Reaction Dynamics for Light Dripline Nuclei

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Angela Bonaccorso

INFN
Sezione di Pisa

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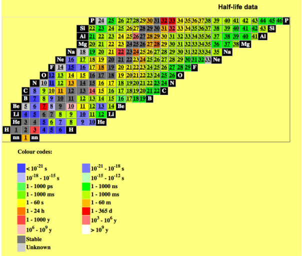
Entering the world of exotic nuclei: probing the unbound by walking at the drip line.

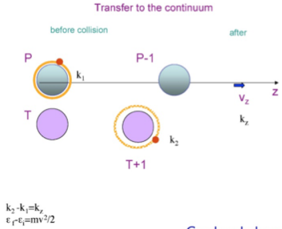


- Is there a life beyond the dripline?
- How can we discover it without getting lost?
- Extend our understanding of the *residual* nuclear force.
- Check the limits of validity of structure models such as the SHELL MODEL or "ab initio" models.
- Challenges in breakup reaction theory.

Transfer to continuum states (inclusive reaction)

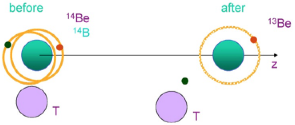
Kinematics and phase space ++

Single particle state properties (shell model)

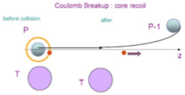


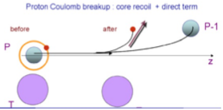
Fragmentation reaction (coincidence)

Let us start with a two neutron halo nucleus like ^{11}Li or ^{14}Be



Coulomb breakup (inclusive or coincidence)





A consistent formalism for all breakup reaction mechanisms

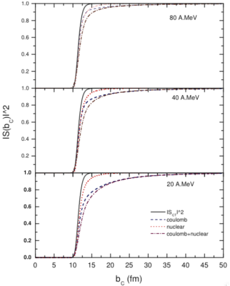
The core-target movement is treated in a semiclassical way, but neutron-target and/or neutron-core with a full QM method.
AB and DM Brink, PRC38, 1776 (1988), PRC43, 299 (1991), PRC44, 1559 (1991).

Early eikonal model: I. Tanihata, Prog. Part. Nucl. Phys. 35, 505 (1995), halo-core decoupling.

$$\frac{d\sigma}{d\xi} = C^2 S \int_0^\infty d\mathbf{b_c} \frac{dP_{-n}(b_c)}{d\xi} P_{ct}(b_c),$$

⊗

$$\xi \to \varepsilon_f, k_z, P_{//} \quad also \quad ANC = \sqrt{C^2 S C_i^2}$$



Use of the simple parametrization
$P_{ct}(b_c) = |S_{ct}|^2 = e^{(-\ln 2 exp[(R_s - b_c)/a])}$,

$$R_s \approx r_s(A_p^{1/3} + A_t^{1/3}) \qquad r_s \approx 1.4 fm$$

'strong absorption radius'

Transfer to the continuum: from resonances to knockout reactions

First order time dependent perturbation theory amplitude: $**$

$$A_{fi} = \frac{1}{i\hbar}\int_{-\infty}^{\infty} dt < \phi_f(\mathbf{r})|V(\mathbf{r})|\phi_i(\mathbf{r}-\mathbf{R}(t)) > e^{-i(\omega t - mvz/\hbar)} \tag{1}$$

$$\omega = \varepsilon_i - \varepsilon_f + \tfrac{1}{2}mv^2 \qquad \mathbf{R}(t) = \mathbf{b_c} + vt$$

$$\begin{aligned} \frac{dP_{-n}(b_c)}{d\varepsilon_f} &= \frac{1}{8\pi^3}\frac{m}{\hbar^2 k_f}\frac{1}{2l_i+1}\Sigma_{m_i}|A_{fi}|^2 \\ &\approx \frac{4\pi}{2k_f^2}\Sigma_{j_f}(2j_f+1)(|1-\bar{S}_{j_f}|^2 + 1 - |\bar{S}_{j_f}|^2)\mathcal{F}, \end{aligned}$$

ϕ_f see $(*)$

$$\mathcal{F} = (1 + F_{l_f,l_i,j_f,j_i})B_{l_f,l_i} \qquad B_{l_f,l_i} = \frac{1}{4\pi}\left[\frac{k_f}{mv^2}\right]|C_i|^2\frac{e^{-2\eta b_c}}{2\eta b_c}M_{l_f l_i}$$

Final continuum wave functions

$(*)$

Final continuum state:

$$\phi_{l_f}(\mathbf{r}) = C_f k \frac{i}{2}(h_{l_f}^{(+)}(kr) - \bar{S}_{l_f} h_{l_f}^{(-)}(kr)) Y_{l_f,m_f}(\Omega_f),$$

$\bar{S}_{l_f}(\varepsilon_f)$ is an optical model (n-core in fragmentation reactions, n-target in knockout reactions) S-matrix.

^{13}Be puzzle or of the "elusive 1/2+ state in Be isotopes

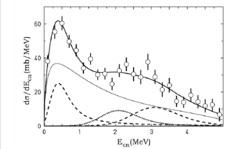


Figure : (a) GSI, H. Simon et al. NPA791 (2007) 267.

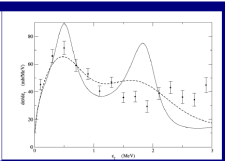
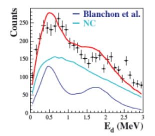
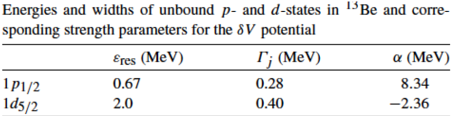


Figure : (b) G.Blanchon et al. NPA784 (2007) 49.

Our level sequence
2s1/2 a_s=-0.8fm
1p1/2
1d5/2



(b) G. Randisi, N. Orr et al. Phys. Rev. C 89, 034320



Energies and widths of unbound p- and d-states in ^{13}Be and corresponding strength parameters for the δV potential

	ε_{res} (MeV)	Γ_j (MeV)	α (MeV)
$1p_{1/2}$	0.67	0.28	8.34
$1d_{5/2}$	2.0	0.40	−2.36

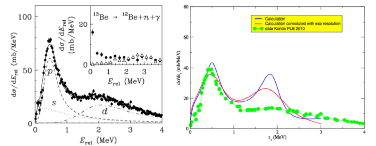


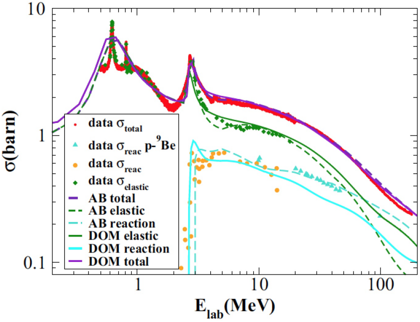
Figure : (b) RIKEN, Y. Kondo et al. PLB690 (2010) 245; G. Blanchon, private communication.

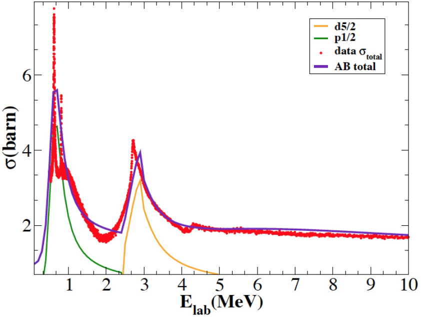
$$(d\delta_l/d\varepsilon)_{res} = 2/\Gamma_j$$

G. Blanchon et al.
PRC82, 034313
NPA A 784 (2007) 49

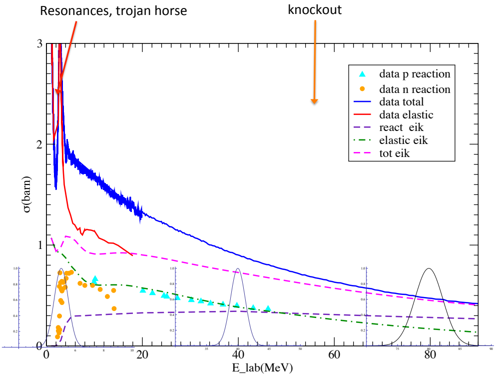
n-^{9}Be optical potential: A.B & R.J. Charity, PRC89, 024619 (2014),

data from https://www-nds.iaea.org/exfor/exfor.htm





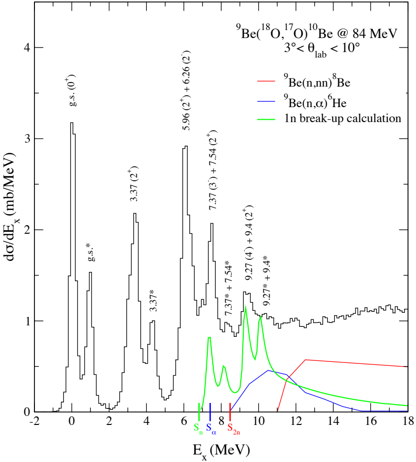
(∗)


Resonances, trojan horse
knockout
data p reaction
data n reaction
data total
data elastic
react eik
elastic eik
tot eik
σ(barn)
E_lab(MeV)
0
1
2
3
0
20
40
60
80

Transfer to ^{10}Be resonances: missing mass experiment.

Paper in preparation

Diana Carbone, AB, Mariangela Bondì, F. Cappuzzello, M Cavallaro et al. MAGNEX Collaboration: 1n and 2n transfer experimental campaign



^{16} O has a degenerate gs (1d5/2,2s1/2)
^{17} O has 5/2+ gs and 1/2+ first excited state at E*=0.87MeV

Position and widths of p1/2 and d5/2 resonances in ^{10}Be perfectly reproduced

Kinematics

From Eq.1 $**$ by the change of variables $dtdxdydz \to dxdydzdz'$ $e^{-i(\omega t - mvz/\hbar)} \to e^{-ik_1 z'} e^{ik_2 z}$ neutron energies to neutron parallel momenta with respect to core

$$k_1 = \frac{\varepsilon_f - \varepsilon_i - \frac{1}{2}mv^2}{\hbar v};$$

to target

$$k_2 = \frac{\varepsilon_f - \varepsilon_i + \frac{1}{2}mv^2}{\hbar v};$$

to core parallel momentum

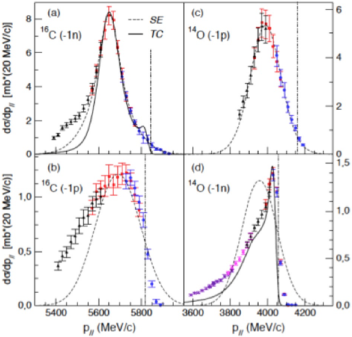
$$\begin{aligned} P_{//} &= \sqrt{E_r^2 - M_r^2} = \sqrt{(T_r + M_r)^2 - M_r^2} \\ &= \sqrt{(T_p + \varepsilon_i - \varepsilon_f)^2 + 2M_r(T_p + \varepsilon_i - \varepsilon_f)}, \end{aligned} \tag{2}$$

breakup threshold at $\varepsilon_f = 0$

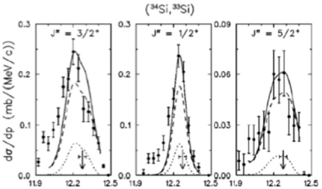
$++**$

Example "deformation" effects due to n-target interaction and kinematical cut-off.

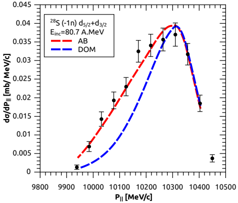
F. Flavigny, A. Obertelli, AB et al., PRL 108, 252501 (2012). **

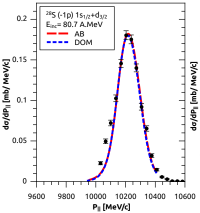


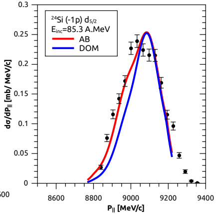
J.Enders et al. PHYSICAL REVIEW C 65 034318

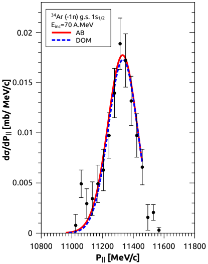


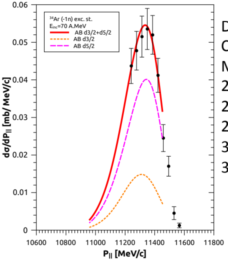
Asymmetries at high incident energy







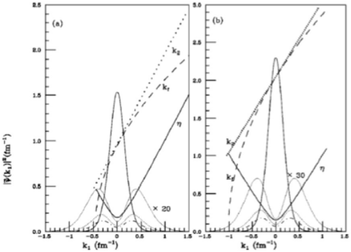




Data courtesy of A. Gade
Calculations G. Salvioni
MSc Thesis in preparation.
28S (-1n) 80.7 d5/2+d3/2
28S (-1p) s1/2+d3/2 A.MeV
24Si(-1p) d5/2 85.3 A.MeV
34Ar (-1n) s1/2 gs 70 A.MeV
34Ar (-1n) d3/2+d5/2

Origin of kinematical cut-off (phase space) and deformation effects

PRC60(1999) 054604,PRC44(1991) 1559,AB and GF Bertsch, PRC63(2001) 044604, F. Flavigny, A. Obertelli, AB et al., PRL 108, 252501 (2012). (+)



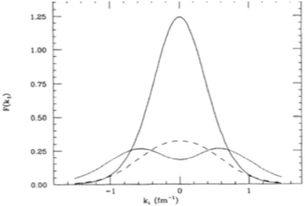
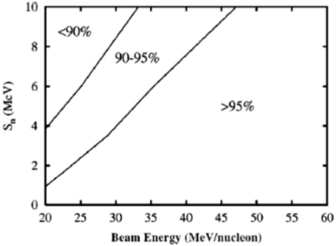
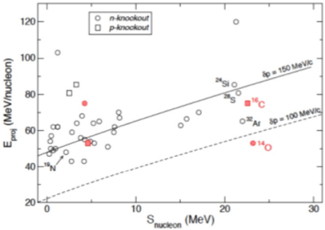
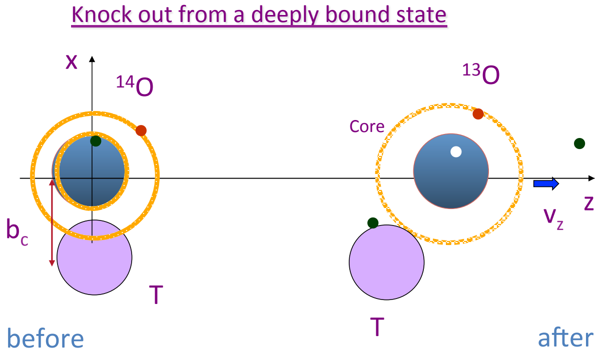


FIG. 11. Initial-state momentum distributions in ^{20}Ne according to Eq. (2.3a). The solid curve is for the $2s_{1/2}$ state, the dashed curve is the for $1p_{1/2}$, while the dotted curve is for the





Removal of a deeply bound n/p while the weakly bound p/n is un-touched ∗



reaction	S_n [MeV]	S_p [MeV]	$E_{inc}^{(m)}$ [A.MeV]	σ^{exp} [mb]
$^{9}C \rightarrow ^{8}C$	14.25	1.3	63.8	3.
$^{36}Ca \rightarrow ^{35}Ca$	19.3	1.3	70	5
$^{13}O \rightarrow ^{12}O$	17.01	1.51	28.5	2.5
$^{33}Cl \rightarrow ^{32}Cl$	15.74	2.3	66.4	9
$^{32}Ar \rightarrow ^{31}Ar$	21.56	2.42	65.1	10.4
$^{28}S \rightarrow ^{27}S$	21.54	2.49	80.7	11.9
$^{24}Si \rightarrow ^{23}Si$	21.09	3.3	85.3	9.8
$^{10}C \rightarrow ^{9}C$	21.28	4.01	116.2	23.4
$^{6}Li \rightarrow ^{5}Li$	5.66	4.43	36.6	38.1
$^{14}O \rightarrow ^{13}O$	23.18	4.63	53	14
$^{34}Ar \rightarrow ^{33}Ar$	17.06 18.42 18.86	4.66	70	4.7 3.2 4.9
$^{7}Be \rightarrow ^{6}Be$	10.68	5.6	65.2	28.1
$^{57}Ni \rightarrow ^{56}Ni$	10.25 14.0 15.04	7.3	70.2	7.7 33.7
$^{32}S \rightarrow ^{31}S$	16.29 17.28 19.5	8.86	62.8	36
$^{46}Ar \rightarrow ^{45}Ar$	8.02 8.56	18.64	70	61.9 3.6
$^{34}Si \rightarrow ^{33}Si$	7.53 8.54 11.82	18.74	73.4	67 41 15
$^{10}Be \rightarrow ^{9}Be$	6.81	19.64 22.33	77.8	69.5
		118.5	71.2	
$^{15}C \rightarrow ^{14}C$	1.22 7.31 8.21 8.23	21.08	103	100.8 27.4 6.5 5.5
$^{16}C \rightarrow ^{15}C$	4.25 4.99	22.56	75	36.5 46

$$\sigma = C^2 S \int_0^\infty d\mathbf{b_c} P_{-n}(b_c)(1 - P_{-p}(b_c)) P_{ct}(b_c)$$

$$e^{-P_{-p}} \approx 1 - P_{-p}(b_c)$$

DPP from phase shift, AB, F. Carstoiu, NPA706, (2002) -typically ∼10% reduction in the cross sections.

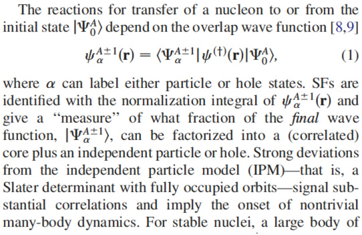
Absolute cross sections $\sigma = \int d\xi \frac{d\sigma}{d\xi}$

Ratios

$$\sigma_{exp}/\sigma_{Theo}$$

have been used to validate spectroscopic factors C^2S (=2j+1, in the IPM) for single particle orbitals from shell model or "ab initio" calculations, when available. This is similar to what has traditionally been done for transfer. However in transfer the core-target interaction is treated almost exactly thanks to optical potentials fitted to the elastic scattering.

C. Barbieri PRL103, 202502 (2009)



The reactions for transfer of a nucleon to or from the initial state $|\Psi_0^A\rangle$ depend on the overlap wave function [8,9]

$$\psi_\alpha^{A\pm1}(\mathbf{r}) = \langle\Psi_\alpha^{A\pm1}|\psi^{(\dagger)}(\mathbf{r})|\Psi_0^A\rangle, \qquad (1)$$

where α can label either particle or hole states. SFs are identified with the normalization integral of $\psi_\alpha^{A\pm1}(\mathbf{r})$ and give a "measure" of what fraction of the *final* wave function, $|\Psi_\alpha^{A\pm1}\rangle$, can be factorized into a (correlated) core plus an independent particle or hole. Strong deviations from the independent particle model (IPM)—that is, a Slater determinant with fully occupied orbits—signal substantial correlations and imply the onset of nontrivial many-body dynamics. For stable nuclei, a large body of

neutron & proton → transfer vs breakup F. Flavigny et al., PRL110 ,122503 (2013)

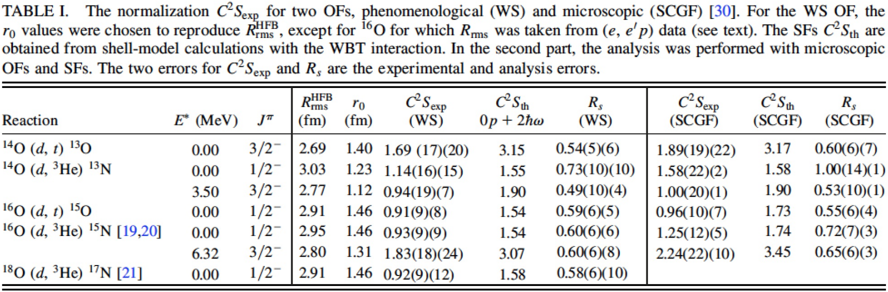


TABLE I. The normalization C^2S_{exp} for two OFs, phenomenological (WS) and microscopic (SCGF) [30]. For the WS OF, the r_0 values were chosen to reproduce $R_{\text{rms}}^{\text{HFB}}$, except for ^{16}O for which R_{rms} was taken from $(e, e'p)$ data (see text). The SFs C^2S_{th} are obtained from shell-model calculations with the WBT interaction. In the second part, the analysis was performed with microscopic OFs and SFs. The two errors for C^2S_{exp} and R_s are the experimental and analysis errors.

Reaction	E^* (MeV)	J^π	$R_{\text{rms}}^{\text{HFB}}$ (fm)	r_0 (fm)	C^2S_{exp} (WS)	C^2S_{th} $0p + 2\hbar\omega$	R_s (WS)	C^2S_{exp} (SCGF)	C^2S_{th} (SCGF)	R_s (SCGF)
^{14}O (d, t) ^{13}O	0.00	$3/2^-$	2.69	1.40	1.69 (17)(20)	3.15	0.54(5)(6)	1.89(19)(22)	3.17	0.60(6)(7)
^{14}O $(d, {}^3\text{He})$ ^{13}N	0.00	$1/2^-$	3.03	1.23	1.14(16)(15)	1.55	0.73(10)(10)	1.58(22)(2)	1.58	1.00(14)(1)
	3.50	$3/2^-$	2.77	1.12	0.94(19)(7)	1.90	0.49(10)(4)	1.00(20)(1)	1.90	0.53(10)(1)
^{16}O (d, t) ^{15}O	0.00	$1/2^-$	2.91	1.46	0.91(9)(8)	1.54	0.59(6)(5)	0.96(10)(7)	1.73	0.55(6)(4)
^{16}O $(d, {}^3\text{He})$ ^{15}N [19,20]	0.00	$1/2^-$	2.95	1.46	0.93(9)(9)	1.54	0.60(6)(6)	1.25(12)(5)	1.74	0.72(7)(3)
	6.32	$3/2^-$	2.80	1.31	1.83(18)(24)	3.07	0.60(6)(8)	2.24(22)(10)	3.45	0.65(6)(3)
^{18}O $(d, {}^3\text{He})$ ^{17}N [21]	0.00	$1/2^-$	2.91	1.46	0.92(9)(12)	1.58	0.58(6)(10)			

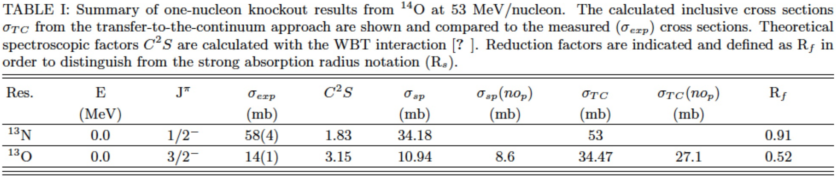
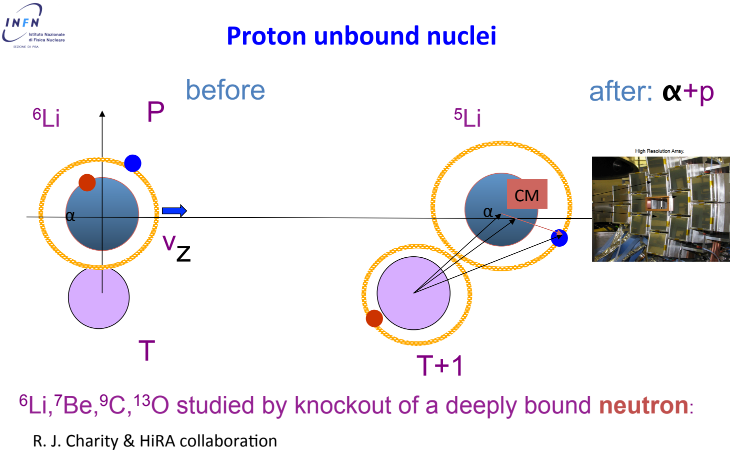


TABLE I: Summary of one-nucleon knockout results from ^{14}O at 53 MeV/nucleon. The calculated inclusive cross sections σ_{TC} from the transfer-to-the-continuum approach are shown and compared to the measured (σ_{exp}) cross sections. Theoretical spectroscopic factors C^2S are calculated with the WBT interaction [?]. Reduction factors are indicated and defined as R_f in order to distinguish from the strong absorption radius notation (R_s).

Res.	E (MeV)	J^π	σ_{exp} (mb)	C^2S	σ_{sp} (mb)	$\sigma_{sp}(no_p)$ (mb)	σ_{TC} (mb)	$\sigma_{TC}(no_p)$ (mb)	R_f
^{13}N	0.0	$1/2^-$	58(4)	1.83	34.18		53		0.91
^{13}O	0.0	$3/2^-$	14(1)	3.15	10.94	8.6	34.47	27.1	0.52

Proton unbound nuclei via invariant mass method

Interest: Two-proton radioactivity vs. 2n-halo by isospin symmetry
^{5}He, ^{6}He,^{8}He,^{12}Be and IMME

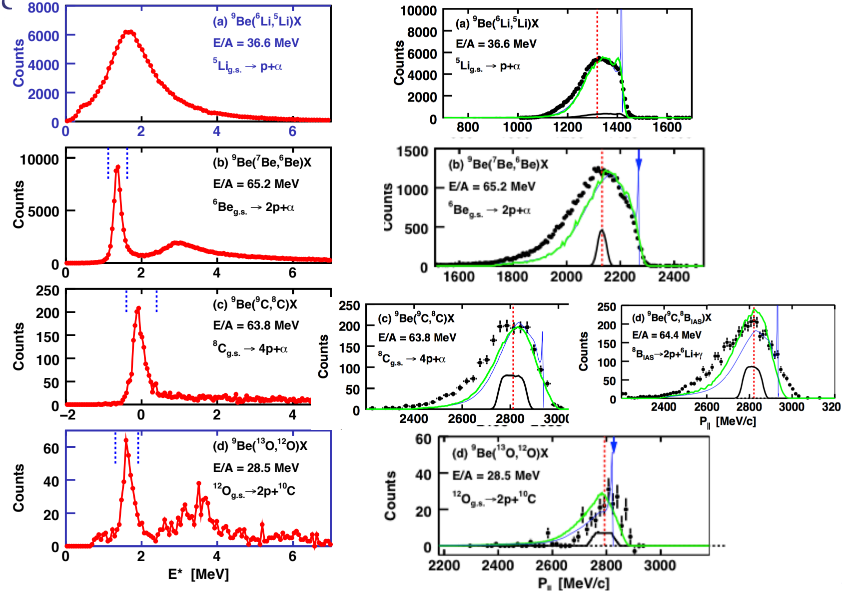


Proton unbound nuclei

^{6}Li,^{7}Be,^{9}C,^{13}O studied by knockout of a deeply bound **neutron**:

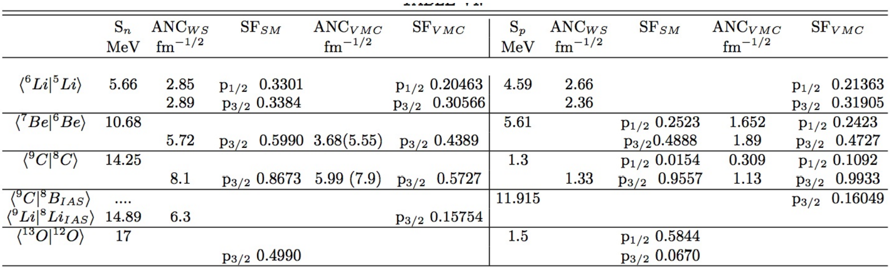
R. J. Charity & HiRA collaboration

Data: R. J. Charity and the HiRA collaboration, **preliminary**. Calculations: G. Salvioni & AB



Structure inputs: Shell model and "ab initio" Variational MonteCarlo

SF_{SM} by Mihai Horoi, private communication.
SF_{VMC} from R. Wiringa website http://www.phy.anl.gov/theory/research/overlap/,
ANC_{VMC} from Kenneth M. Nollett and R. B. Wiringa, PRC83, 041001(R) (2011).



	S_n MeV	ANC_{WS} $fm^{-1/2}$	SF_{SM}	ANC_{VMC} $fm^{-1/2}$	SF_{VMC}	S_p MeV	ANC_{WS} $fm^{-1/2}$	SF_{SM}	ANC_{VMC} $fm^{-1/2}$	SF_{VMC}
$\langle ^6Li \vert ^5Li \rangle$	5.66	2.85	$p_{1/2}$ 0.3301		$p_{1/2}$ 0.20463	4.59	2.66			$p_{1/2}$ 0.21363
		2.89	$p_{3/2}$ 0.3384		$p_{3/2}$ 0.30566		2.36			$p_{3/2}$ 0.31905
$\langle ^7Be \vert ^6Be \rangle$	10.68					5.61		$p_{1/2}$ 0.2523	1.652	$p_{1/2}$ 0.2423
		5.72	$p_{3/2}$ 0.5990	3.68(5.55)	$p_{3/2}$ 0.4389			$p_{3/2}$0.4888	1.89	$p_{3/2}$ 0.4727
$\langle ^9C \vert ^8C \rangle$	14.25					1.3		$p_{1/2}$ 0.0154	0.309	$p_{1/2}$ 0.1092
		8.1	$p_{3/2}$ 0.8673	5.99 (7.9)	$p_{3/2}$ 0.5727		1.33	$p_{3/2}$ 0.9557	1.13	$p_{3/2}$ 0.9933
$\langle ^9C \vert ^8B_{IAS} \rangle$	....					11.915				$p_{3/2}$ 0.16049
$\langle ^9Li \vert ^8Li_{IAS} \rangle$	14.89	6.3			$p_{3/2}$ 0.15754					
$\langle ^{13}O \vert ^{12}O \rangle$	17					1.5		$p_{1/2}$ 0.5844		
			$p_{3/2}$ 0.4990					$p_{3/2}$ 0.0670		

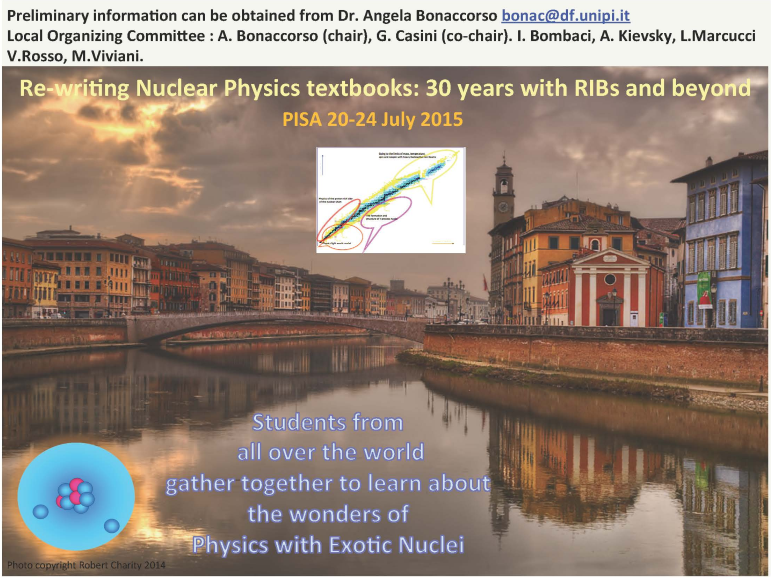
	E_{inc} A.MeV	σ_{exp} mb	σ_{-n} mb	σ_{-p} mb	$\sigma_{-n_{nop}}$ mb	r_s fm
$\langle ^6Li \vert ^5Li \rangle$	36.6	38.1	44.53	47.41	38.5	1.53
$\langle ^7Be \vert ^6Be \rangle$	65.2	28.1	34.14	15.22	27.5	1.38
$\langle ^9C \vert ^8C \rangle$	63.8	3.		1.57(-1p$_{CB}$)		1.4
			9.8	19.3 (22.3)	4.48	1.59
$\langle ^9C \vert ^8B_{IAS} \rangle$	64.4	1.24	...			1.4
$\langle ^9Li \vert ^8Li_{IAS} \rangle$			1.47			1.4
$\langle ^{13}O \vert ^{12}O \rangle$	28.5	2.5		2.32(-1p$_{CB}$)		1.5
			3.9	1.9	3.6	

(-1p$_{CB}$) direct proton Coulomb breakup

- Inclusive breakup reactions are dominated by final state interaction with the target at small incident energy: use as surrogate reaction
- At intermediate incident energy: strong interplay between projectile and target characteristics: ”deformed’ momentum distributions and cutoff effects. PROTON TARGET? see A. Obertelli and T. Aumann talks
- .... by the valence particle projectile momentum distribution at high incident energy: information on angular momentum of the initial state and possible dynamical core-target excitations
- Coincidence experiments of breakup particle experiments (using invariant mass method) are more INdependent on incident energy but possible dependence on the initial state: necessity to link with methods discussed above and angular correlation of the decaying particles... : one the most interesting experiment to make...and interpret? Can enlighten different channels and reaction mechanisms.
- IN ADDITION
- Elastic scattering experiments and or total reaction cross section measurements: they can tell us about the typical interaction distances and help fixing the optical potentials.
- In the future more and more strongly bound nuclei will be studied at lower energies at ISOL-type facilities. In Europe: HI-Isolde, SPES, Spiral2, EURISOL (?).

Some of my co-authors and collaborators in historical order.

D. M. Brink
N. Vinh Mau
G. Blanchon
F. Carstoiu
G. F. Bertsch
Ravinder Kumar
MAGNEX collaboration at INFN-LNS
F. Flavigny, A. Obertelli
R. J. Charity
G. Salvioni... see his talk at DREB2014 in Darmstadt



Preliminary information can be obtained from Dr. Angela Bonaccorso bonac@df.unipi.it
Local Organizing Committee : A. Bonaccorso (chair), G. Casini (co-chair). I. Bombaci, A. Kievsky, L.Marcucci V.Rosso, M.Viviani.

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