Second 0^+ state of unbound ^{12}O via the (*p*, *t*) reaction

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Direct Reactions with Exotic Beams (DREB2016)

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^{12}O (Z = 8, N = 4) mirrors ^{12}Be with N = 8

N = 8

^{16}O

^{14}C

^{12}Be

0_2^+ isomer in ^{12}Be

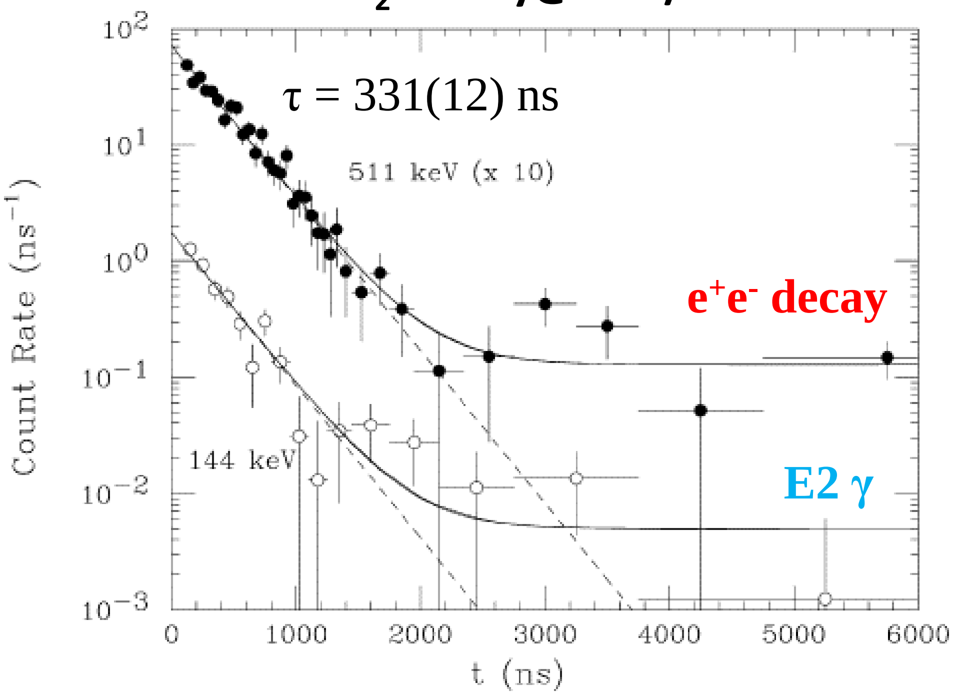
N = 8

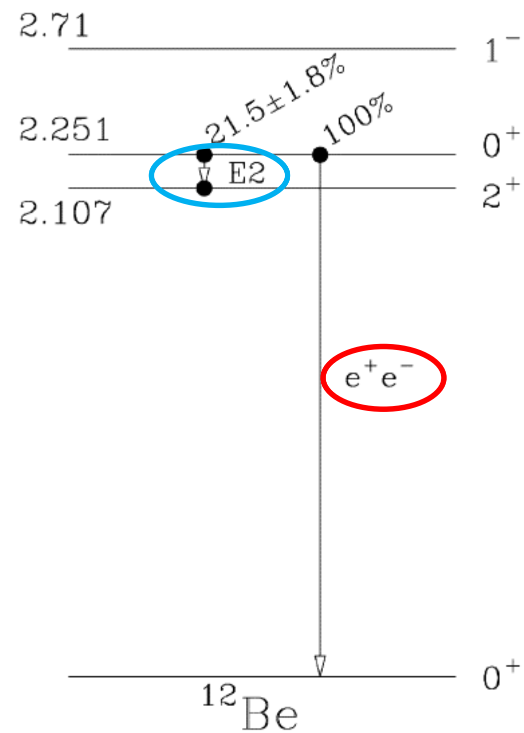
^{16}O

^{14}C

^{12}Be

0_2^+ decay@RIPS/RIKEN

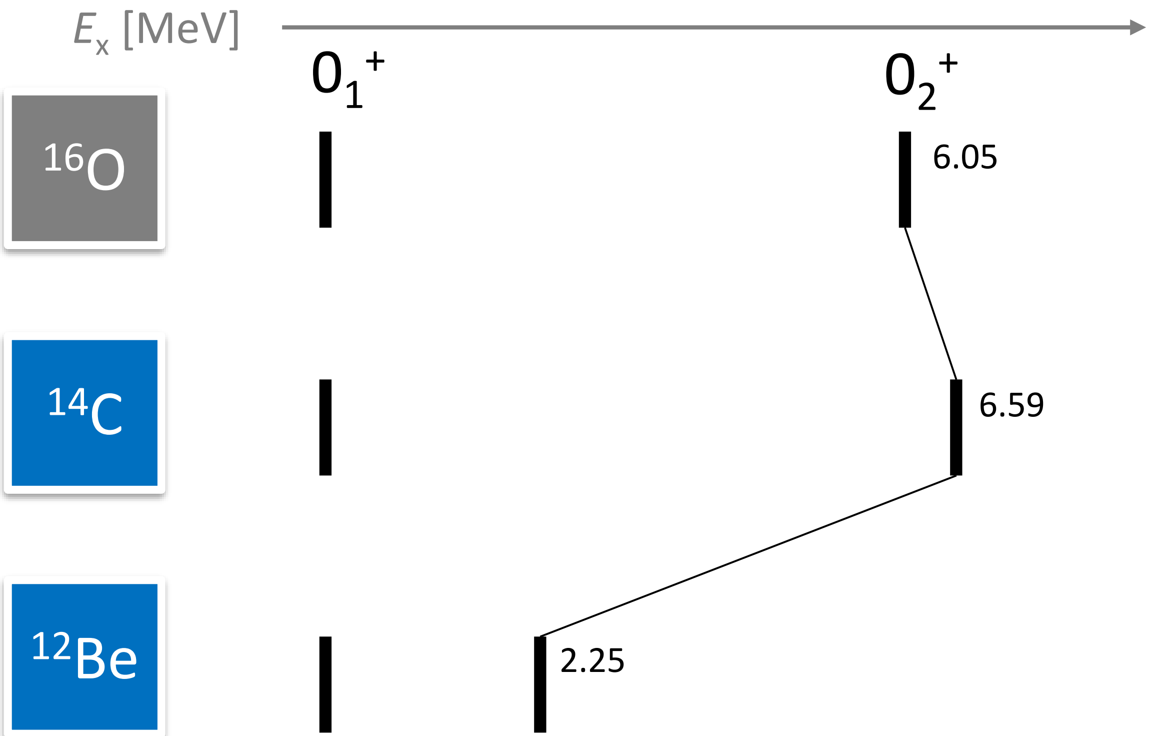


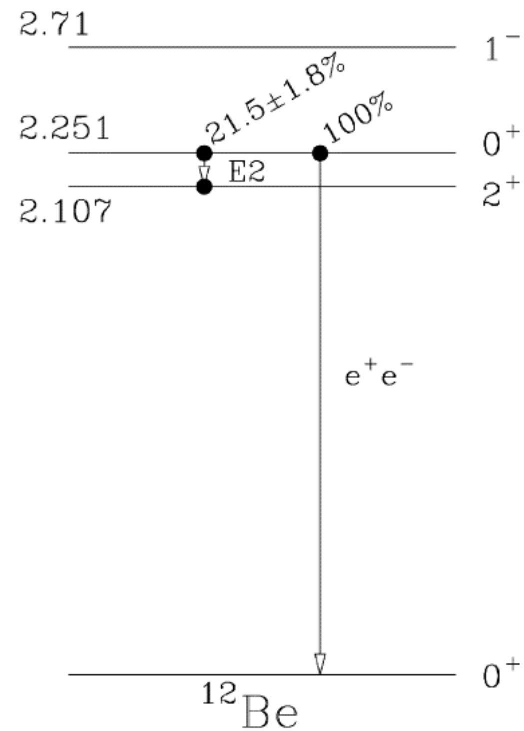


S. Shimoura *et al.*, Phys. Lett. B 560, 31 ('03)

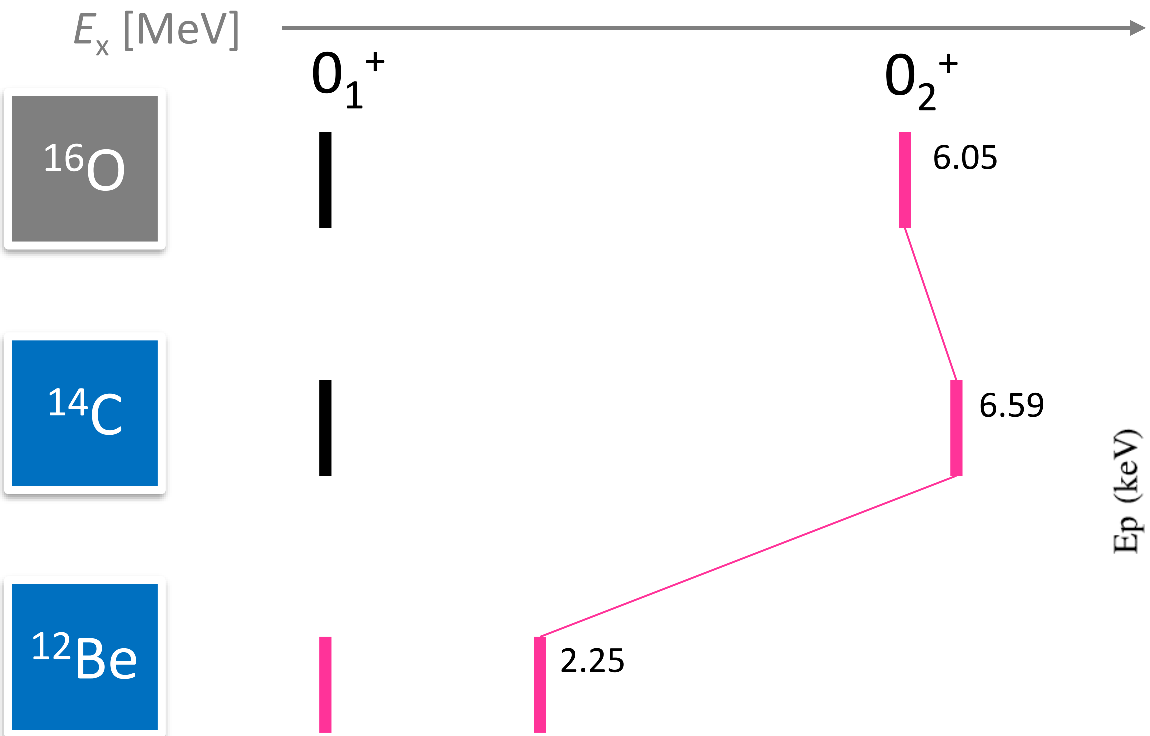
S. Shimoura *et al.*, Phys. Lett. B 654, 87 ('07)

0_2^+ energies and shell quenching at $N = 8$

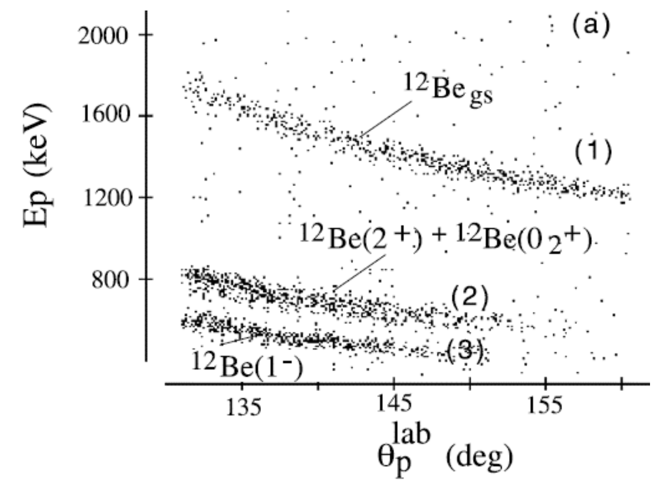




Intruder $2s_{1/2}$ component in 0_1^+ and 0_2^+



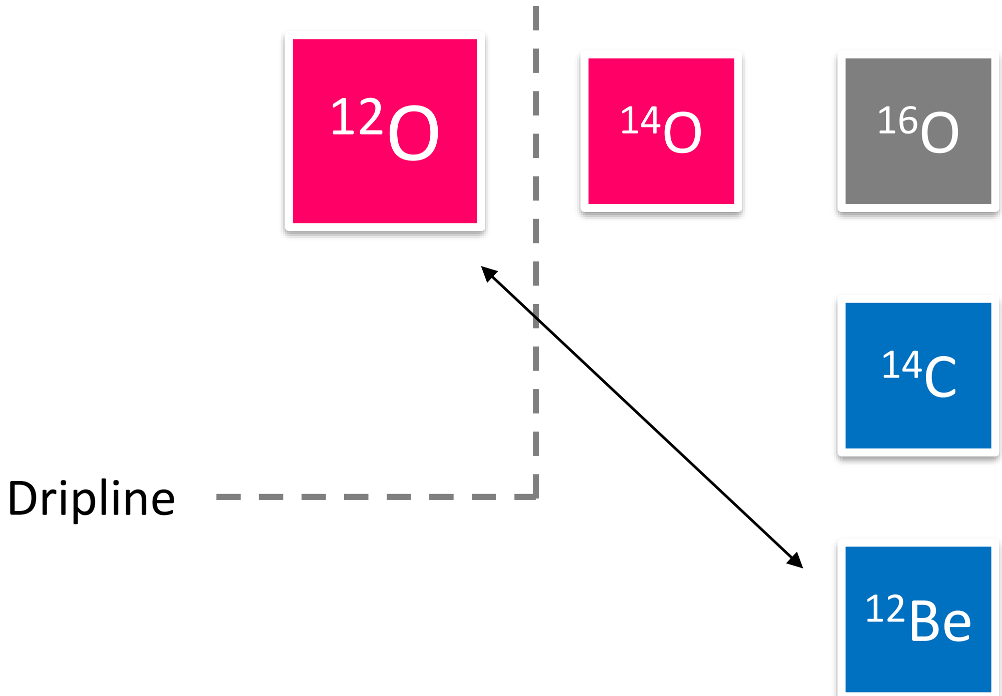
$^{11}Be(d,p)^{12}Be$ @ISAC II/Triumf



J	(l)	E_{exp} (MeV)	S_{exp}
0^+	(s)	0.00	$0.28^{+0.03}_{-0.07}$
0^+	(s)	2.24(2) [13]	$0.73^{+0.27}_{-0.40}$

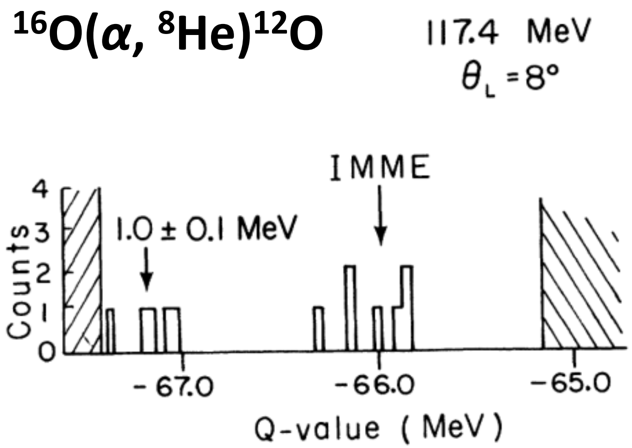
R. Kanungo *et al.*, Phys. Lett. B 682, 391, 108 ('10)

^{12}O and its mirror symmetry

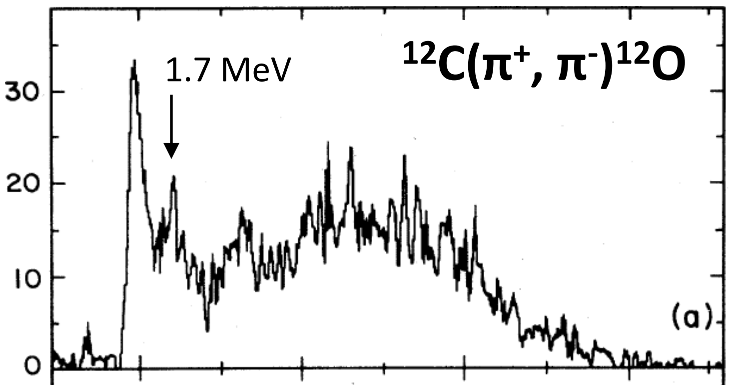


- Shell breaking at $Z = 8$?
- Weakly-bound $2s_{1/2}$
  → Reduces Coulomb energy ?
  → Enhances Thomas-Ehrman shift ?

Experimental history

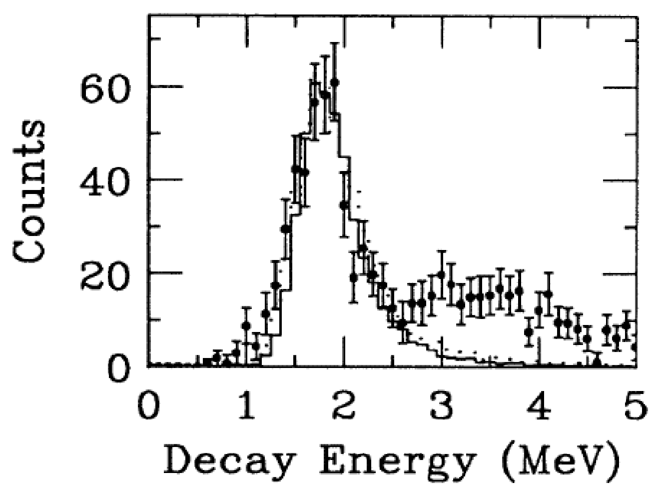


G.J. KeKelis *et al.*, Phys. Rev. C 17, 1929 ('78)



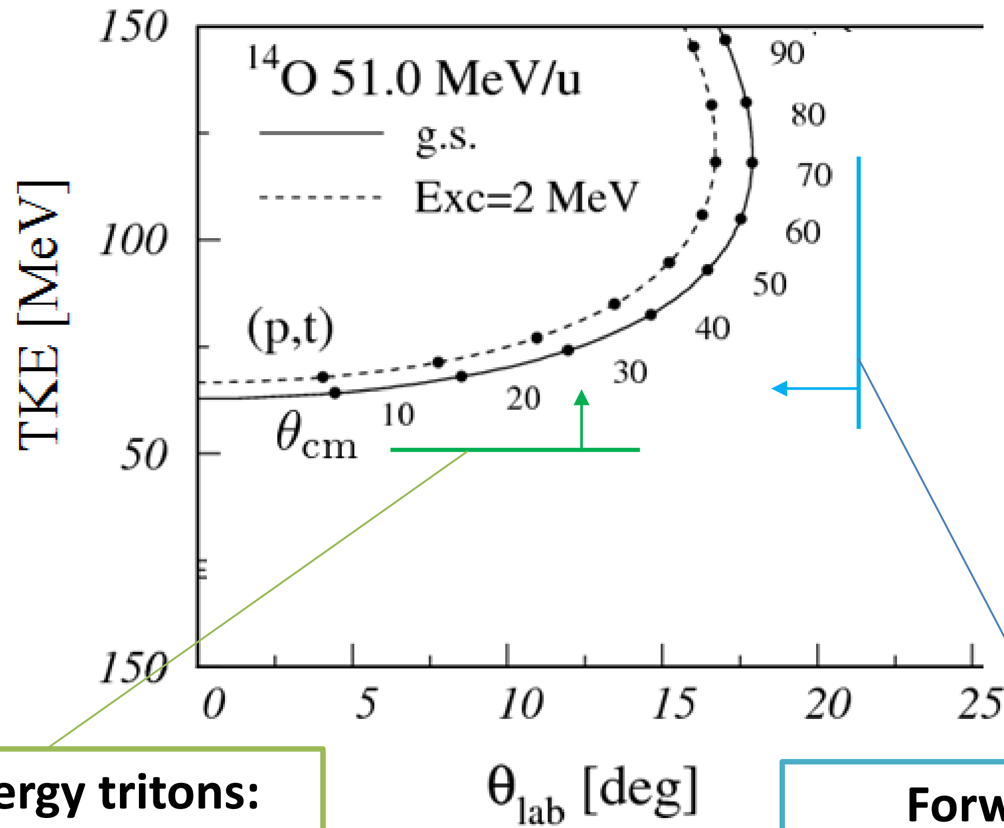
S. Mordechai *et al.*, Phys. Rev. C 32, 999 ('85)

^{13}O 1*n* knockout @NSCL



R.A. Kryger *et al.*, Phys. Rev. Lett. 74, 860 ('95)

Missing mass method with (*p*, *t*) reaction

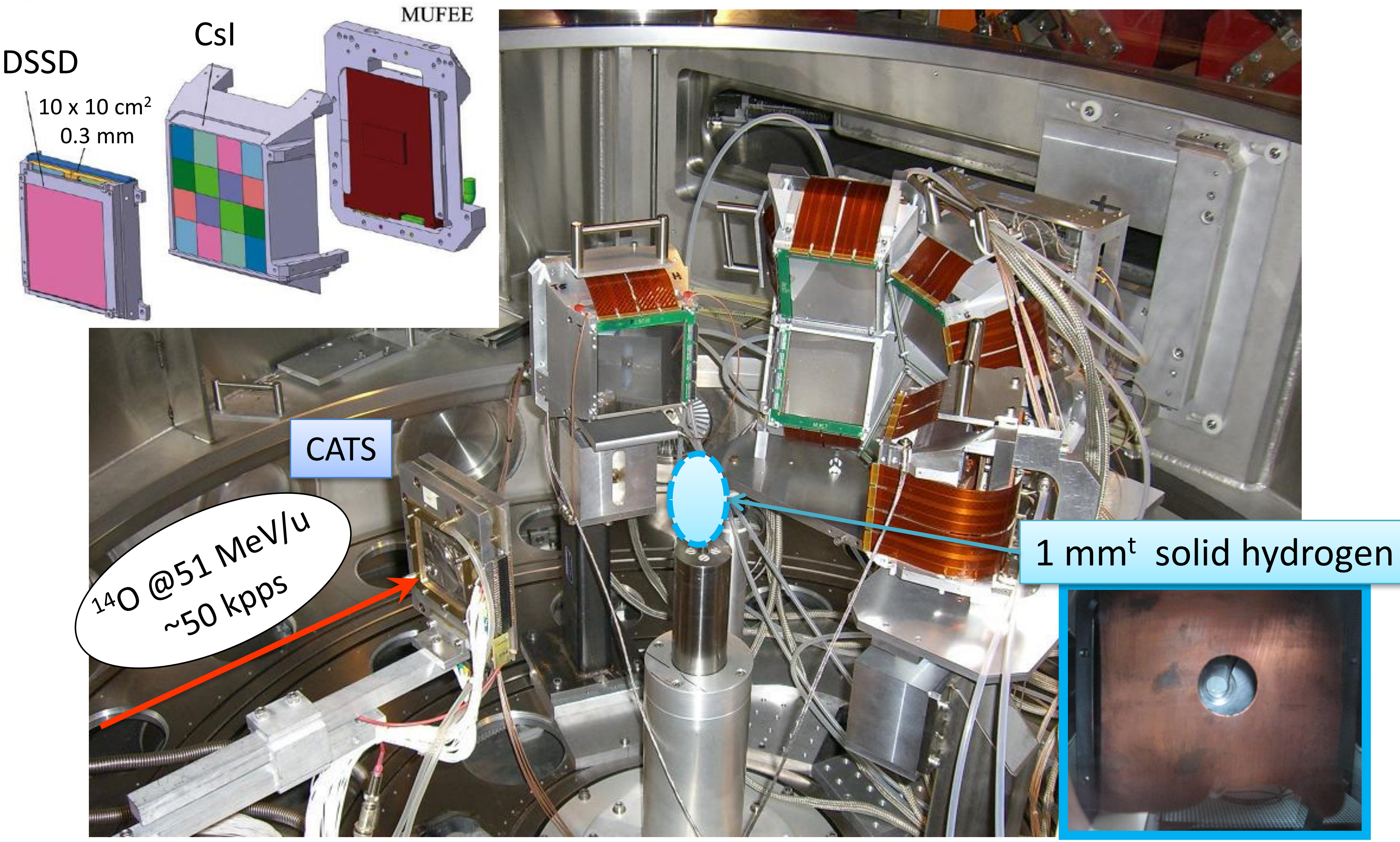


High energy tritons:
cryogenic hydrogen target
(1 mm ~7 mg/cm^2)

Forward focus:
High efficiency by Si array

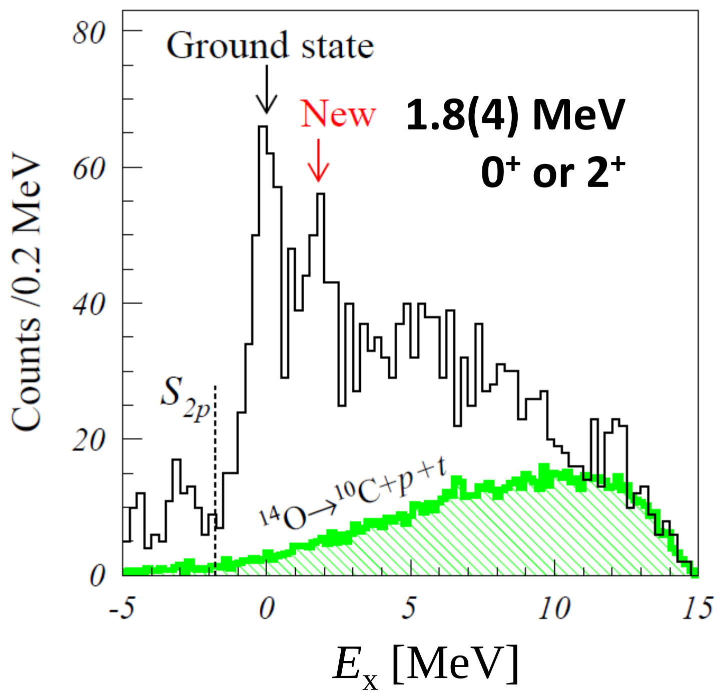
Very efficient measurement

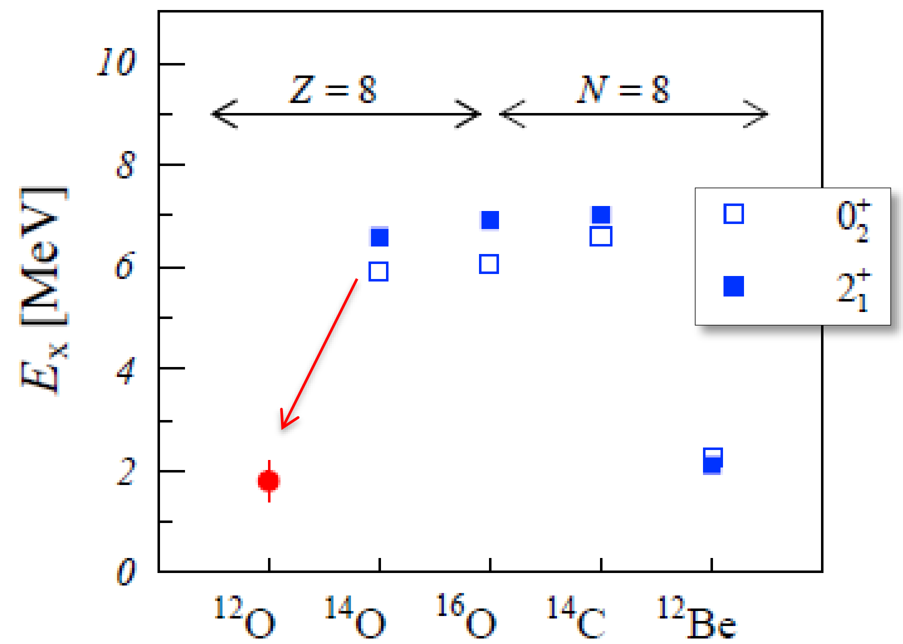
Setup



CATS: S. Ottini-Hustache *et al.*, Nucl. Instr. Meth. A 431, 476 ('99).
Target: P. Dolégiéviez *et al.*, Nucl. Instr. Meth. A 564, 32 ('06).
MUST2: E. Pollacco *et al.*, Eur. Phys. J. A 25, 287 ('05).

First study (1 day) at SPEG/GANIL

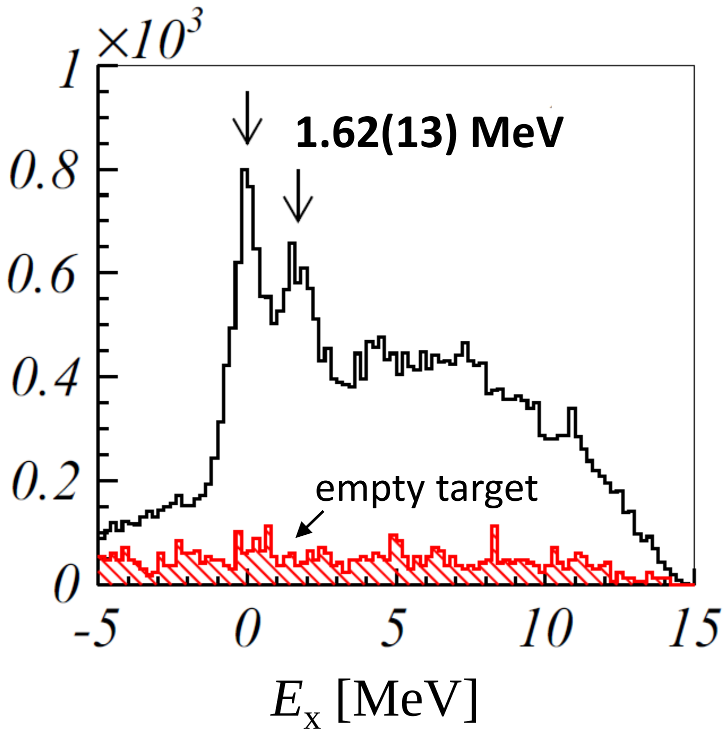


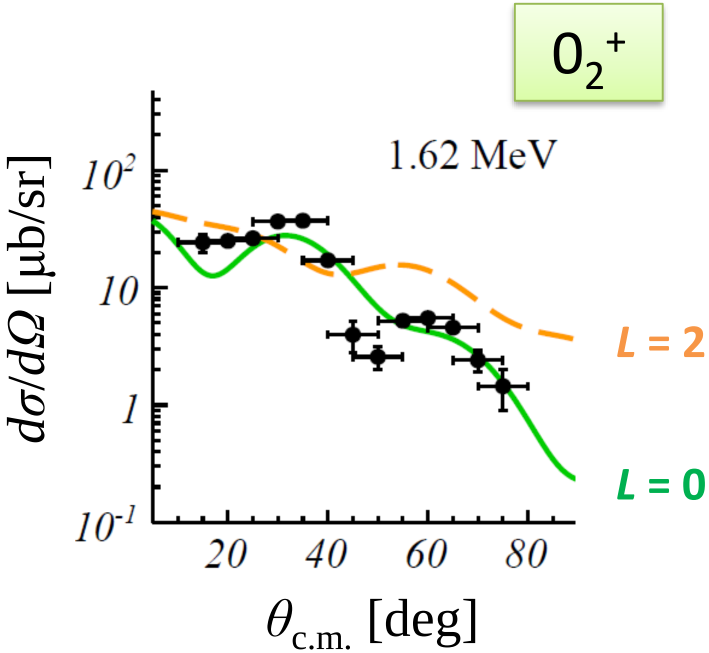


No shell closure at *Z* = 8

D. Suzuki, H. Iwasaki, D. Beaumel *et al.*, Phys. Rev. Lett. 103, 152503 ('09).
D. Suzuki, Euro. Phys. J. A 48, 130 ('12).

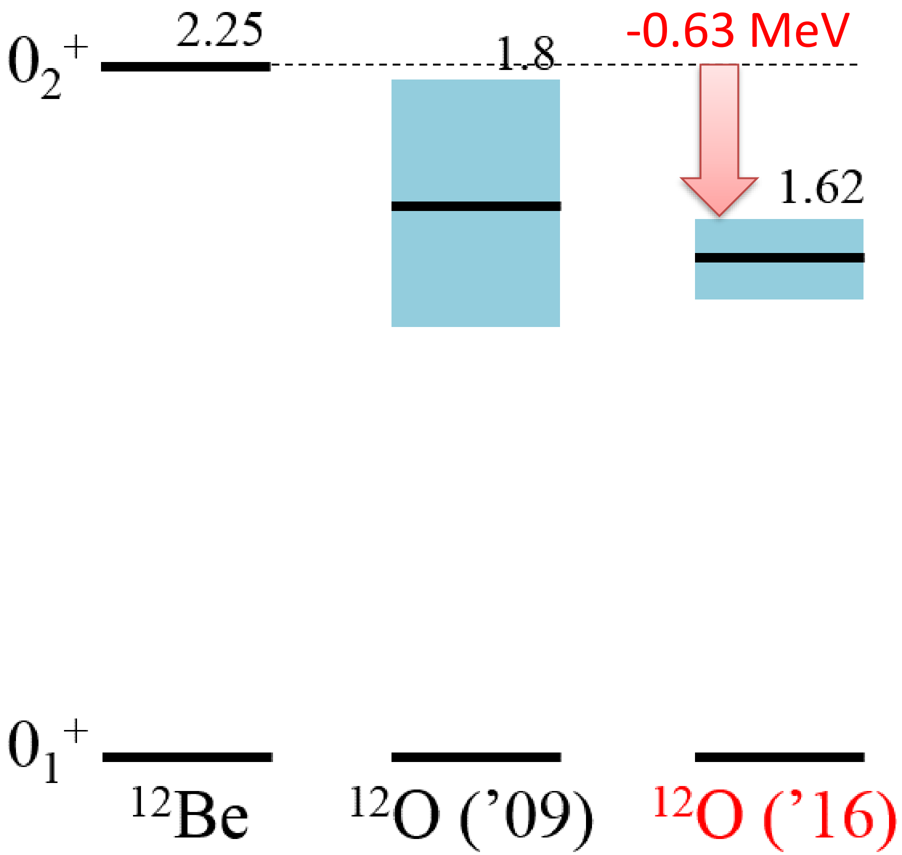
Second study (7 days) at LISE/GANIL





D. Suzuki, H. Iwasaki, D. Beaumel *et al.*, Phys. Rev. C 93, 024316 ('16)

Mirror energy difference of the 0_2^+ state

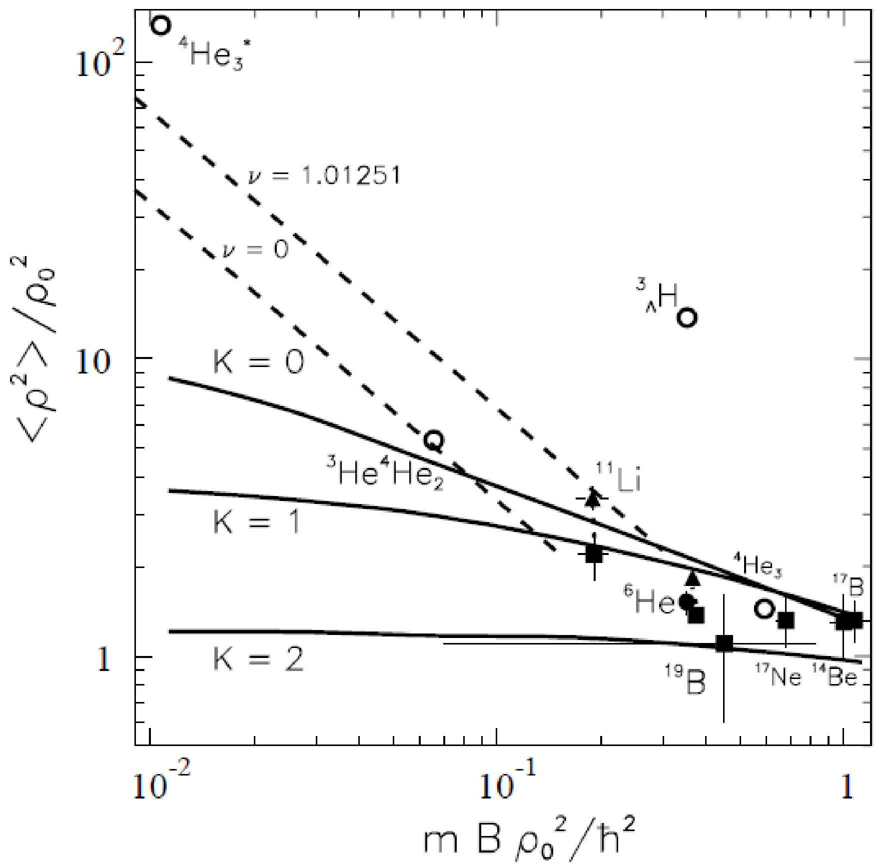


- How to quantify impact of weak binding to level shift?
- Systematics of 0^+ mirror pairs' energy differences
- Scaling for charge and mass (= size)

Riisager's universal scaling for 2*n* halo radii

K. Riisager, D.V. Fedrov, A.S. Jensen, Europhys. Lett. 49, 547 ('00)

Radius



Binding energy

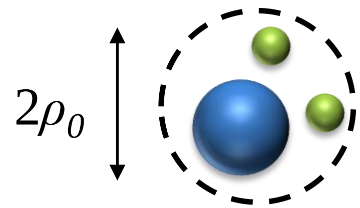
**B*: binding energy

Scaling by 3-body hyperradii

$$\rho_0^2 = \sum_{i<k} \frac{m_i m_k}{m m_{\text{tot}}} R_{ik}^2$$

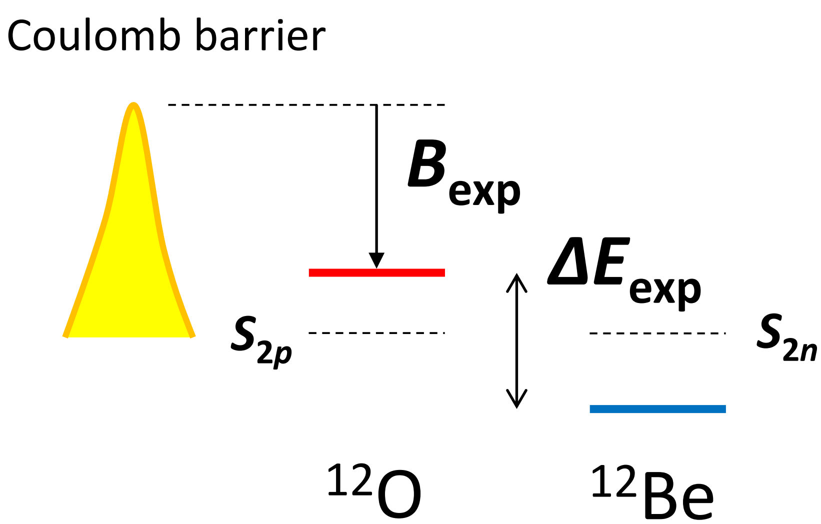
m: unit mass

R_{ik}: length for *i*-th and *k*-th particles

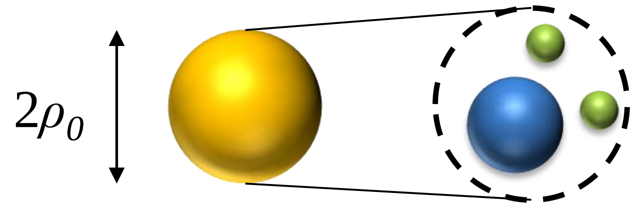


Scaling of mirror energy differences

Experimental observables



Scales



Riisager's universal scaling [1]

$$B(\rho_0) = \hbar^2/m\rho_0^2$$

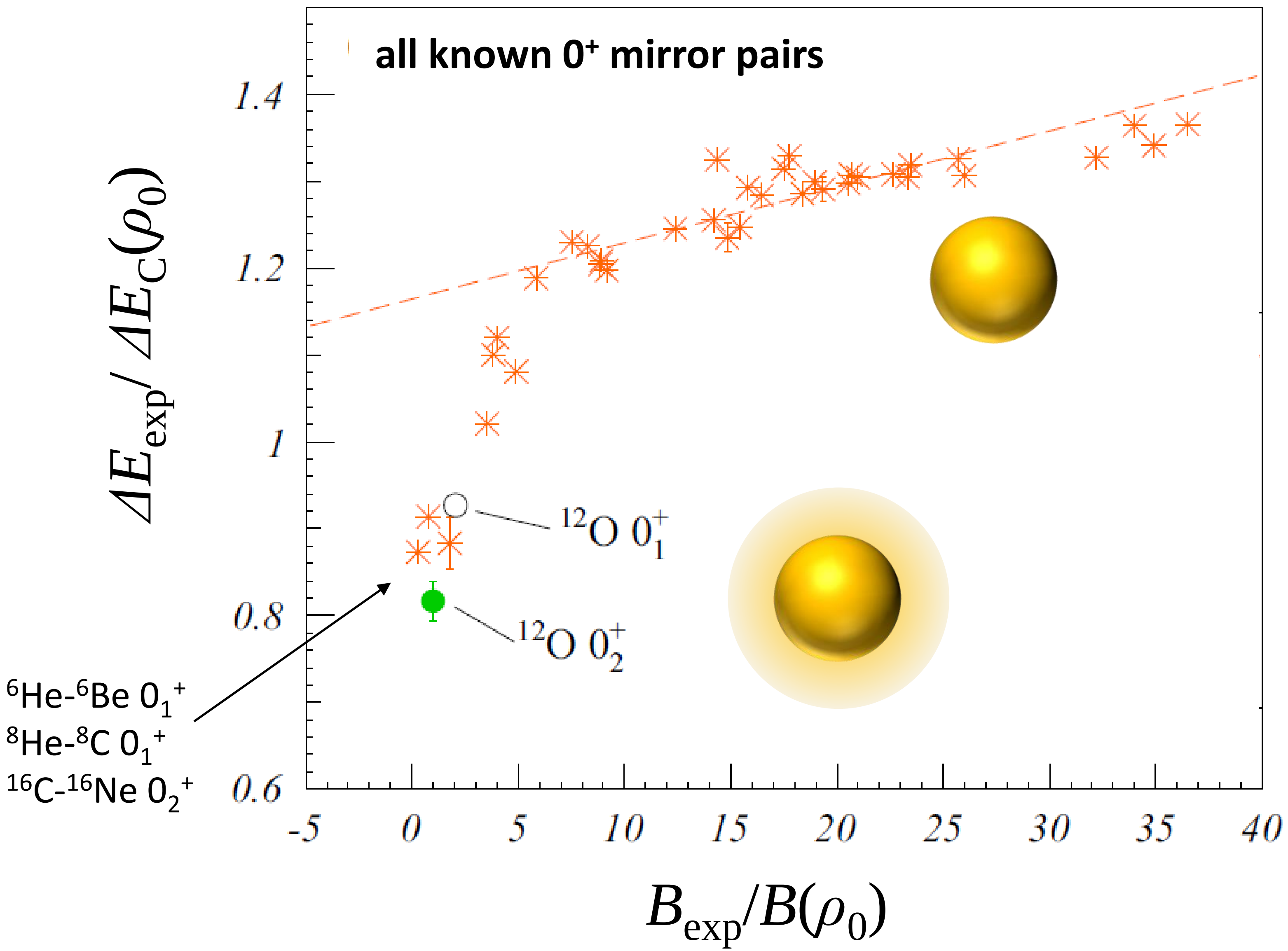
Coulomb energy with core in sphere [2]

$$\Delta E_C(\rho_0) = 2\alpha \frac{6(Z-2)}{5\rho_0}$$

[1] K. Riisager, D.V. Fedrov, A.S. Jensen, Europhys. Lett. 49, 547 ('00)
[2] A. Muta, T. Otsuka, Prog. Theo. Phys. Suppl. 142, 355 ('01)

Universality of 0^+ mirror energies

D. Suzuki *et al.*, Phys. Rev. C 93, 024316 ('16)



Summary

- Unbound ^{12}O was studied by the (p, t) reaction at GANIL.
- Missing mass spectra were obtained from tritons detected by MUST2 telescopes.
- The 0_2^+ state of ^{12}O was discovered at 1.62(13) MeV.
  - ❑ Shell closure disappearing at Z = 8
  - ❑ Level energy shift -0.63 MeV relative to ^{12}Be
- Systematics of known 0^+ states
  - ❑ Scaling relation of mirror energy differences and binding energies.
  - ❑ ^{12}O 0_2^+ state, under the influence of weak binding, represents the lowest energy difference.

Collaborators

H. Iwasaki, D. Beaumel, M. Assié, Y. Blumenfeld, N. De Séréville, S. Franchoo, S. Giron, J. Guillot, F. Hammache, F. Maréchal, A. Matta, L. Perrot, C. Petrache, A. Ramus, J-A. Scarpaci, I. Stefan

F. de Oliveira Santos, S. Grévy, D.Y. Pang, O. Sorlin, P.C. Srivastava, C. Stodel

A. Drouart, A. Gillibert, V. Lapoux, L. Nalpas, J. Pancin, E. Pollacco, P. Roussel-Chomaz

F. Naqvi, W. Rother

J. Gibelin

H. Baba, H. Otsu, H. Sakurai, S. Terashima

S. Mitimasa

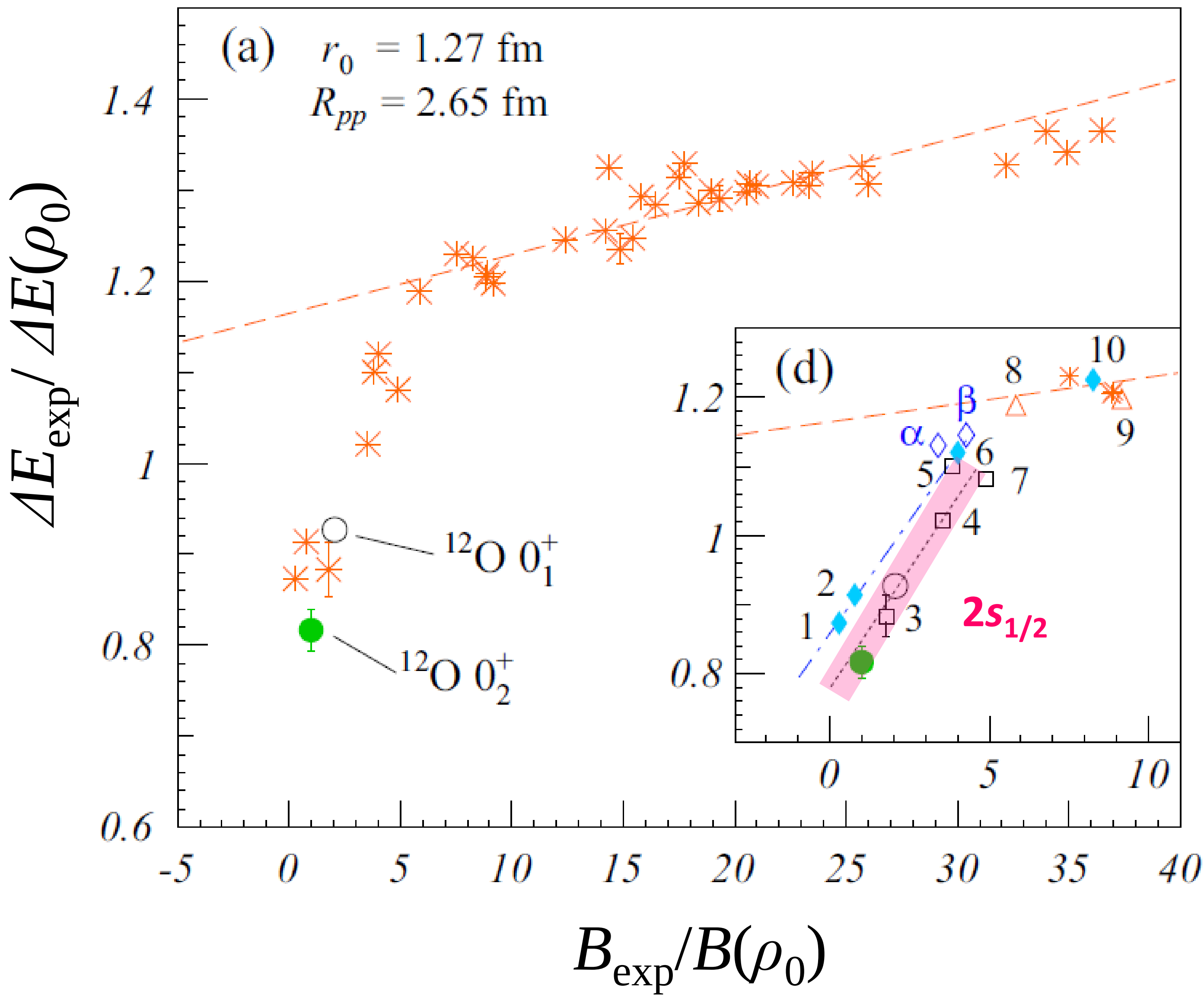
H. Okamura

N. Keeley

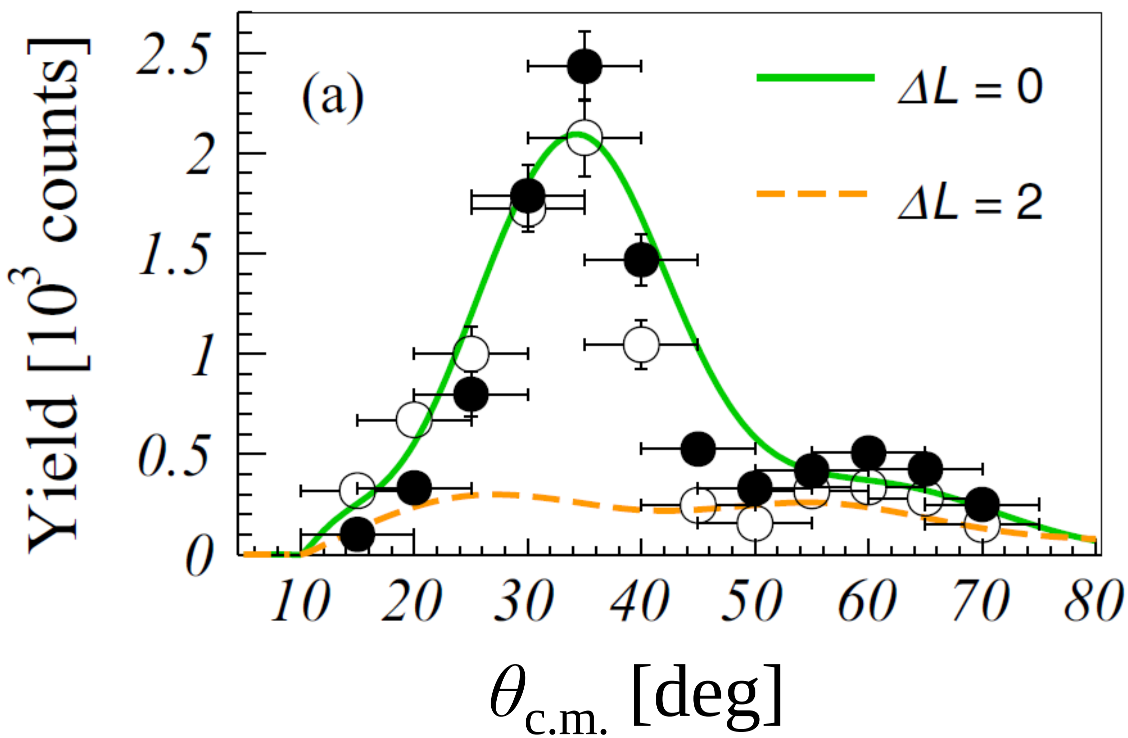
Backup

Systematics of all known 0⁺ mirror pairs

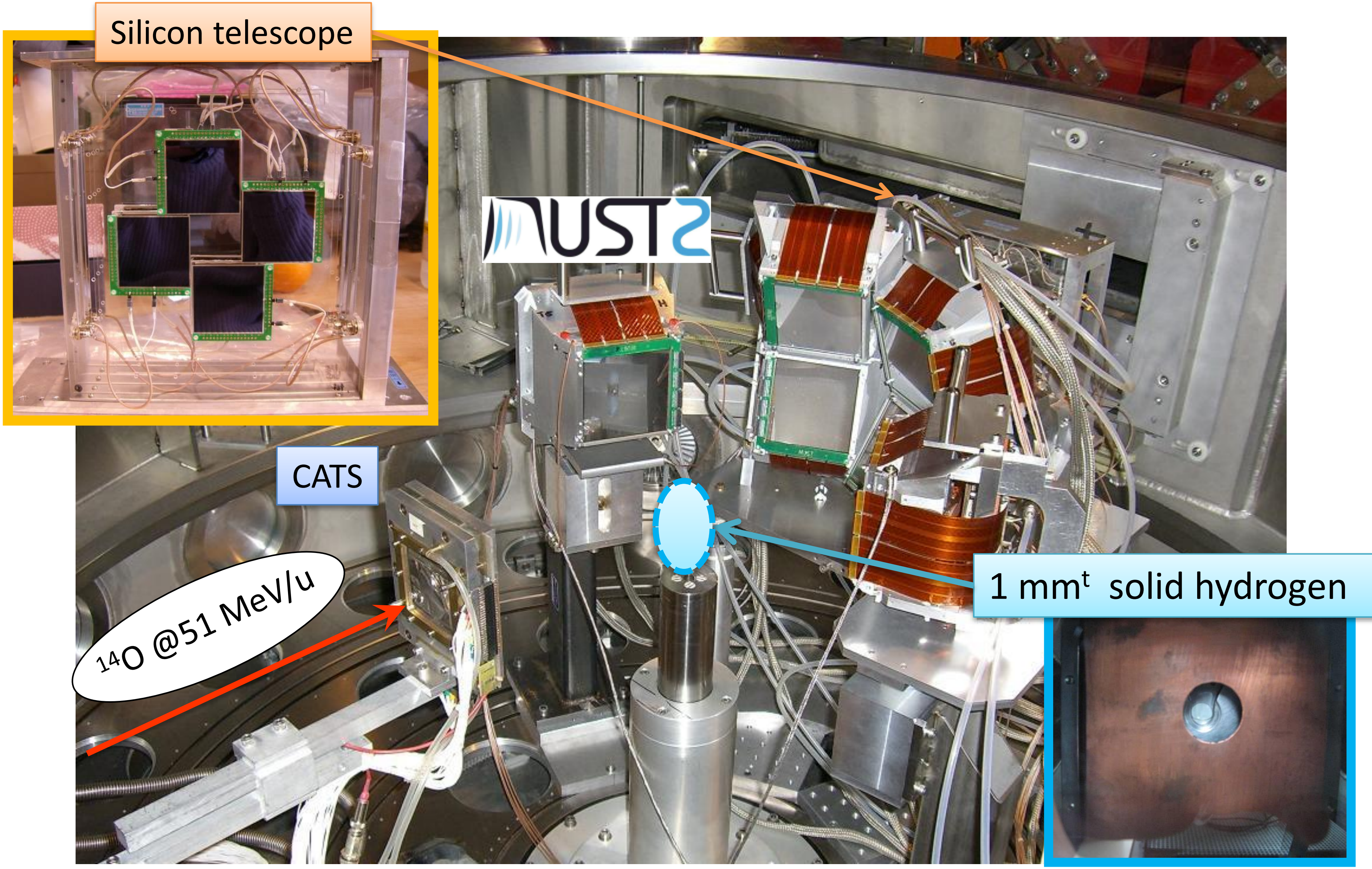
D. Suzuki *et al.*, Phys. Rev. C 93, 024316 ('16).



Level mixing



Setup



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Target: P. Dolegieviez *et al.*, Nucl. Instr. Meth. A 564, 32 (2006).
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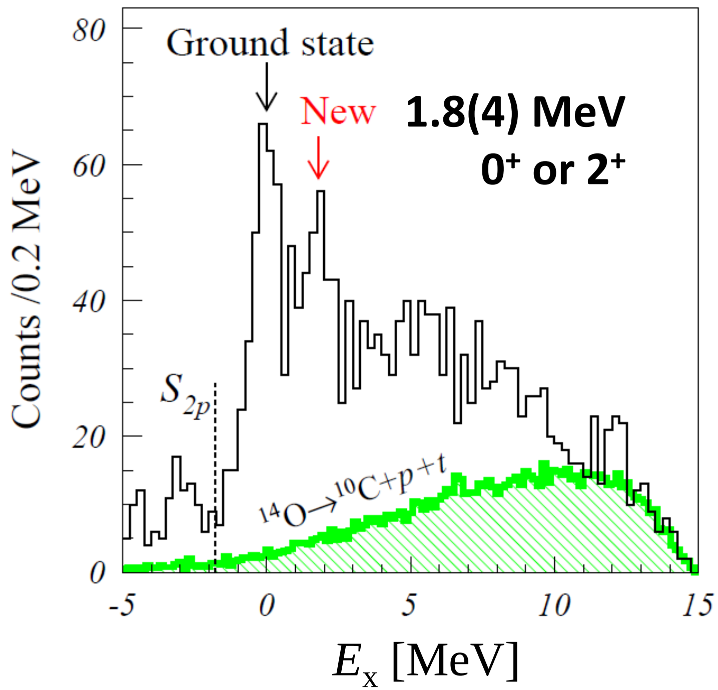
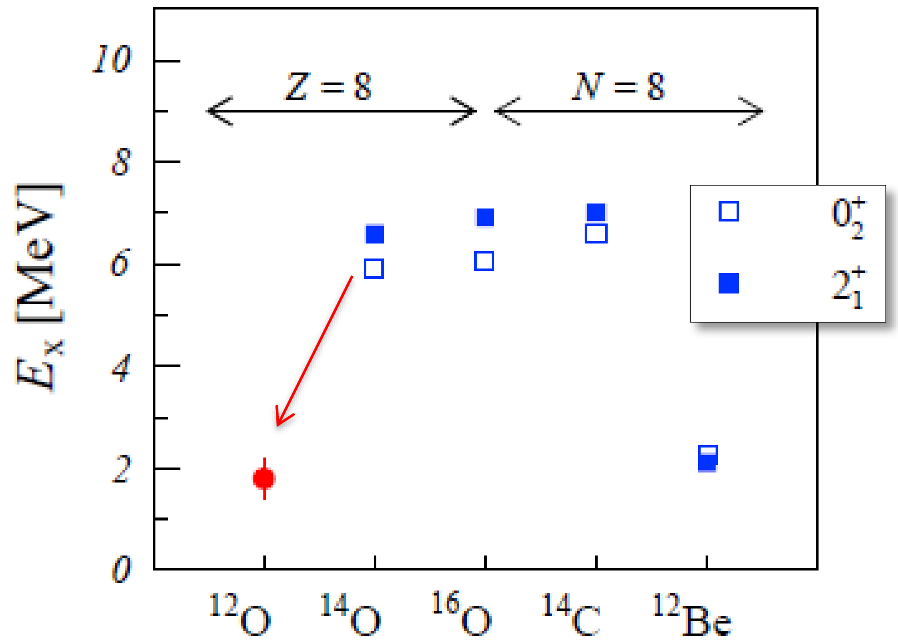
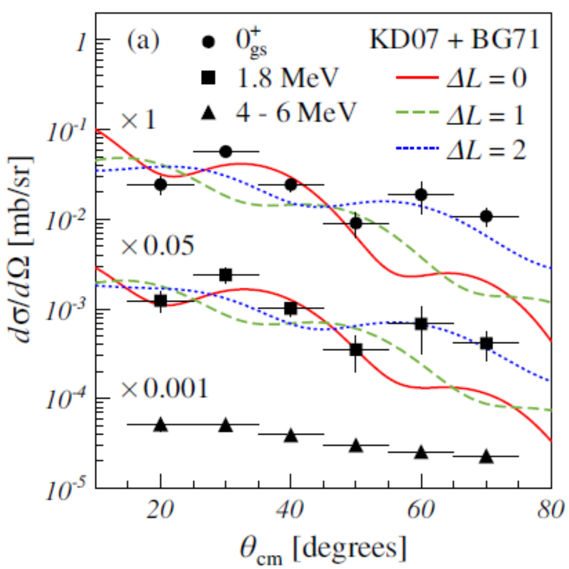
First study (1 day) at SPEG/GANIL







D. Suzuki *et al.*, Phys. Rev. Lett. 103, 152503 ('09).
D. Suzuki, Euro. Phys. J. A 48, 130 ('12).

Z = 8 shell closure vanishes

Radius & hyperradius

$$\rho_0^2 = \frac{2(a-2)}{a} R_{cp}^2 + \frac{1}{a} R_{pp}^2$$

K. Riisager, D.V. Fedrov, A.S. Jensen, Europhys. Lett. 49, 547 ('00)

$$R_{cp} = 1.27(a-2)^{1/3}\mathrm{fm} \longleftarrow$$

Assumed. Not given in the literatures.

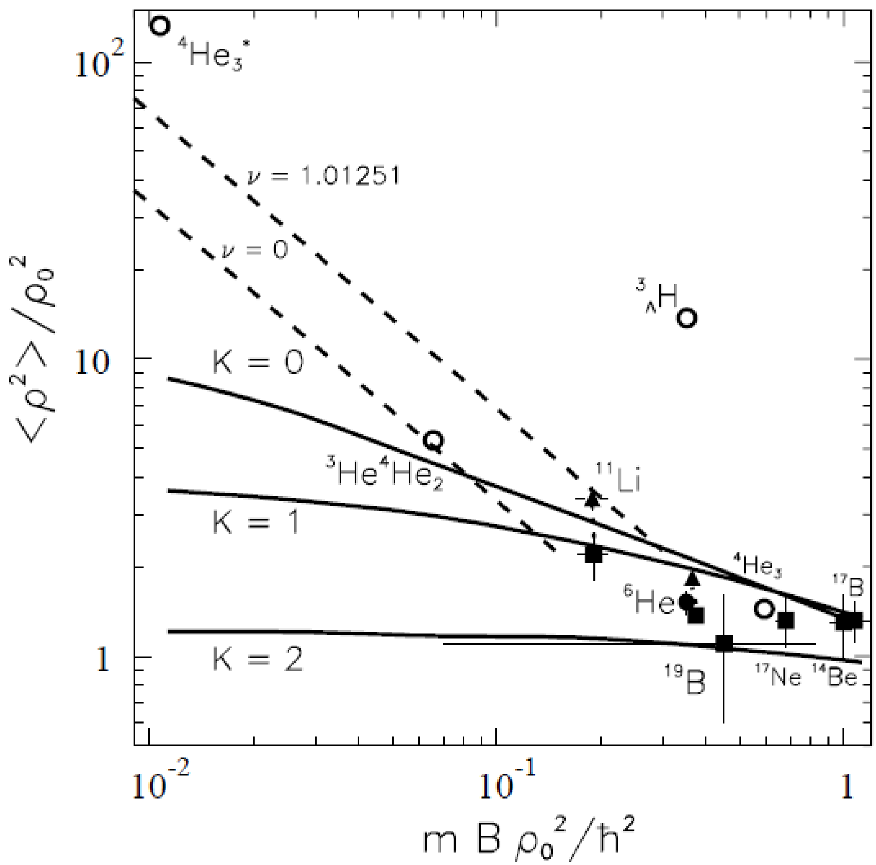
$$R_{pp} = 2.65\ \mathrm{fm} \longleftarrow$$

D.V. Fedrov, A.S. Jensen, K. Riisager, Phys. Rev. C 49, 201 ('94)

a: mass number of the nucleus

	ρ_0 [fm]	**S_{2n} [MeV]**	**B_{3BD} ***
^{6}He	2.57	0.975	0.321
^{11}Li	3.47	0.369	0.223
^{14}Be	3.87	1.266	0.949
^{17}B	4.21	1.330	1.178

*) Present work: $B_{3BD} = mS_{2n}\rho_0/h^2$



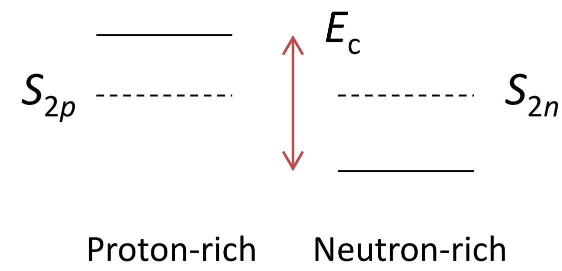
The calculated values in the table reasonably agree with the values in the literature.

MED & binding energies

Mirror energy difference (experimental values)

$$E_c = (S_{2n} - E_x^n) - (S_{2p} - E_x^p)$$

S_{2n}: 2*n* separation energy (neutron-rich partner)
S_{2p}: 2*p* separation energy (proton-rich partner)
E_x^n: excitation energy (neutron-rich state)
E_x^p: excitation energy (proton-rich state)



Mirror energy difference (reference)

$$U_{3BD} = 2\alpha \frac{6(Z-2)}{5\rho_0}$$

z: atomic number of proton-rich partner

A. Muta, T. Otsuka,
Prog. Theo. Phys. Suppl. 142, 355 ('01)

Binding energy for 2*p* (unscaled)

$$B = U_{\mathrm{barrier}} + S_{2p} - E_x^p$$

Coulomb barrier energy for 2*p*

$$U_{\mathrm{barrier}} = 2\alpha \frac{Z-2}{\rho_0}$$

Assumed. Not given in the literatures.

Binding energy for 2*p* (scaled)

$$B_{3BD} = mB\rho_0^2/\hbar^2$$

K. Riisager, D.V. Fedrov, A.S. Jensen,
Europhys. Lett. 49, 547 ('00)

m = 938.27 MeV/c^2 (unit mass)

For 2 body scaling, replace ρ_0 with R_{cp}