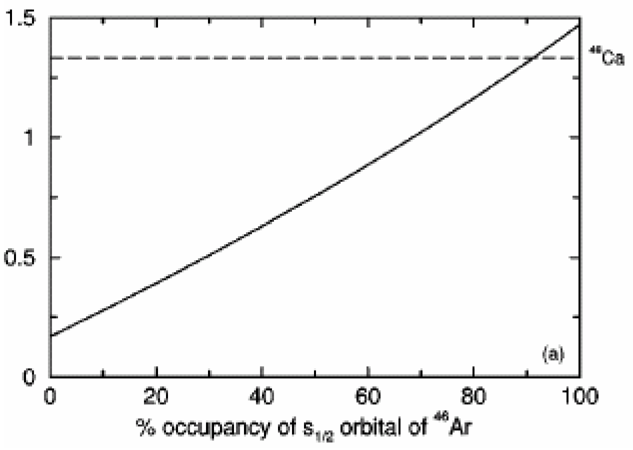


FIG. 5. Spin-orbit splittings of the *p* orbitals (in MeV) for ^{46}Ar and ^{206}Hg as a function of the occupancy of the $s_{1/2}$ proton orbital. The dashed lines show spin-orbit splittings for the two doubly magic nuclei ^{48}Ca and ^{208}Pb, respectively.

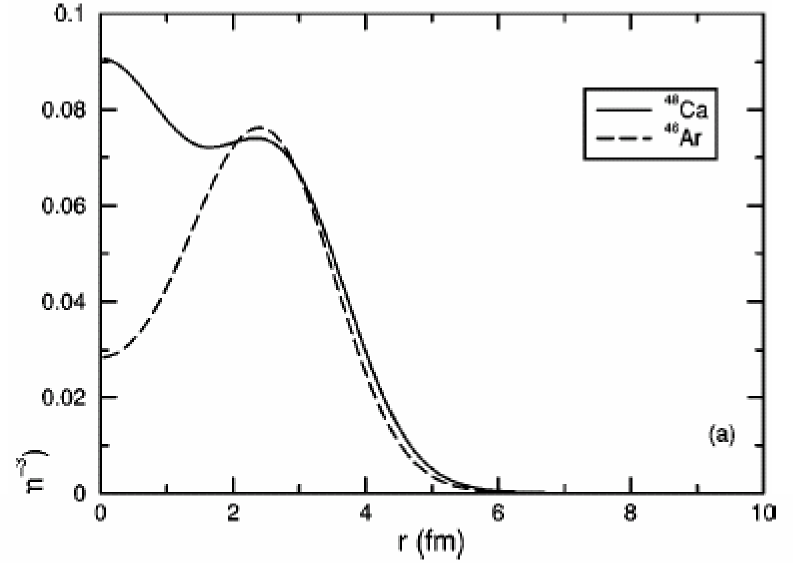


FIG. 1. Proton (point) densities for (a) ^{46}Ar and ^{48}Ca and for (b) ^{206}Hg and ^{208}Pb computed using the relativistic parametrization of Ref. [24]. The development of a "proton hole" in the interior of the nucleus is readily observed.