RIBF Nuclear Physics Seminar
March 29, 2016 RIBF, Wako

Illuminating alpha clusters in an active target and time projection chamber

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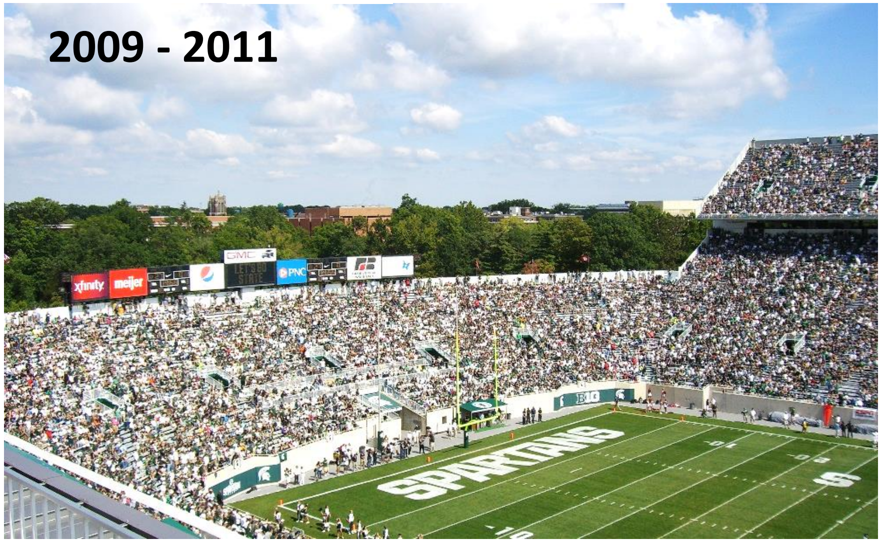
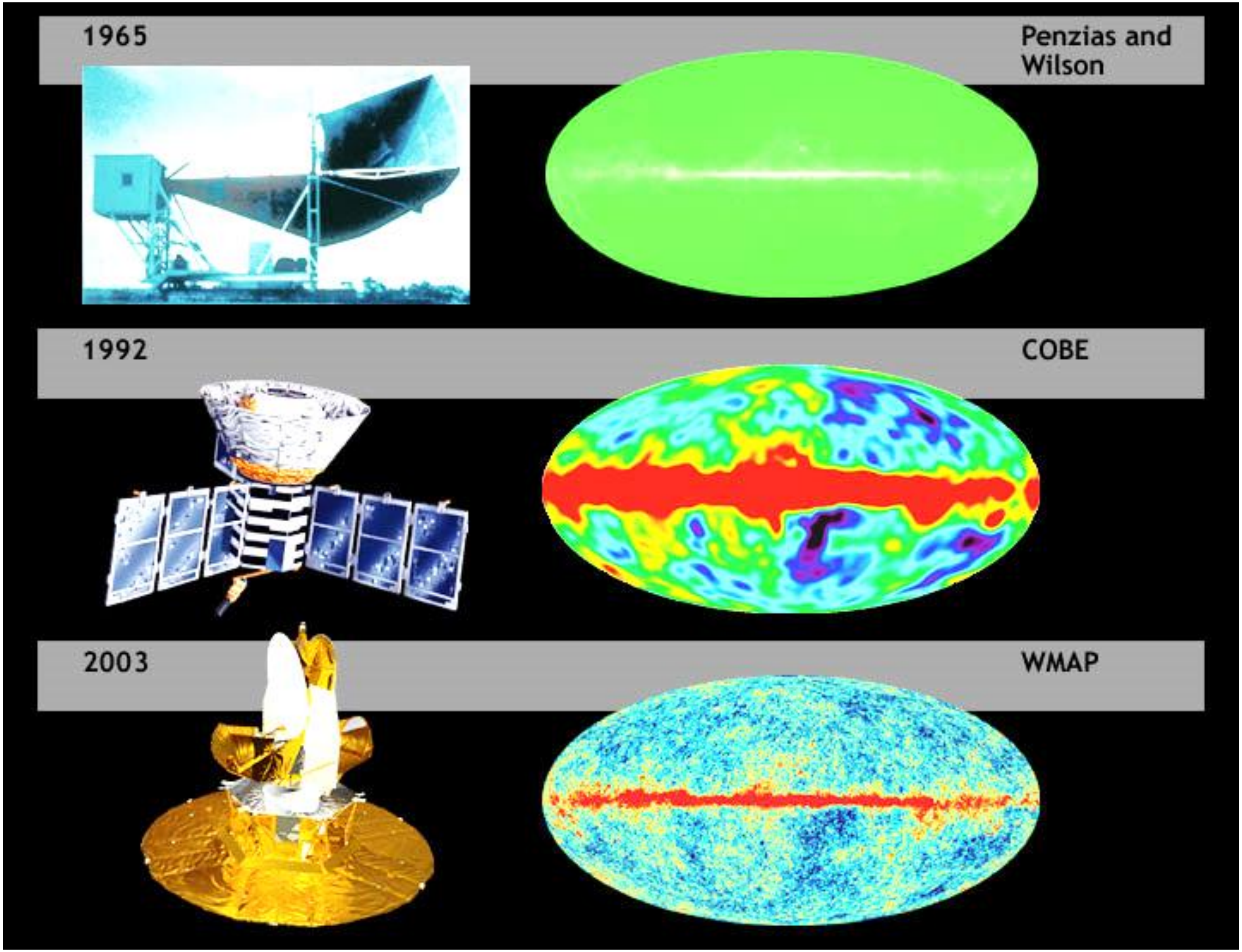


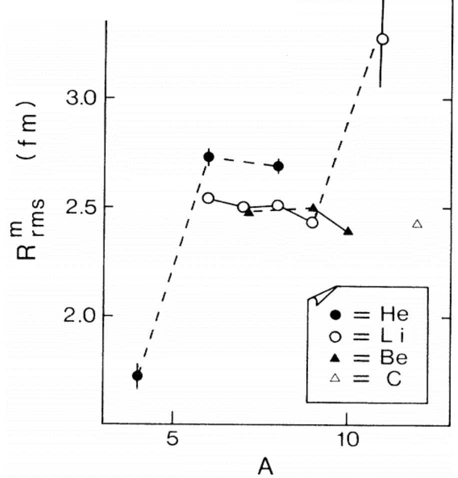
Uniformity to anisotoropy

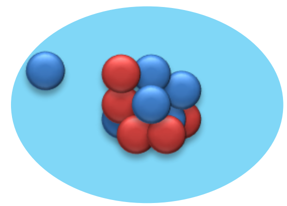


NASA (http://map.gsfc.nasa.gov)

Imhomogenious nuclei

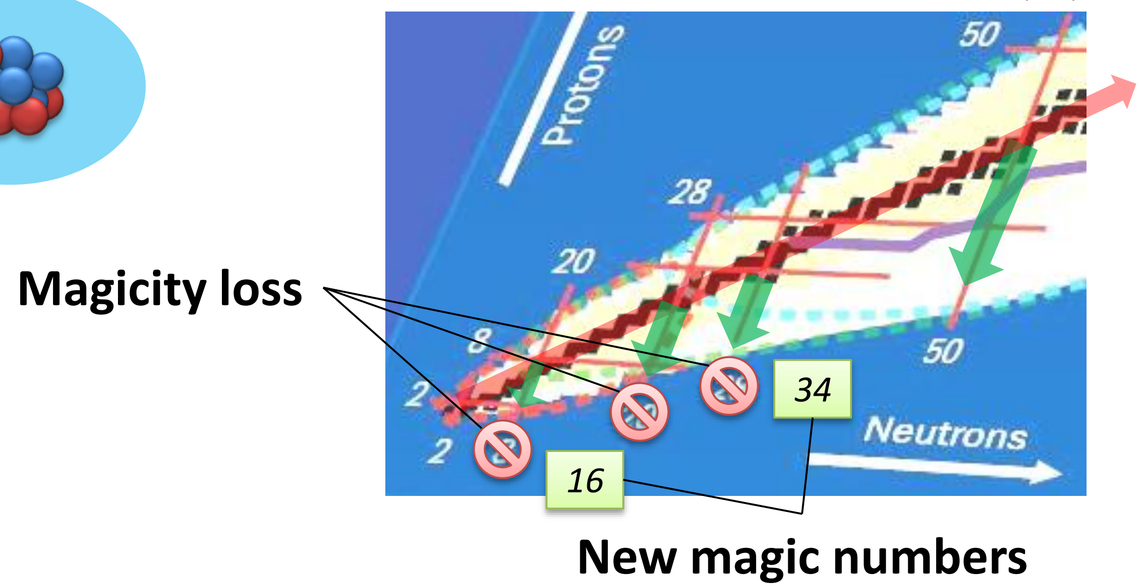
Neuton halo



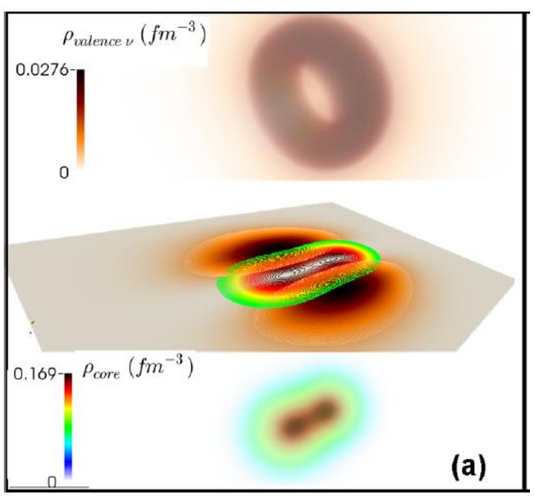


I. Tanihata *et al.* Phys. Rev. Lett. 55, 2676 ('85)

G.F. Bertsch *et al.*, SciDAC Review 6, 42 ('07)

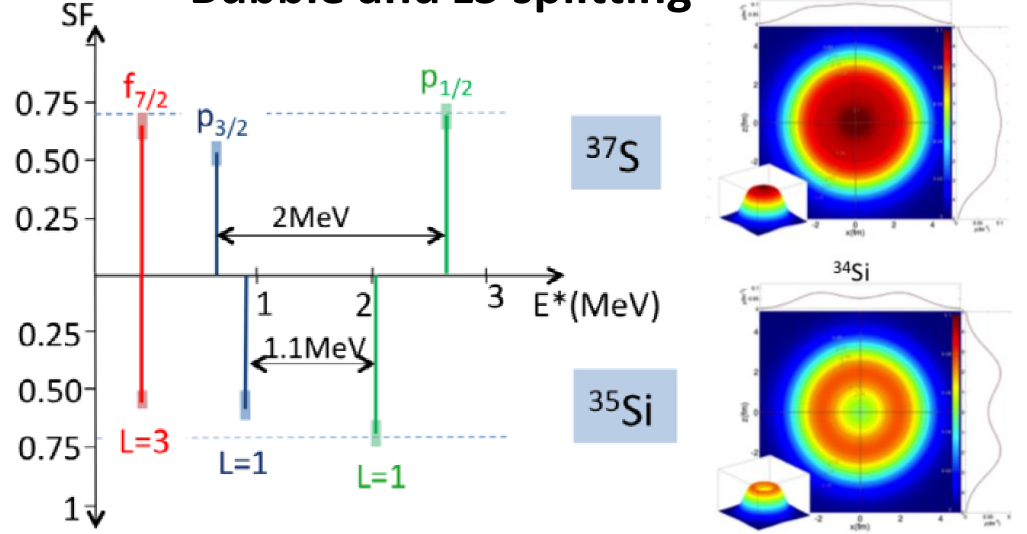


Alpha clustering



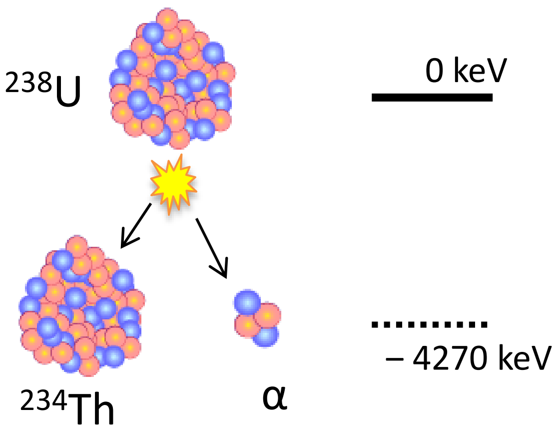
J-P. Ebran *et al.* Phys. Rev. C 90, 054329 ('14)

Bubble and *LS* splitting



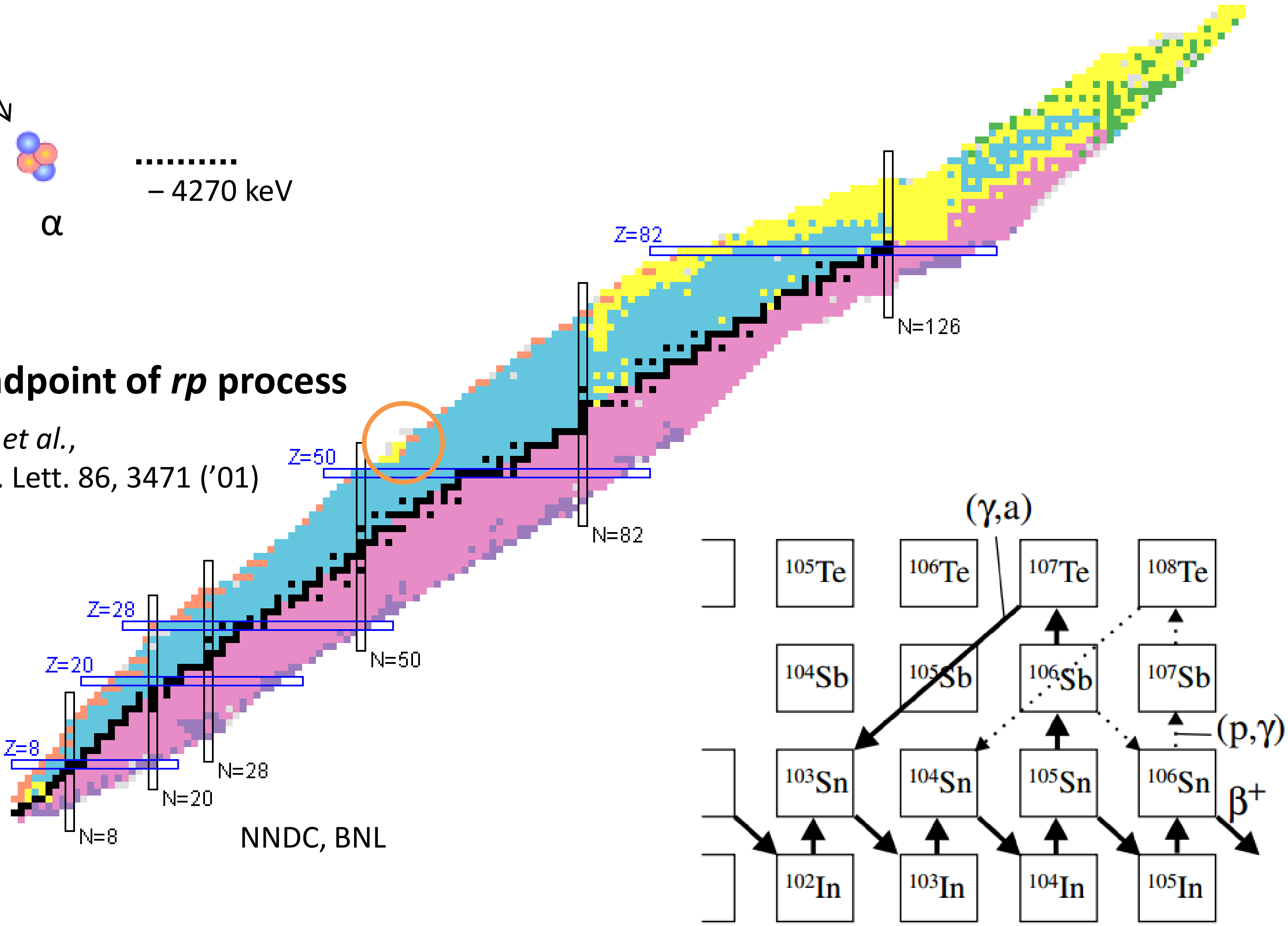
O. Sorlin, M-G. Porquet, Phys. Scr. T152, 014003 ('13)

Alpha decay (Rutherford, 1899)



Endpoint of *rp* process

H. Schatz *et al.*,
Phys. Rev. Lett. 86, 3471 ('01)



NNDC, BNL

Resonating Group Method (RGM, ’37)

Molecular Viewpoints in Nuclear Structure

Phys. Rev. C 52, 1083 (’37)

JOHN ARCHIBALD WHEELER[1]
University of North Carolina, Chapel Hill, North Carolina

(Received August 17, 1937)

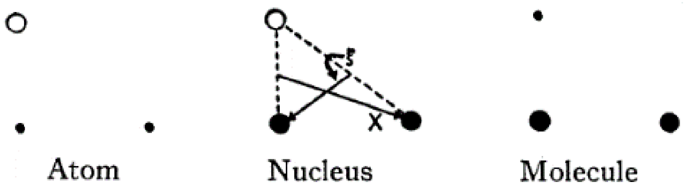
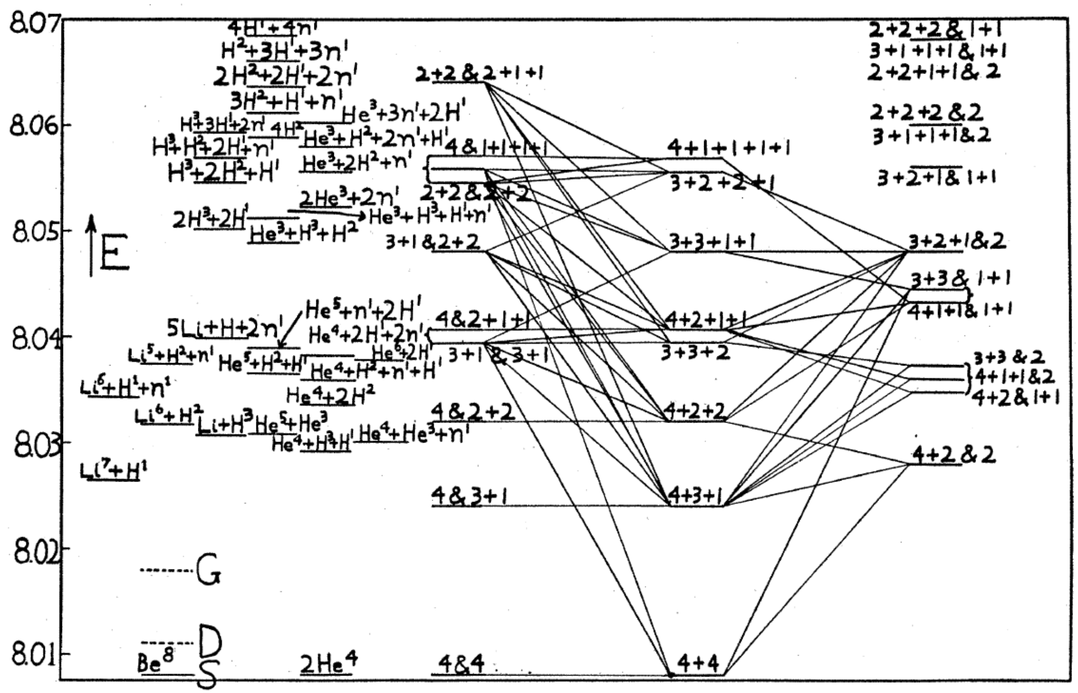


FIG. 1.

$$\psi = \mathscr{A}\Big\{\sum_i \phi(\mathrm{A}_i)\phi(\mathrm{B}_i)F_i(\boldsymbol{R}_i) + \sum_j \phi(\mathrm{A}_j)\phi(\mathrm{B}_j)\phi(\mathrm{C}_j)F_j(\boldsymbol{R}_{j1}, \boldsymbol{R}_{j2}) + \sum_k \phi(\mathrm{A}_k)\phi(\mathrm{B}_k)\phi(\mathrm{C}_k)\phi(\mathrm{D}_k)F_k(\boldsymbol{R}_{k1}, \boldsymbol{R}_{k2}, \boldsymbol{R}_{k3}) + \ldots\ldots + \sum_m c_m\zeta_m\Big\}Z(\boldsymbol{R}_{\mathrm{cm}}).$$

Tang, LeMere, Thompson, Rev. Mod. Phys. 47, 167 (’78)



Molecular orbital model ('73)

^{8}Be

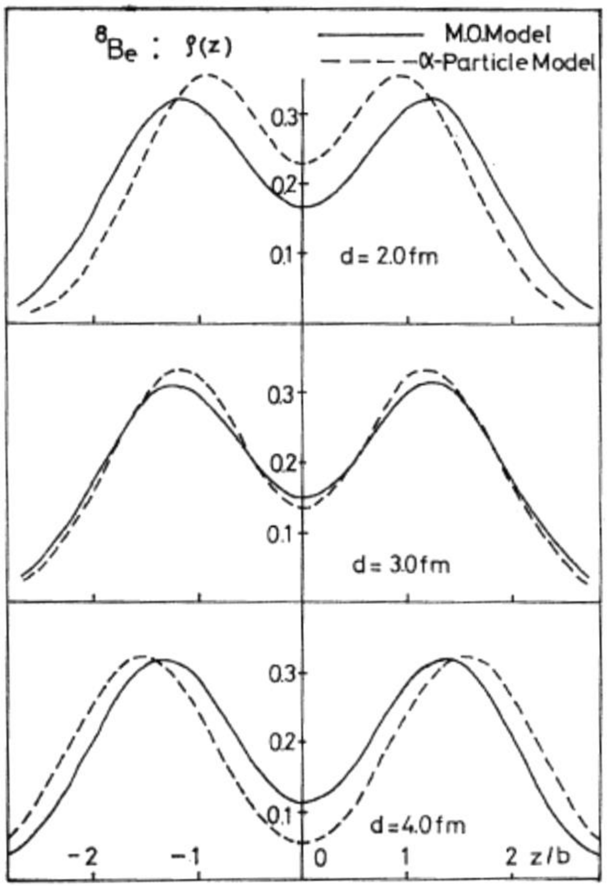
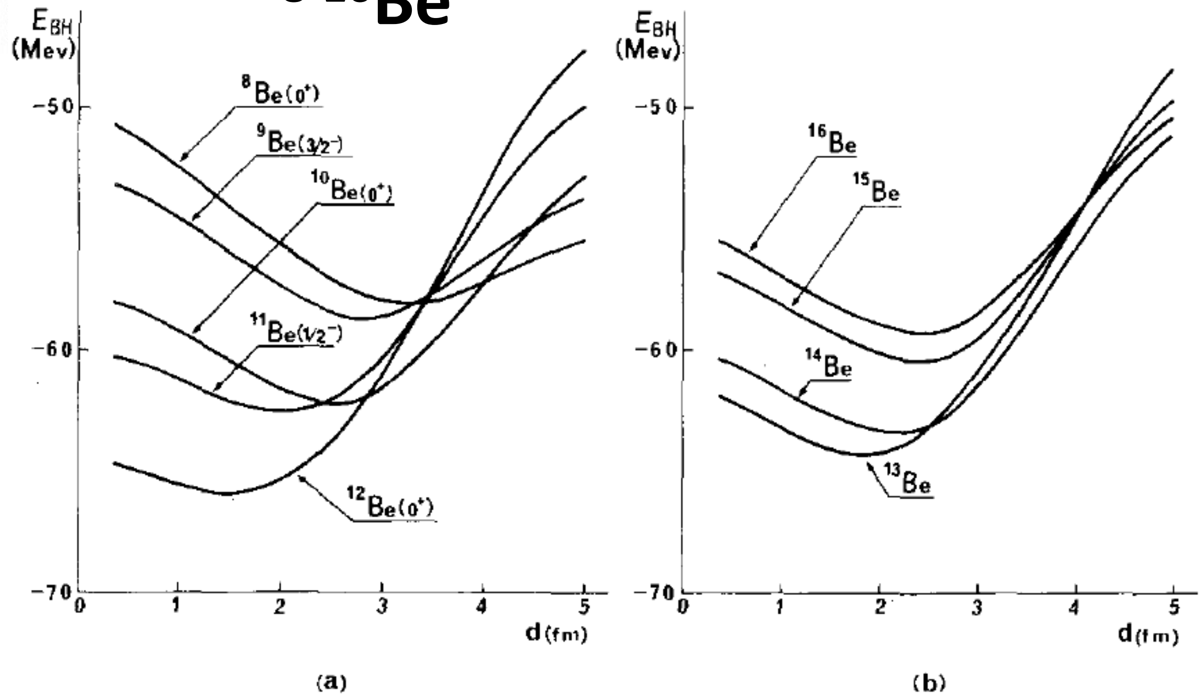


Fig. 8. The density distributions for ^{8}Be along z-axis. The solid lines are given by the molecular-orbital model and the broken lines by the alpha-particle model.

Y. Abe, J. Hiura, H. Tanaka, PTEP 49, 800 ('73)

$^{8\text{-}16}$Be



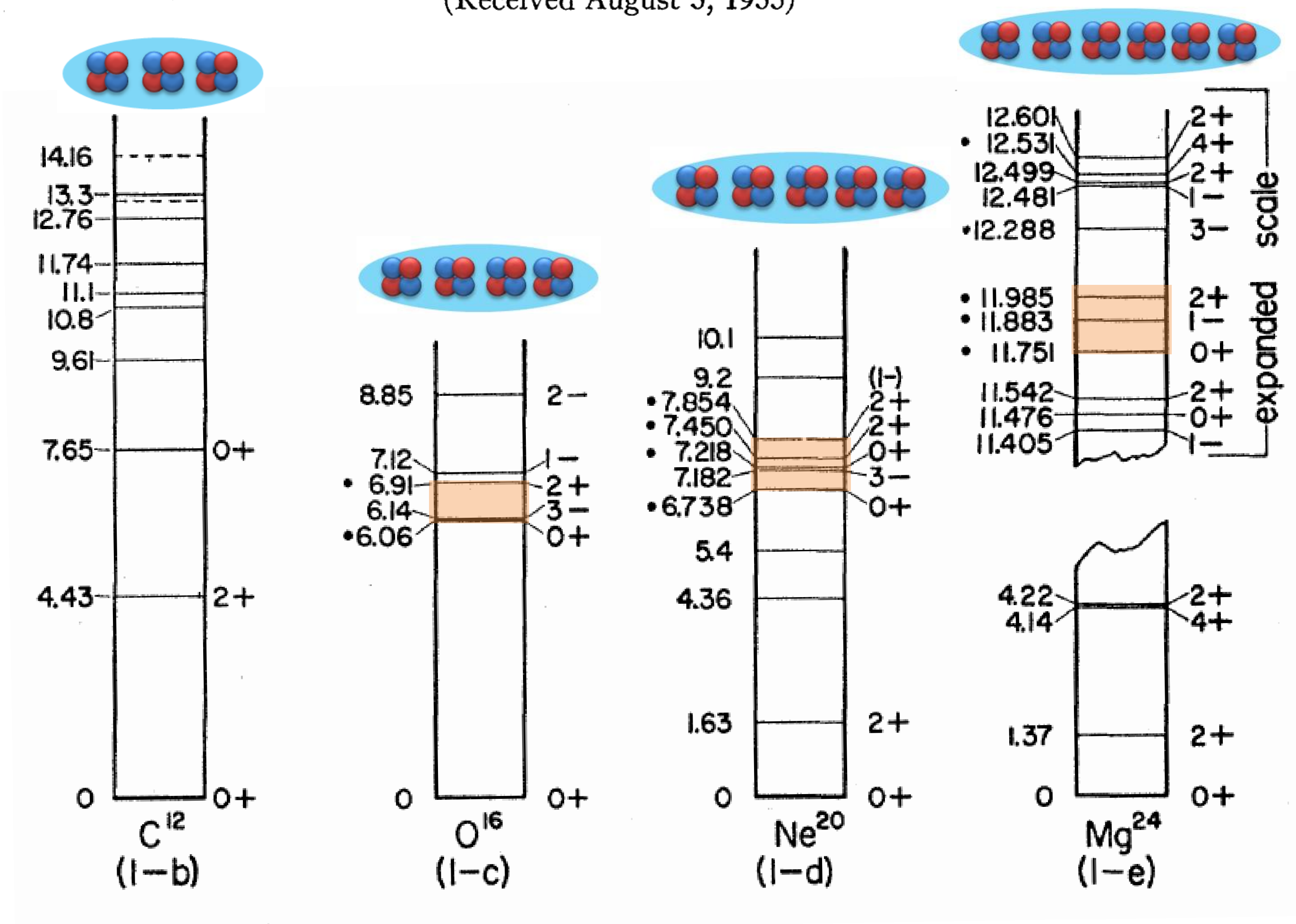
. 10. Total energy curves of the lowest normal parity states of Be isotopes.

M. Seya, M. Kohno, S. Nagata, PTEP 65, 204 ('81)

Linear chain alpha states ('56)

Interpretation of Some of the Excited States of 4*n* Self-Conjugate Nuclei*

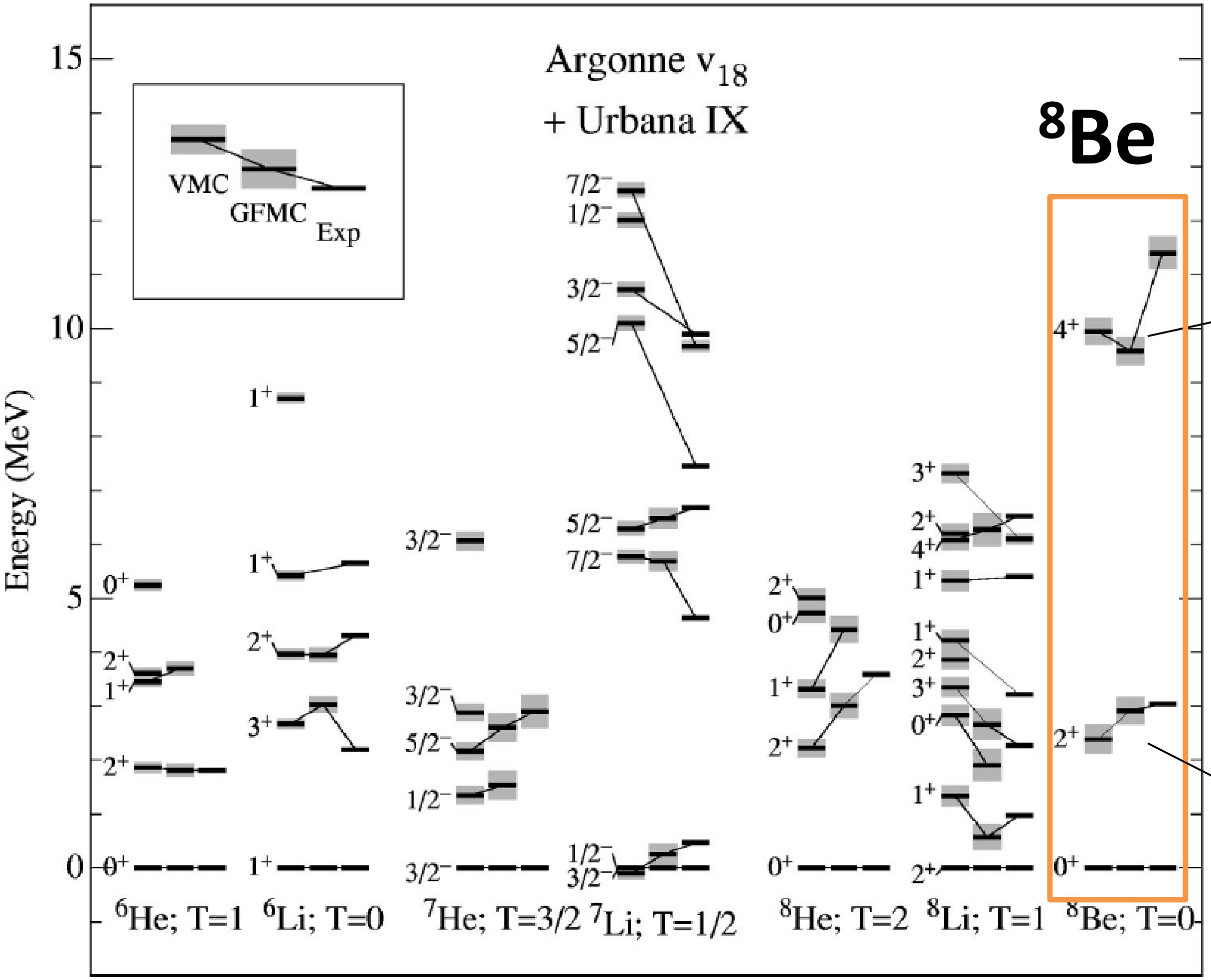
H. Morinaga†
Department of Physics, Purdue University, Lafayette, Indiana
(Received August 5, 1955)



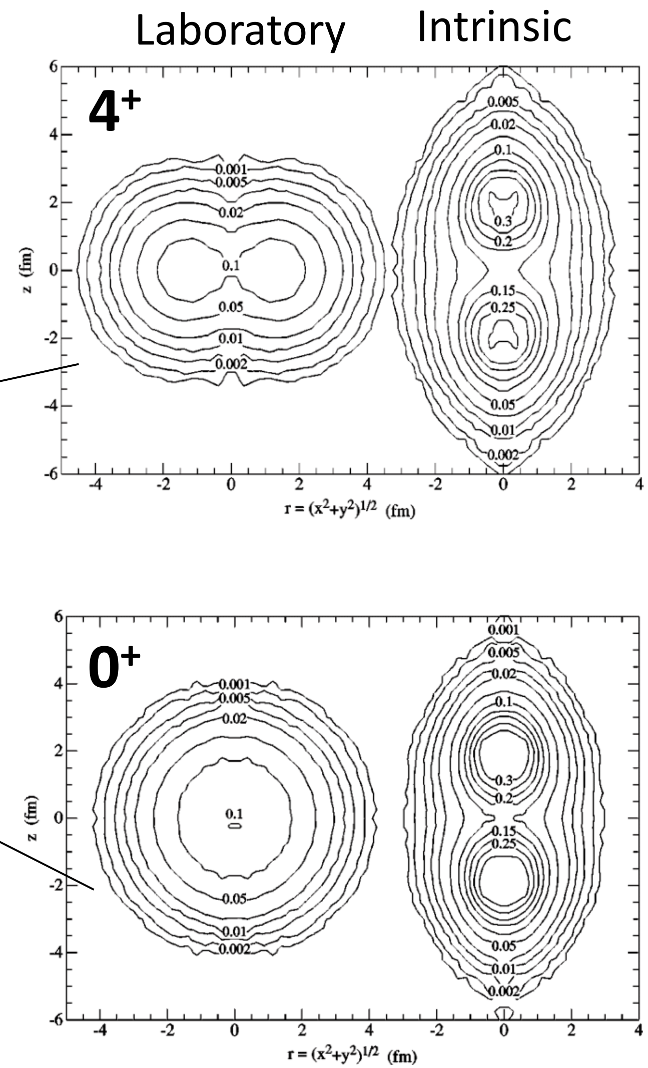
Phys. Rev. 101, 254 ('56)

Game changer 1: no or least assumption of clusters

Quantum Monte-Carlo

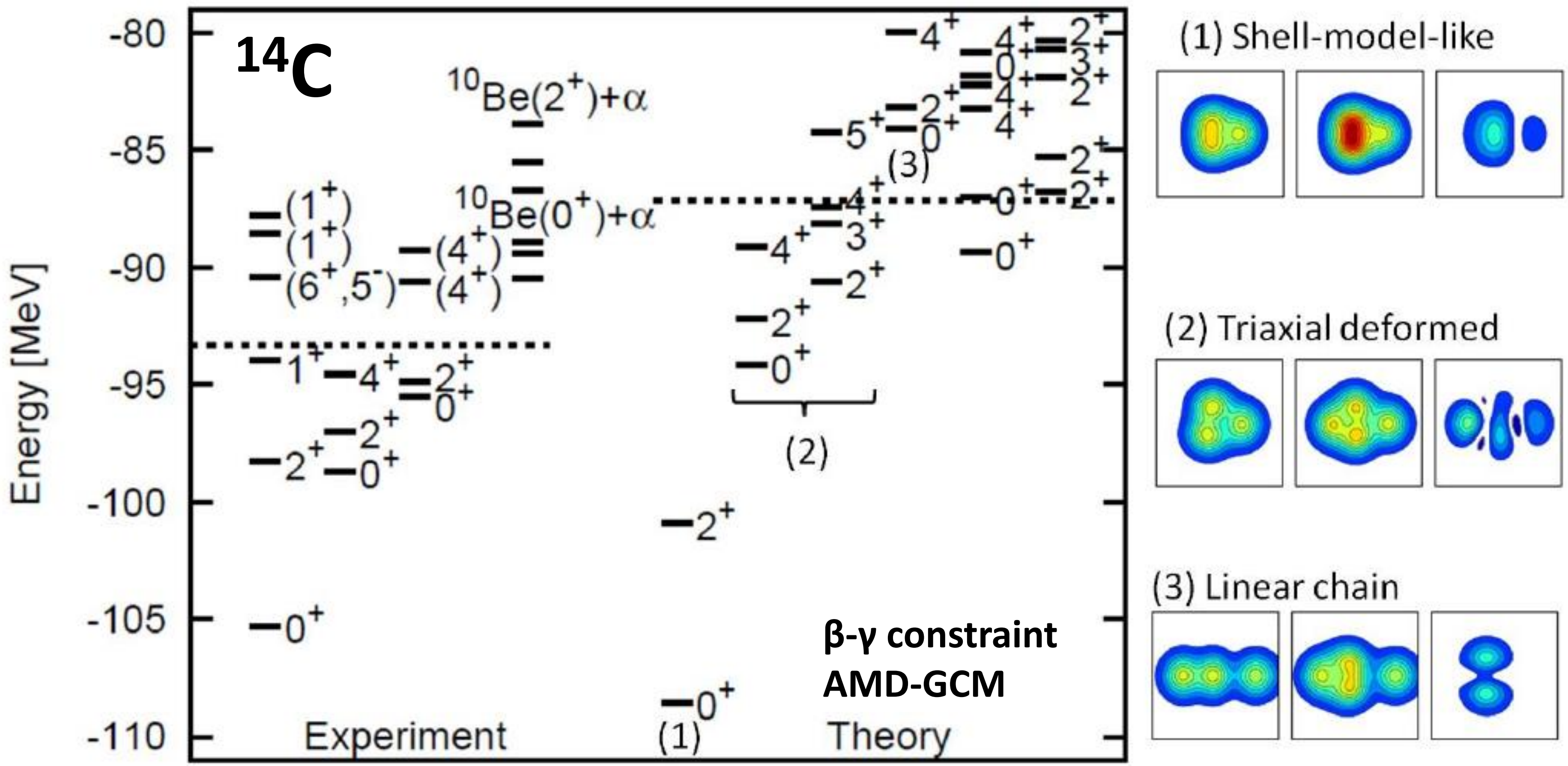


R.B. Wiringa *et al.*, Phys. Rev. C 62, 014001 ('00)



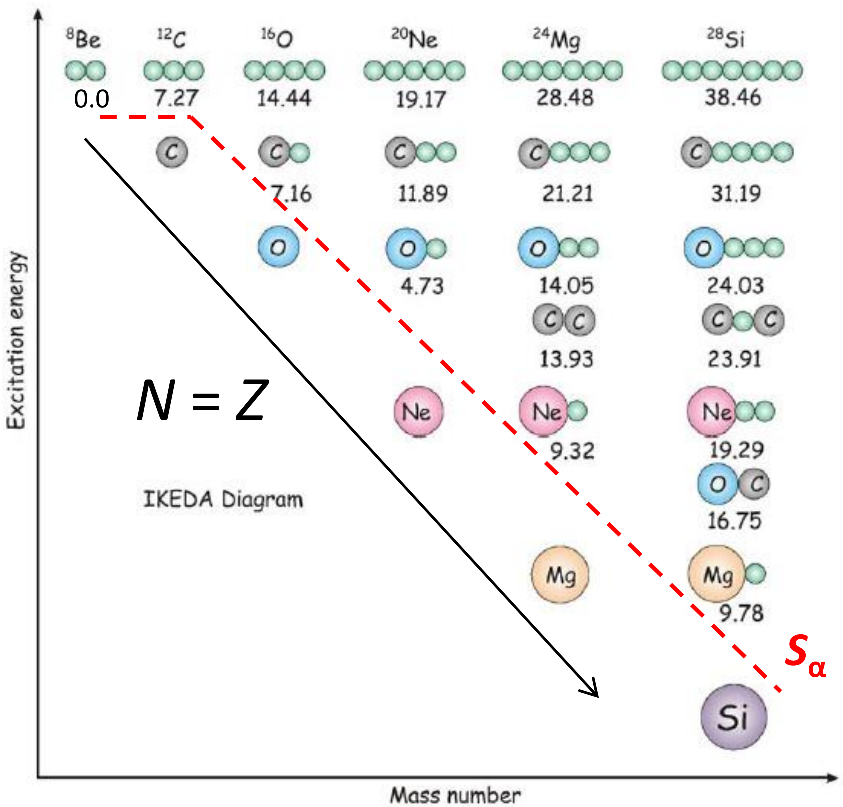
Game changer 1: no or least assumption of clusters

Anti-symmetrized Molecular Dynamics (AMD)

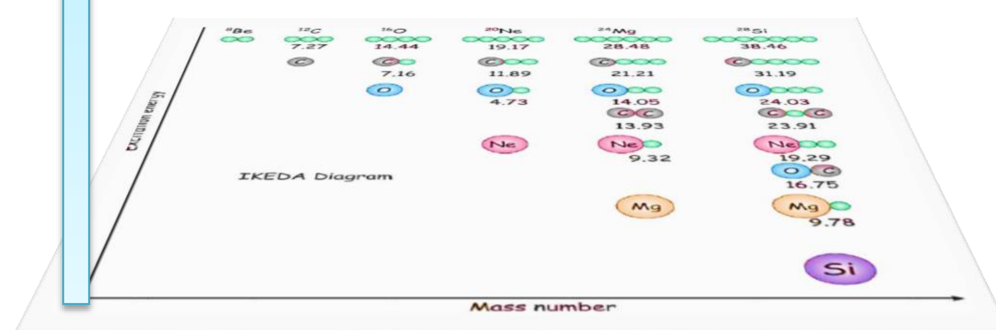


T. Suhara and Y. Kanada-En'yo,
Phys. Rev. C 82, 044301 ('10); J. Phys. Conf. Ser. 321, 012047 ('11)

Game changer 2: radioactive beams

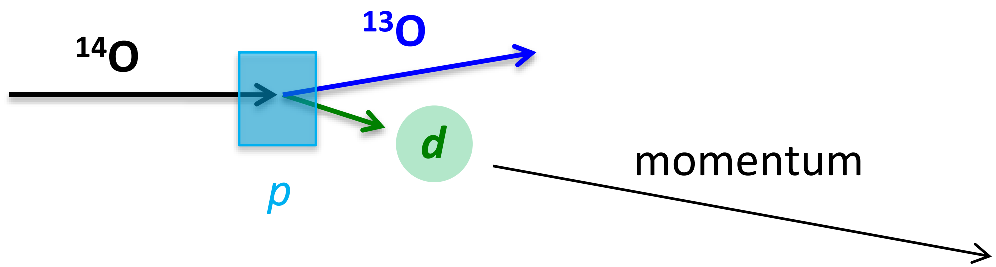


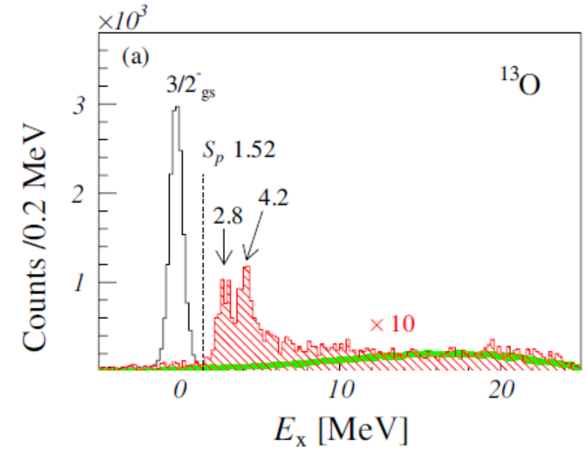
- Extra n/p (degree of hybrid of α and N)
- Binding energy
- Shell effects



Ikeda, Takigawa, Horiuchi, Prog. Theor. Phys. E68, 464 ('68)
Figure from von Oertzen, Freer, Kanada-En'yo, Phys. Rep. 432, 43 ('06)

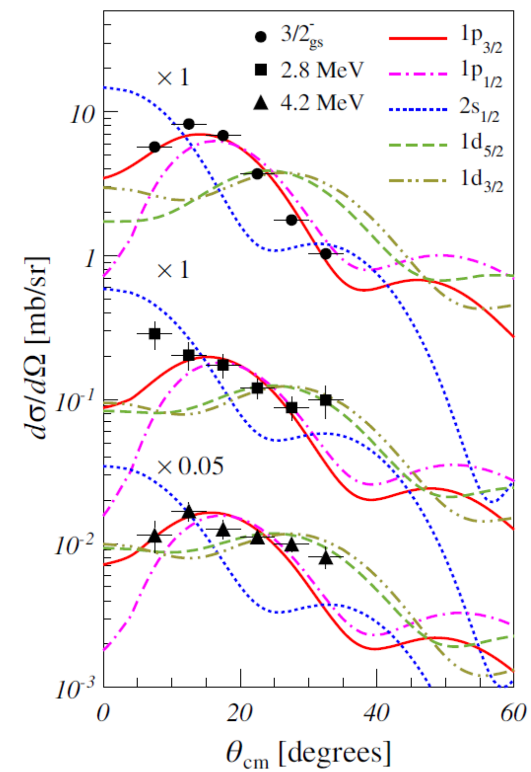
Game changer 3: RI-beam light-ion reactions





- Analysis methods
  - ❑ DWBA, DWIA, CRC … (direct reactions)
  - ❑ *R*-Matrix (Resonance)

- Versatile observables
  - ❑ Spin and parity
  - ❑ Spectroscopic factor
    <A+*n*|A> (single-particle strength)
  - ❑ Decay width
    <A+α|A> (alpha clustering)



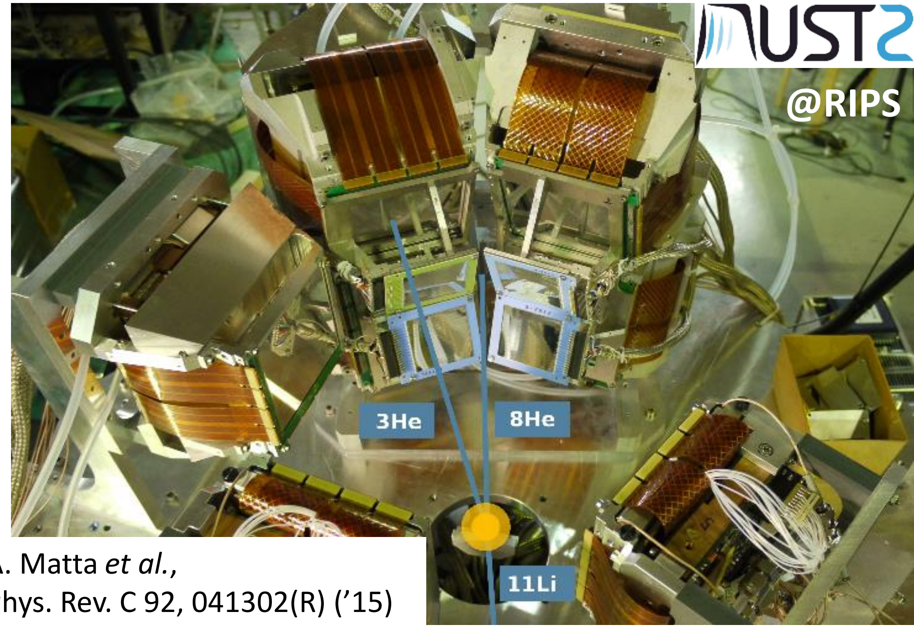
D. Suzuki, Eur. Phys. J. A 48, 130 ('12)

Game changer 3: detectors for RIB reactions

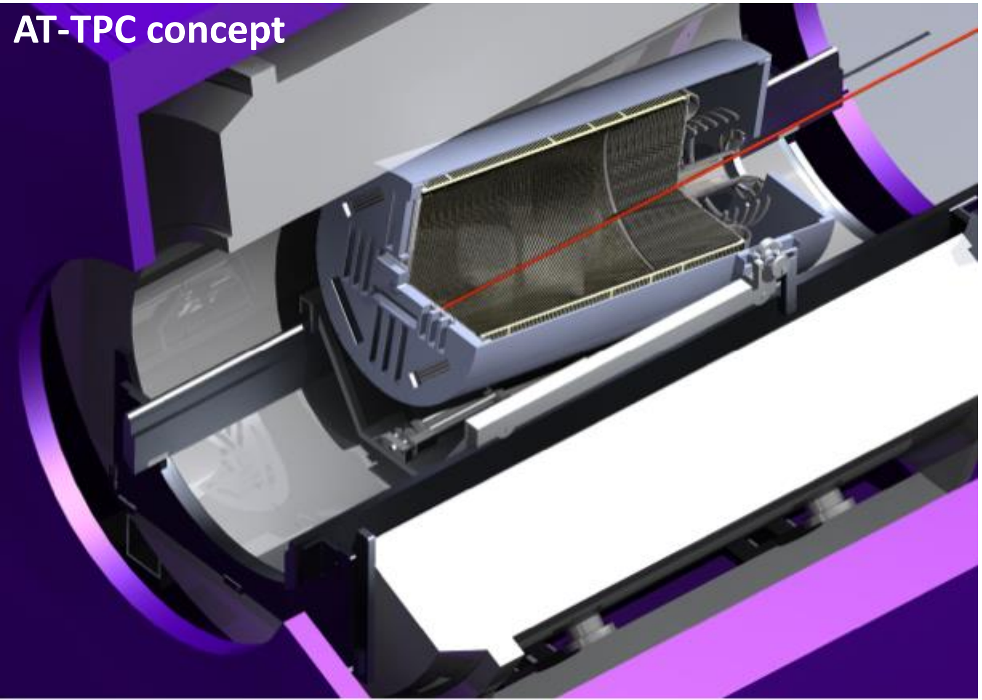
Type I: Strip-silicon array

- MUST[1]/MUST2[2] (GANIL)
- HiRA[3] (NSCL)
- Tiara[4] (UK)
- Helios[5] (ANL)

[1] Y. Blumenfeld *et al.*, Nucl. Instr. Meth. A 421, 471 ('99)
[2] E. Pollacco *et al.*, Eur. Phys. J. A 25, 287 ('05)
[3] N.S. Wallace *et al.*, Nucl. Instr. Meth. A 583, 302 ('07)
[4] M. Labiche *et al.*, Nucl. Instr. Meth. A 614, 439 ('10)
[5] J.C. Lighthall *et al.*, Nucl. Instr. Meth. A 622, 97 ('10)



A. Matta *et al.*,
Phys. Rev. C 92, 041302(R) ('15)



Type II: Active gas target

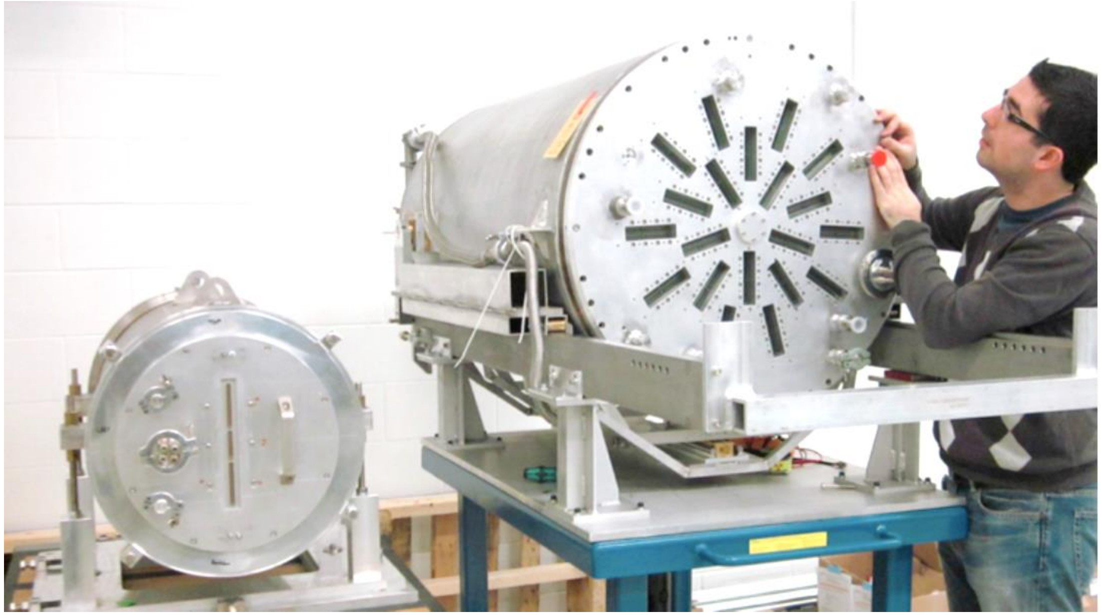
- MSTPC[1] (RIPS)
- TACTIC[2] (TRIUMF)
- Maya[3] (GANIL)
- AT-TPC (NSCL)
- CAT[4] (CNS)
- Maiko[5] (Kyoto)

[1] Y. Mizoi *et al.*, Nucl. Instr. Meth. A 431, 112 ('99)
[2] A.M. Laird *et al.*, Nucl. Instr. Meth. A 573, 306 ('07)
[3] C.E. Demonchy *et al.*, Nucl. Instr. Meth. A 583, 341 ('07)
[4] S. Ota *et al.*, J. Radioanal. Nucl. Chem. 305, 907 ('15)
[5] T. Furuno *et al.*, J. Phys.: Conf. Ser. 569, 012042 ('14)

AT-TPC collaboration since 2008

<u>A</u>ctive <u>T</u>arget <u>T</u>ime <u>P</u>rojection <u>C</u>hamber

P.I.: D. Bazin, W. Mittig



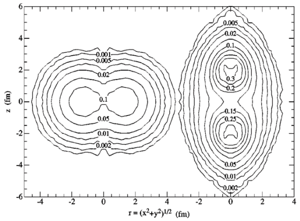
First experiments in 2011

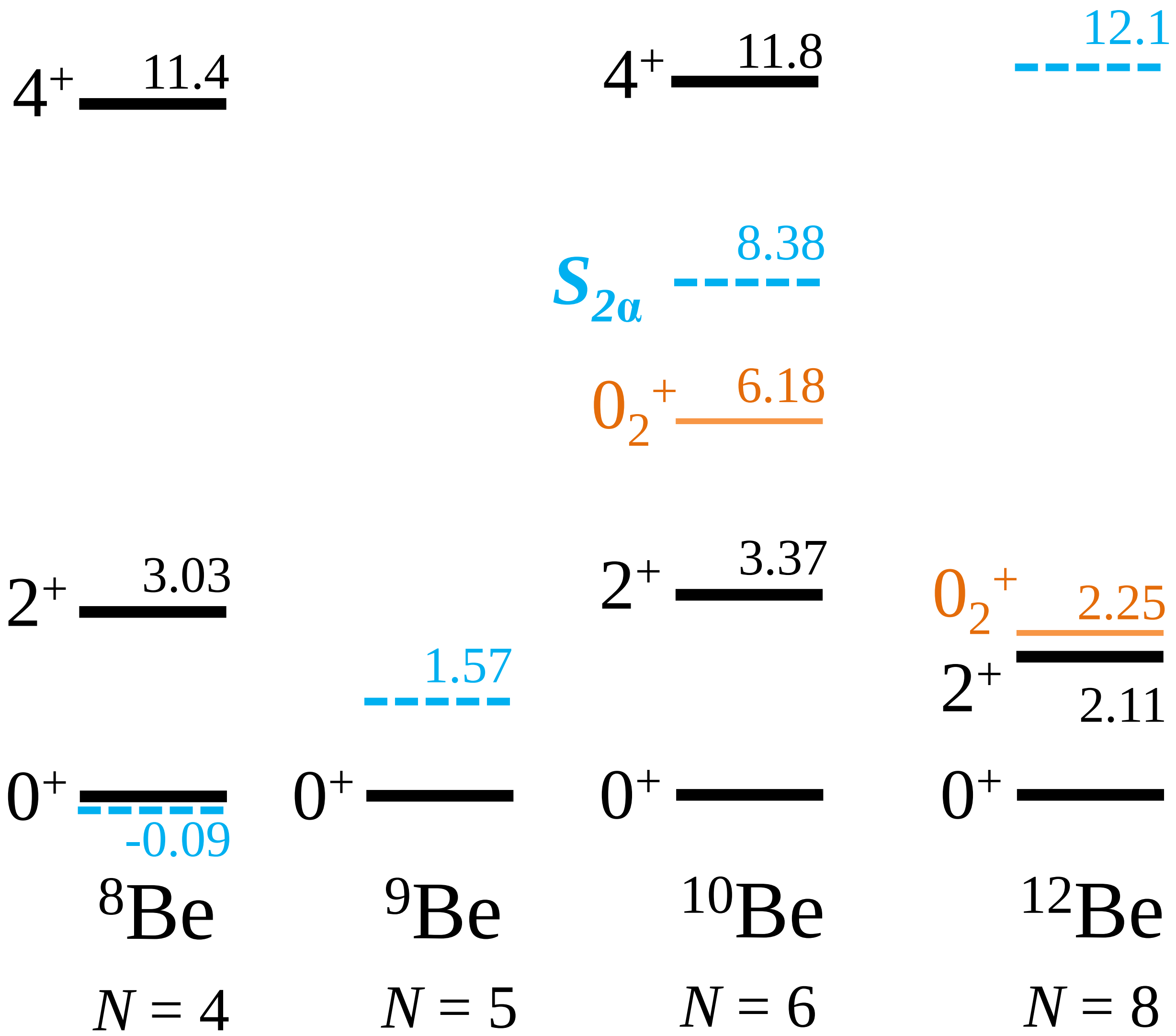
- ^{10}Be (^{8}Be + 2*n*) and ^{14}C (^{12}C + 2*n*) via resonant α scattering.
- Essential roles of 2*n* from the simplest systems.

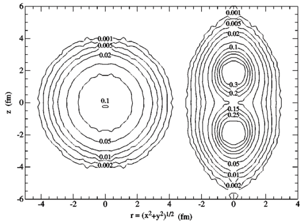
^{10}Be:
when molecules meet shells

D. Suzuki, A. Shore, W. Mittig, J.J. Kolata *et al.*, Phys. Rev. C 87, 054301 ('13)

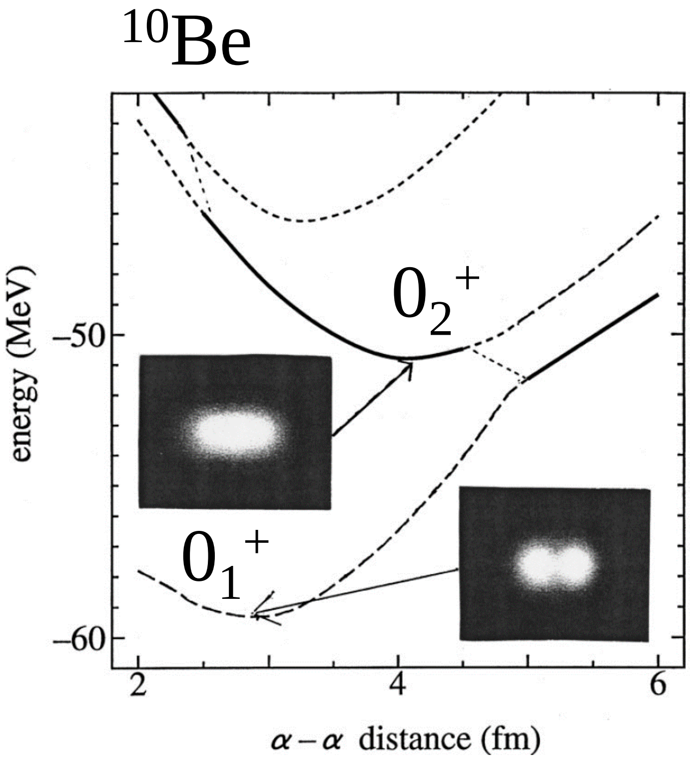
Evolution of berylium isotopes







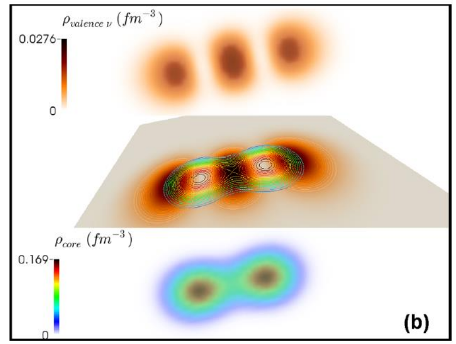
Molecular orbitals



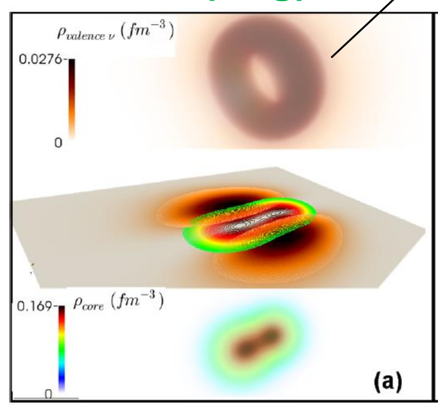
Microscopic 2*α*+2*n* cluster model

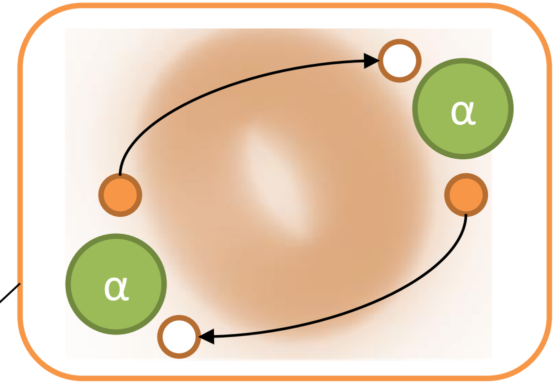
N. Itagaki and S. Okabe,
Phys. Rev. C 61, 044306 ('00)

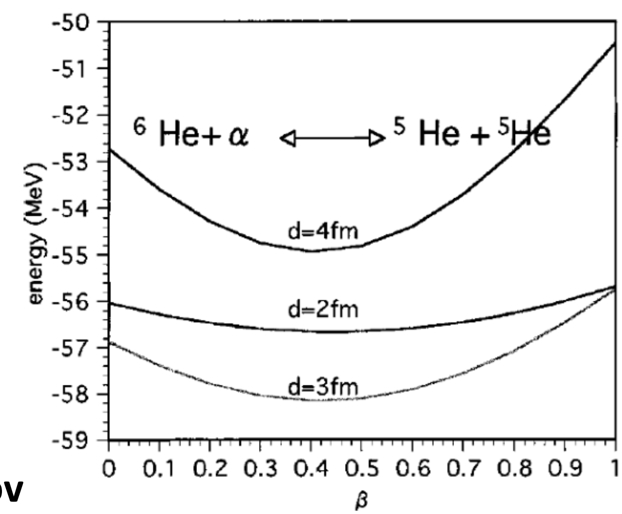
σ-orbital (chain)



π-orbital (ring)



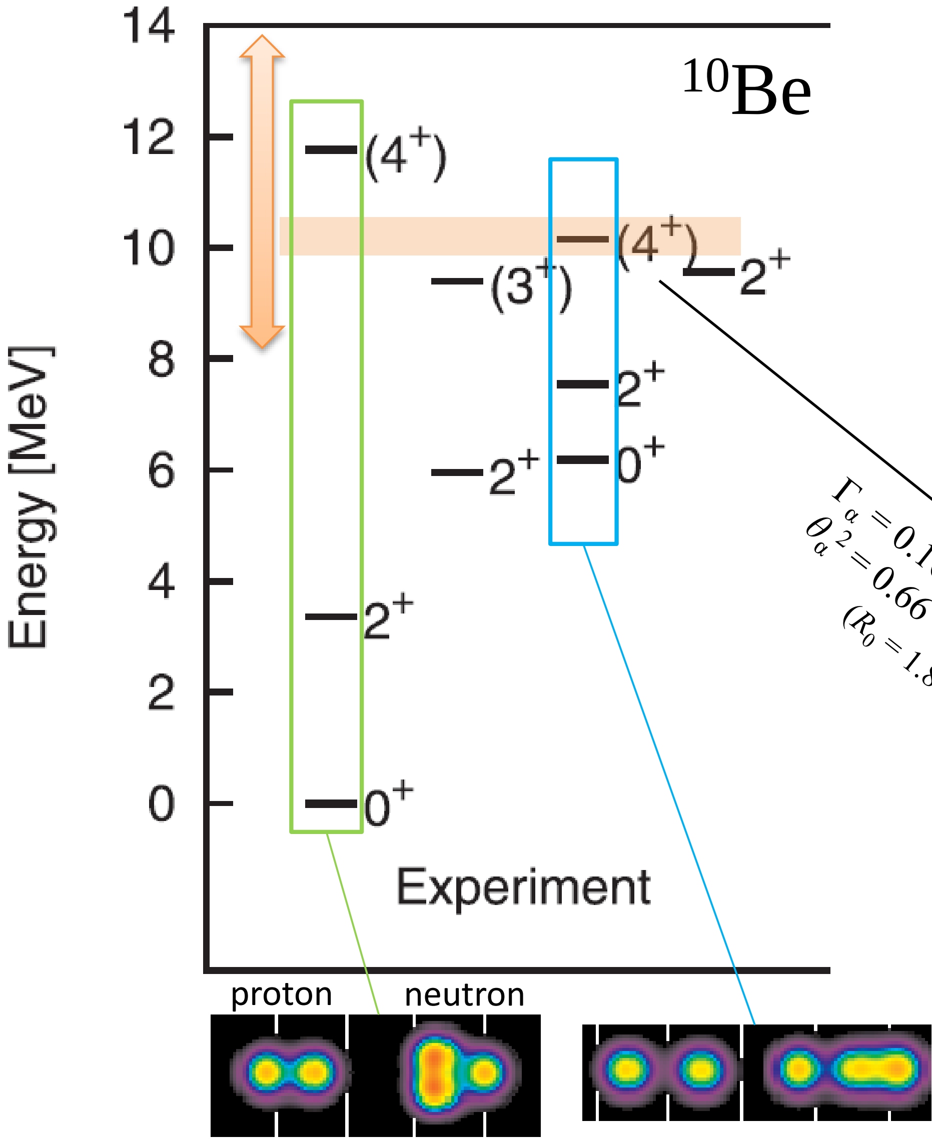




Relativistic Hartree-Bogoliubov

J-P. Ebran *et al.*
Phys. Rev. C 90, 054329 ('14)

Signature of molecular orbitals

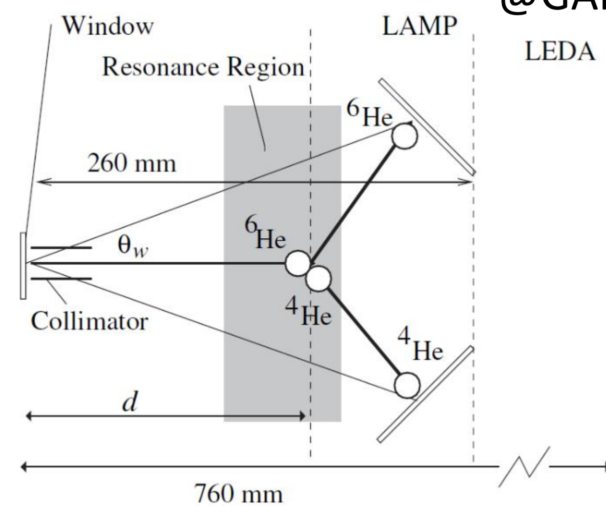


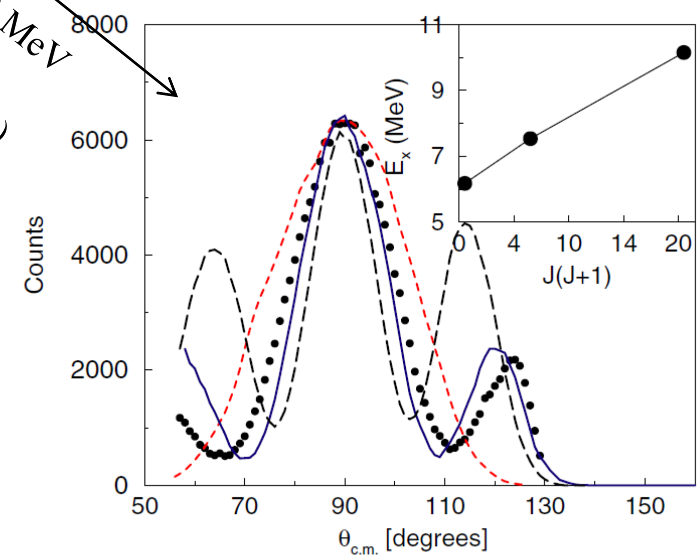
π-orbital **σ-orbital**

Y. Kanada-En'yo *et al.*, J. Phys. G24, 1499 ('98)

$\Gamma_\alpha = 0.10 - 0.13$ MeV
$\theta_\alpha^2 = 0.66 - 2.23$
$(R_0 = 1.8 - 1.4$ fm$)$

Resonant α scattering of ^{6}He beam @GANIL

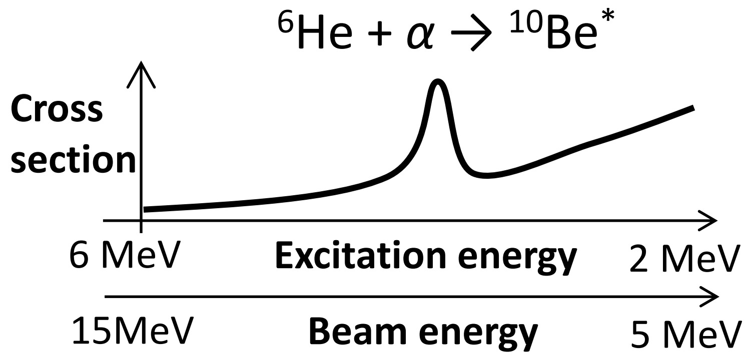


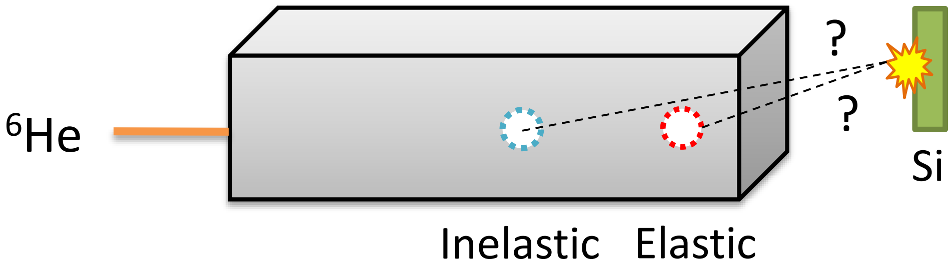


M. Freer *et al.*, Phys. Rev. Lett. 96, 042501 ('06)

Thick target method

K. P. Artemov *et al.*, Sov. J. Nucl. Phys. 55, 1460 ('92)

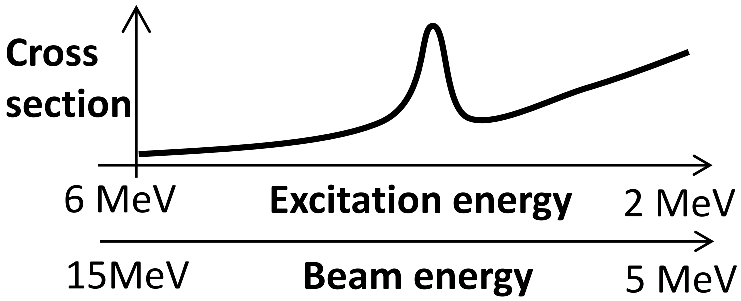


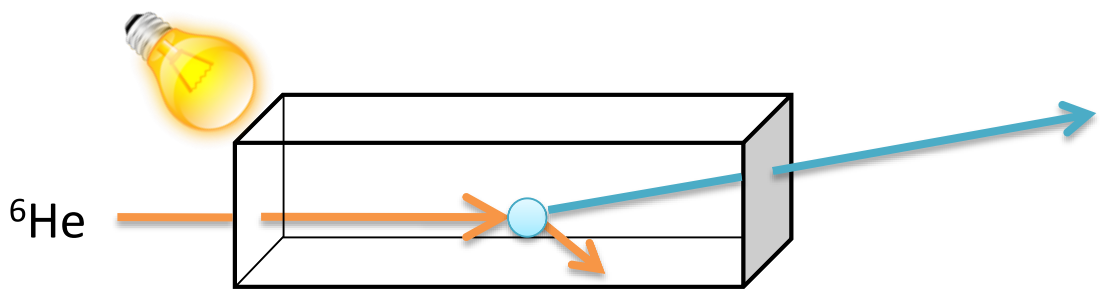


Thick target method

K. P. Artemov *et al.*, Sov. J. Nucl. Phys. 55, 1460 ('92)

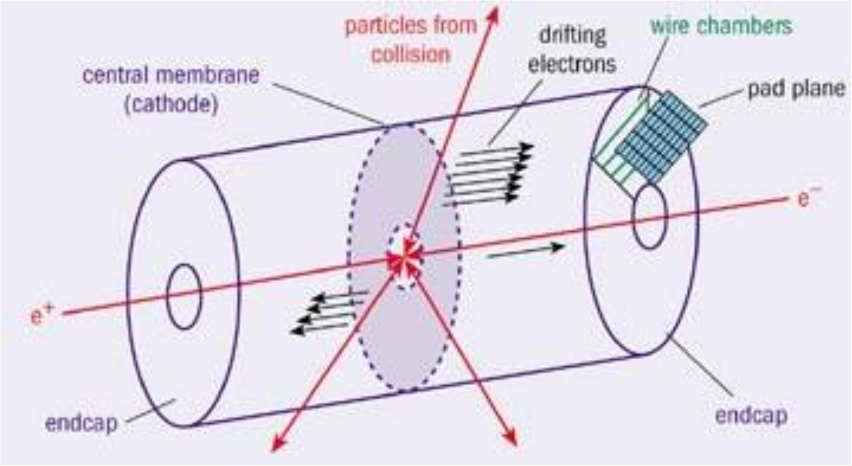
$^{6}He + \alpha \rightarrow {}^{10}Be^{*}$





Time Projection Chamber (TPC)

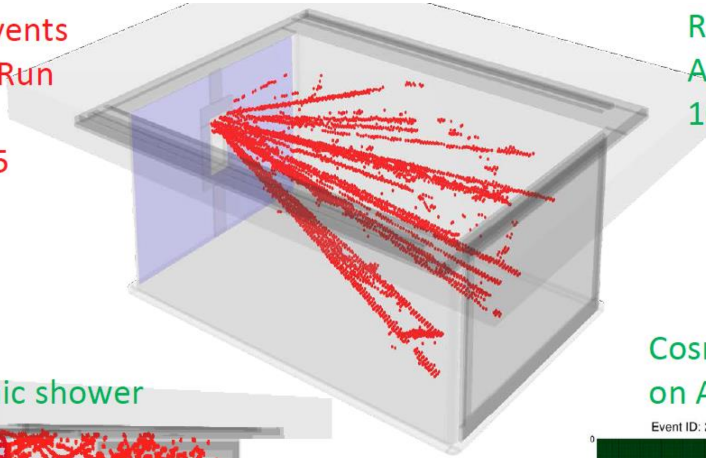
The first realization for **PEP-4** with the 29 GeV e^+-e^- collider at Stanford ('70s)



D.R. Nygren and J.N. Marx, Physics Today 31, 46 ('78)

Spirit TPC @RIBF
(run in April and May)

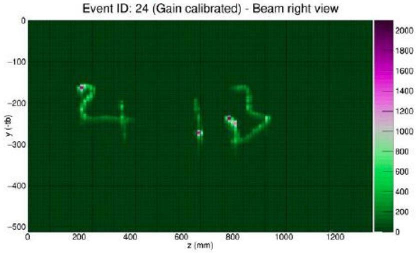
SpiRIT TPC events Commission Run at RIKEN in October 2015



Reactions from 200 AMeV 79Se+Al 10/23/2015, RIKEN

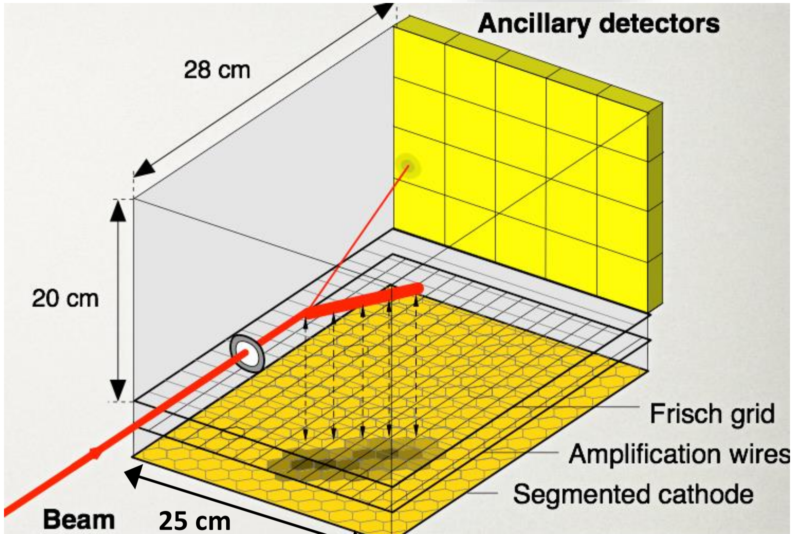
Cosmic shower

Cosmic phone home: on April 13, 2016

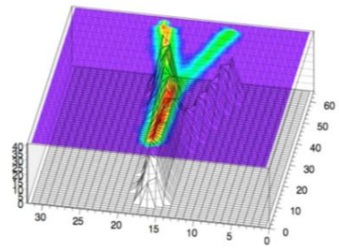


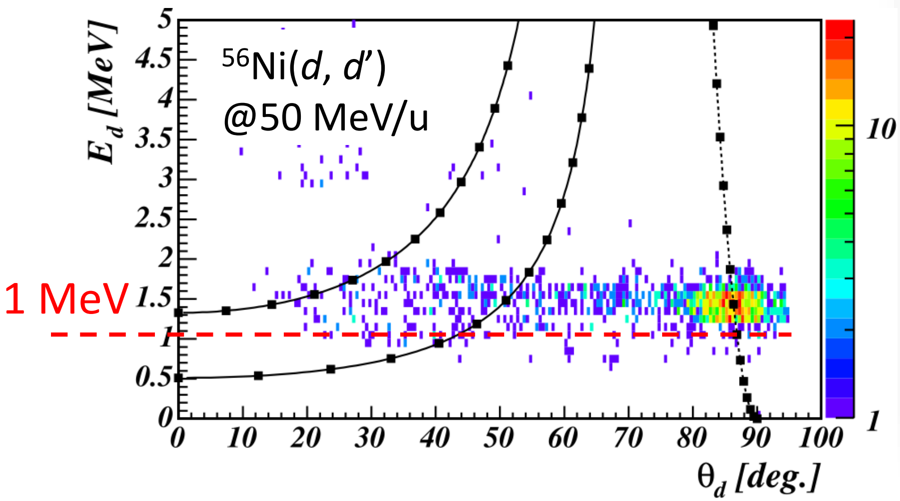
Coutesy B. Tsang

since 2003 at GANIL



C.E. Demonchy *et al.*, Nucl. Instr. Meth. A 583, 341 ('07)





C. Monrozeau *et al.*, Phys. Rev. Lett. 100, 042501 ('08)

Beam/Energy [MeV/u]	Date	Reaction	Gas	Mixture [%]	Pressure [mbar]
^{8}He @ 3.9	2003	^{8}He(p,p')	C_4H_{10}	100	1000
^{8}He @ 3.5	2003	^{8}He(p,d)^{7}He	C_4H_{10}	100	525
^{25,26}F @ 50.0	2004	^{25}F(d,^{3}He)^{24}O	D_2	100	2200
^{56}Ni @ 50.0	2005	^{56}Ni(d,d')	D_2	100	1050
^{8}He @ 15.4	2005	^{8}He(^{12}C,^{13}N)^{7}H	C_4H_{10}	100	30
^{11}Li @ 3.6	2006	^{11}Li(p,d)^{10}Li	C_4H_{10}	100	150
		^{11}Li(p,t)^{9}Li	C_4H_{10}	100	664
^{6}He @ 3.5	2007	^{6}He(p,n)^{6}Li	C_4H_{10}	100	107
^{68}Ni @ 50.0	2010	^{68}Ni(d,d')	D_2	100	1040
		^{68}Ni(α,α')	He + CF_4	98/2	500
^{56}Ni @ 50.0	2011	^{56}Ni(α,α')	He + CF_4	98/2	1200
^{8}He @ 15.4	2011	^{8}He(^{19}F,^{20}Ne)^{7}H	He + CF_4	10/90	175
^{12}Be @ 3.0	2012	^{12}Be(p,p')	C_4H_{10}	100	100

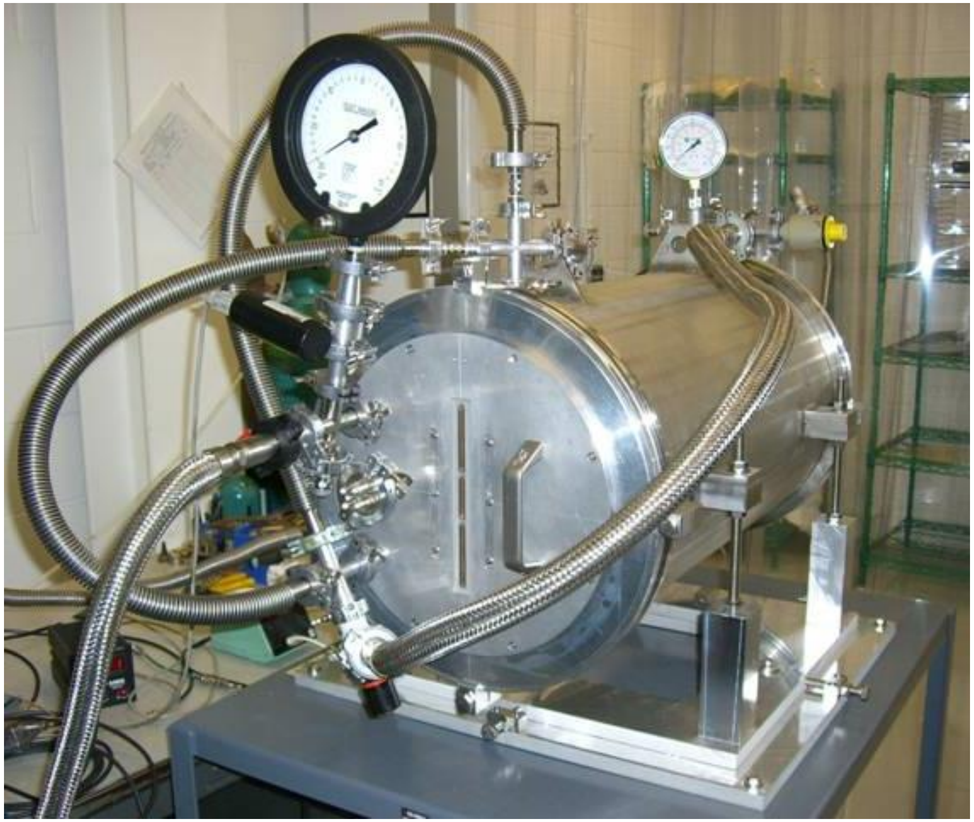
TRIUMF (^{11}Li @ 3.6, 2006 rows)

ISOLDE (^{12}Be @ 3.0, 2012 row)

Half-scale prototype of AT-TPC (2011 -)

PAT-TPC

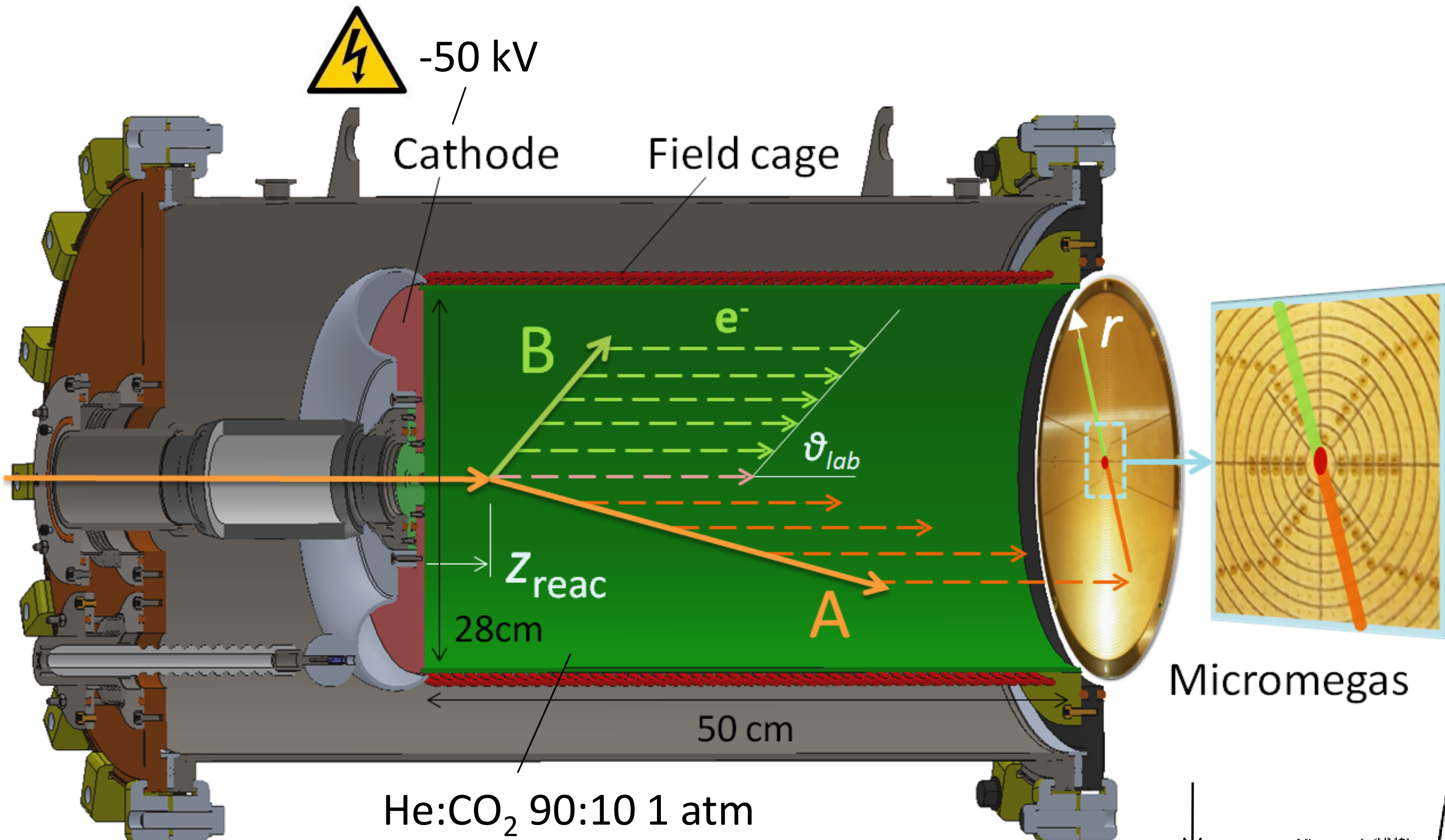
D. Suzuki, M. Ford, D. Bazin, W. Mittig *et al.*, Nucl. Instr. Meth. A 691, 39 ('12)

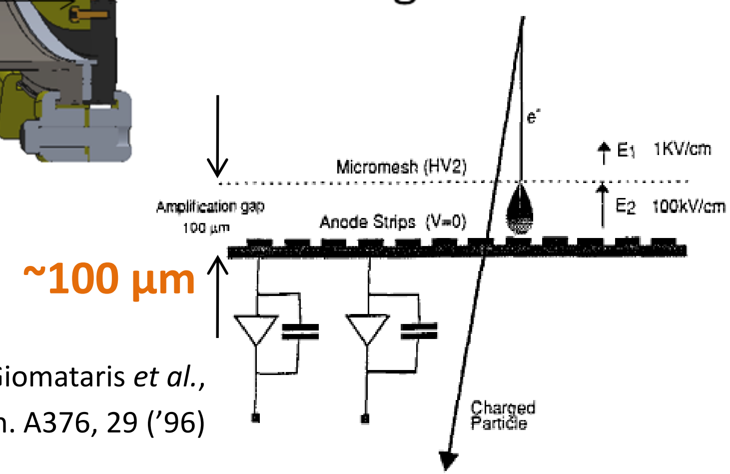


Not just a prototype!

	PAT-TPC	**Maya**
Gas thickness	50 cm	28 cm
Pad size	2 mm (strip)	9 mm (hexagonal)

PAT-TPC: principle of operation



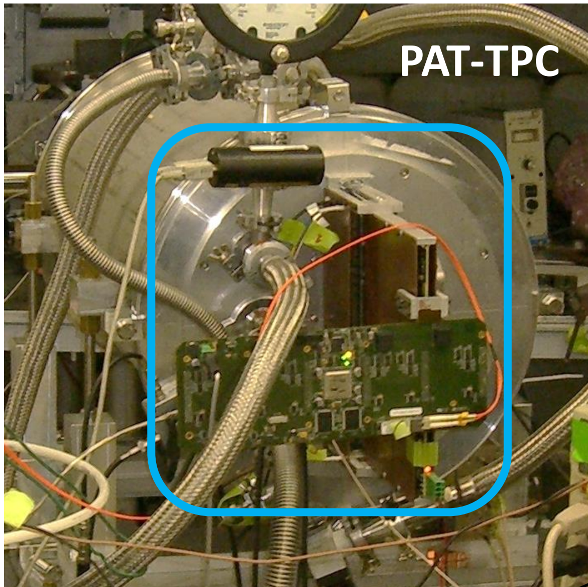


Y. Giomataris *et al.*,
Nucl. Instr. Meth. A376, 29 ('96)

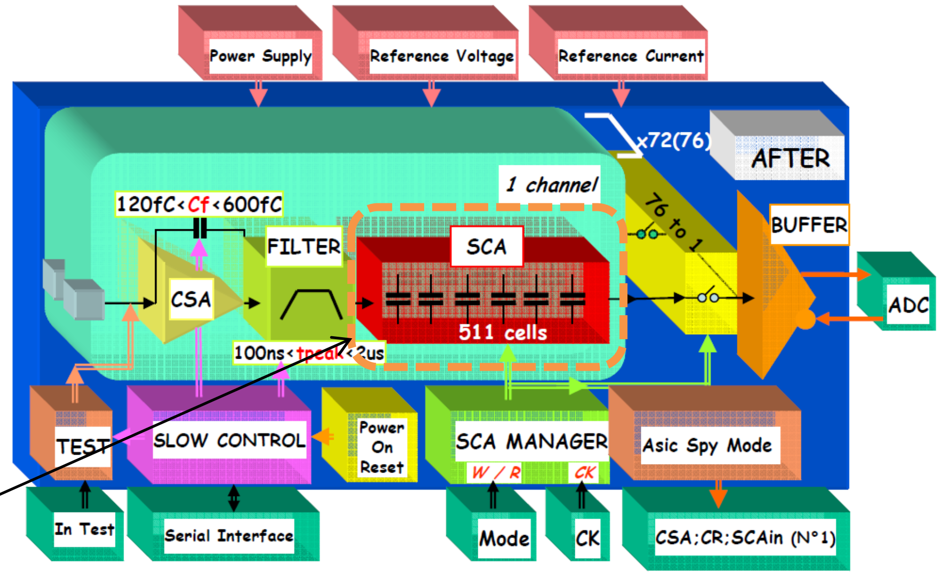
Waveform digitizer

Neutrino flux monitor TPCs in Tokai-to-Kamiokande (T2K) experiment

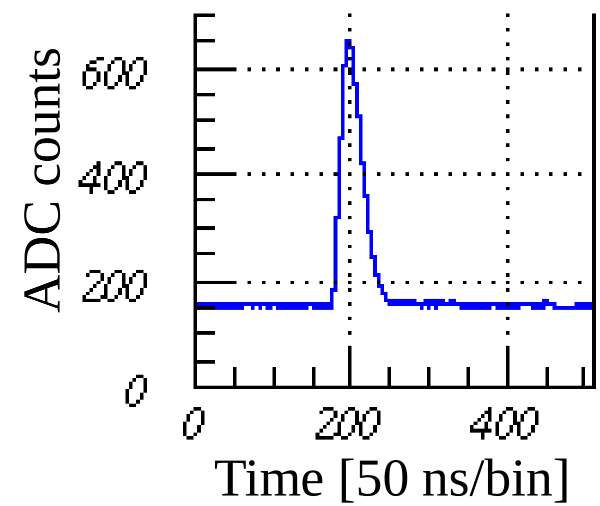
T. Lux, J. Phys: Conf. Ser. 65, 012018 ('07)



P. Baron *et al.*, IEEE Trans. Nucl. Sci. 55, 1744 ('08)



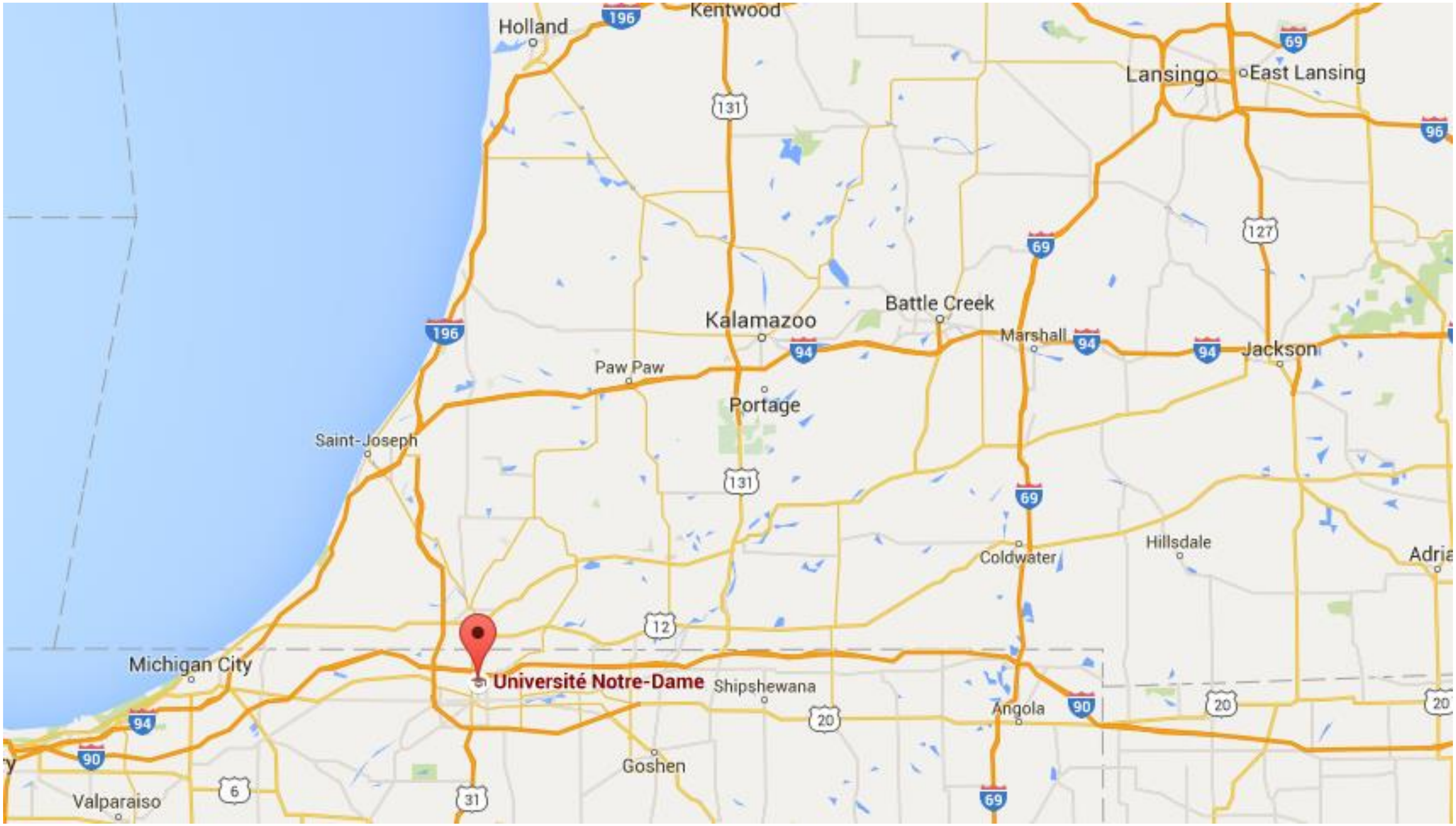
- 511 switching capacitors array memory
- 10 ~ 100 MHz sampling (Time window 5 ~ 50 μs)
- 12-bit ADC
- 288 channels /board



GET (General Electronics for TPCs)

E. Pollacco *et al.*, Phys. Proc. 37, 1799 ('12)

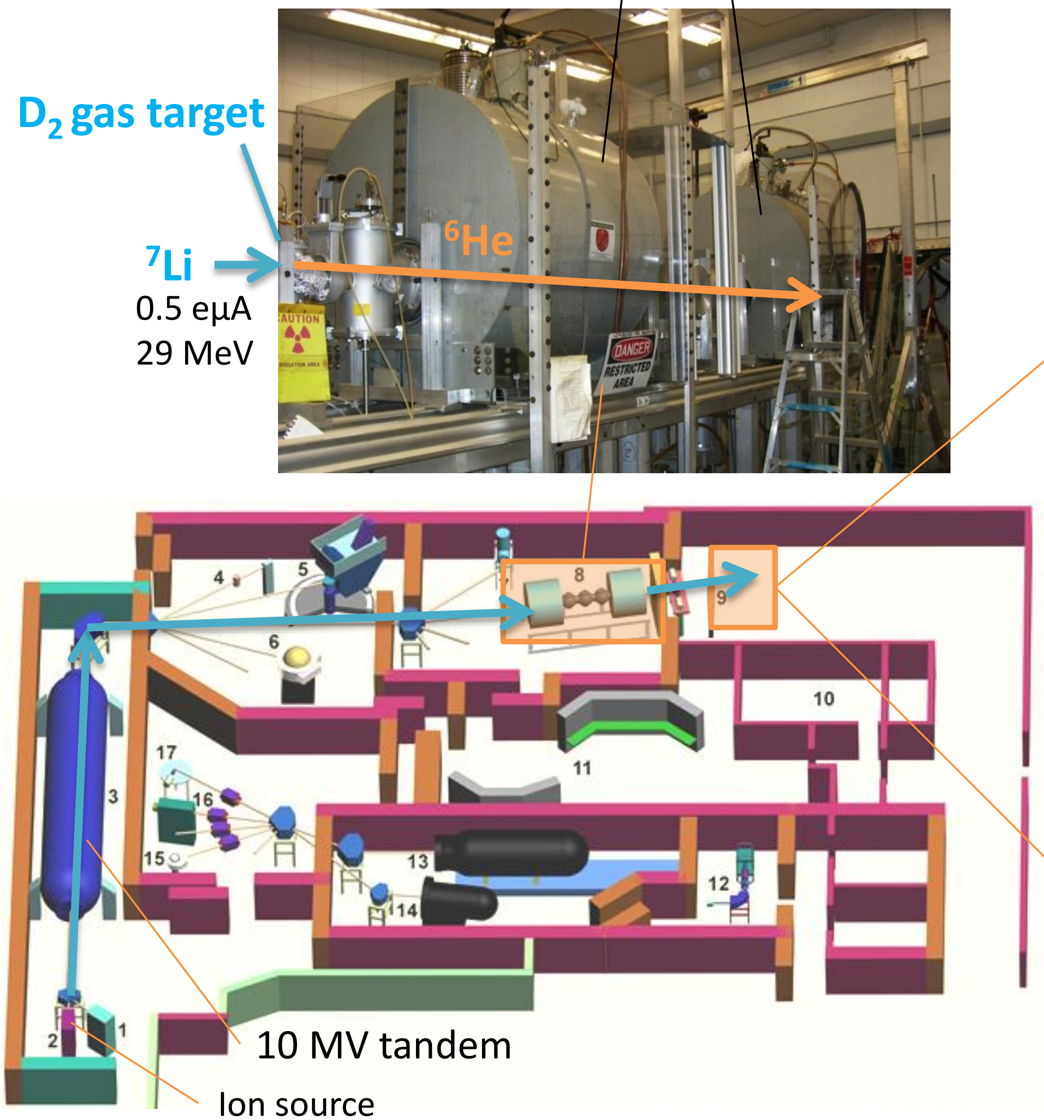
Travel to South Bend

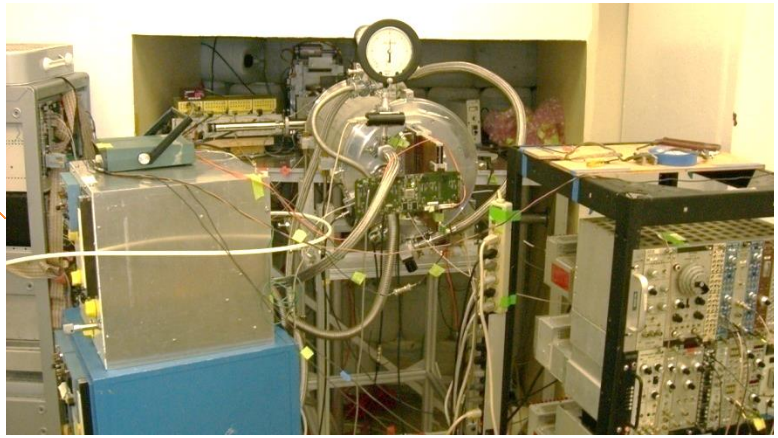


Twinsol facility at Notre Dame

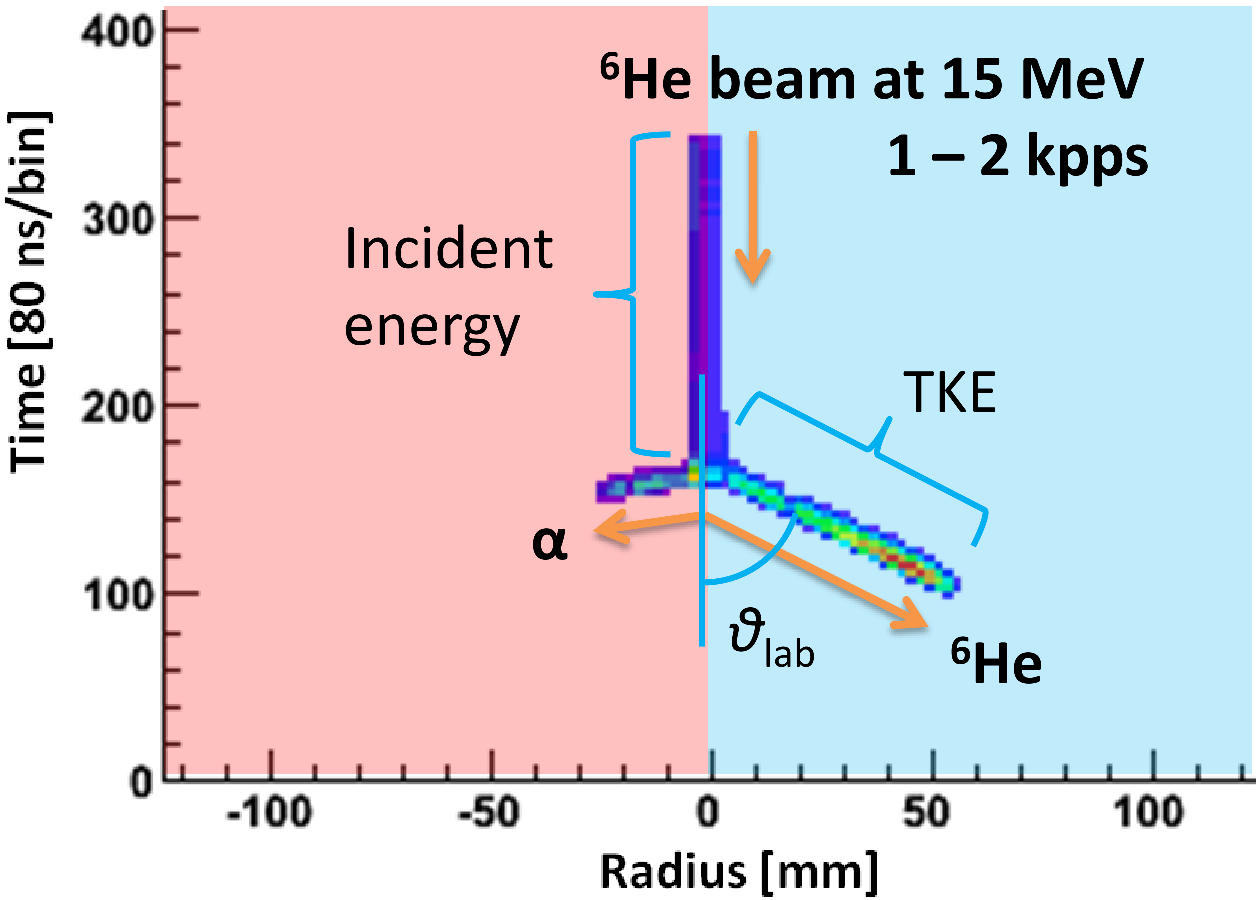
F. Becchetti *et al.*, Nucl. Instr. Meth. A 505, 377 ('03)

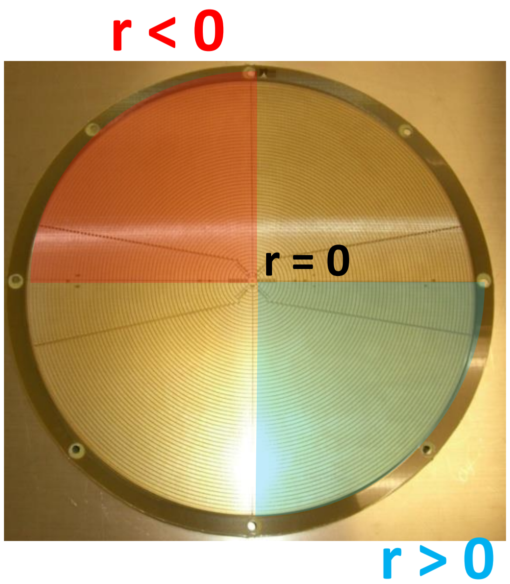
A pair of solenoid

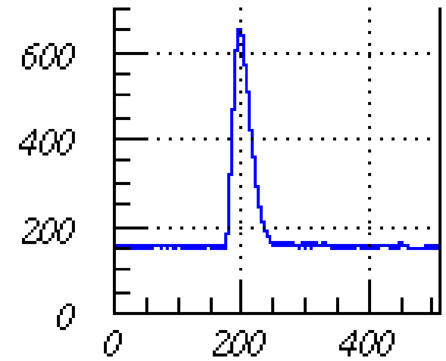




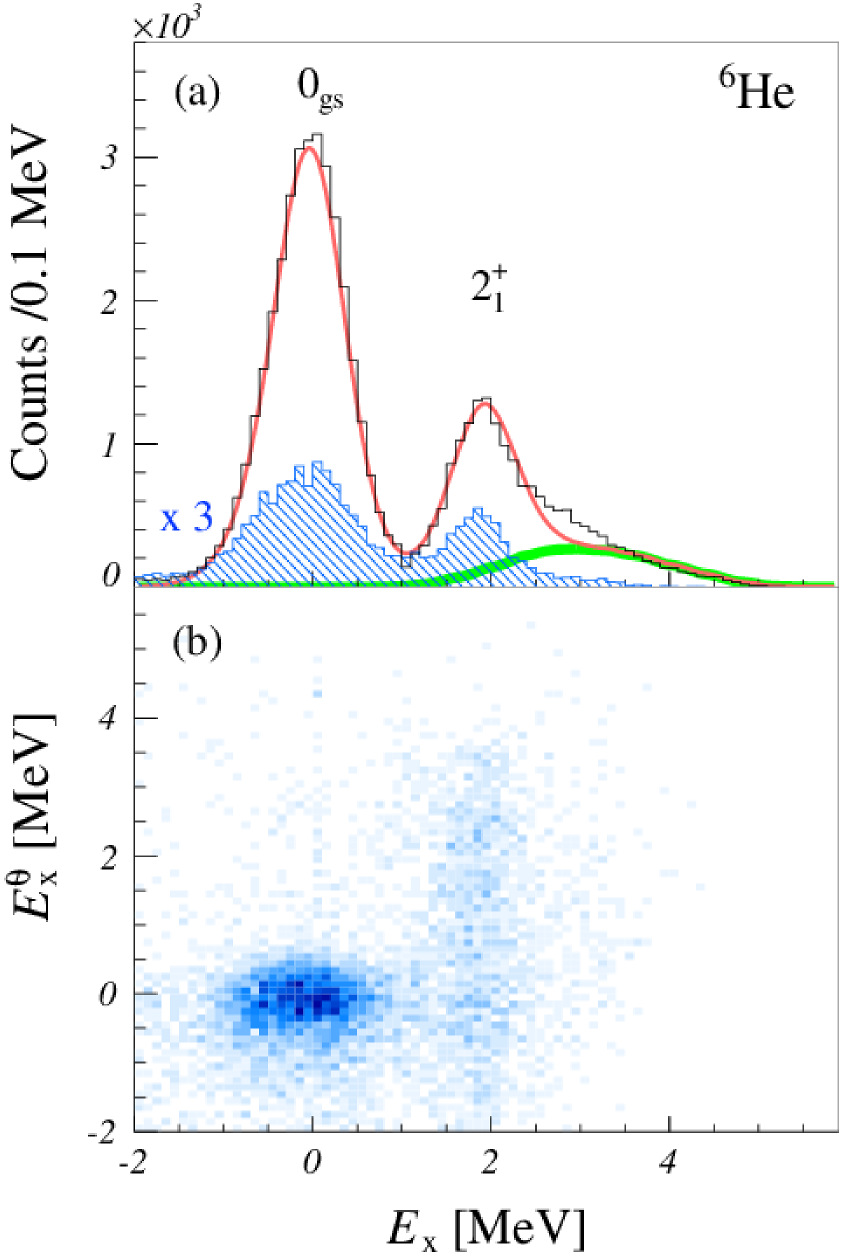
Reaction imaging



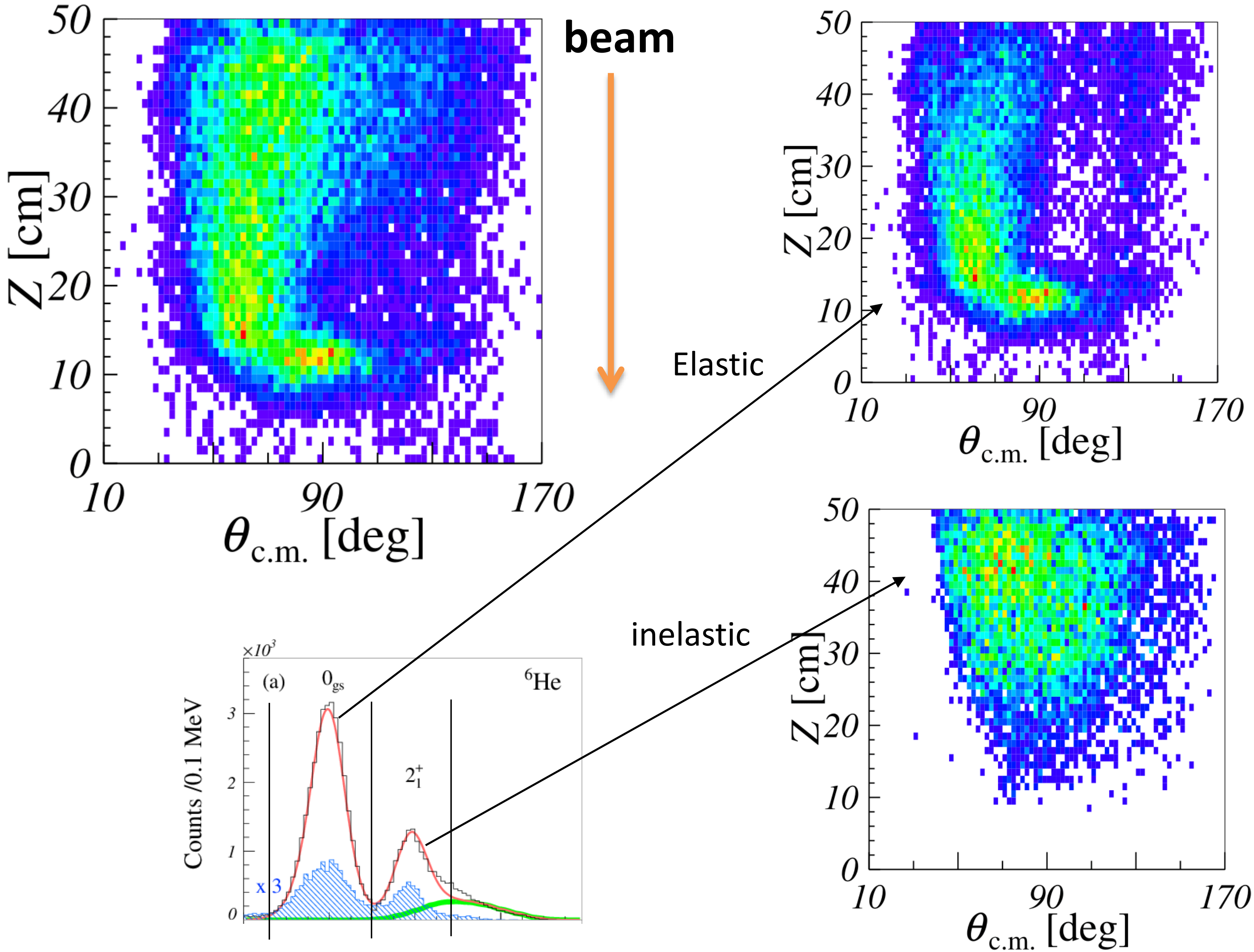




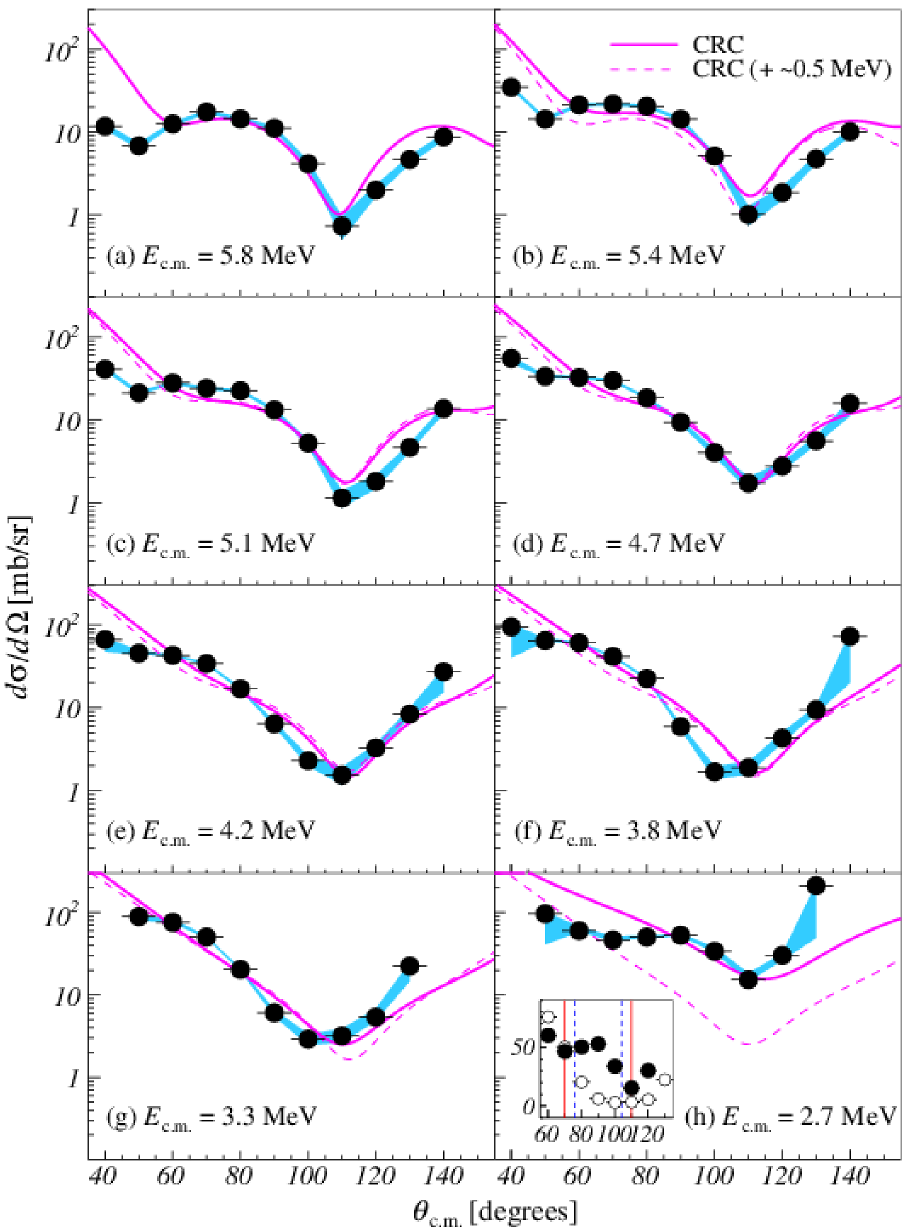
$^6He(\alpha,\alpha)$: excitation energy spectrum

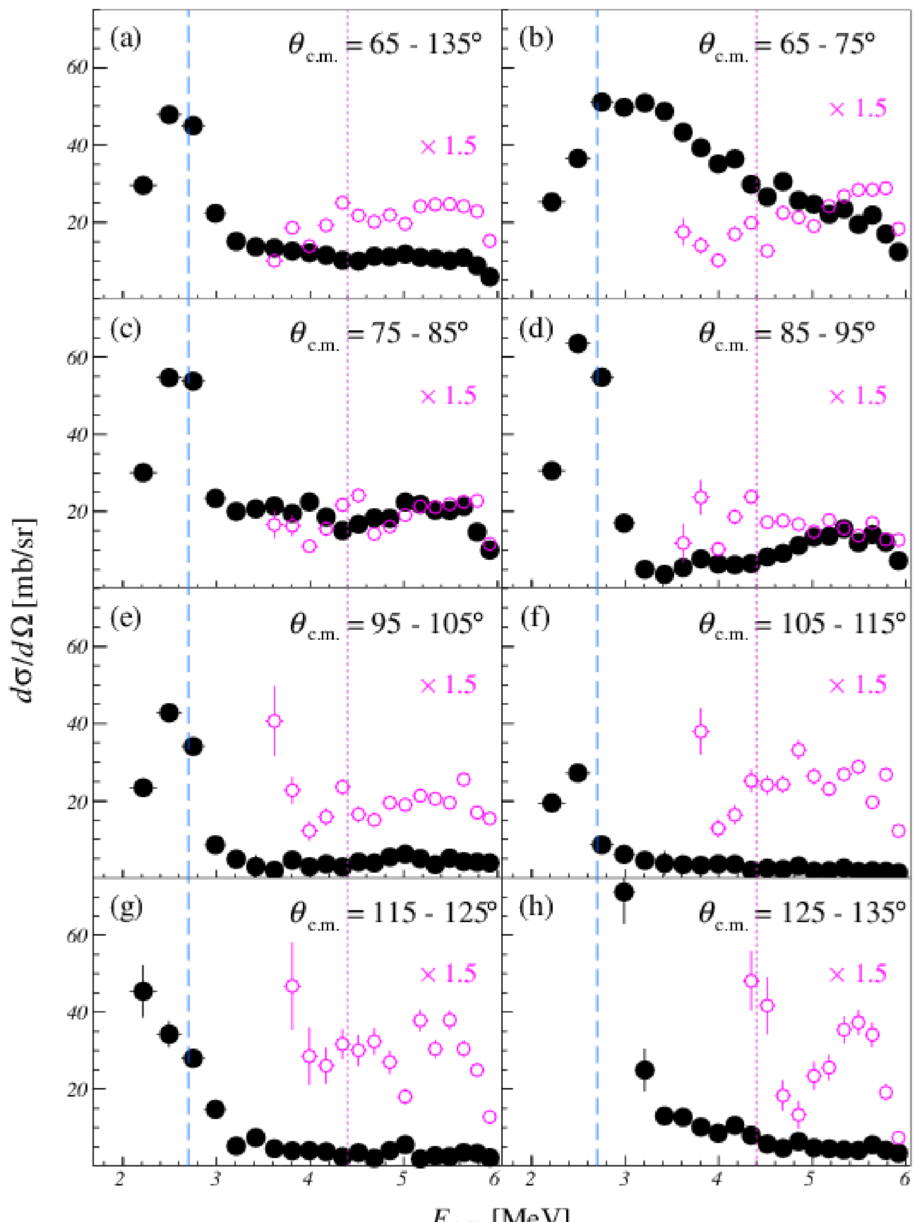


^{6}He(α,α): reaction vertices map

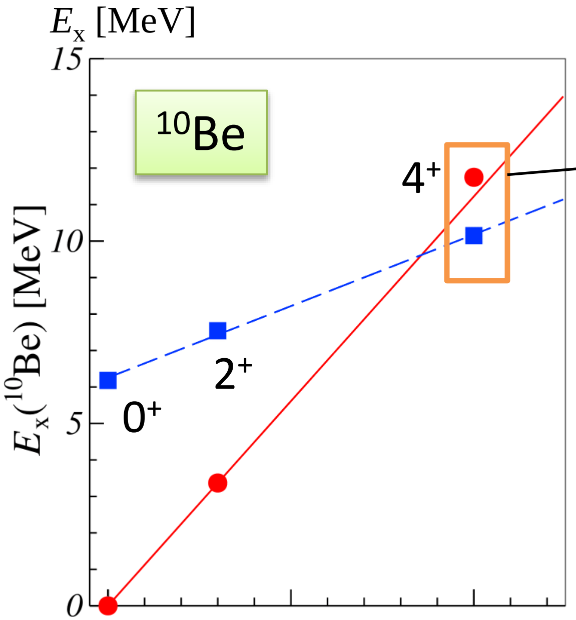


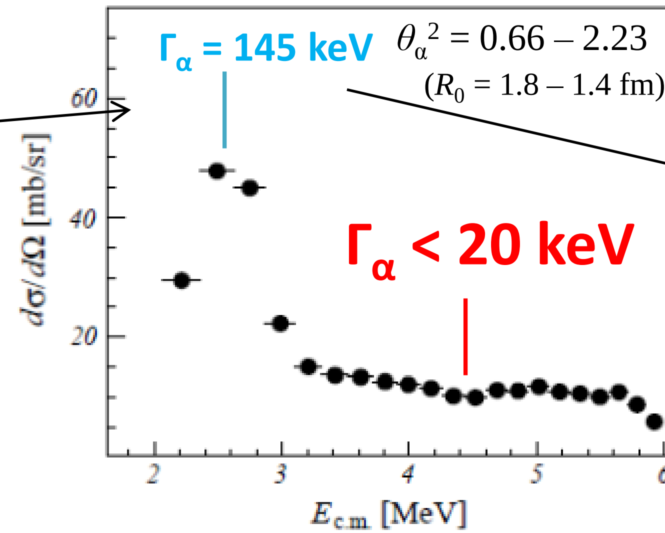
$^6He(\alpha,\alpha)$: cross sections breakdown

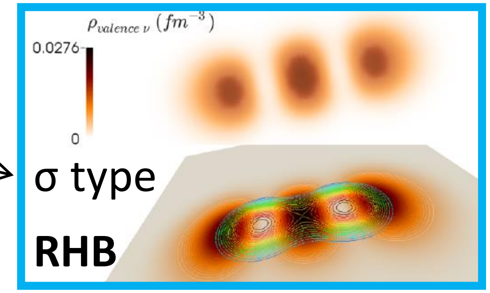




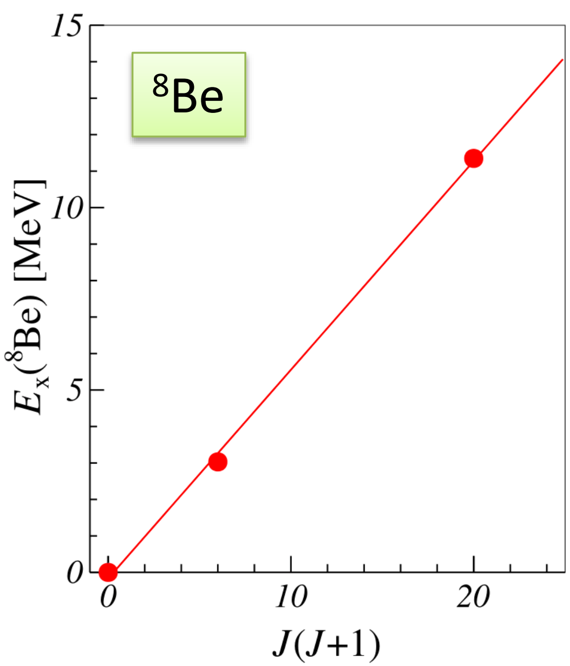
Suppression of alpha decay width



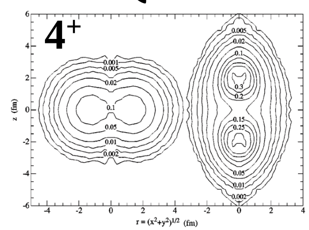


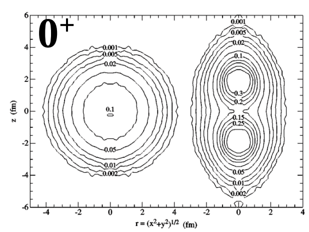


J-P. Ebran *et al.*
Phys. Rev. C 90, 054329 ('14)



QMC





α+α **scattering analysis**

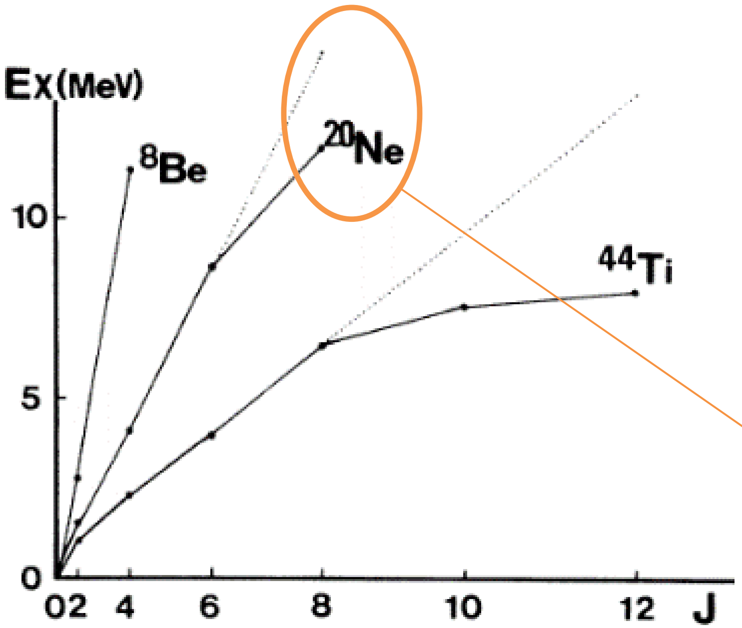
$S(4^+) = 1.39$

$S(2^+) = 1.46$

$S(0^+) = 1.48$

P. Mohr *et al.*
Z. Phys. A 349, 339 ('94)

Melting alpha clusters in ^{20}Ne



T. Yamada, Phys. Rev. C 42, 1432 ('90)

Deformed-basis AMD

TABLE I. Observed [10] and calculated α-RW (θ_α^2), multiplied by 100 at the channel radius $a=6$ fm, for $K^\pi=0_1^+$, 0_4^+ and 0_1^- band members. For comparison, the results of the $(sd)^4$ shell model (SM) [18], $\alpha+{}^{16}$O RGM (RGM) [19], and $(\alpha+{}^{16}\mathrm{O})+({}^8\mathrm{Be}+{}^{12}\mathrm{C})$ coupled channel OCM (OCM) [20] are shown.

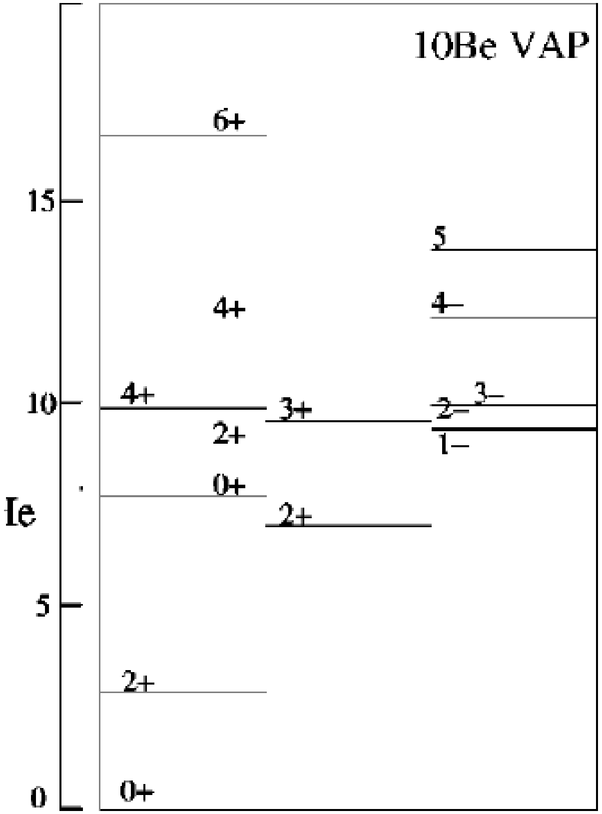
K^π	J^π	$\theta_{obs}(a)^2\times 100$	SM	RGM	OCM	AMD
0_1^+	6_1^+	1.0±0.2	0.20	1.4	0.50	0.53
	8_1^+	0.094±0.027	0.020	0.24	0.10	0.08

K^π	J^π	W^J	$\langle \hat{V}_{ls} \rangle$
0_1^+	0_1^+	0.70	−5.2
	2_1^+	0.68	−5.3
	4_1^+	0.54	−5.9
	6_1^+	0.34	−8.4
	8_1^+	0.28	−10.9

M. Kimura, Phys. Rev. C 69, 044319 ('04)

Melting alpha clusters in ^{10}Be 2^+, 4^+ states

AMD VAP (variation after spin-parity projection)



Kanada-En'yo, Horiuchi, Doté, Phys. Rev. C 60, 064304 ('99)

In the $K^{\pi}=0_1^+$ band, the 2α cores weaken with the increase of the total spin due to the spin-orbit force. The reduction of the clustering structure is more rapid in the case of interaction (2) with the stronger spin-orbit force, and the 2_1^+ and 4_1^+ states in case (2) interactions contain the dissociation of α.

$$V_{LS}=\{u_I\exp(-\kappa_I r^2)+u_{II}\exp(-\kappa_{II}r^2)\}\frac{(1+P_\sigma)}{2}\frac{(1+P_\tau)}{2}\mathbf{L}\cdot(\mathbf{S}_1+\mathbf{S}_2), \quad (15)$$

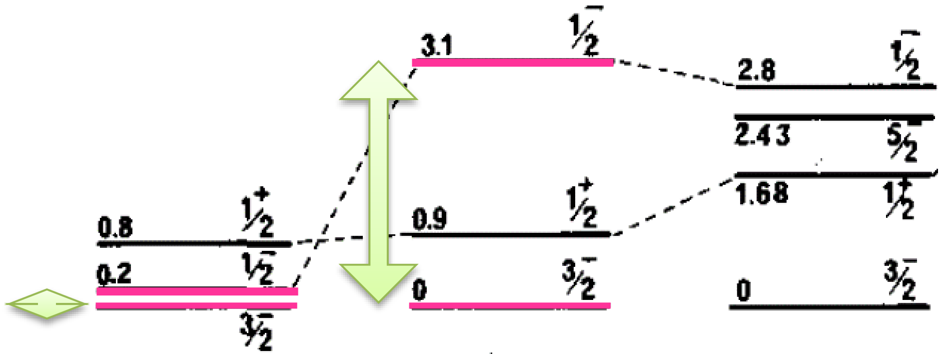
(1) $u_I = -u_{II} = 3000$ MeV
(2) $u_I = -u_{II} = 3700$ MeV

- Clustering and shell effects seem to be highly competitive in Be isotopes
- Effects of N = 6 subshell closure?

Effects of *1p*$_{1/2}$-*1p*$_{3/2}$ splitting

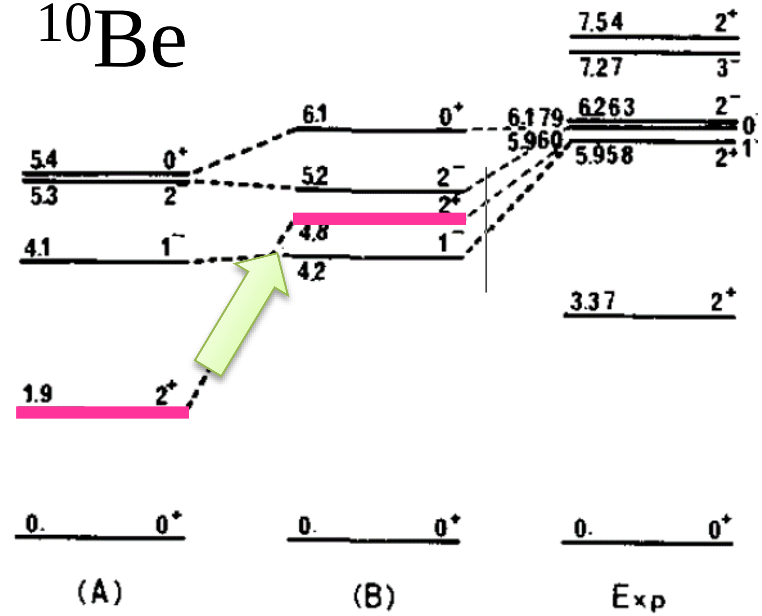
Molecular Orbital Model

^{9}Be



W/o spin-orbit W/ spin-orbit

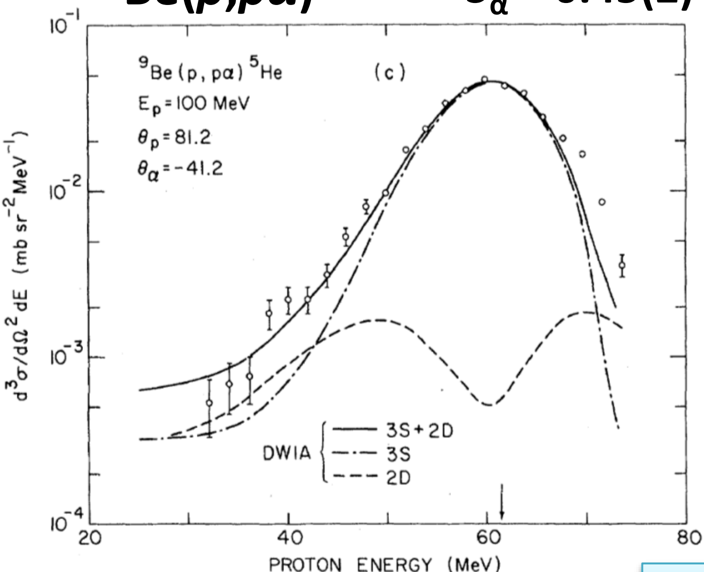
^{10}Be



M. Seya, M. Kohno, S. Nagata, PTEP 65, 204 ('81)

Probe ground state alpha clustering

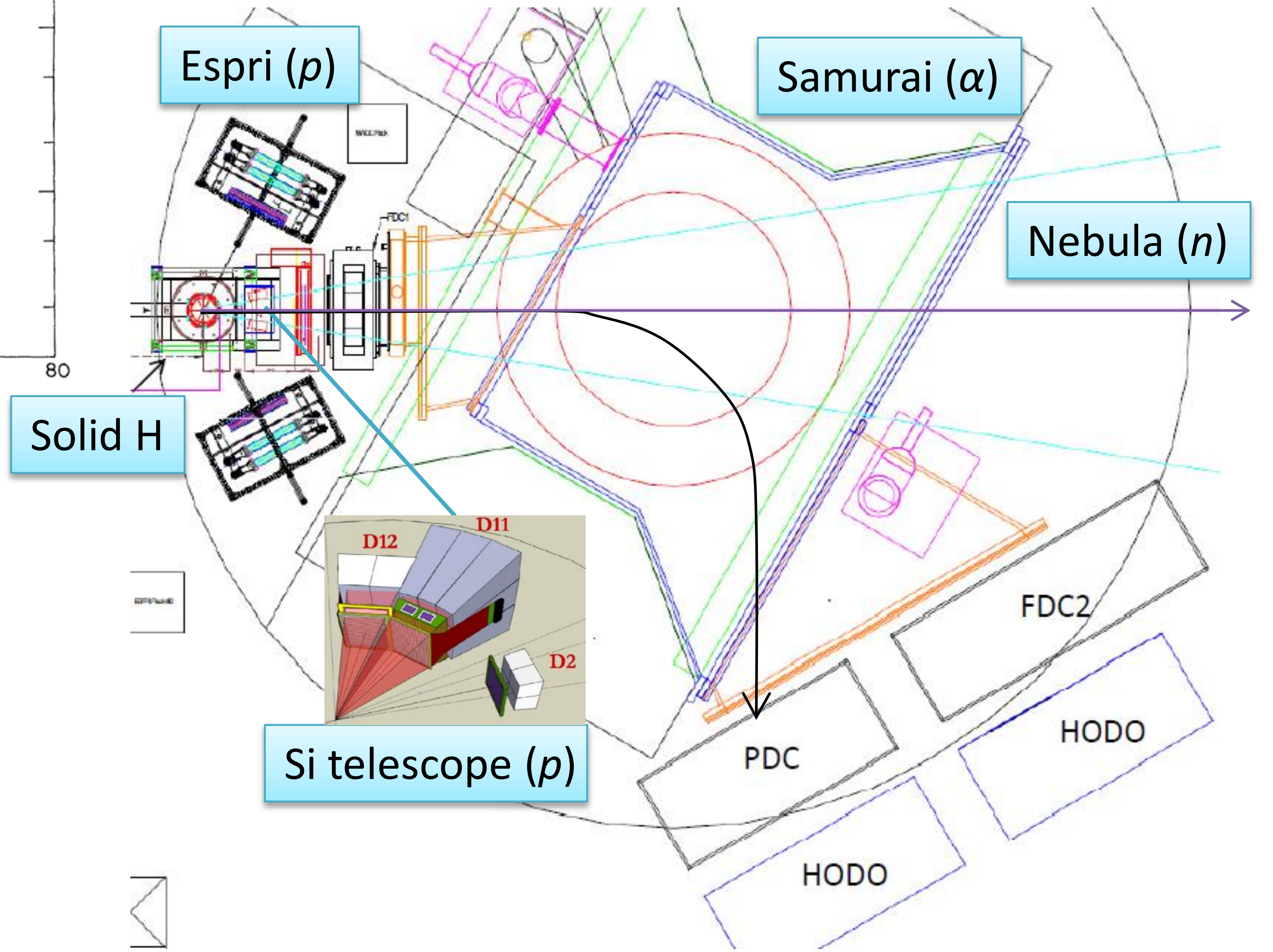
^{9}Be(p,$p\alpha$) **S_α = 0.45(2)**



P.G. Roos *et al.*,
Phys. Rev. C 15, 69 ('77)

^{10,12,14}Be(p,$p\alpha$)

Samurai 13
(D. Beaumel)



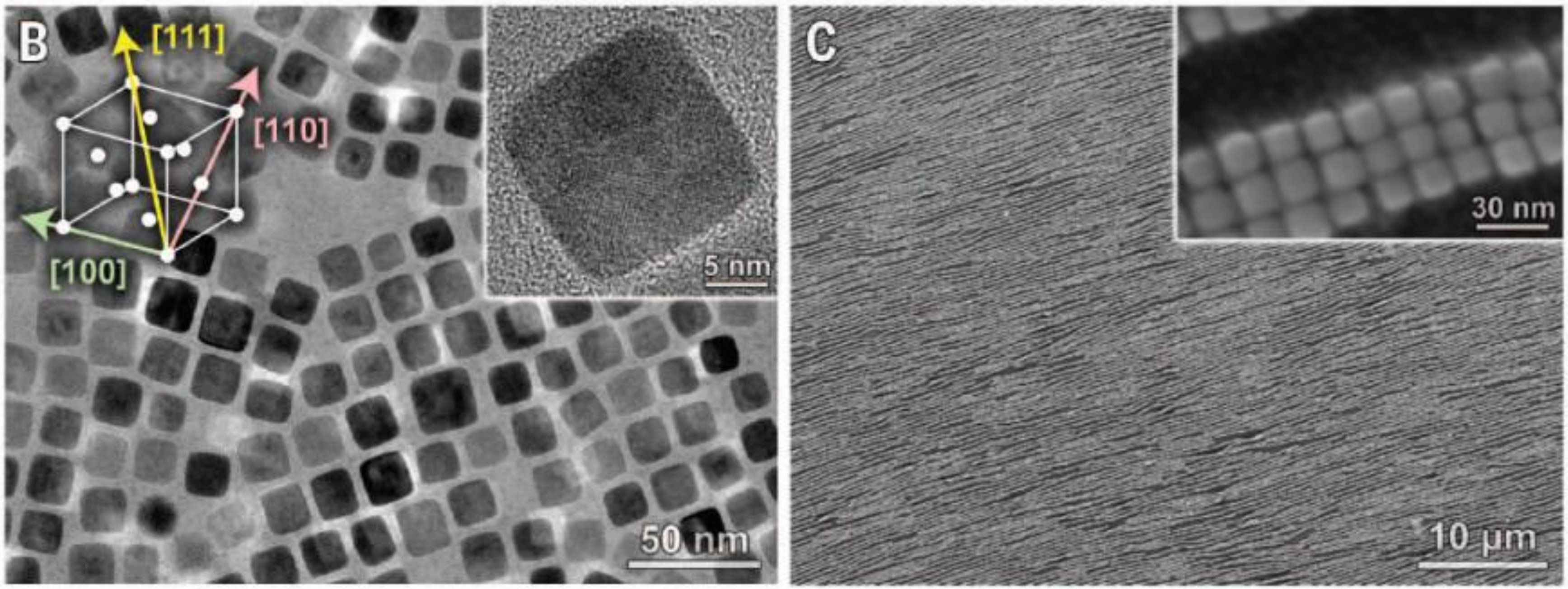
^{14}C:
When nuclei become linear

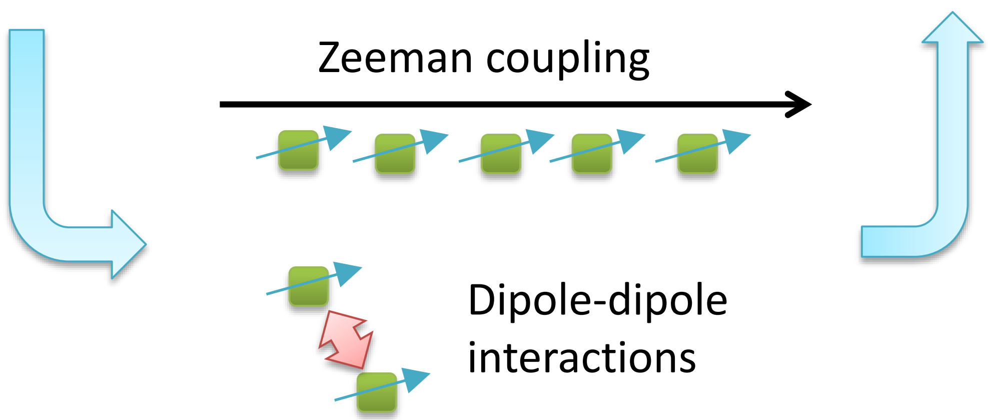
A. Fritsch, S. Beceiro-Novo, D. Suzuki, W. Mittig *et al.*, Phys. Rev. C 93, 014321 ('16)

Clusters and geometry

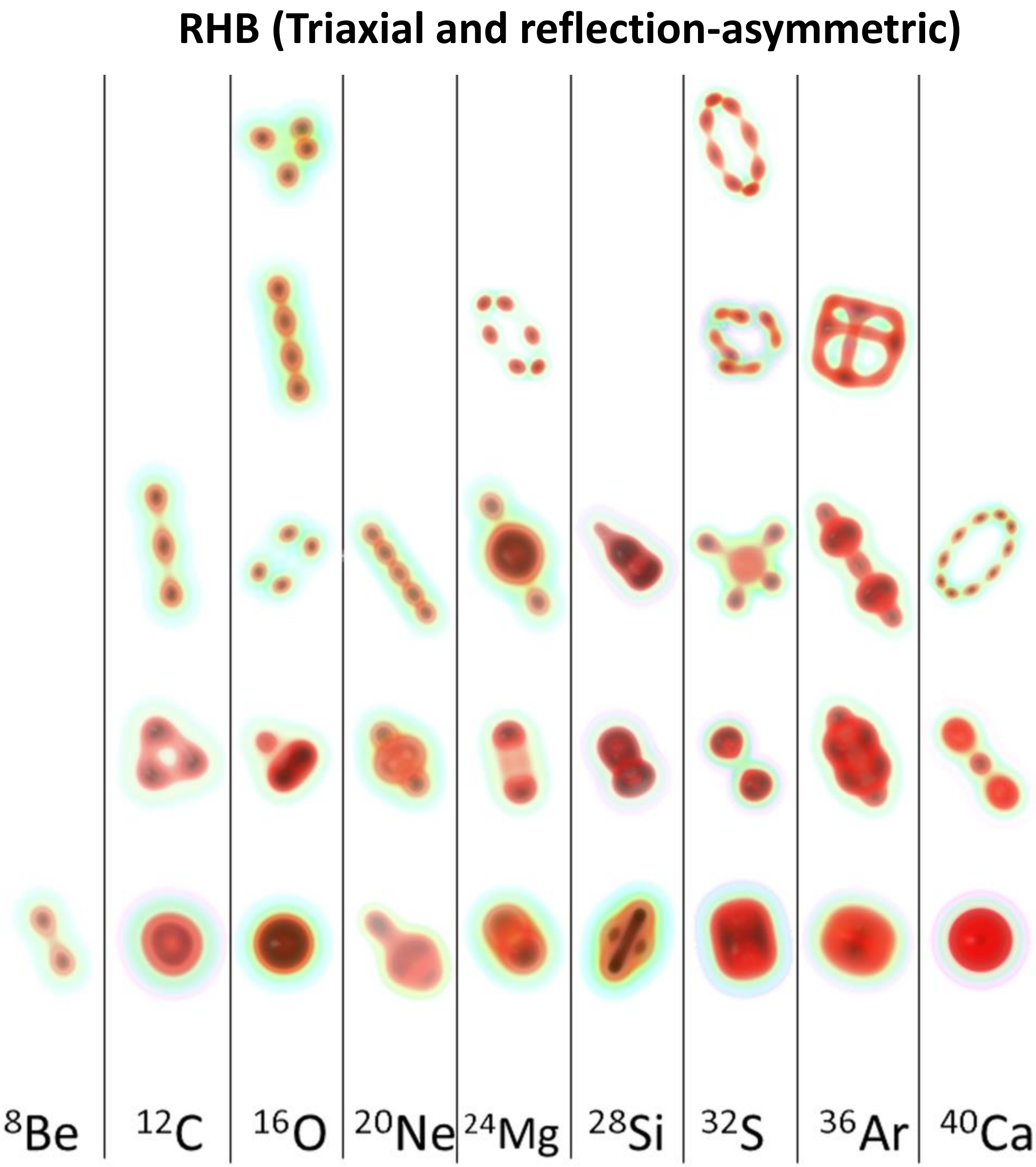
Magnetic nano cubic

G. Singh *et al.*, Science 345, 1149 ('14)





Atlas of femto-scale geometries



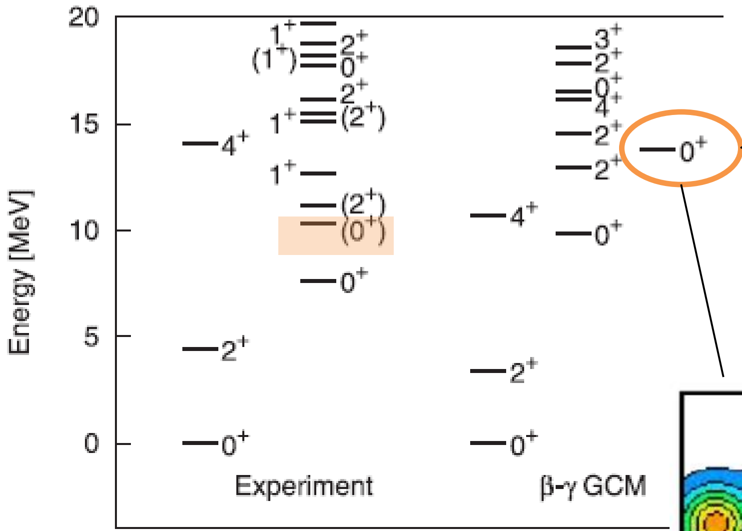
J.-P. Ebran *et al.*, Phys. Rev. C 90, 054329 ('14)

3α linear chain puzzle in ^{12}C

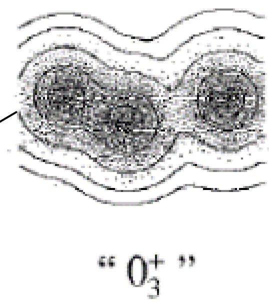
Fermionic Molecular Dynamics (FMD, '04)

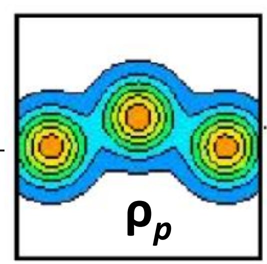
T. Neff and H. Feldmeier, Nucl. Phys. A 738, 357

AMD ('12)

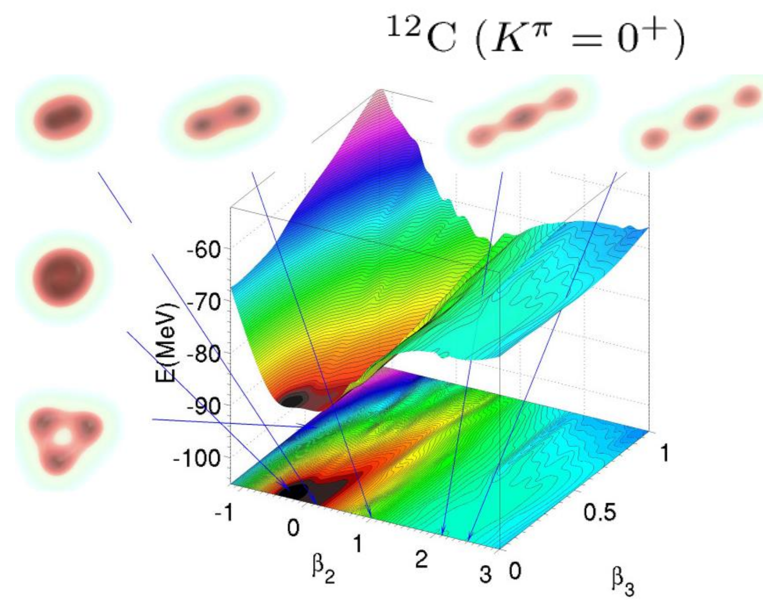


T. Suhara, Y. Kanada-En'yo, Prog. Theo. Phys. 123, 303 ('12)





RHB ('14)

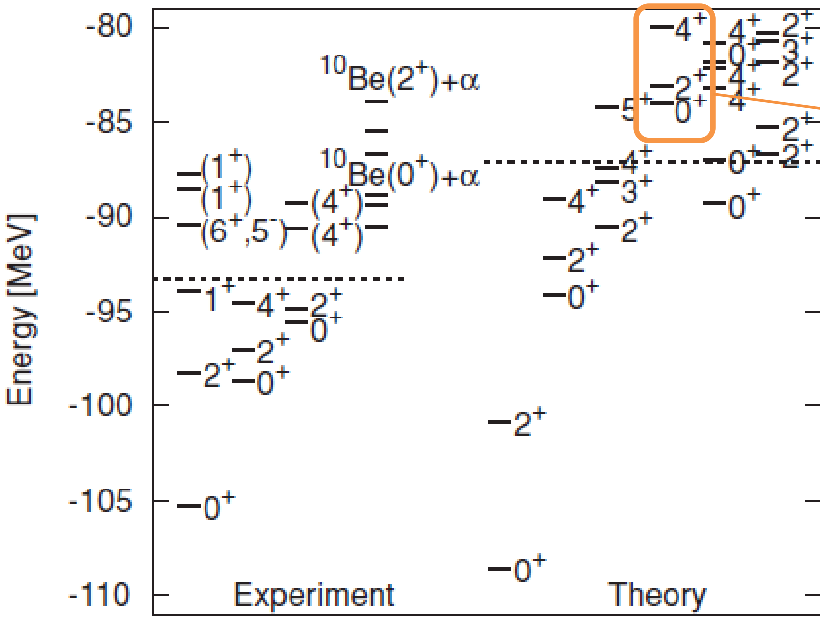


J-P. Ebran *et al.* Phys. Rev. C 90, 054329 ('14)

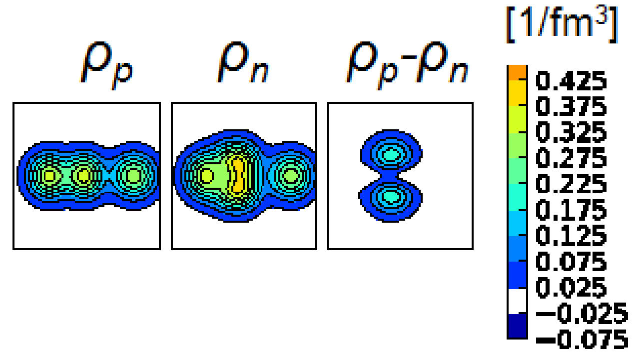
- Simplest linear chain
- Predicted slightly-bent chain for 0_3^+ at 10.3 MeV
- And yet no experimental evidence

Linear chain prediction in ^{14}C

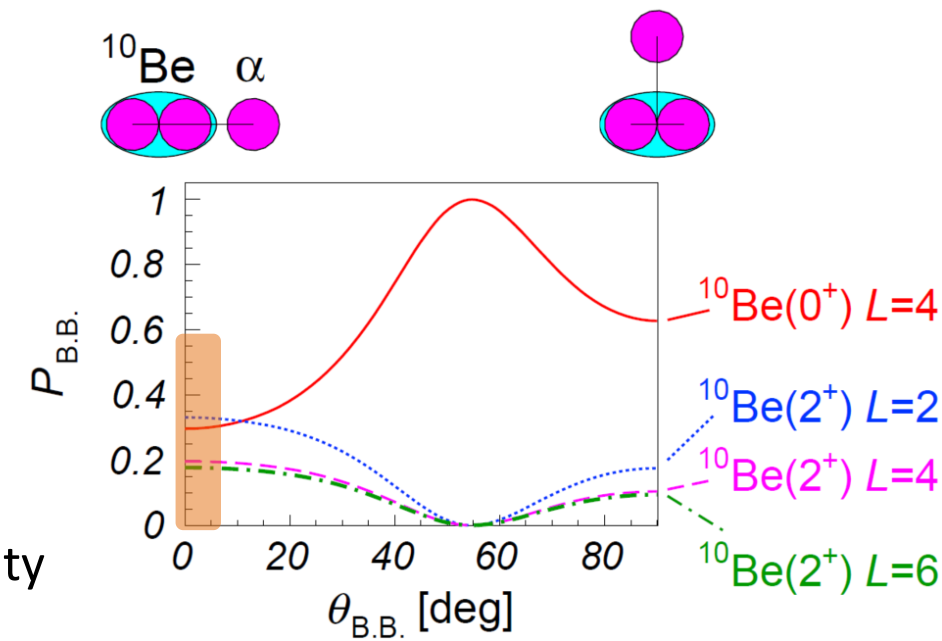
AMD ('10)



T. Suhara, Y. Kanada-En'yo, Phys. Rev. C 82, 044301



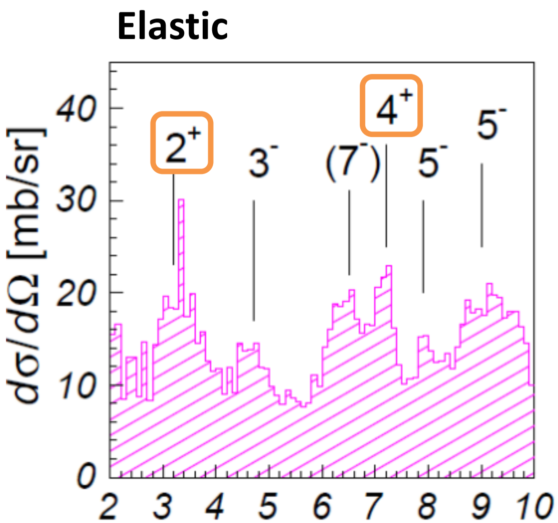
Bethe-Bloch wavefunction

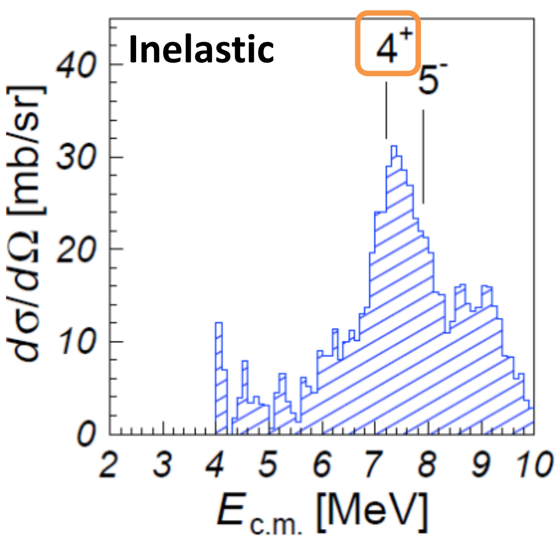


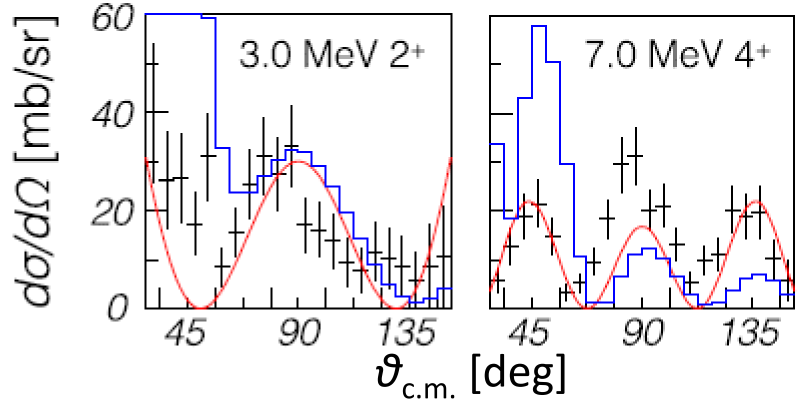
Linear chain's signal

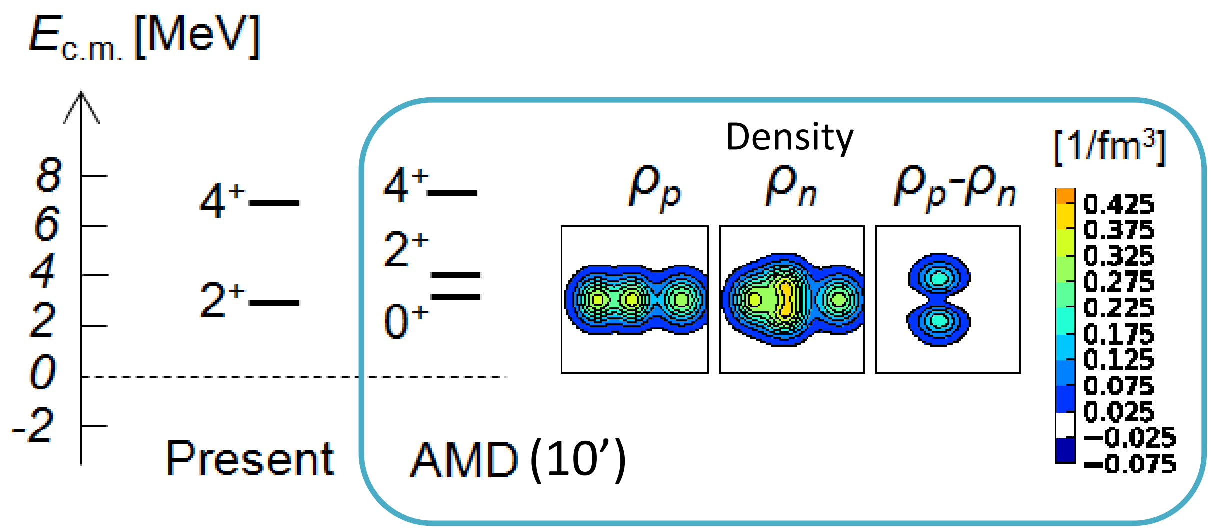
- Rotational band
- Inelastic branching: degree of linearity

Resonant α scattering of ^{10}Be with PAT-TPC







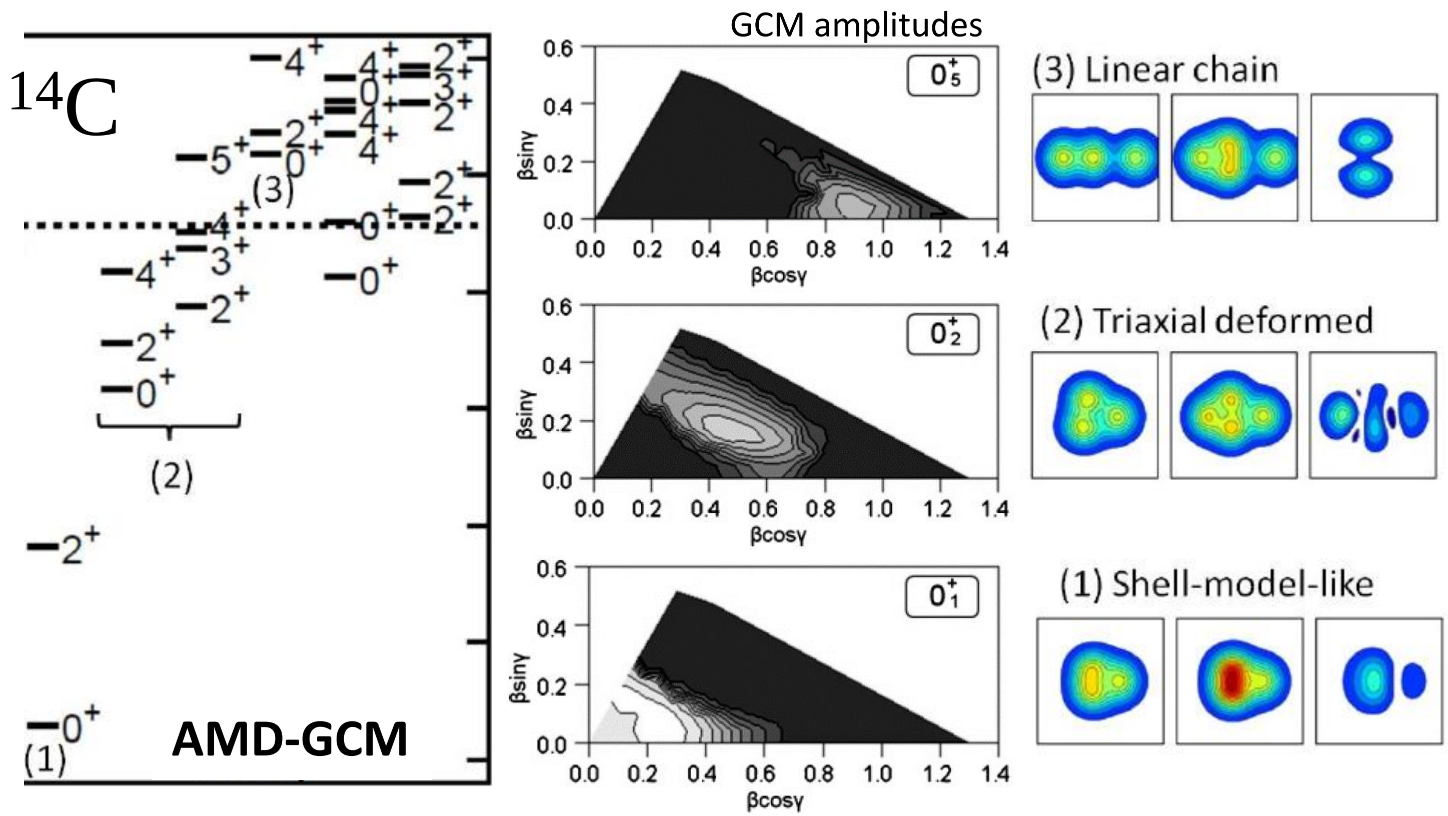


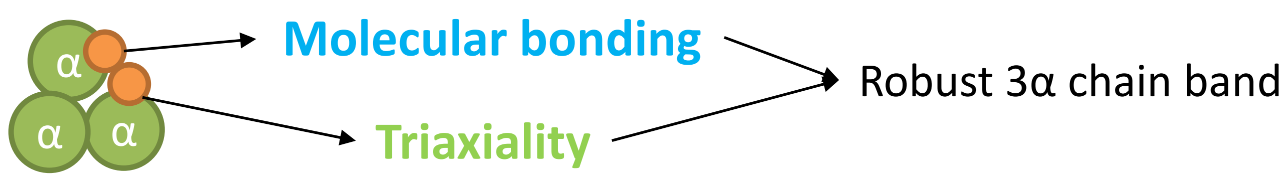
T. Suhara, Y. Kanada-En'yo, Phys. Rev. C 82, 044301

promising candidate of 3α linear chain

How elusive is linear chain in ^{12}C

Or why linear chain emergies in ^{14}C?





T. Suhara, Y. Kanada-En'yo, Phys. Rev. C 82, 044301 ('10); J. Phys. Conf. Ser. 321, 012047 ('11)

Summary

- Halfscale PAT-TPC developped at the NSCL.
- First experiments carried out for clustering in ^{10}Be and ^{14}C.
  - Thick 'active' target method for resonant scatteirng
  - ^{6}He and ^{10}Be beam from Twinsol facility at Notre Dame
  - Only 2 neutrons, but significant and essential evolution of cluster structures.
- Bibliography

  - Review: S. Beceiro-Novo, T. Ahn, W. Mittig, D. Bazin, Prog. Part. Nucl. Phys. 84, 124 ('15)
  - PAT-TPC: D. Suzuki *et al.*, Nucl. Instr. Meth. A 691, 39 ('12)
  - ^{10}Be: D. Suzuki *et al.*, Phys. Rev. C 87, 054301 ('13)
  - ^{14}C: A. Fritsch *et al.*, Phys. Rev. C 93, 014321 ('16)

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H. Wang

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