ABSOLUTE SPECTROSCOPIC FACTORS FROM RADIOACTIVE-BEAM EXPERIMENTS

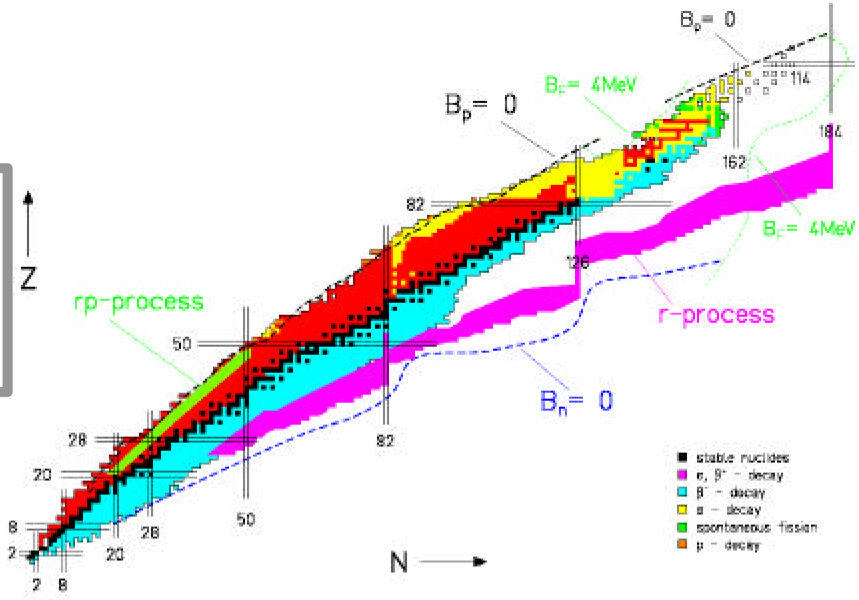
Knockout Reactions in Inverse Kinematics

Spectroscopic factors and *l*-value assignments

Two-nucleon knockout reactions and correlations

Absolute spectroscopic factors: What is the occupancy of physical nucleons in the states that make up the usual shell-model representations?

Workshop on
SPECTROSCOPIC FACTORS
ECT*, Trento
March 2-12, 2004



Collaborators (not complete)

T Aumann, D. Bazin, B.A. Brown, J. Enders, A. Gade, T. Glasmacher, V. Maddalena, W.F. Mueller, A. Navin, B. Sherrill, J.R. Terry, M. Thoennessen (National Superconducting Cyclotron Laboratory, Michigan State University), J.A. Tostevin (University of Surrey, U.K.)

Reviews:

P.G. Hansen and B.M. Sherrill, Nucl. Phys. A 693, 133-168 (2001)

P.G. Hansen and J.A. Tostevin, Annual Review of Nuclear and Particle Science 53, 219 (2003)

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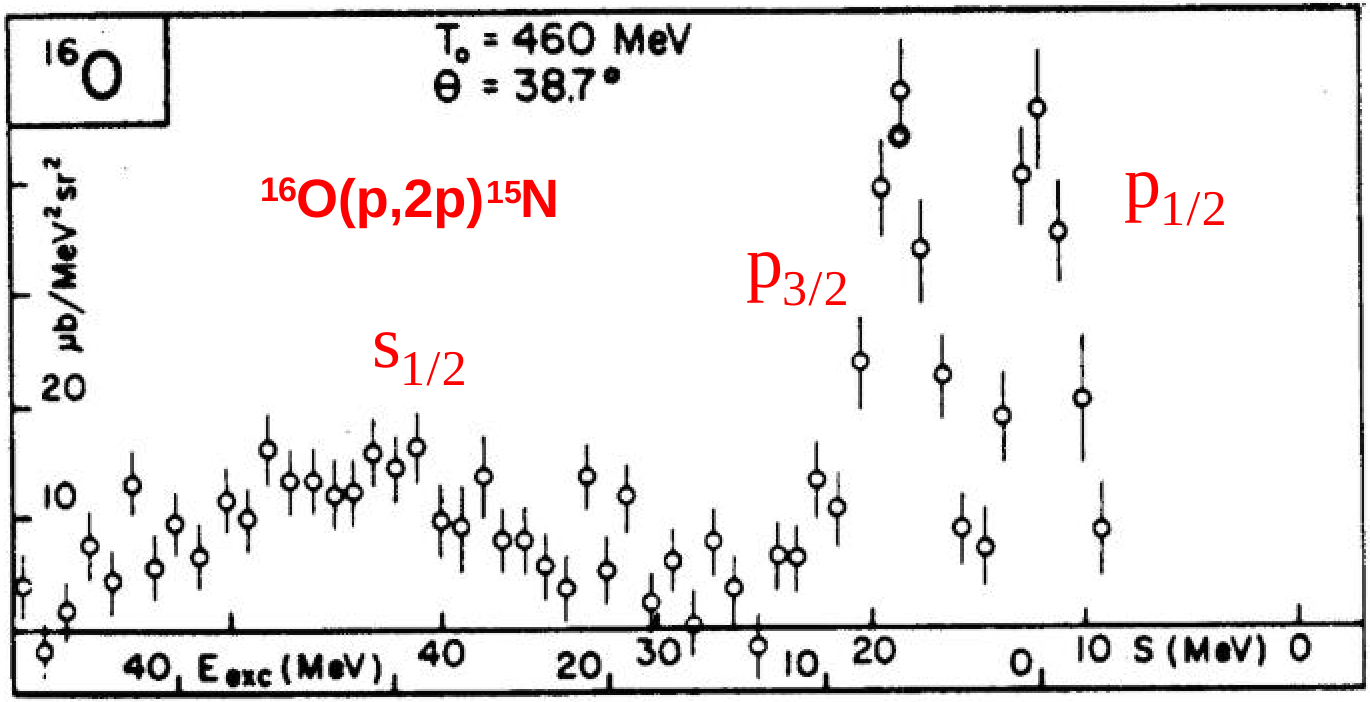
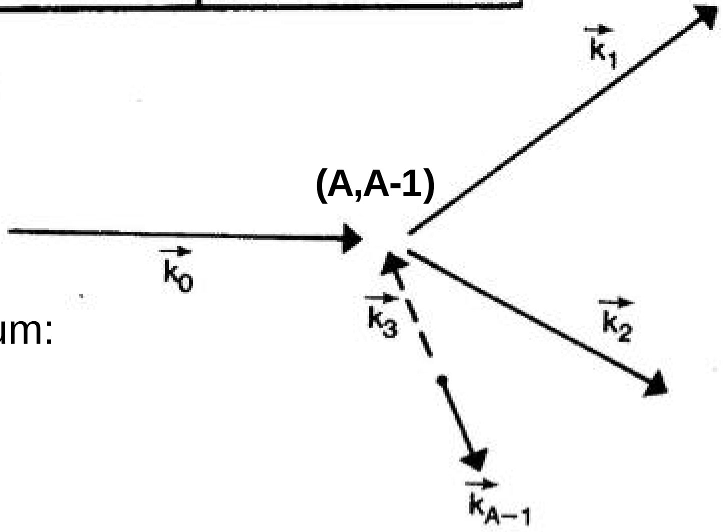
INNER SHELLS ARE REAL: THE (p,2p) KNOCKOUT REACTION



H. Tyren et al., Nucl. Phys. 79, 321 (1966)

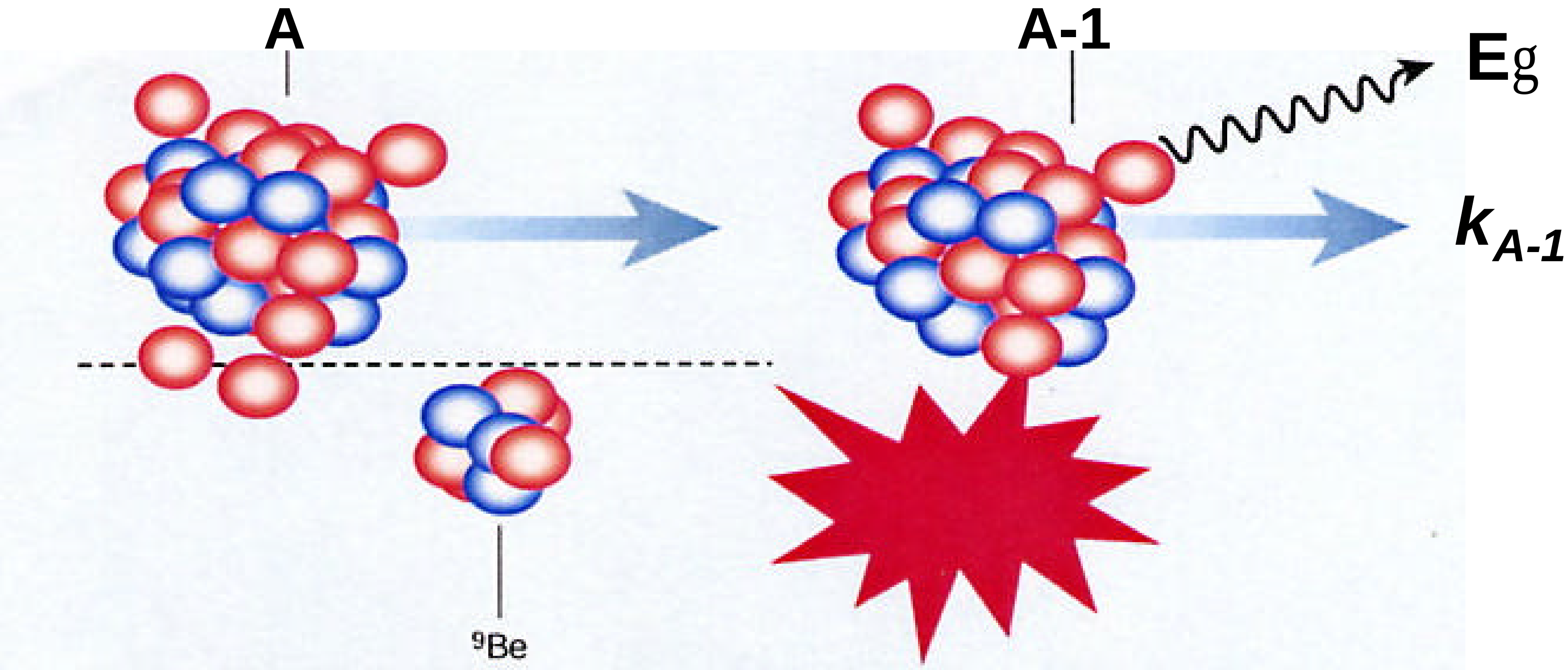


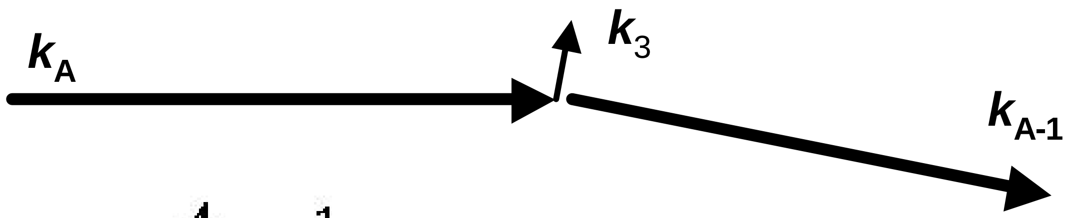
Reconstruction of the recoil momentum:

$$\boldsymbol{k}_{A\text{-}1} = \boldsymbol{k}_0 - \boldsymbol{k}_1 - \boldsymbol{k}_2 = -\boldsymbol{k}_3$$

KNOCKOUT REACTION IN INVERSE KINEMATICS

In the sudden approximation, the momentum picked up by the residue is identical to that of the struck nucleon





$$\vec{k}_3 = \frac{A-1}{A}\vec{k}_A - \vec{k}_{A-1}$$

The National Superconducting Cyclotron Laboratory
Michigan State University

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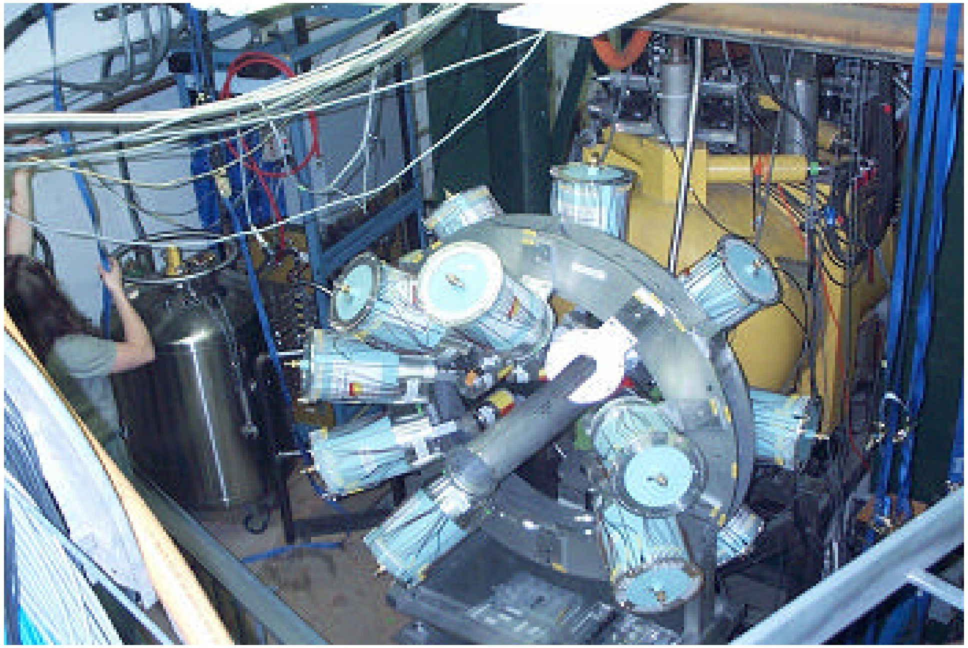
S-800 Magnetic Spectrograph with SeGA Segmented High-Purity Germanium Array



W.F. Mueller et al., Nucl. Instr. Meth. A 466 (2001) 492.

D. Bazin et al., Nucl. Instr. Meth. B 204 (2003) 629.

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CALCULATION OF THE CROSS SECTION

The theoretical cross section for a given *j* channel is

$$\sigma_{exp} = R_s \left(\frac{A}{A-1}\right)^{N} C^2 S_j \;\; \sigma_{sp}(j, B_n)$$

where the quantity R_s is an empirical reduction factor describing the effect of contributions that go beyond effective-interaction theory

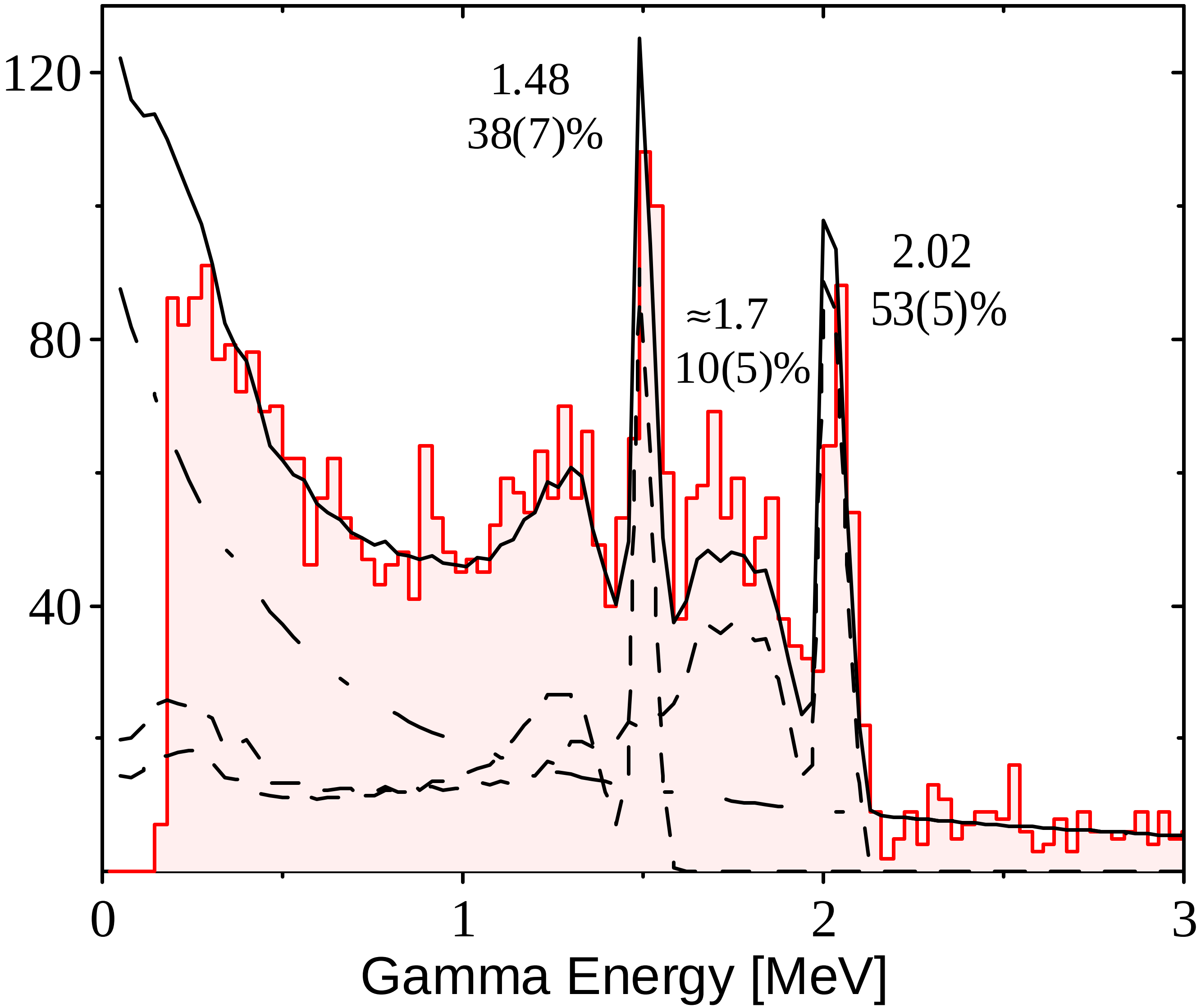
The single-particle cross sections for stripping is calculated in eikonal reaction theory:

$$s_{sp}(j, B_n) = \frac{1}{2j+1}\sum_{m} 2p \int b\,\mathrm{d}b \,\langle\, jm \,\left|(1-\left|S_N\right|^2)\left|S_C\right|^2\right|\, jm >$$

with a similar expression for diffraction dissociation

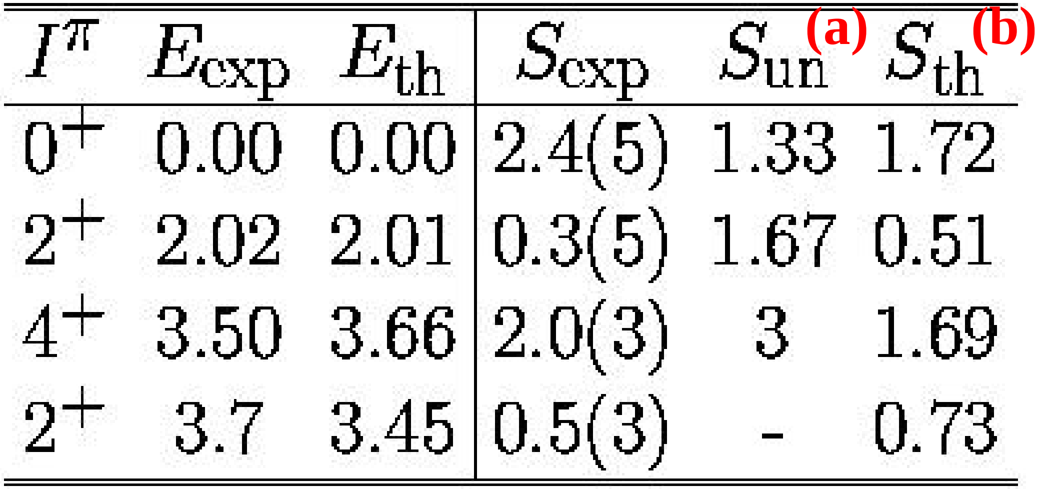
J.A. Tostevin, J. Phys. G **25**, 735 (1999)
K. Hencken, G. Bertsch and H. Esbensen, Phys. Rev. C **54**, 3043 (1996)
P.G. Hansen and J.A. Tostevin, Ann.Rev. Nucl. Part. Sci. **53**, 219 (2003)

Gamma rays from the ^{9}Be(^{28}Mg, ^{26}Ne+γ)X Reaction



Spectroscopic factors[1)] $S(I^{p})$ in the two-nucleon knockout reaction ^{9}Be(^{28}Mg, ^{26}Ne)X

$$S = \sigma/\sigma_{22}$$



I^π	E_{exp}	E_{th}	S_{exp}	S_{un} (a)	S_{th} (b)
0^+	0.00	0.00	2.4(5)	1.33	1.72
2^+	2.02	2.01	0.3(5)	1.67	0.51
4^+	3.50	3.66	2.0(3)	3	1.69
2^+	3.7	3.45	0.5(3)	-	0.73

Unit:

σ_{22} = 0.29 mb

(a) No correlations, $(d_{5/2})^4$ subshell assumed

(b) Full sd shell amplitudes combined with reaction amplitudes from 4-body eikonal model[2)]

(1) D. Bazin, B.A. Brown, C.M. Campbell, J.,A.Church, D.C. Dinca, J. Enders, A. Gade, T. Glasmacher, P.G. Hansen, W.F. Mueller, H. Olliver, B.C. Perry, B.M. Sherrill, J.R. Terry, J.A. Tostevin, Phys. Rev. Lett., 91, 012501 (2003)

(2) J.A. Tostevin *et al.*, to be published

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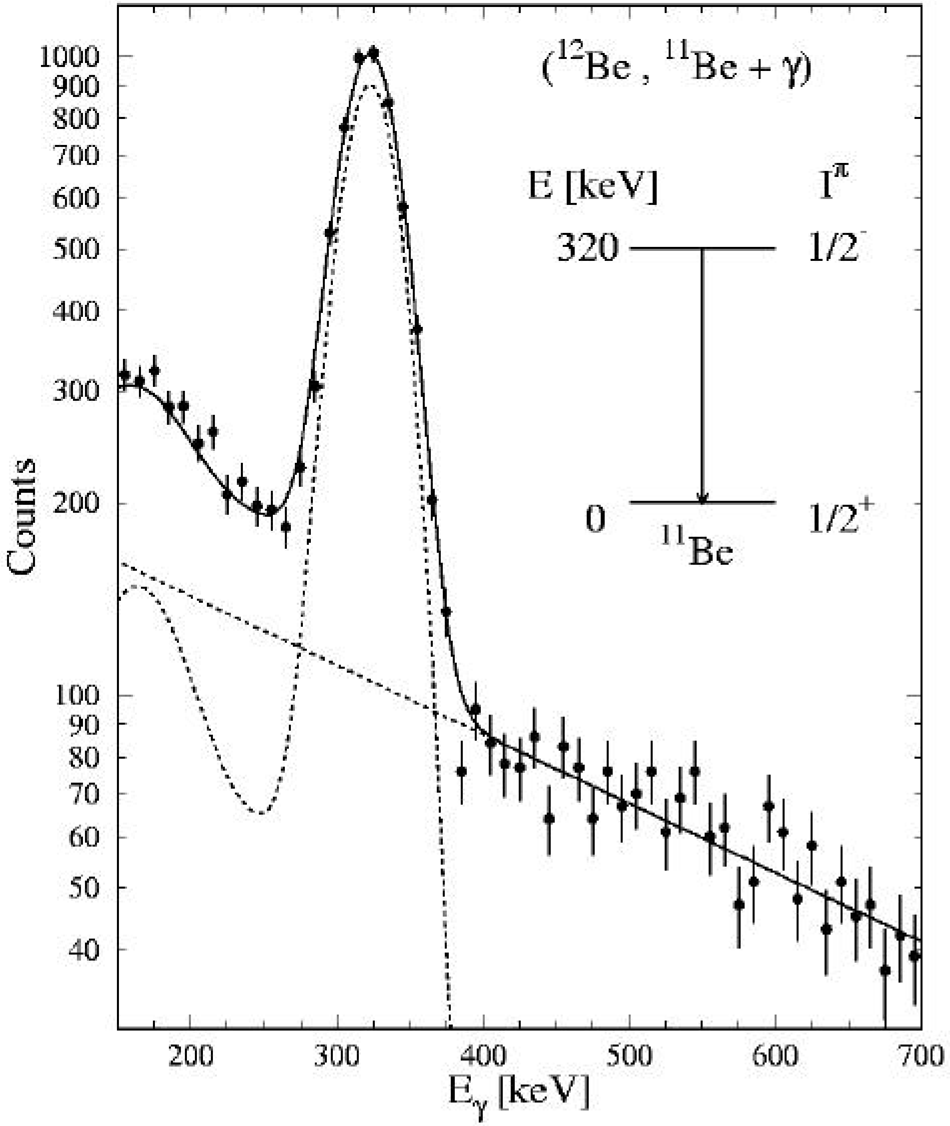
Preservation of the Magic Numbers at the Neutron Drip Line?

The N=8 Shell Gap Disappears in ^{12}Be

A. Navin *et al.*, Phys Rev. Lett. 85, 266 (2000)



Cross Sections (mb)

18±3

32±5

For a magic N=8 the $1/2^-$ spectroscopic factor would be 2.18

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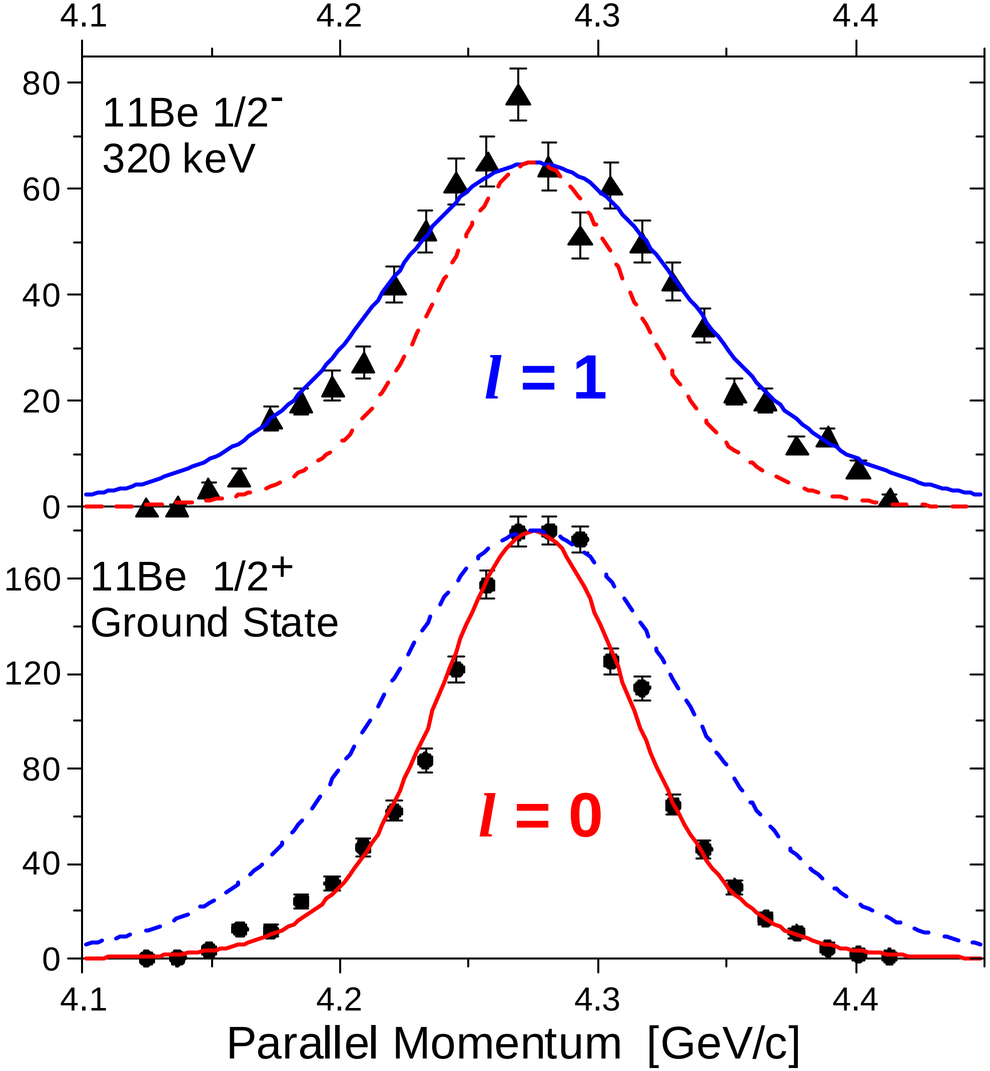
PARALLEL-MOMENTUM DISTRIBUTIONS IN THE LABORATORY FRAME FOR ^{11}Be RESIDUES



Eikonal theory of the parallel-momentum distribution:

P.G. Hansen, Phys. Rev. Lett. 77, 1016 (1996)

H. Esbensen, Phys. Rev. C 53, 2007 (1996)

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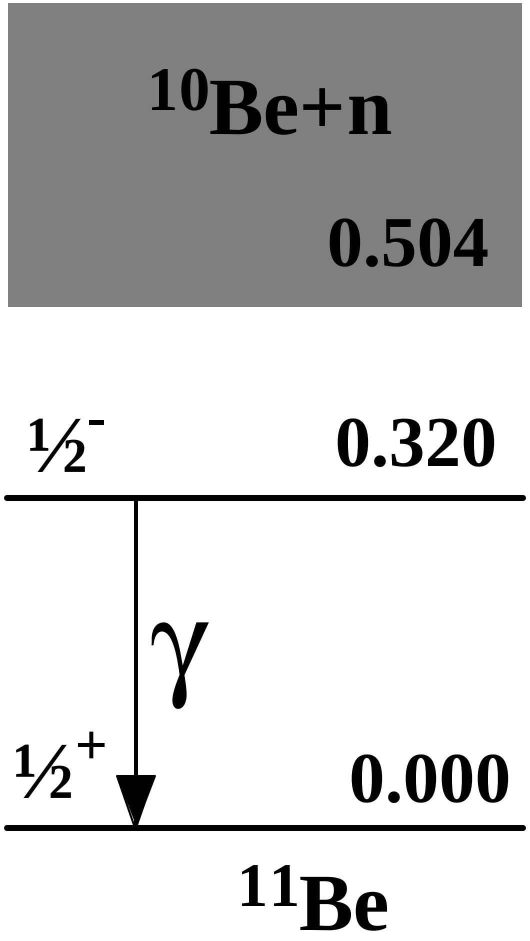
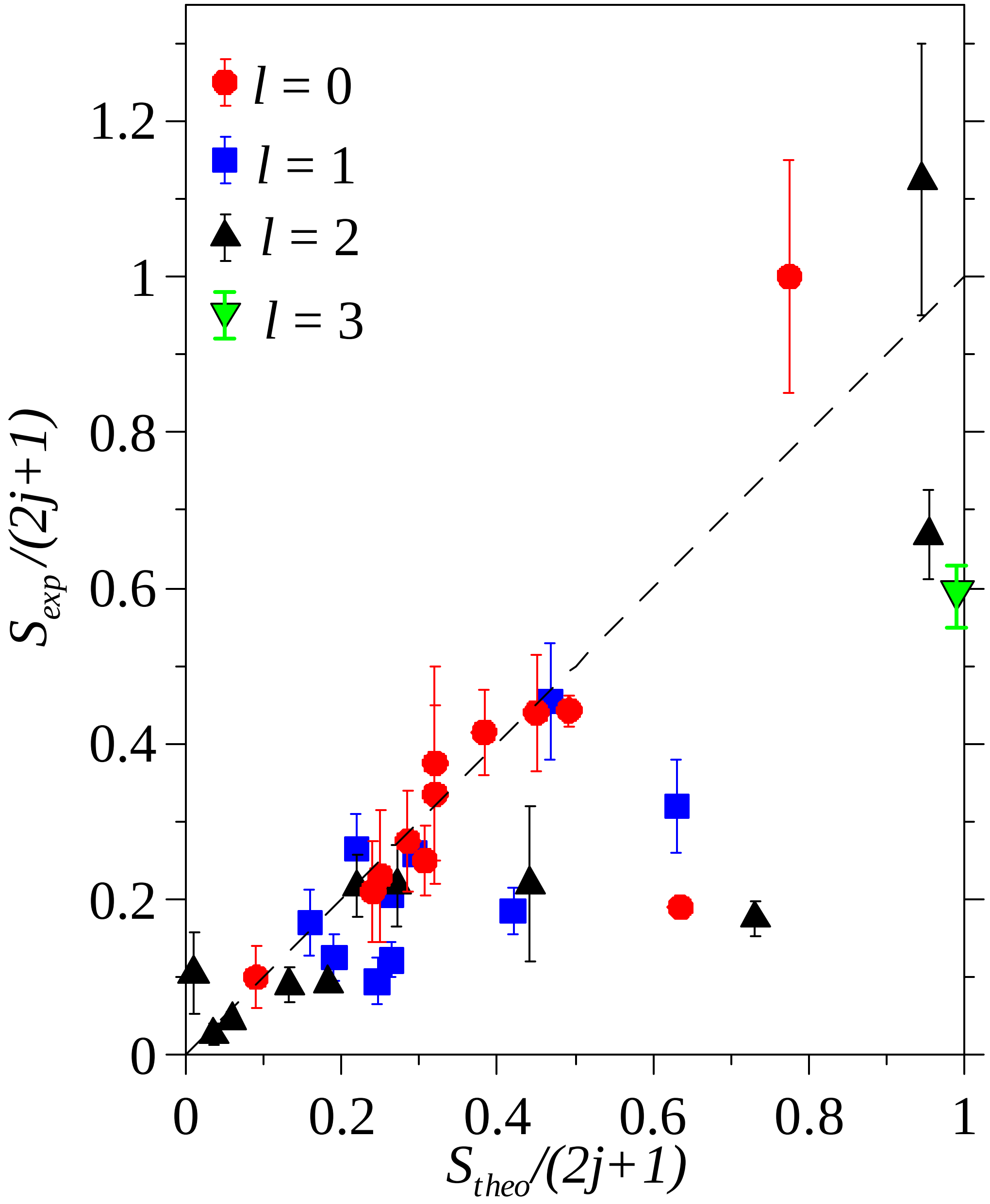
SPECTROSCOPIC FACTORS IN THE REACTION ^{9}Be(^{12}Be,^{11}Be+g)X at 78 MeV/nucleon



$(A/(A-1))^{N}\,C^{2}S$

0h	WBT	Exp[a)]
2.18	0.99	0.42(6)
0.00	0.61	0.50(7)

(a) Corrected for mismatch
Factors 0.83 and 0.79 (shakeoff)



Measured vs. Theoretical Spectroscopic Factors in Units of the Maximum Sum-Rule Value

P.G. Hansen and B.M. Sherrill, Nucl. Phys. A 693, 133-168 (2001)

J. Enders, A. Bauer, D. Bazin, A. Bonaccorso, B.A. Brown, T. Glasmacher, P.G. Hansen, V. Maddalena, K.L. Miller, A. Navin, B.M. Sherrill and J.A. Tostevin, Phys. Rev. C 65, 034318 (2002).

P.G. Hansen and J.A. Tostevin, Annual Review of Nuclear and Particle Science 53, 219 (2003)

Update Feb. 2004

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^{12}C and ^{16}O on a carbon target: comparison with (e,e'p)

^{A-1}Z	E_B A MeV	s_{exp} mb	Rs	Rs Average	Rs (e,e'p)
^{11}B	250	65.6(26)	0.65(3)	**0.57(2)**	**0.51(3)**
	1050	48.6(24)	0.50(3)		
	2100	53.8(27)	0.56(3)		
^{11}C	250	56.0(41)	0.54(4)	**0.49(2)**	--
	1050	44.7(28)	0.47(2)		
	2100	46.5(23)	0.49(2)		
^{15}N	2100	54.2(29)	0.59(4)	**0.59(4)**	**0.67(5)**
^{15}O	2100	42.9(23)	0.48(3)	**0.48(3)**	--

B.A. Brown, PGH, B.M. Sherrill and J.A. Tostevin, Phys. Rev. C 65, 061601 (2002)
(recalculated with HF input for radii and sp wave functions)

Experimental data: D.L.Olson *et al.*, Phys. Rev. C. 28, 1602 (1983); J.M.Kidd *et al.*, Phys. Rev. C. 37, 2613 (1988); G. van der Steenhoven *et al.*, Nucl. Phys. A. 480, 547 (1988); M.B. Leuschner *et al.* Phys. Rev. C 49, 955 (1994)

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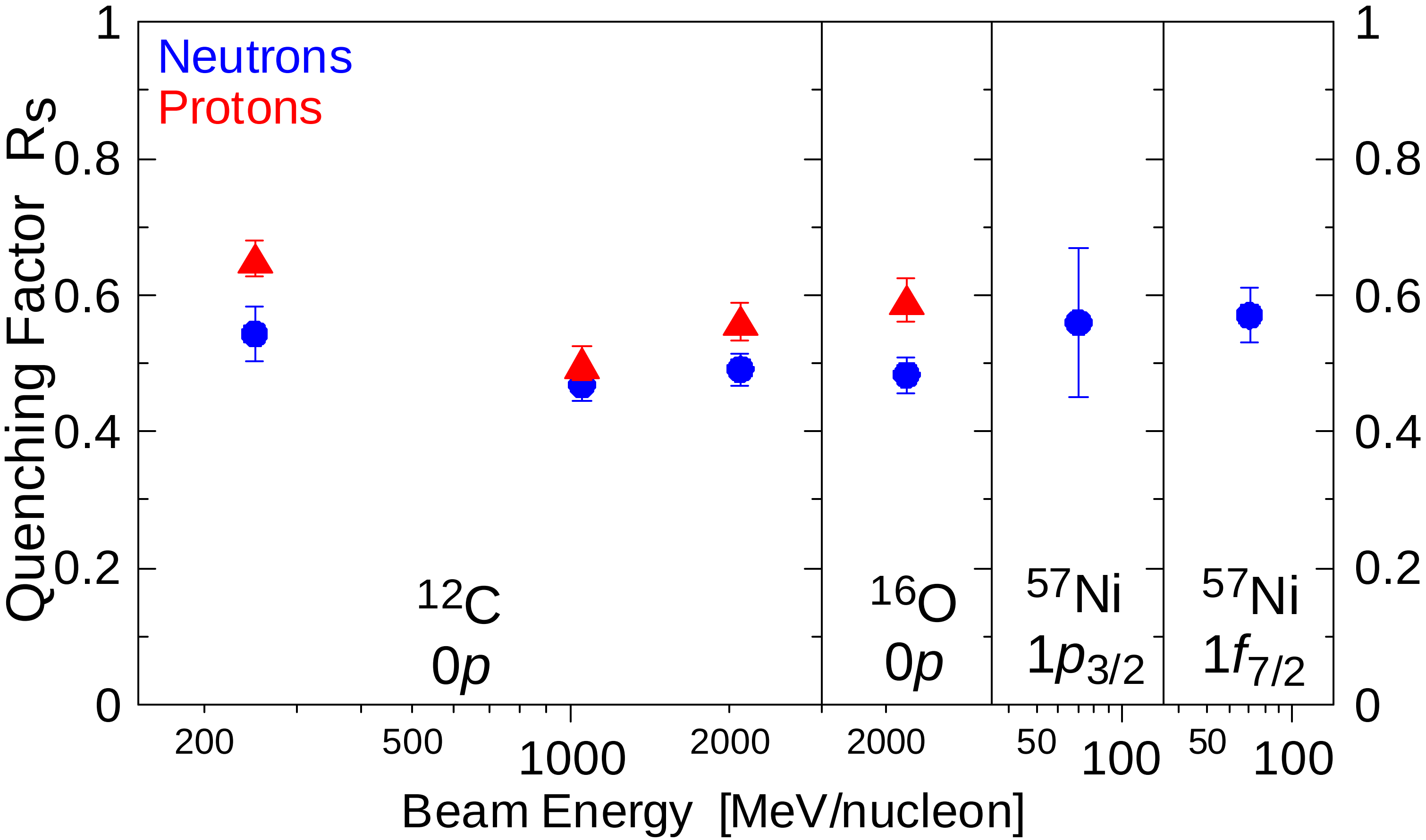
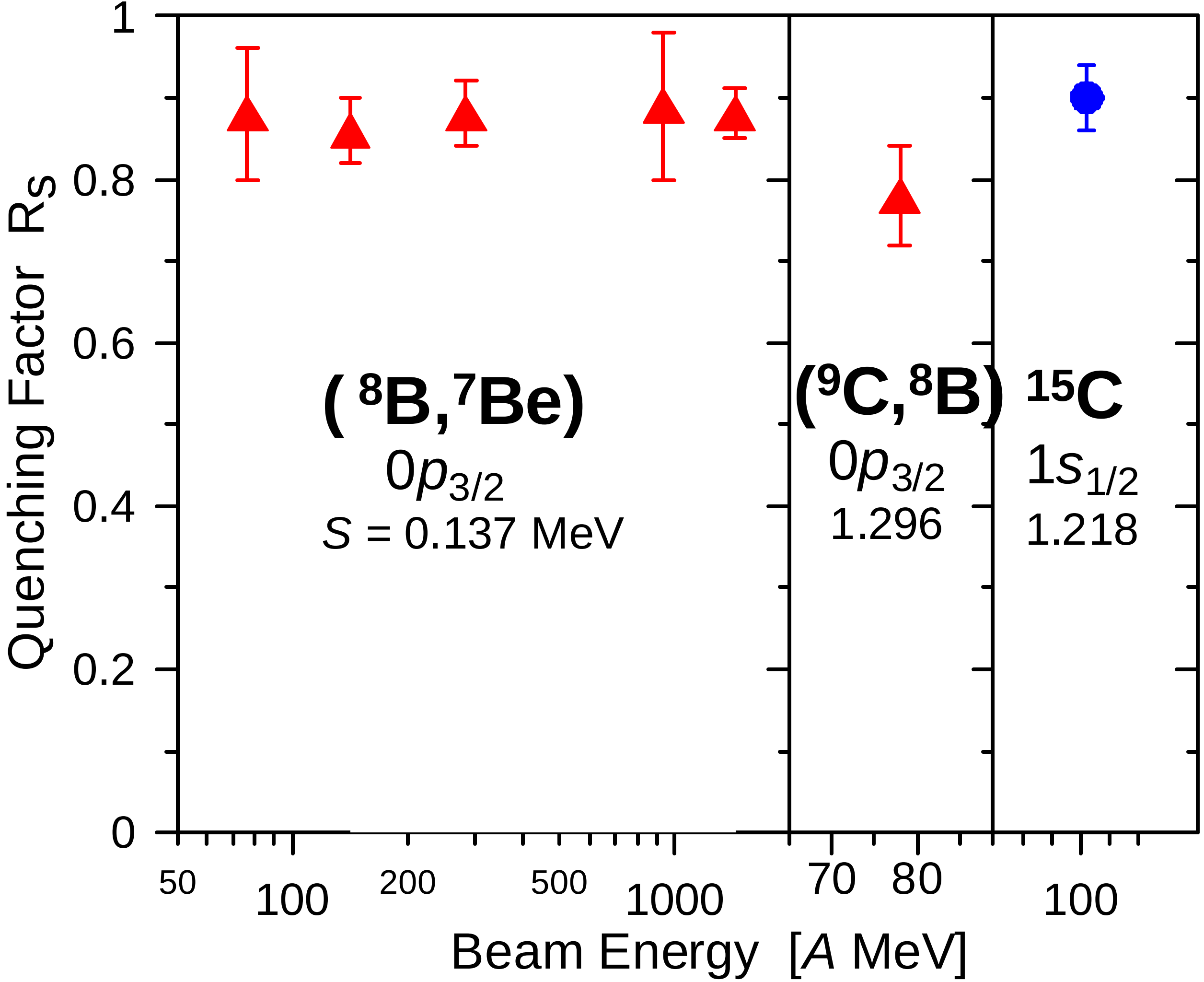
QUENCHING FACTOR R_s FOR DEEPLY-BOUND PROTON AND NEUTRON STATES (S_N = 10-19 MeV)



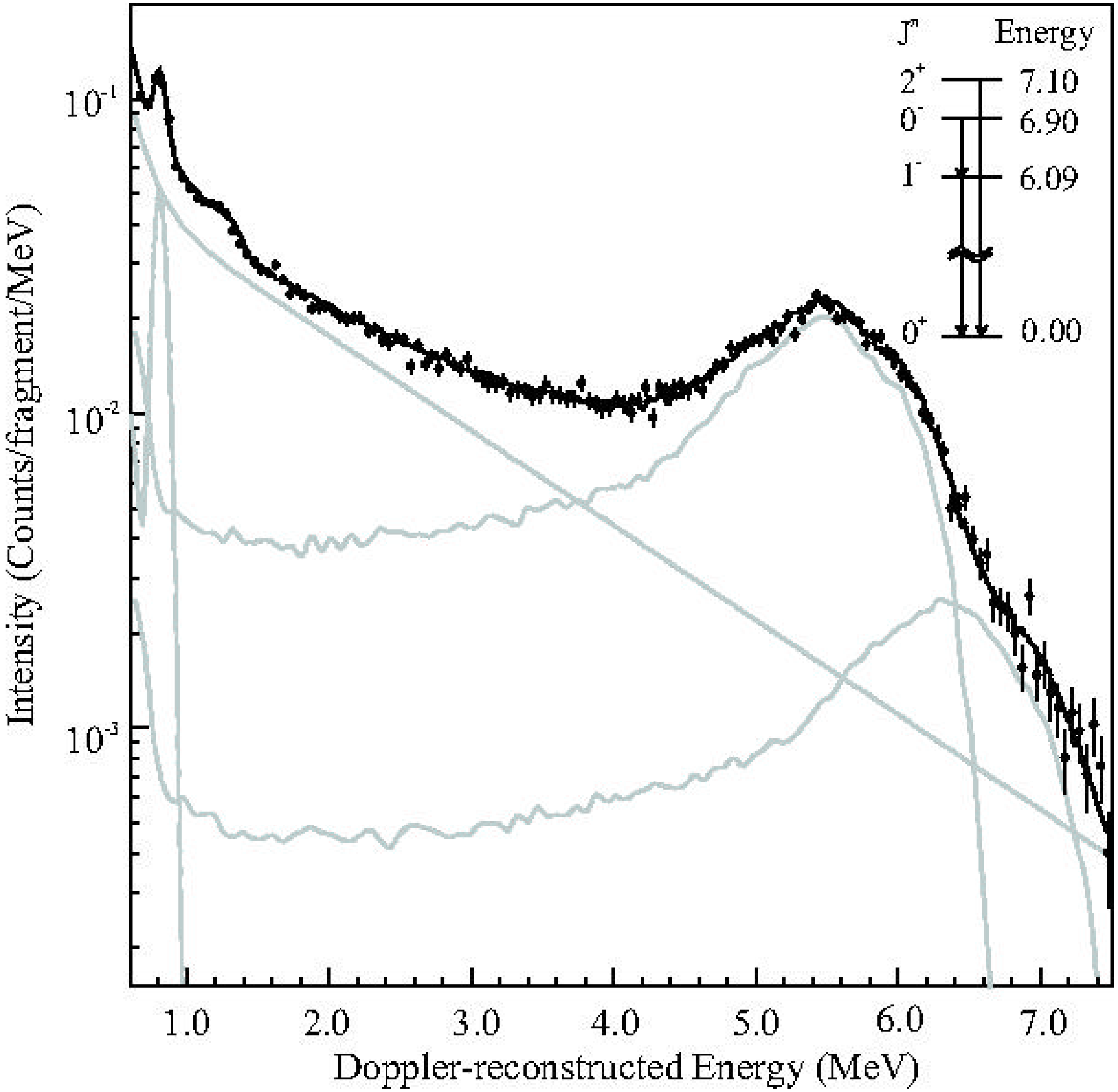
B.A. Brown, PGH, B.M. Sherrill and J.A. Tostevin, Phys. Rev. C 65, 061601 (2002)
K. Miller et al, to be published
Data O,C D.L. Olson et al. Phys. Rev. C 28, 1602 (1983)
J.M. Kidd et al. Phys. Rev. C 37, 2613 (1988)

QUENCHING FACTOR R_s FOR LOOSELY BOUND (S_N = 0.14 - 1.3 MeV) RADIOACTIVE NUCLEI



B.A. Brown, PGH, B.M. Sherrill and J.A. Tostevin, Phys. Rev. C 65, 061601 (2002)
J.Enders et al., Phys. Rev. C 67, 064301 (2003);
J.R. Terry et al., to be published
D.Cortina-Gil et al., Phys. Lett. B 529, 36 (2002) and references therein

THE $^{9}Be(^{15}C,^{14}C_{0+})X$ REACTION



^{15}C ½+ S_n = 1.218 MeV

s_{incl} = 140.2(46) mb

(Average of two measurements)

Branch to 0^{+} 71.8(24)%

$s(0^{+})$ = 100.8(44) mb

Theoretical spectroscopic factor $C^{2}S(0^{+})$ = 0.983

J.R. Terry et al., to be published

THE ^{9}Be(^{15}C,^{14}C$_{0+}$)X SPECTROSCOPIC FACTOR

$$\sigma_{exp} = R_s \left(\frac{A}{A-1}\right)^{N} C^2 S_j \;\; \sigma_{sp}(j, B_n)$$

$$R_{sp}^2 = \langle r^2 \rangle = \left(\frac{A}{A-1}\right) \langle r^2_{HF} \rangle$$

R_{sp} = 5.185 fm (from Skyrme X Hartree-Fock)

σ_{strp} = 62.1 mb

σ_{diff} = 34.5 mb

σ_{Cou} = 2.9 mb, hence σ_{sp} = 99.4 mb

$$\delta\sigma_{sp}/\sigma_{sp} = 0.44\delta R_{sp} - 0.04\delta a - 0.3\delta R_C - 0.3\delta R_T$$

R_s = 0.90(4)(5)

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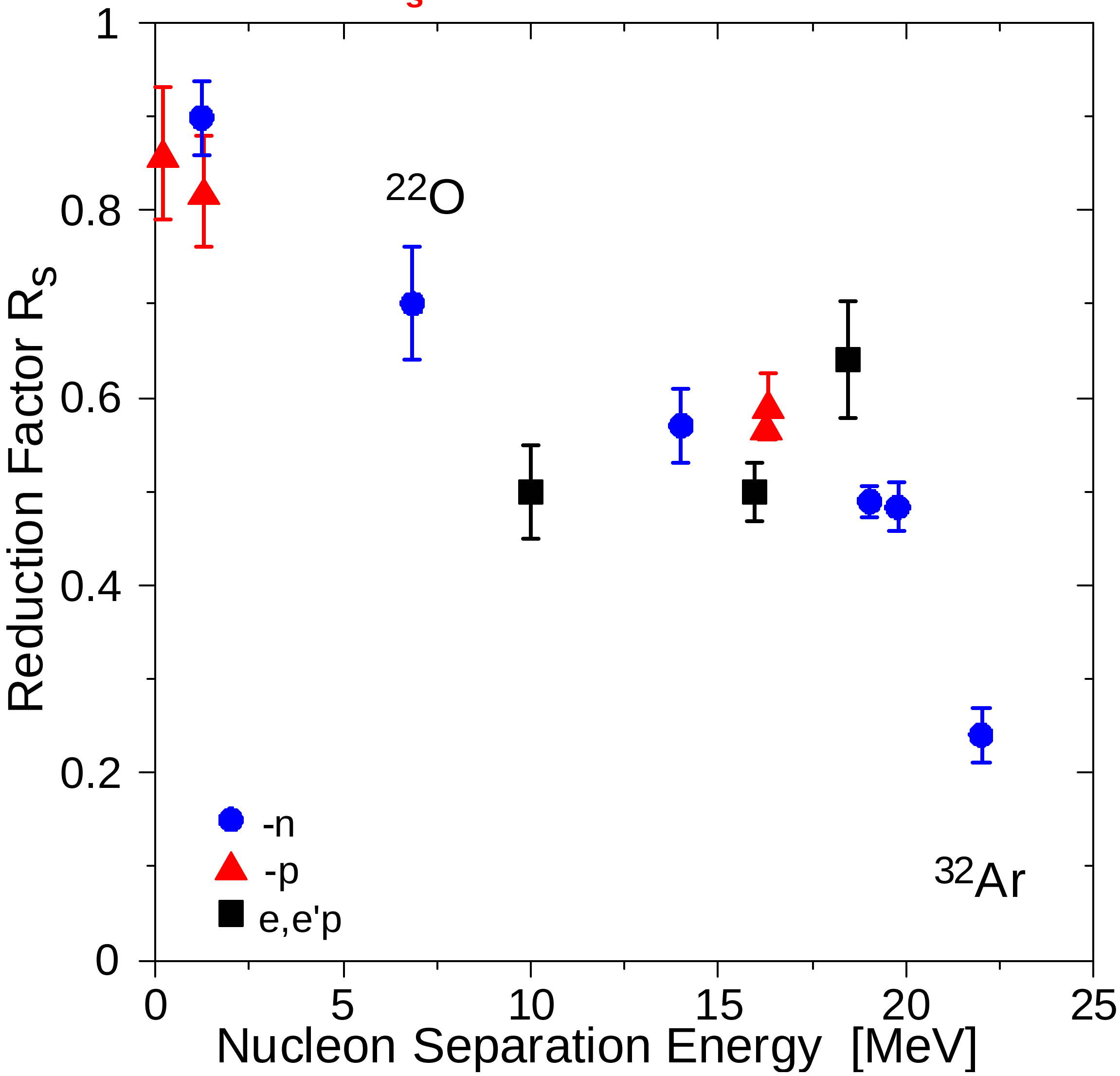
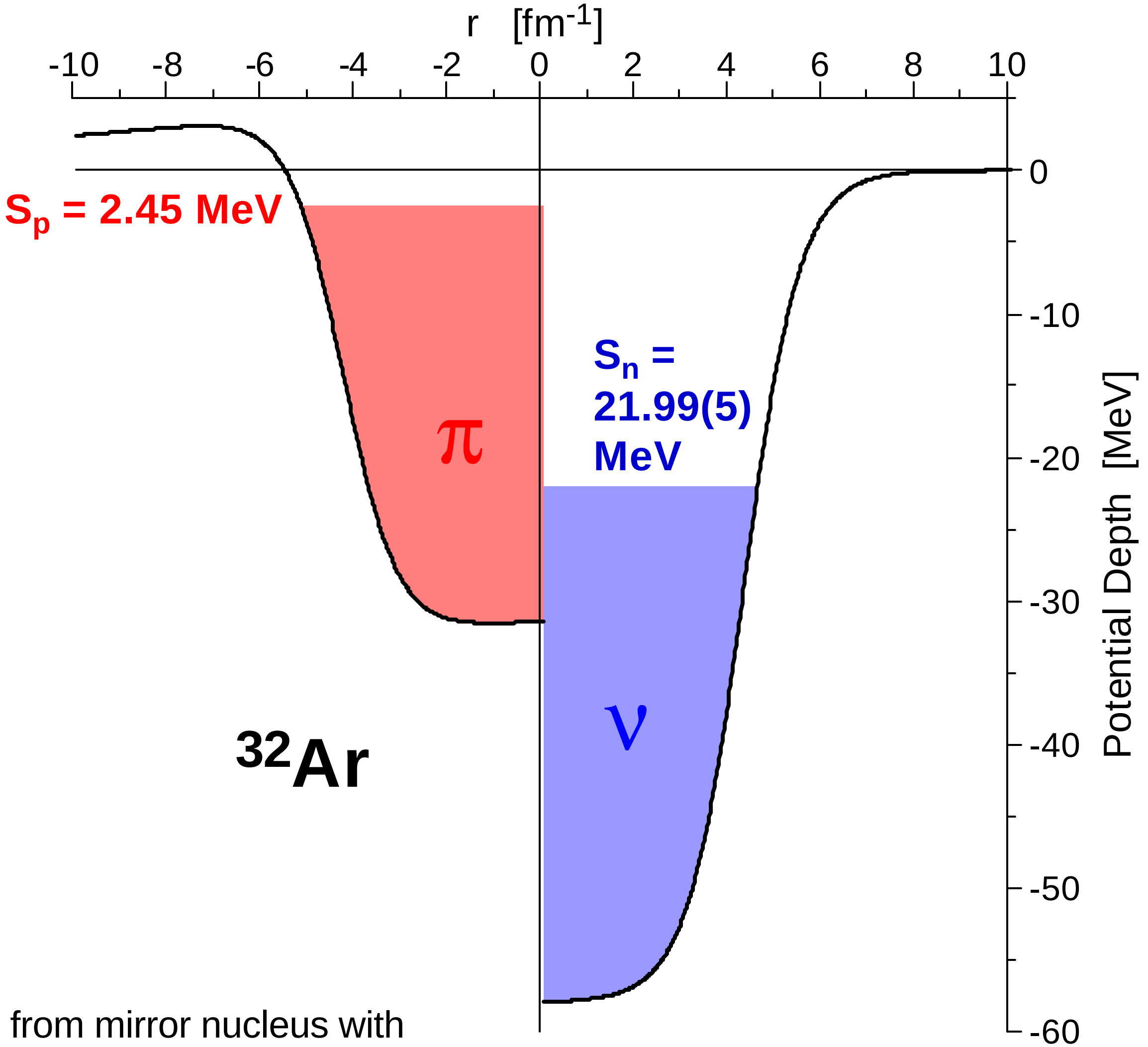
QUENCHING FACTOR R_s FOR PROTON AND NEUTRON STATES



B.A. Brown, PGH, B.M. Sherrill and J.A. Tostevin, Phys. Rev. C 65, 061601 (2002)
J.Enders *et al.*, Phys. Rev. C 67, 064301 (2003)
A. Gade *et al.*, to be published
K. Miller *et al.*, to be published
J.R. Terry *et al.*, to be published

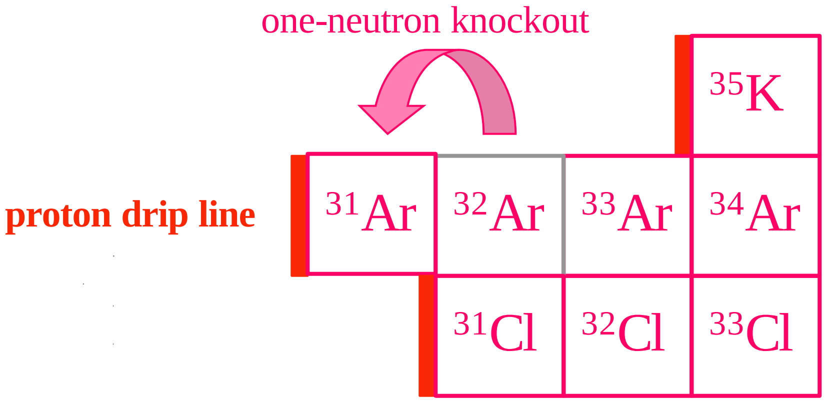
THE N=14 NUCLEUS ^{32}Ar: ASYMMETRIC FERMI SURFACES AT THE PROTON DRIP LINE

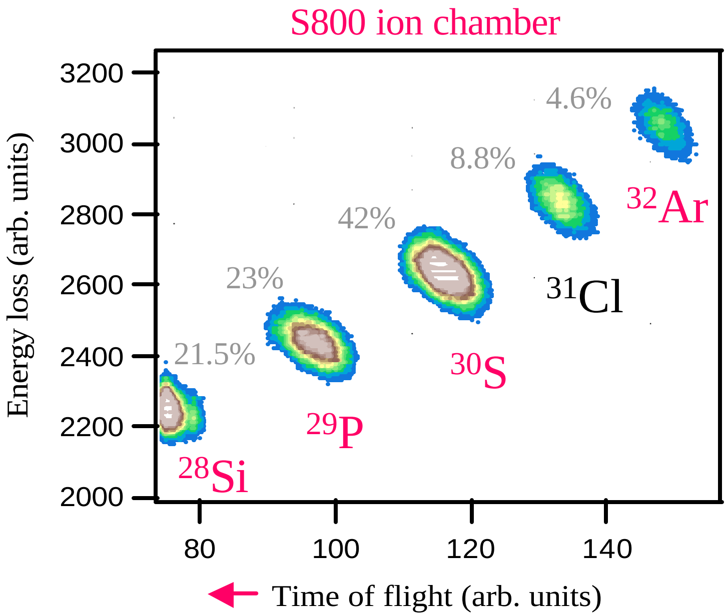


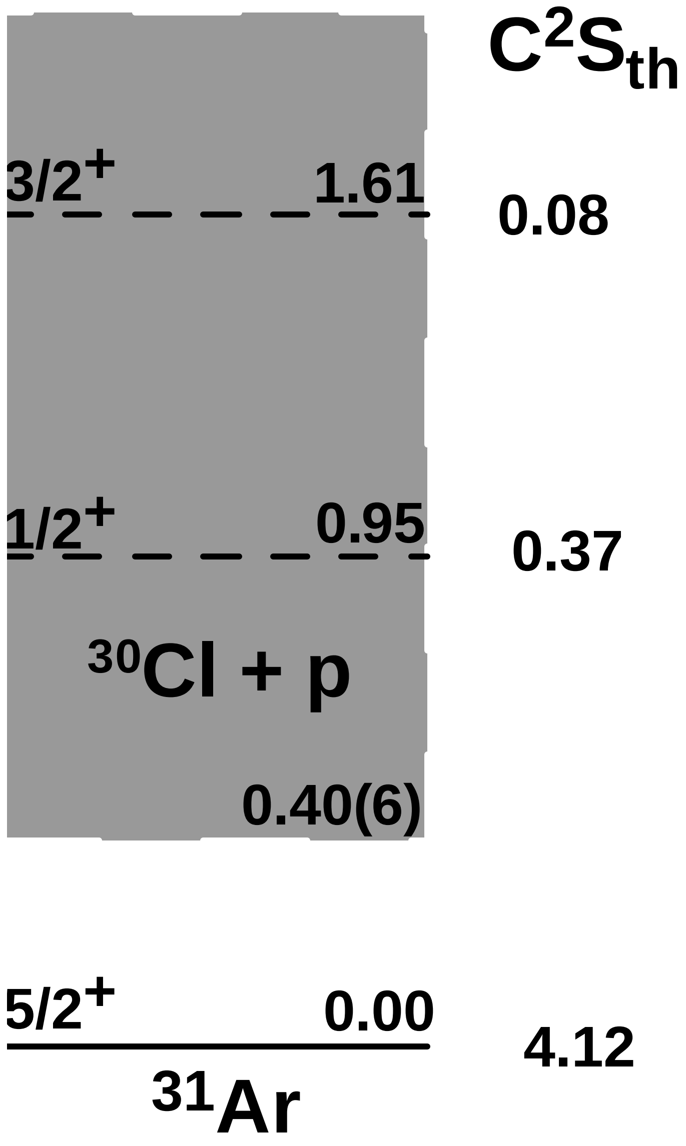
S_n and also S_p (^{31}Ar) from mirror nucleus with Coulomb correction:

B.J. Cole, Phys. Rev. C 58, 2831 (1998)

^{31}Ar: REACHING THE PROTON DRIP LINE







C^2S_{th}

$3/2^+$ 1.61 — 0.08

$1/2^+$ 0.95 — 0.37

^{30}Cl + p

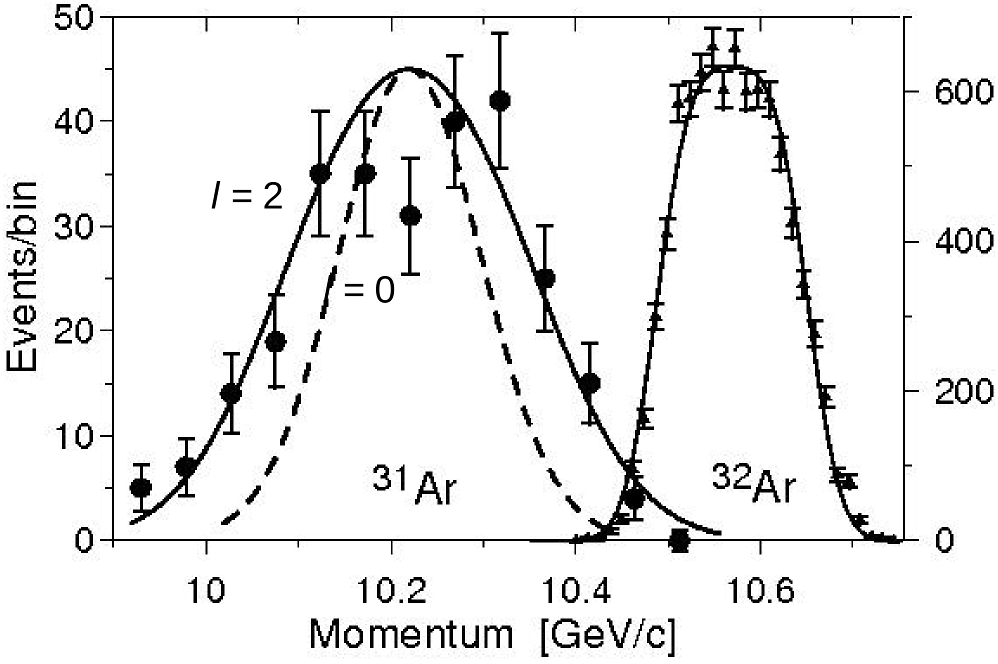
0.40(6)

$5/2^+$ 0.00 — 4.12

^{31}Ar

MOMENTUM DISTRIBUTION AND CROSS SECTION 31Ar

Less than 300 counts in the
momentum distribution,
but we can assign the ℓ-value



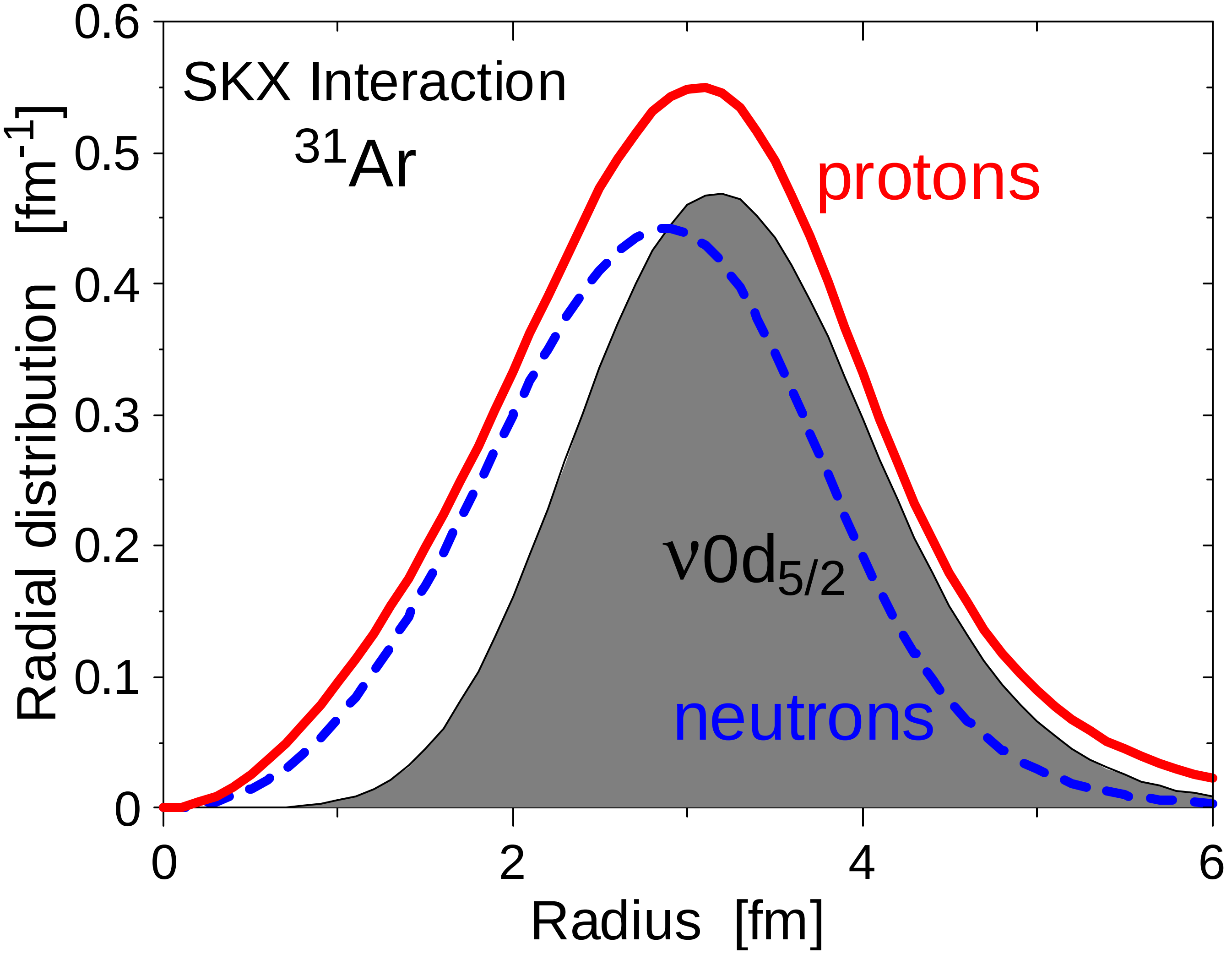
Alexandra Gade *et al*., to be published

σ_{exp} = 10.4(13) mb

Theory:
C^2S = 4.12
σ_{sp} = 9.92 mb

R_s = 0.24(4)(4)

RADIAL NUMBER DISTRIBUTIONS OF THE $d_{5/2}$ PROTON IN ^{32}Ar AND OF PROTONS AND NEUTRONS IN ^{31}Ar



CALCULATION OF THE SINGLE-PARTICLE CROSS SECTIONS FOR ^{22}O AND ^{32}Ar

Cross sections (mb) for *l*=2 calculated assuming density distributions

	$(p+n)_{HF}$	matter_{HF}	Gaussian+rms
^{22}O	22.3	22.3	20.6
^{32}Ar	9.9	10.0	9.7

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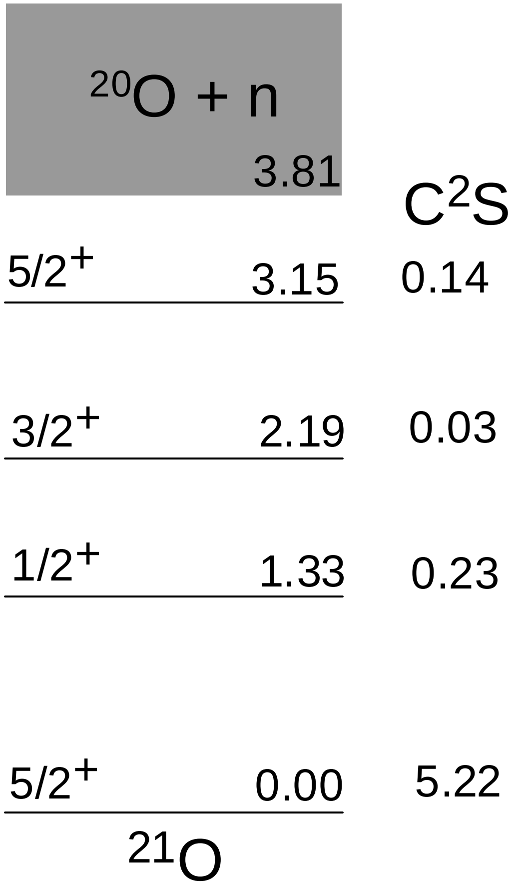
THE ^{9}Be(^{22}O,^{21}O)X REACTION



^{20}O + n	3.81	C^{2}S
5/2$^+$	3.15	0.14
3/2$^+$	2.19	0.03
1/2$^+$	1.33	0.23
5/2$^+$	0.00	5.22

^{21}O

Sn = 6.85(6) MeV

Measured inclusive cross section

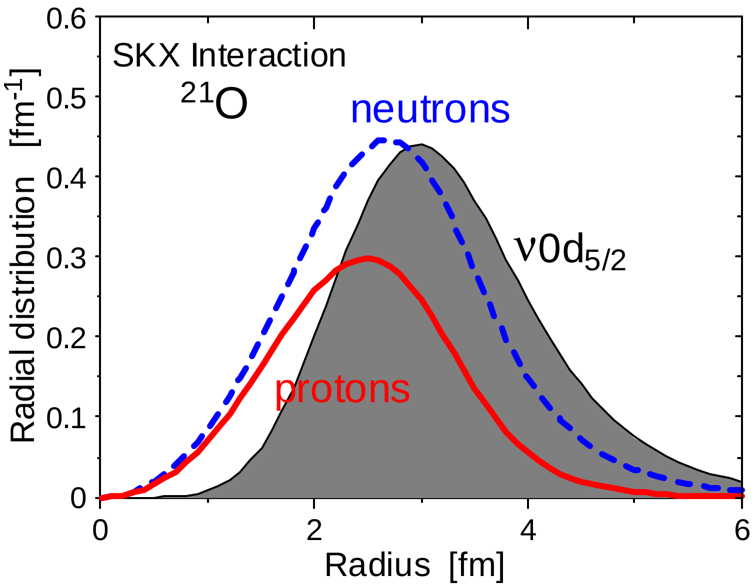
GANIL[a)] 51 MeV/nucleon: 120(14) mb

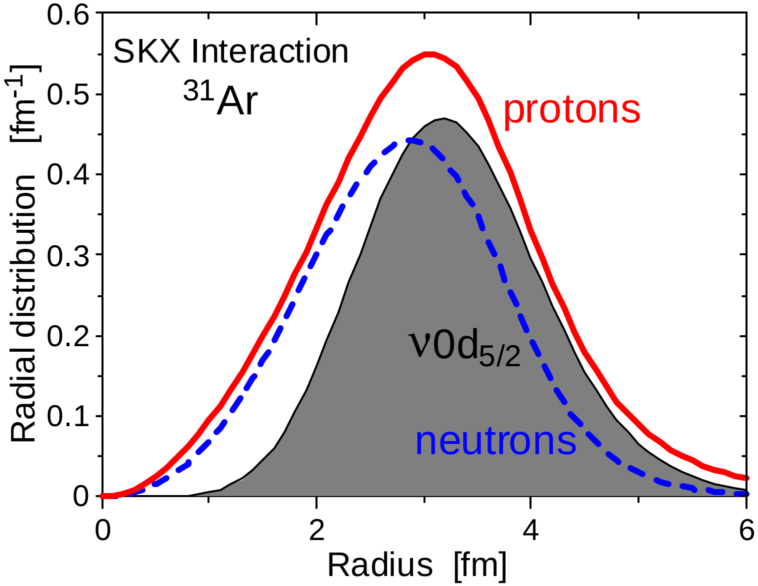
GSI[b)] 938 MeV/nucleon: 70(9) mb

$$R_s = 0.70(6)$$

- a) **E. Sauvan et al. Phys. Lett B 491,1 (2000)**
- b) **T. Aumann and B. Jonson, personal communication (2004)**

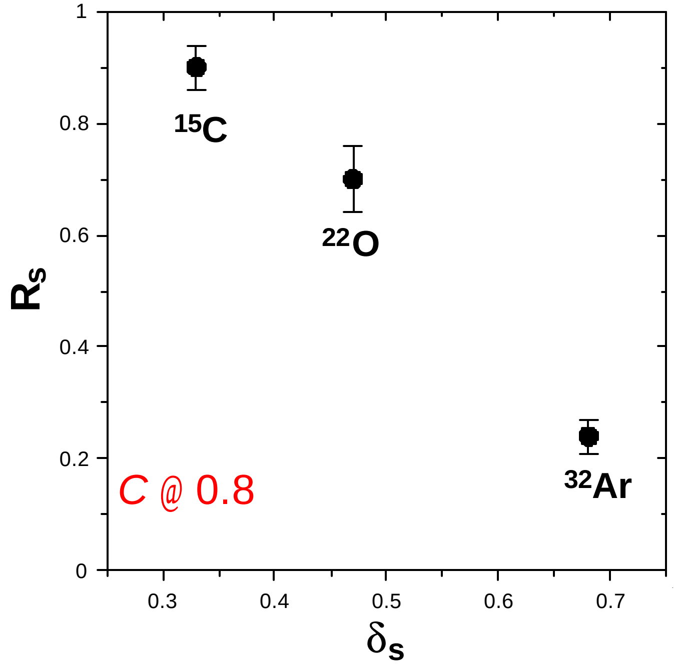
QUALITATIVE ESTIMATE OF CONTRIBUTIONS FROM SHORT-RANGE INTERACTIONS[a)]



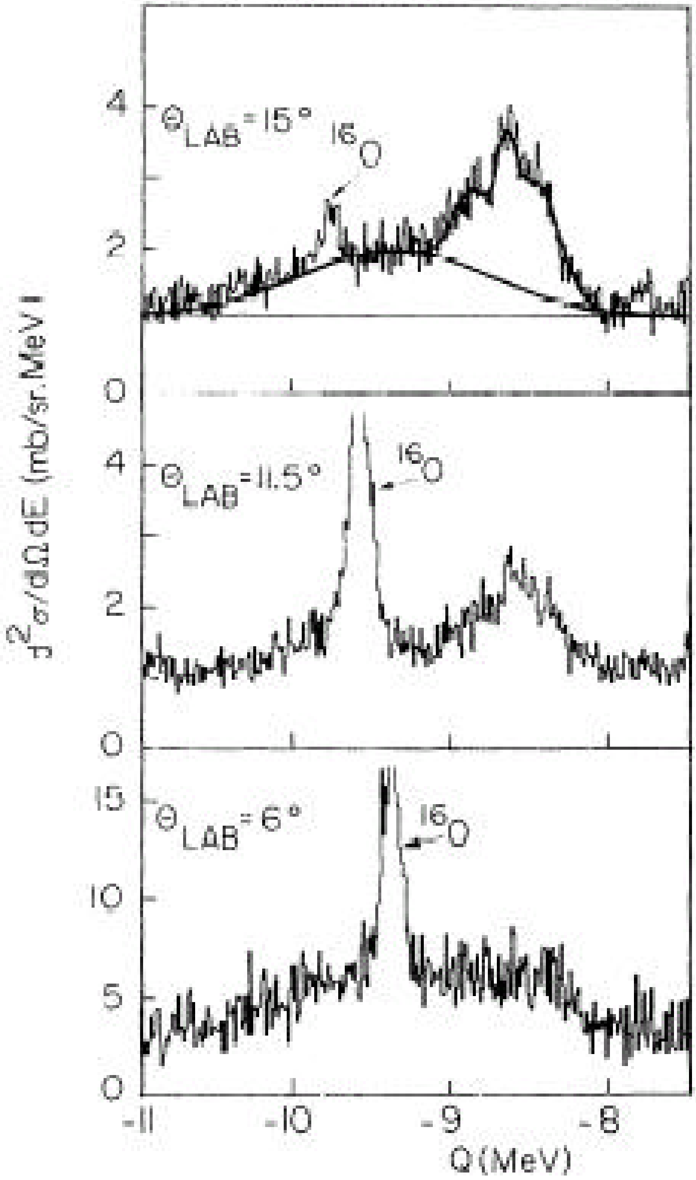


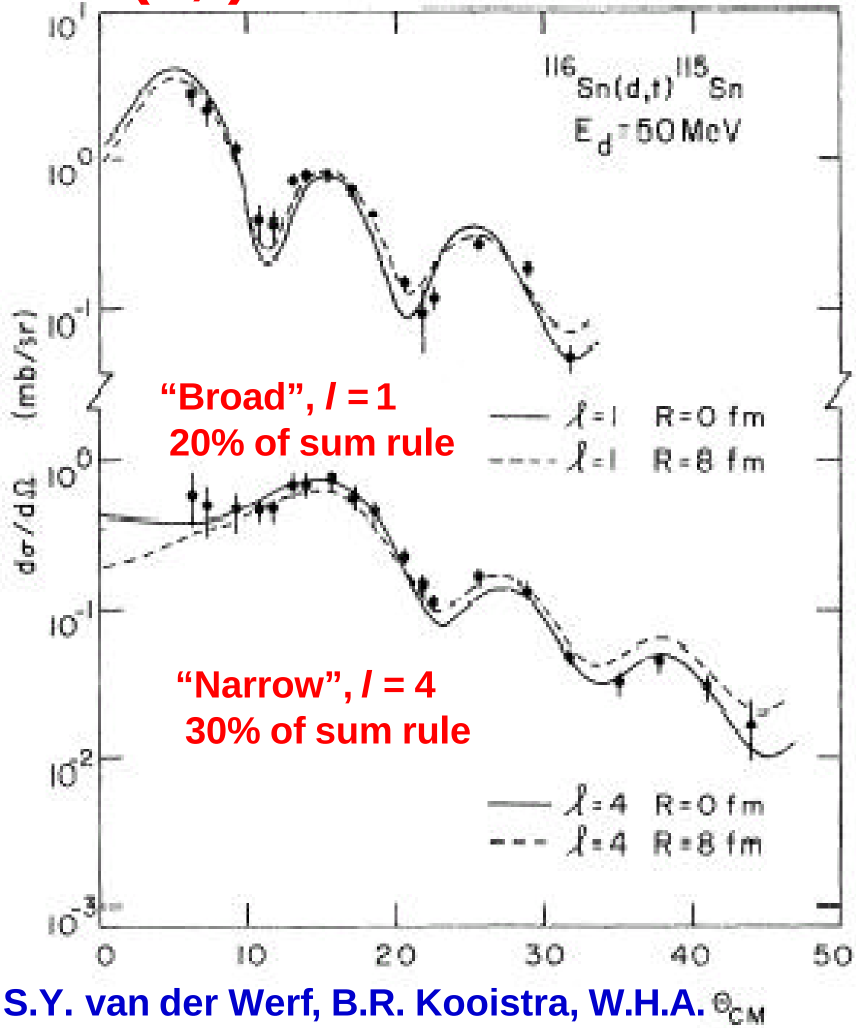
$$\delta_s = 4\pi C \int R^2_{t_z}(r)\left[\frac{1}{2}\rho^{(r)}_{t_z}(r)+\rho^{(r)}_{-t_z}(r)\right] r^2 dr$$

a) M.C. Birse and C.F. Clement, Nucl. Phys. A. 351, 112 (1981)



Deep-hole states $g_{9/2}$ and $p_{1/2,3/2}$ near 5.5 MeV in ^{116}Sn(d,t)^{115}Sn





"Broad", *l* = 1
20% of sum rule

"Narrow", *l* = 4
30% of sum rule

S.Y. van der Werf, B.R. Kooistra, W.H.A. Hesselink, F. Iachello, L.W. Put and R.H. Siemssen, Phys. Rev. Lett. 33, 712 (1974)

-and compare with ^{88}Sr(^{3}He, ^{4}He)^{87}Sr

S. Fortier *et al.*, Phys. Rev. C 39, 82 (1989)

COMPARISON WITH THEORETICAL SPECTROSCOPIC FACTORS OBTAINED BY THE VARIATIONAL MONTE-CARLO METHOD a)

The quenching factors are in units of the *p*-shell effective-interaction spectroscopic factor b) (A/A-1)*C^2S

Initial State	Final State(s)	R_s(VMC)	R_s(exp)	Method
^{7}Li(3/2^{-},1/2)	^{6}He(0^{+}+2^{+},1)	0.60	0.58(5)	(e,e'p) c)
^{7}Li(3/2^{-},1/2)	^{6}Li(0^{+},1)	0.60	-	
^{7}Li(3/2^{-},1/2)	^{6}Li(1^{+},0)	0.77	-	
^{8}B(2+,1)	^{7}Be(3/2^{-},1)	0.82	0.86(7)	Knockout
^{9}C(3/2^{-},3/2)	^{8}B(2^{+},1)	-	0.82(6)	Knockout

a) S.C. Pieper and R.B Wiringa, Annu. Rev. Nucl. Part. Sci. 51, 53 (2001); R. B. Wiringa, personal communication.

b) B.A. Brown, Prog. Part. Nucl. Phys. 47, 517 (2001).

c) L. Lapikás, J. Wesseling and R.B. Wiringa, Phys. Rev. Lett. 82, 4404 (1999)

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CONCLUDING REMARKS

Structure of nuclei
Knockout reactions in inverse kinematics are a powerful tool for identifying single-particle structure. Two-nucleon knockout has been shown to be a direct reaction for nuclei away from the stability line. It can give information on two-nucleon correlations in the wave function.

Foundations of the shell model
Experiments on drip-line nuclei, an option that is unique to a rare-isotope accelerator, suggest that the absolute occupancies of single-particle orbitals depend strongly on structure and nucleon separation energy.