The 3rd Light Ion Nuclear Collision Workshop

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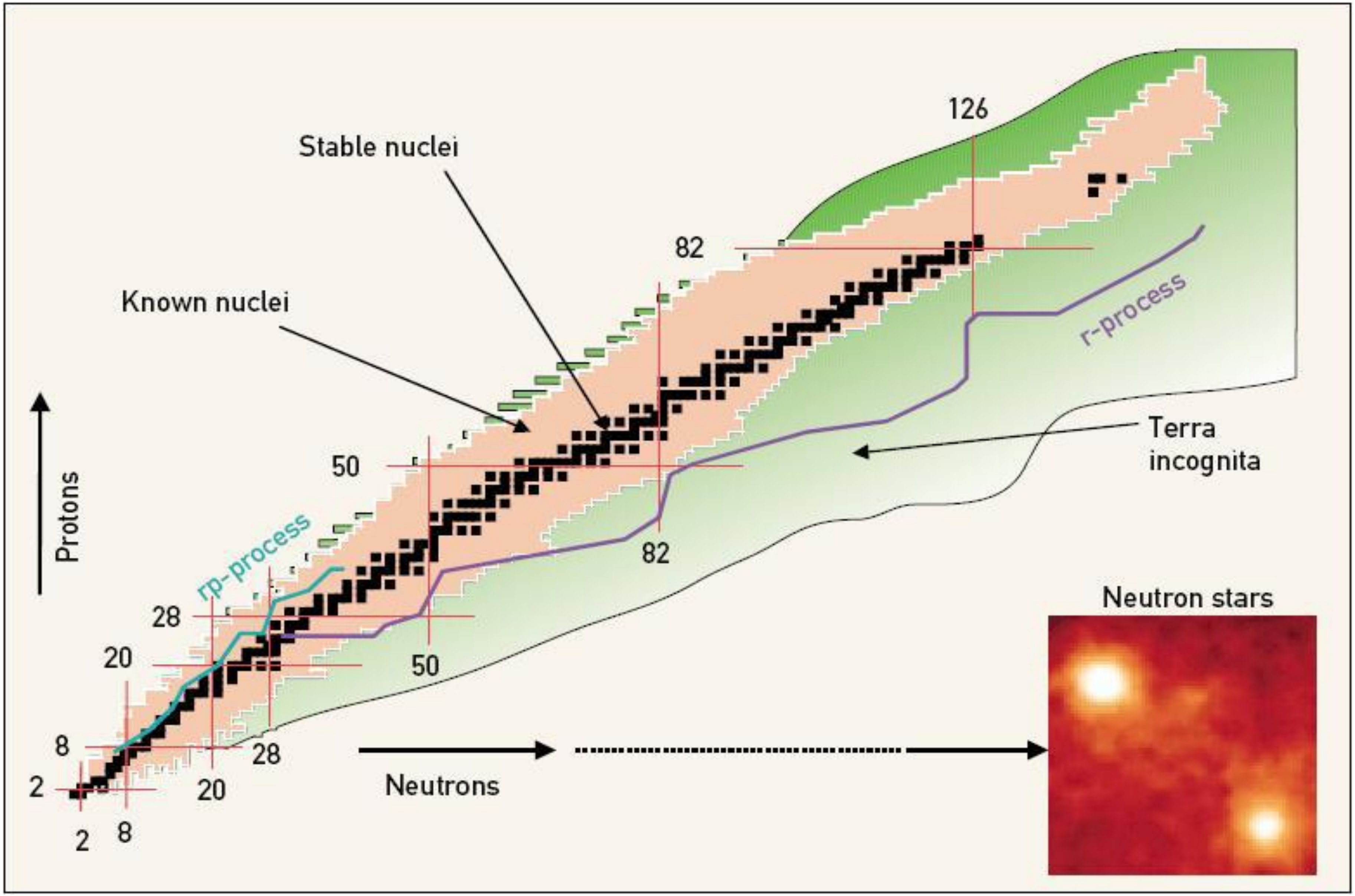
Joint Institute for Nuclear Research

Radioactive Nuclei:
Structure and Reactions



Presently ~ *3600* nuclei have been observed, less than *300* nuclei are *stable*

NUCLEAR STRUCTURE NEAR THE VALLEY OF STABILITY

exhibit similar binding for neutrons and protons

density and diffuseness of the surface are nearly constant

the resulting ***shell structure*** is well established

Nobel Prize Medal

M. Goeppert-Mayer, J.H.D. Jensen, nobel prize in 1963
"for their discoveries concerning nuclear shell structure"

magic numbers : 2, 8, 20, 28, 50, 82, 126 are the same for neutrons and protons

^{4}He, ^{16}O, ^{40}Ca, ^{48}Ca, ^{208}Pb : stable double – magic nuclei

nuclear potential is well parametrized

pronounced shell closures define the effective degrees of freedom needed for a quantitative understanding of atomic nuclei

A.N. Bohr, B.R. Mottelson, L.J. Raynwater **, nobel prize in 1975**

"for the discovery of the connection between collective motion and particle motion in atomic nuclei and the development of the theory of the structure of the atomic nucleus based on this connection"

Conceptual framework of nuclear structure is the nuclear shell model

Qualitative picture:

nucleons are moving almost independently in a mean-field (self-consistent) potential obtained by averaging out the interactions between a single nucleon and all remaining protons and neutrons.

Quantitative results:

accounting for the residual interaction between the nucleons

Nuclear structure of exotic nuclei is different from that around the stability line and represent a formidable challenge for the nuclear many-body theories and their power to predict nuclear properties

Unique factors for exotic nuclei

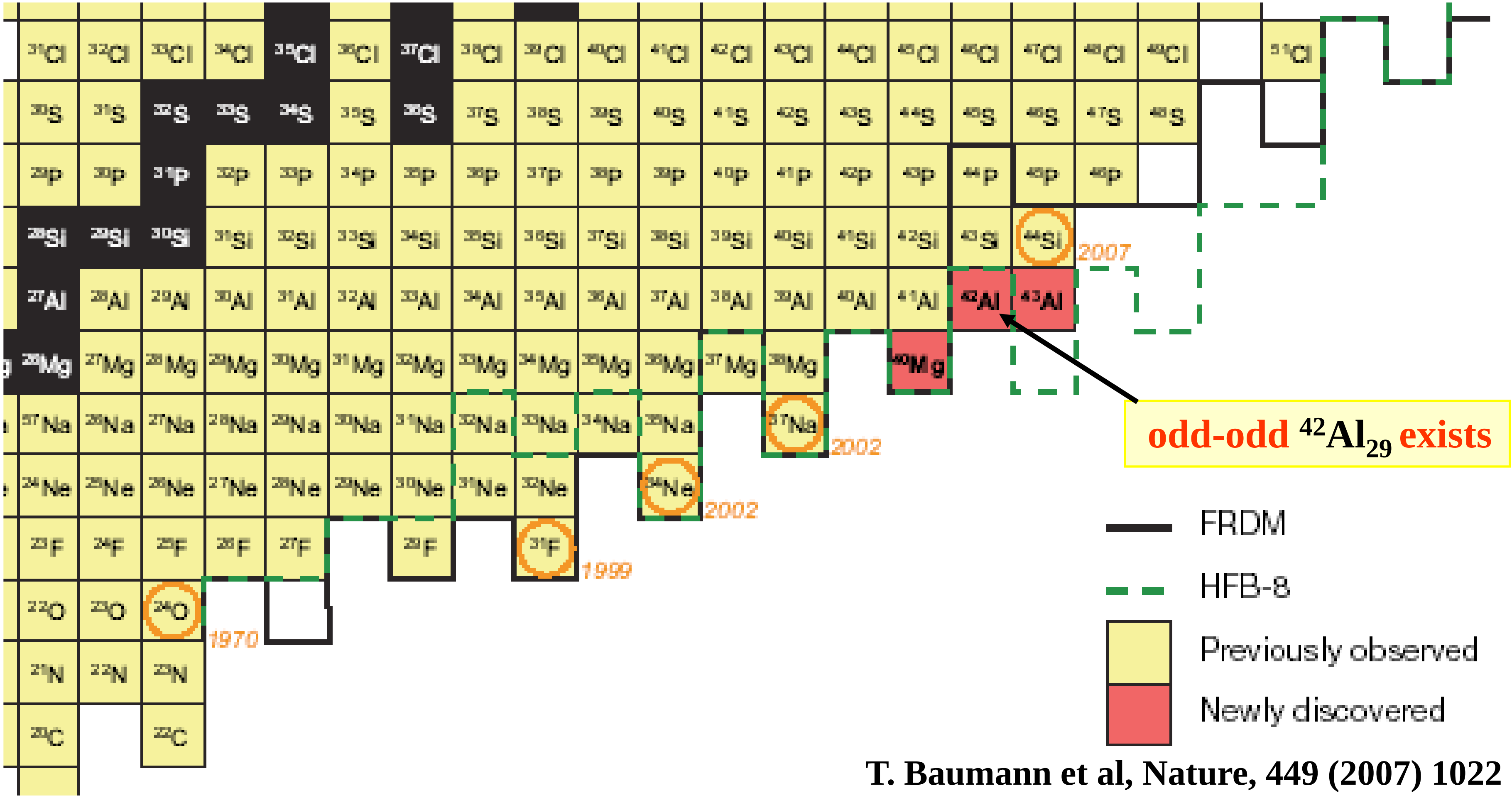
the weak binding, closeness of the particle continuum (a large diffuseness of the nuclear surface, extreme spatial dimensions for the outermost nucleons)

exotic combinations of proton and neutron numbers (prospects for completely new structural phenomena)

For exotic nuclei there are many fundamental questions about :

- limits of nuclear existence ?
- properties of nuclei with an extreme N / Z ratio ?
- the shell structure evolution towards driplines ?
  (disappearance of magic numbers, new magic numbers, …)
- the mechanism of binding of exotic nuclei ?
- exotic few-body systems ?
- nuclear systems beyond driplines ?
- the effective nucleon-nucleon forces at limits of stability ?
- the role of correlations in the low-density nuclear zone ?
- clusters features of exotic nuclei ?

. . . . .



odd-odd $^{42}\text{Al}_{29}$ exists

T. Baumann et al, Nature, 449 (2007) 1022

The location of the neutron drip line is known up to Oxygen

FRDM : P. Moller et al, At. Data Nucl. Data Tables 59 (1995) 185.

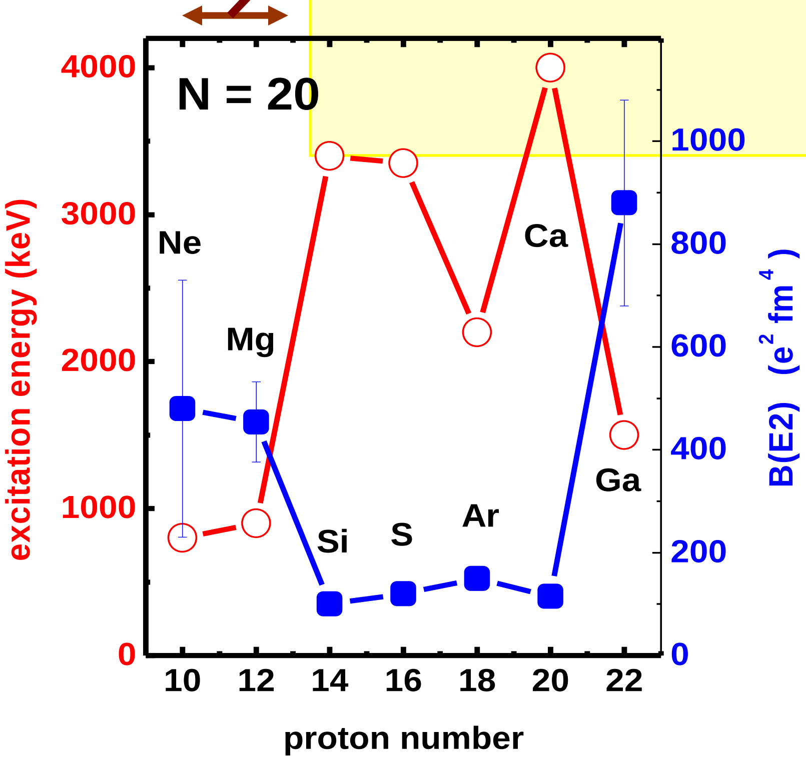
HFB-8 : M. Samyn et al, Phys. Rev. C70, 044309 (2004).

BREAKDOWN OF THE N = 20 SHELL CLOSURE IN EXOTIC NUCLEI

in stable nuclei the shell gap N = 20 is formed between the *$d_{3/2}$* and *$f_{7/2}$* orbits originating from the N = 2 and N = 3 major oscillator shells

In neutron-rich isotopes with Z= 10-12 *fp* shells are intruder states in *sd* shells
("island of inversion" ⟸ strong mixing ⟹ deformation)

Evidences: anomalies in binding energies
mean-square radii,
nuclear spectra,
doubly magic nucleus $^{28}O_{20}$ is unbound



low excitation energy of the first 2^+ state and a large deformation for $^{32}Mg_{20}$

(B(E2) = 454+-78 e^2 fm^4)

T. Motobayashi et al, PLB 346 (1995) 9

BREAKDOWN OF THE N = 8 SHELL CLOSURE IN EXOTIC NUCLEI

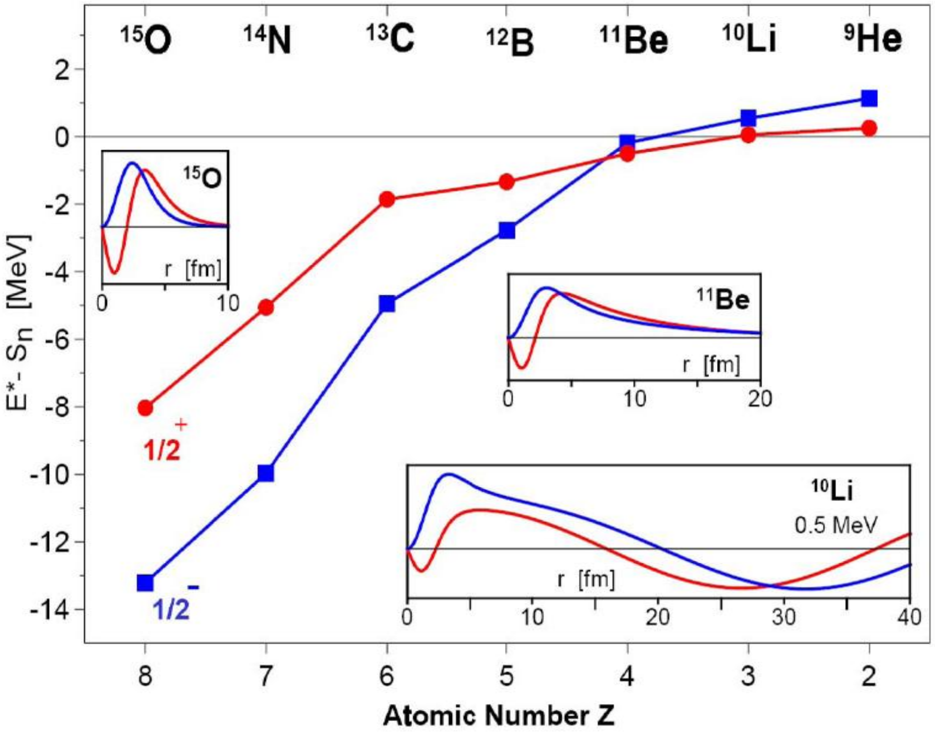
Magic number 8 comes from any mean-field description. Large distances in energy for any central potential (square well, harmonic oscillator, Woods-saxon, ...)

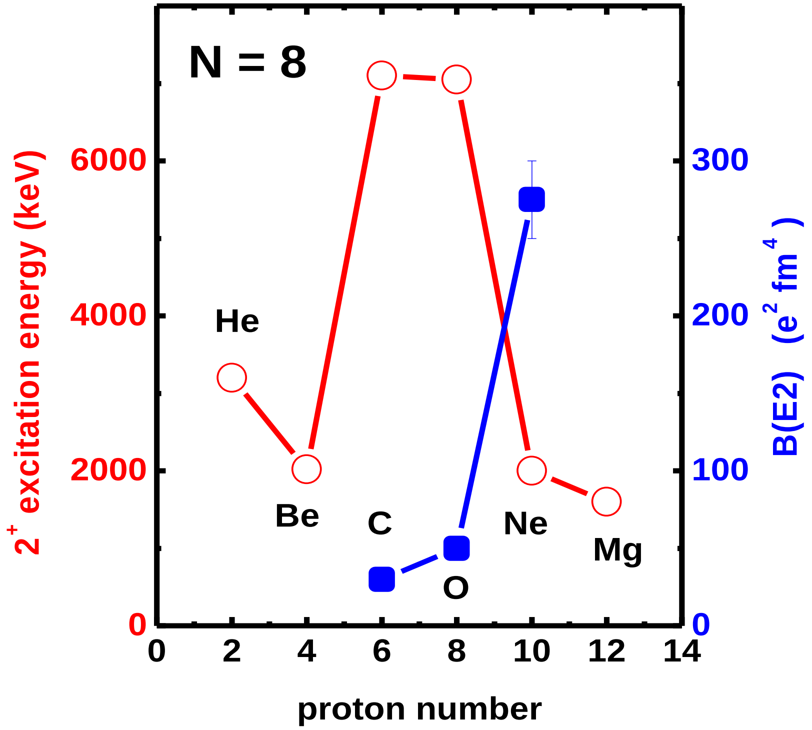
⟹ **the *0p* states are well separated from the *1s0d* ones.**

Evidences:

The inversion of the *p* and *s* shell for the ground-states of the *N* = 7 isotones close and beyond the dripline reflects the disappearance of the *N* = 8 shell gap. The ground state of ^{11}Be is 1/2$^+$ instead of 1/2$^-$

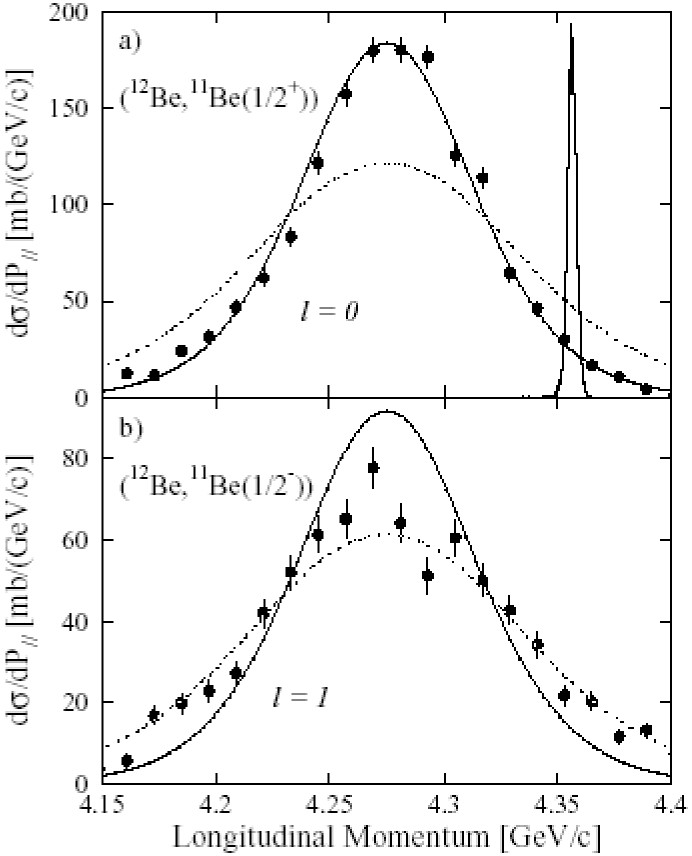
N = 7 1/2$^-$ - 1/2$^+$ level inversion



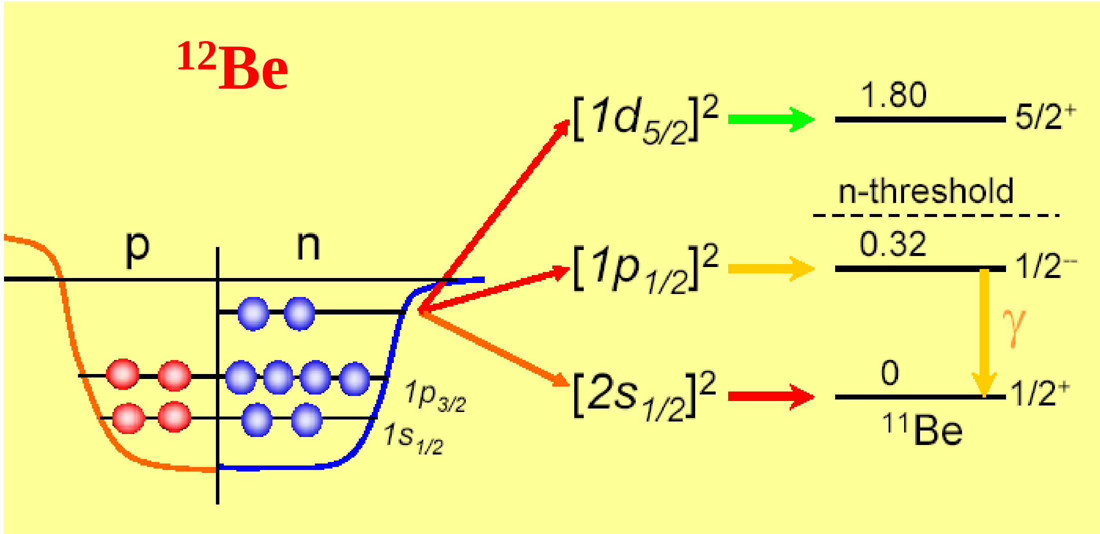


ground state wave function of ^{12}Be → significant admixtures of *sd* states

Evidences: **knockout reaction ^{9}Be(^{12}Be,^{11}Be + g) at 78 MeV/nucleon**



The ground state of ^{11}Be accounts for approximately two-thirds of the cross section. It is direct proof of a significant occupancy of the *1s$_{1/2}$* state in ^{12}Be



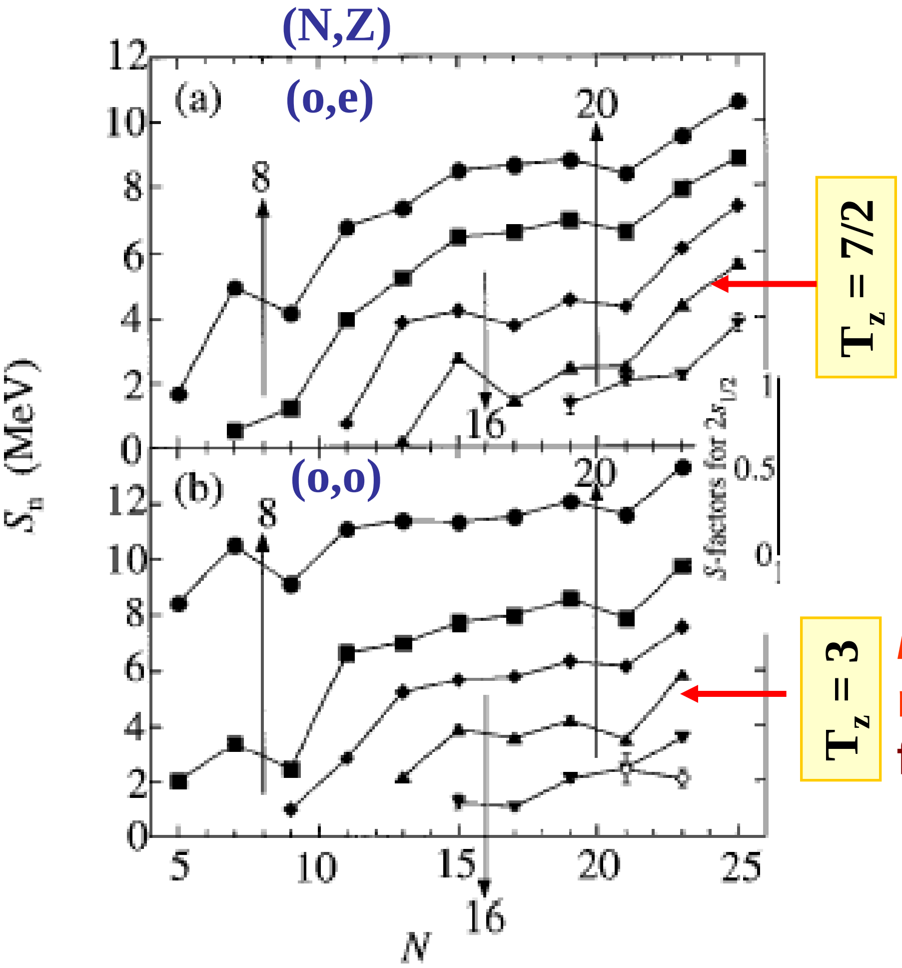
A. Navin et al, PRL 85 (2000) 266

Spectroscopic factors

$C(s_{1/2}) \sim 0.42$; $C(p_{1/2}) \sim 0.37$

THE EMERGENCE OF A NEW SHELL FOR OXYGEN ISOTOPES AT N = 16

A consequence of the disappearance of the N = 20 shell closure is the emergence of a new magic number at N = 16, formed in $^{24}O_{16}$ between the occupied $s_{1/2}$ and the unbound valence $d_{3/2}$ orbit. This gap amounts to about 4 MeV and the $d_{3/2}$ orbit is unbound by about 1.5 MeV. The neutron-neutron interactions due to the filling of this orbit do not suffice to bind the $^{26,28}O_{18,20}$



Evidences:

Survey of neutron separation energies.

Sudden increase of interaction cross sections σ_I were observed in the F, O and N sotopes at $N \simeq 15$. The σ_I values for the ^{23}O and ^{25}F isotopes could be reproduced with a dominance of the $s_{1/2}$ shell for a valence orbit.

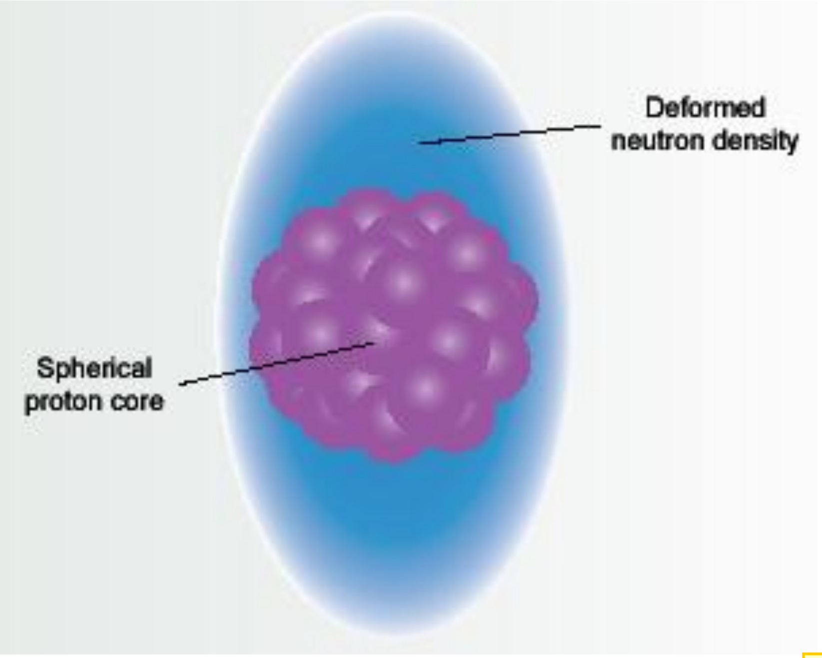
N = 16 corresponds to the last bound nucleus not only for oxygen (^{24}O) but also for nitrogen (^{23}N) and even carbon (^{22}C).

T. Ozawa et al, PRL 84 (2000) 5493

ANOMALOUS DEFORMATION MODES

the density distributions of neutrons and protons are similar in nuclei close to stability: if one distribution is spherical, then the other will be spherical. (one has a prolate deformation, the other will have a prolate deformation)

experimental studies of the collectivity of the first excited 2^+ state in ^{16}C suggest pure neutron prolate deformation, with the protons residing in a spherical core



A remarkably small $B(E2) = 0.26$ W.u. was found for ^{16}C through a lifetime measurement (probes the charge contribution). The observed value (in W.u.) is far smaller than any other $B(E2)$ measured on the nuclear chart.

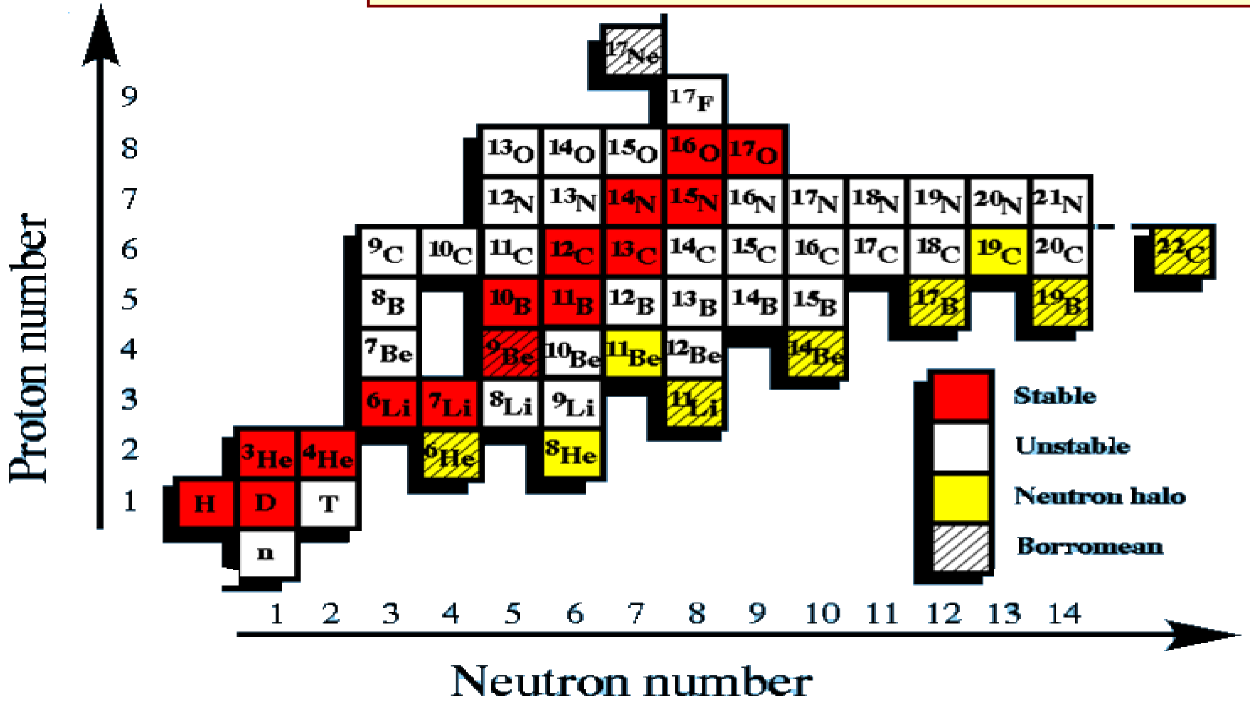
Inelastic proton scattering on ^{16}C (sensitive to both proton and neutron contributions) was used to determine the neutron collectivity of the 2^+ state.

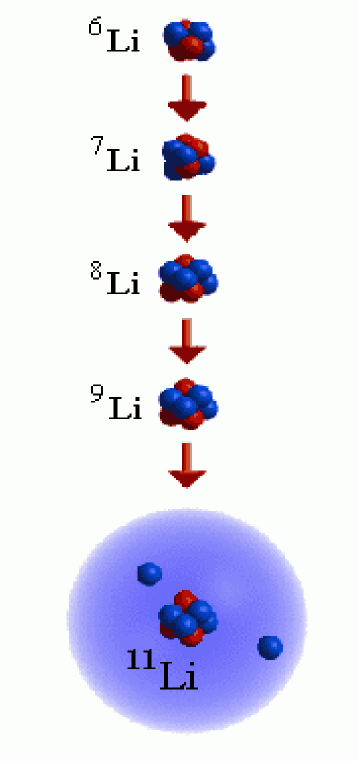
N. Imai et al, PRL 92 (2004) 062501

H. J. Ong et al, PRC 73 (2006) 062501

A combination of these two measurements allows one to disentangle the proton and neutron collectivities for the 2^+ state.

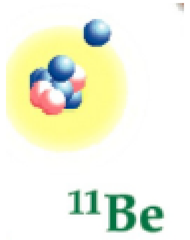
HALO: ⇨ ***new dripline*** **phenomenon with clusterization into an ordinary core nucleus and a veil of halo nucleons – forming very dilute neutron matter**





Chains of the lightest isotopes
(He, Li, Be, B, …) end up with two neutron halo nuclei

Two neutron halo nuclei (^{6}*He* , ^{11}*Li* , ^{14}*Be* , …)
break into three fragments and are all Borromean nuclei



One neutron halo nuclei (^{11}Be , ^{19}C , …)
break into two fragments

Neutron halo nuclei

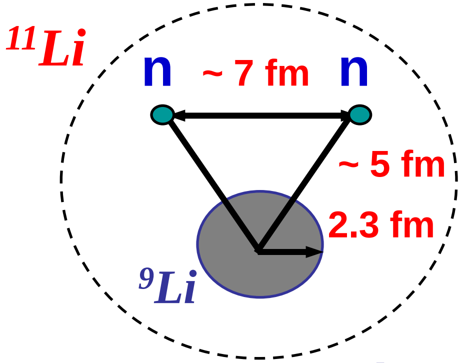
Halo

(^{6}*He*, ^{11}*Li*, ^{11}*Be*, ^{14}*Be*, ^{17}*B*, …)

weakly bound systems with large extension and space granularity

"Residence in *forbidden* regions"

Appreciable probability for dilute nuclear matter extending far out into *classically forbidden* region



Separation energies of last neutron (s) :

halo	*stable*
< 1	6 - 8 MeV

$\varepsilon(^{11}Li) = 0.3$ MeV

$\varepsilon(^{11}Be) = 0.5$ MeV

$\varepsilon(^{6}He) = 0.97$ MeV

***Large size* of halo nuclei**

$< r^2 (^{11}Li) >^{1/2} \sim 3.5$ fm

(r.m.s. for $A \sim 48$)

***Two-neutron* halo nuclei**
(^{11}*Li*, ^{6}*He*, ^{14}*Be*, ^{17}*B*, . . .)

***Borromean* systems**

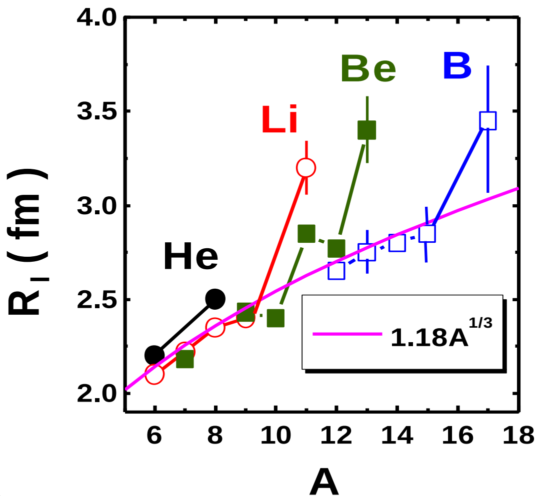
Borromean* system is *bound

none of the constituent *two-body* subsystems *are* bound

Peculiarities of halo nuclei: the example of ^{11}Li

(i) **weakly bound**: the two-neutron separation energy (~300 KeV) is about 10 times *less* than the energy of the first excited state in ^{9}*Li* .

(ii) **large size**: interaction cross section of ^{11}*Li* is about 30% *larger* than for ^{9}*Li*



This is very unusual for *strongly interacting* systems held together by *short-range interactions*

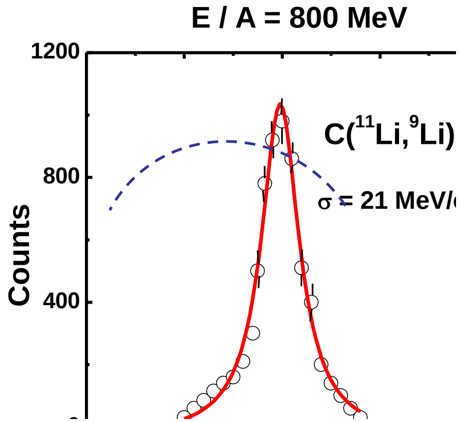
Interaction radii : $\sigma_I = \pi\left(R_I(\mathrm{proj}) + R_I(\mathrm{targ})\right)^2$

E / A = 790 MeV, *light targets*

I. Tanihata et al.,
Phys. Rev. Lett., 55 (1985) 2676

(iii) **very narrow momentum distributions**, compared to stable nuclei, of *both neutrons and* ^{9}*Li* measured in high energy fragmentation reactions of ^{11}*Li .*

No narrow fragment distributions in breakup on *other fragments*, say ^{8}*Li* or ^{8}*He*



(naive picture)
narrow momentum distributions
⇩
large spatial extensions

(iv) Relations between interaction and neutron removal cross sections (mb) at 790 MeV/A

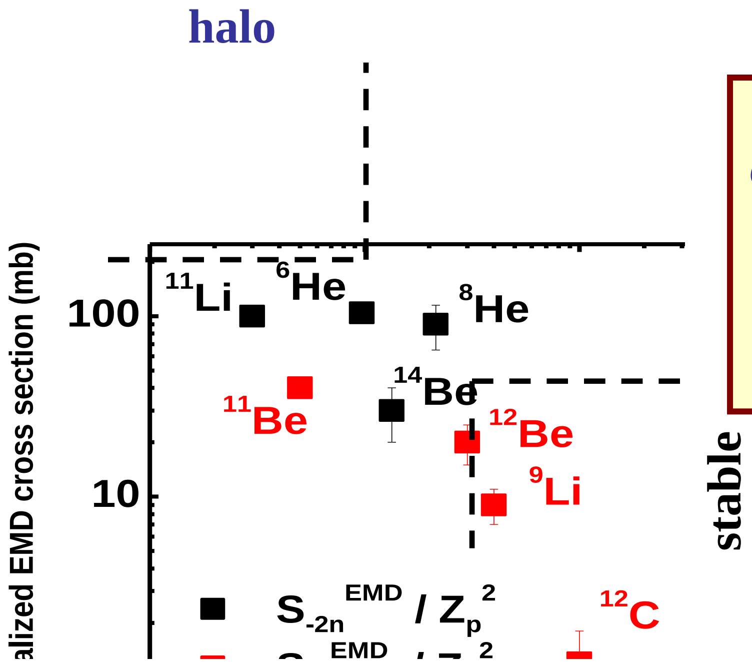
A + ^{12}C	σ_I	σ_{-2n}	σ_{-4n}
^{9}Li	796 μ 6		
^{11}Li	1060μ 10	220μ 40	
^{4}He	503μ 5		
^{6}He	722μ 5	189μ14	
^{8}He	817μ 6	202μ17	95μ 5

$$\sigma_I\,(A=C+xn) = \sigma_I\,(C) + \sigma_{-xn}$$

Strong *evidence* for the well defined clusterization into the core and two neutrons

Tanihata I. et al.
PRL, 55 (1987) 2670;
PL, B289 (1992) 263

(v) Electromagnetic dissociation cross sections per unit charge are *orders* of magnitude *larger* than for stable nuclei



Evidence for a rather large difference between *charge* and *mass* centers in a body fixed frame

⇓

concentration of the dipole strength at *low excitation* energies

T. Kobayashi, Proc. 1st Int. Conf. On Radiactive Nuclear Beams, 1990.

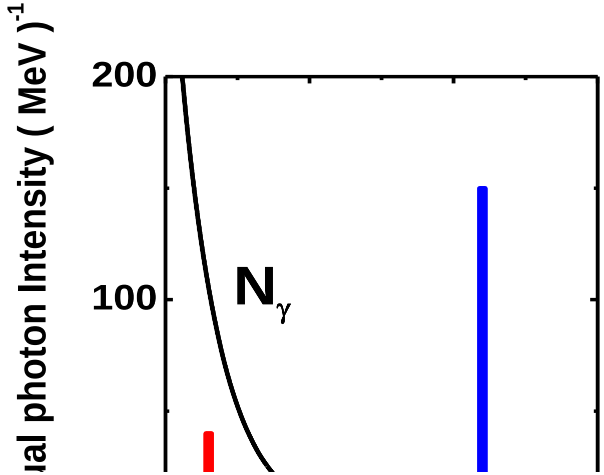
Soft Excitation Modes

(peculiarities of low energy halo continuum)

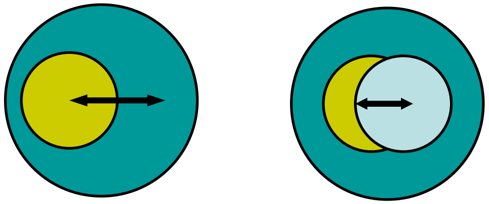
Large **EMD cross sections** ⇨ **specific nuclear property of *extremely* neutron-rich nuclei**

$$\sigma_{\mathrm{EMD}} = \int \mathrm{N}(E_{\mathrm{X}})\,\sigma_{\gamma}(E_{\mathrm{X}})\,dE_{\mathrm{X}}$$

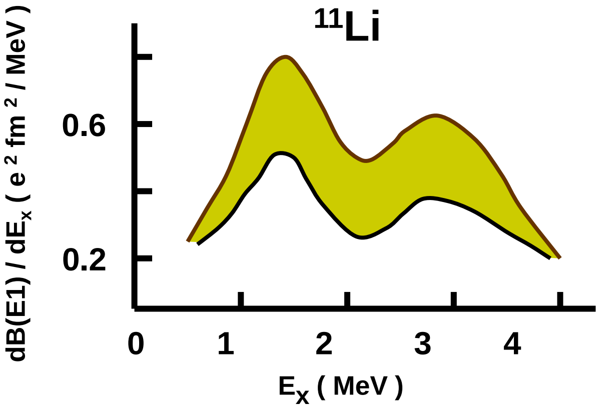
$$\sigma_{\gamma}(E_{\mathrm{X}}) = \frac{16\pi^{3}}{9\hbar c}\,E_{\mathrm{X}}\,\frac{d\mathrm{B}(\mathrm{E1})}{dE_{\mathrm{X}}}$$



soft DR **normal GDR**



E_x ~ 1 MeV ~ 20 MeV



M. Zinser et al., Nucl. Phys. A619 (1997) 151

excitations of soft modes with

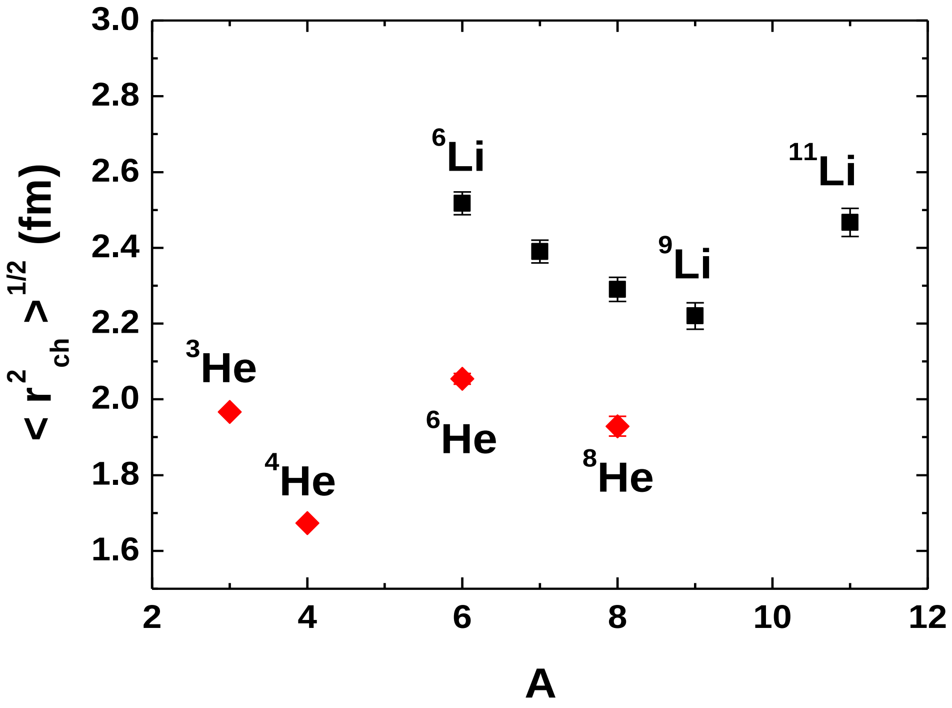
- **different multipolarity**
- **collective excitations *versus* direct transition from weakly bound to continuum states**

(vi) Ground state properties of ^{11}Li and ^{9}Li :

	^{9}Li	^{11}Li
Spin J^{π} :	$3/2^-$	$3/2^-$
quadrupole moments :	–27.4 μ 1.0 mb	–31.2 μ 4.5 m
magnetic moments :	3.4391 μ 0.0006 n.m.	3.6678 μ 0.0025 n.m.

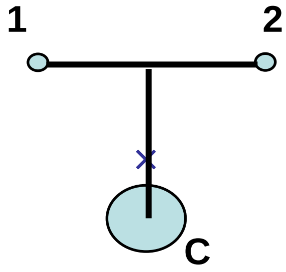
Schmidt limit : 3.71 n.m.

Previous peculiarities cannot arise from large deformations core is not *significantly* perturbed by the two valence neutrons



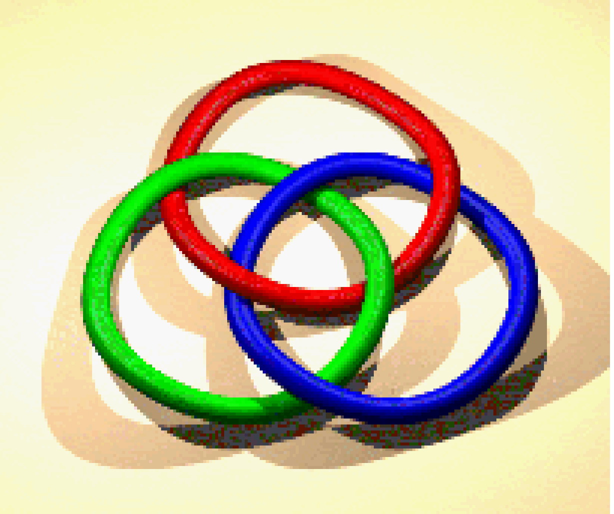
Nuclear charge radii
by laser spectroccopy

R. Sanches et al., PRL 96 (2006) 033002
L.B. Wang et al., PRL 93 (2004) 142501



(vii) The three-body system ^{11}Li (^{9}Li + n + n) is Borromean : neither the two neutron nor the core-neutron subsytems *are bound*

Three-body correlations are the most important: due to them the system becomes bound.



"The Borromean rings, the heraldic symbol of the Princes of Borromeo, are carved in the stone of their castle in Lake Maggiore in northern Italy. The three rings are interlocked in such a way that any of them were removed, the other two would also fall apart. In nuclear physics ^{11}Li and ^{6}He have been found to have this property (although for quite different physical reasons) when described in a three-body model. "

M.V. Zhukov et al., Phys. Rep. 231 (1993) 151

Peculiarities of halo

in *ground* state

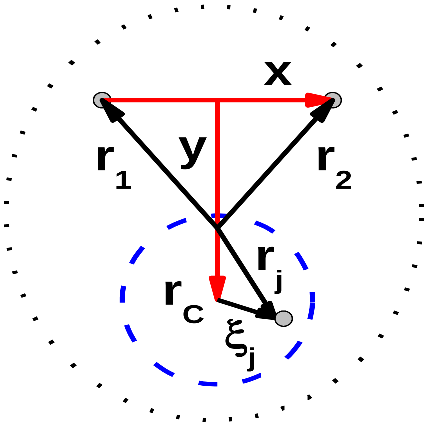
weakly bound,
with large extension
and space granularity

elastic scattering
some inclusive observables
(reaction cross sections, …)

in *low-energy* continuum

concentration of the transition strength near break up threshold - *soft modes*

nuclear reactions
(transition properties)

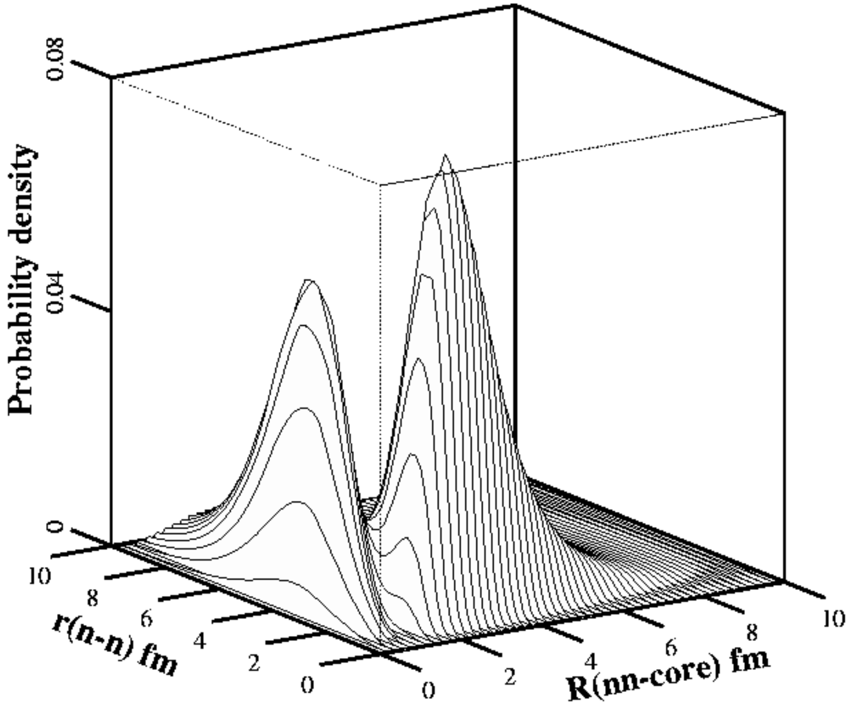


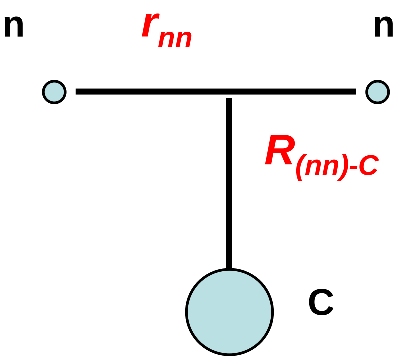
***BASIC* dynamics of halo nuclei** → ***Decoupling* of *halo* and nuclear *core* degrees of freedom**

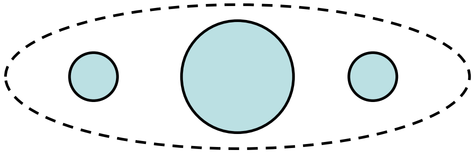
$$\Phi\left(\overline{r}_1,\dots,\overline{r}_A\right)=\phi_C\left(\overline{\xi}_1,\dots,\overline{\xi}_{A_C}\right)\psi\left(\overline{x},\overline{y}\right)$$

Correlation density for the ground state of ^{6}He

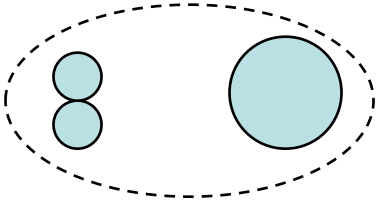
$$P\left(r_{nn}, R_{nn\text{-}C}\right) = r_{nn}^{2}\, R_{nn\text{-}C}^{2}\, \frac{1}{2J+1} \sum_{M} \int d\Omega_{nn}\, d\Omega_{nn\text{-}C} \left|\Phi_{JM}\left(\bar{r}_{nn}, \bar{R}_{nn\text{-}C}\right)\right|^{2}$$







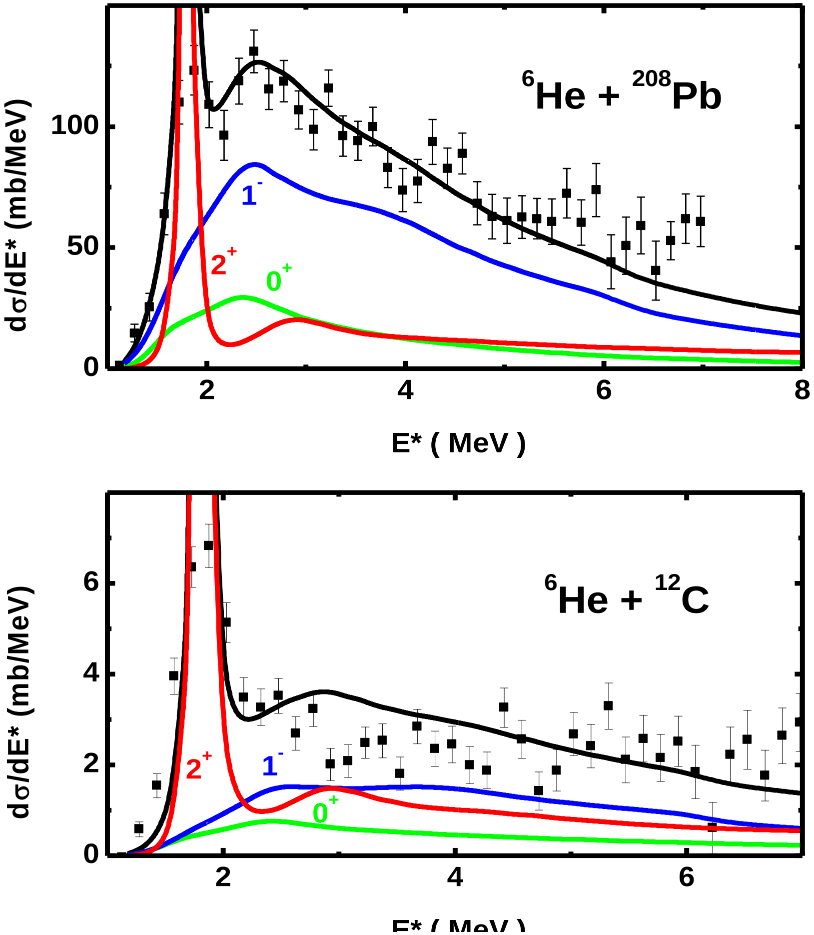
cigar-like configuration



dineutron configuration

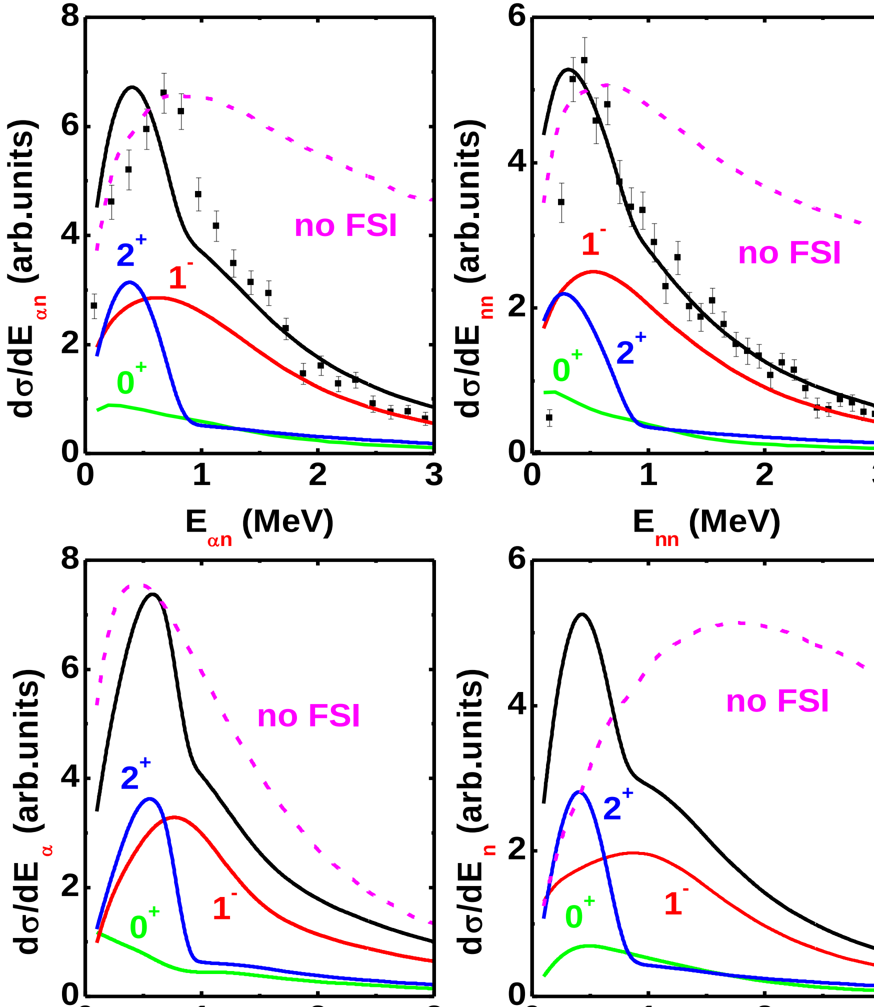
Halo scattering on nuclei

E / A = 240 MeV



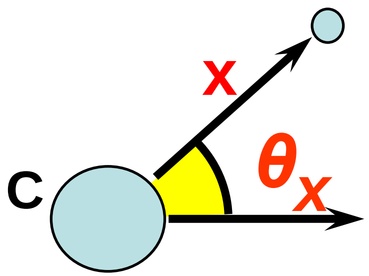
^{6}He + ^{208}Pb

E / A = 240 MeV/A

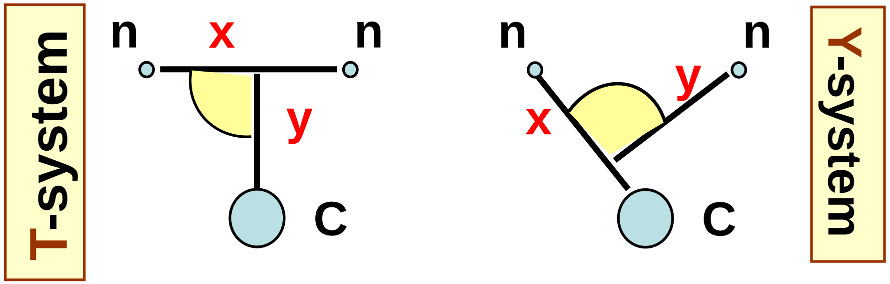


Continuum Spectroscopy

Two-body breakup



Three-body breakup



Excitation Energy

$$E_\kappa = \hbar^2 k_X^2/2\mu_X$$

$$E_\kappa = \hbar^2 k_X^2/2\mu_X + \hbar^2 k_Y^2/2\mu_Y$$

Orbital angular momenta

$$Y_{l_X m_X}(\Omega_X)$$

$$\left[Y_{l_X}(\Omega_X)\otimes Y_{l_Y}(\Omega_Y)\right]_{LM_L}$$

Spin of the fragments

$$\left[S_1 \otimes S_C\right]_{SM_S}$$

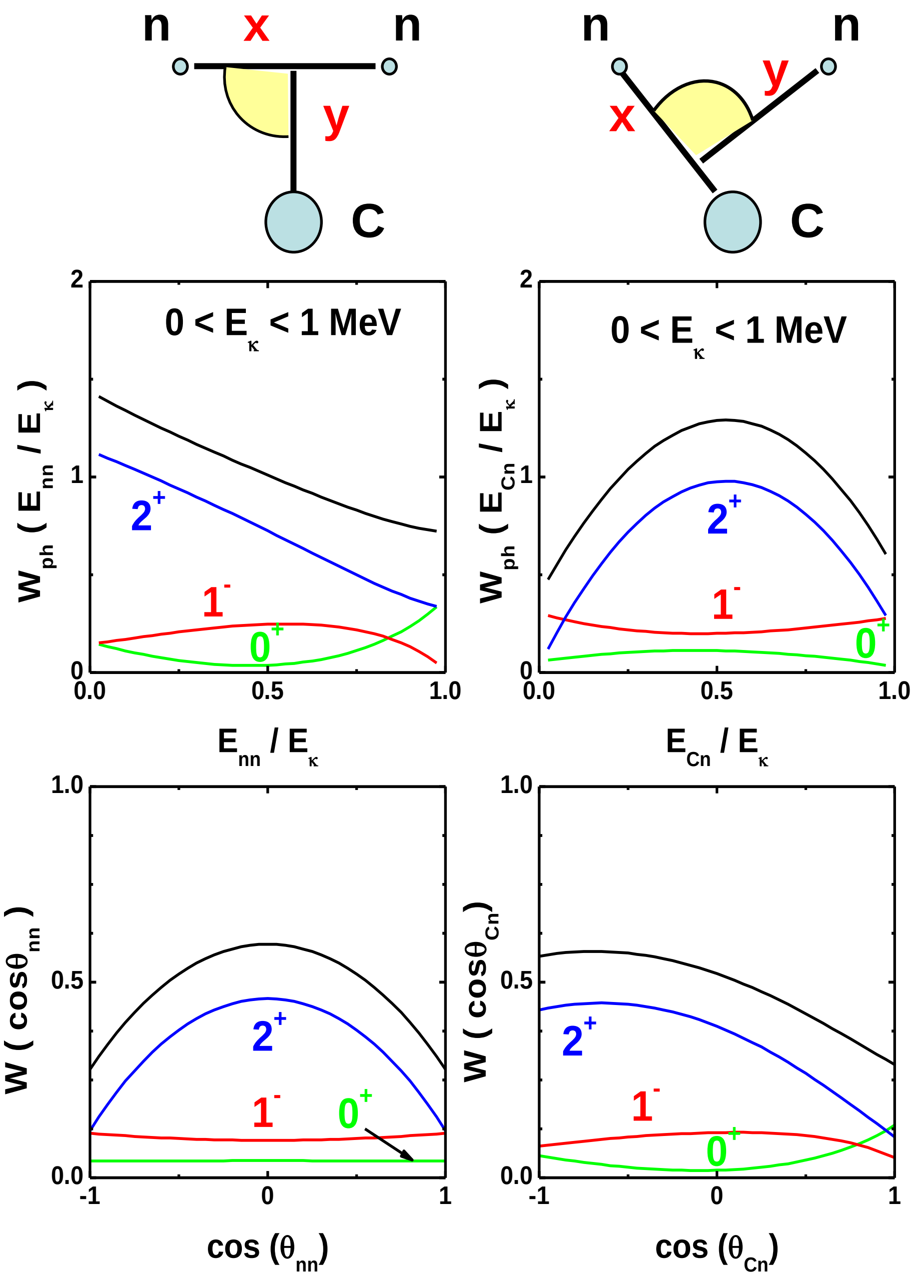
$$\left[S_1 \otimes S_2 \otimes S_C\right]_{SM_S}$$

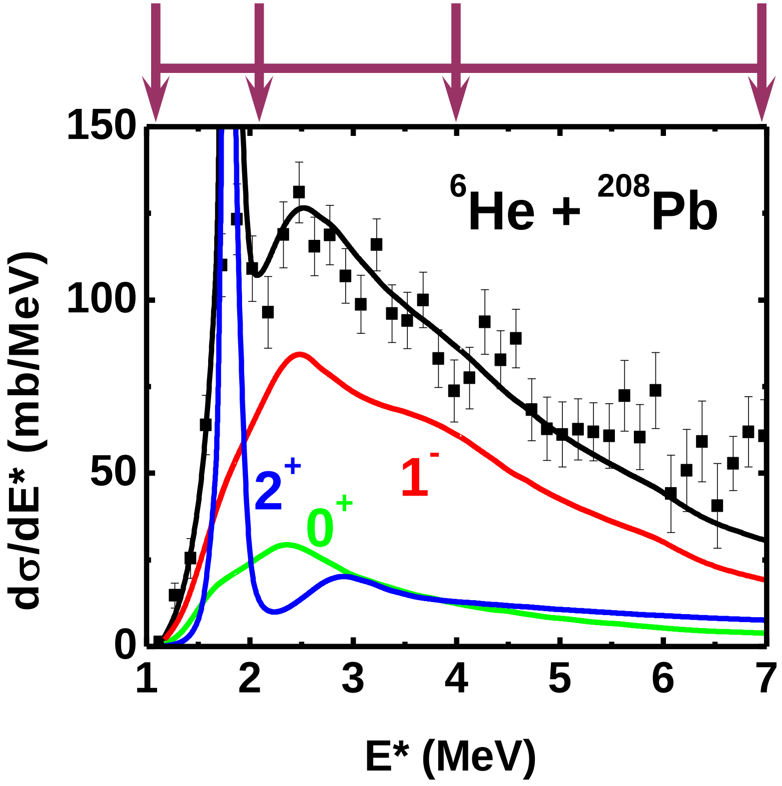
Hypermoment

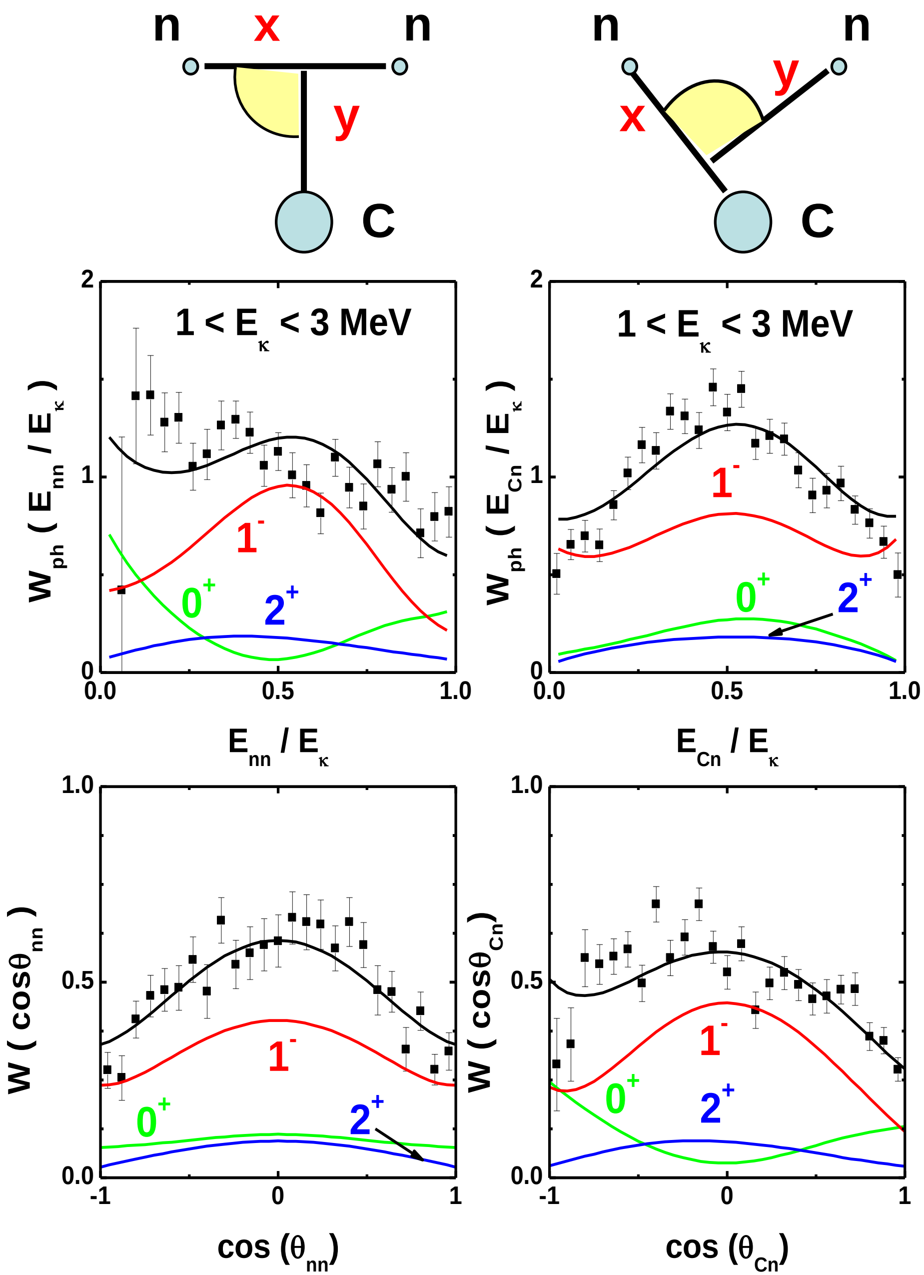
$$N = 2n + l_X$$

$$K = 2n + l_X + l_Y$$

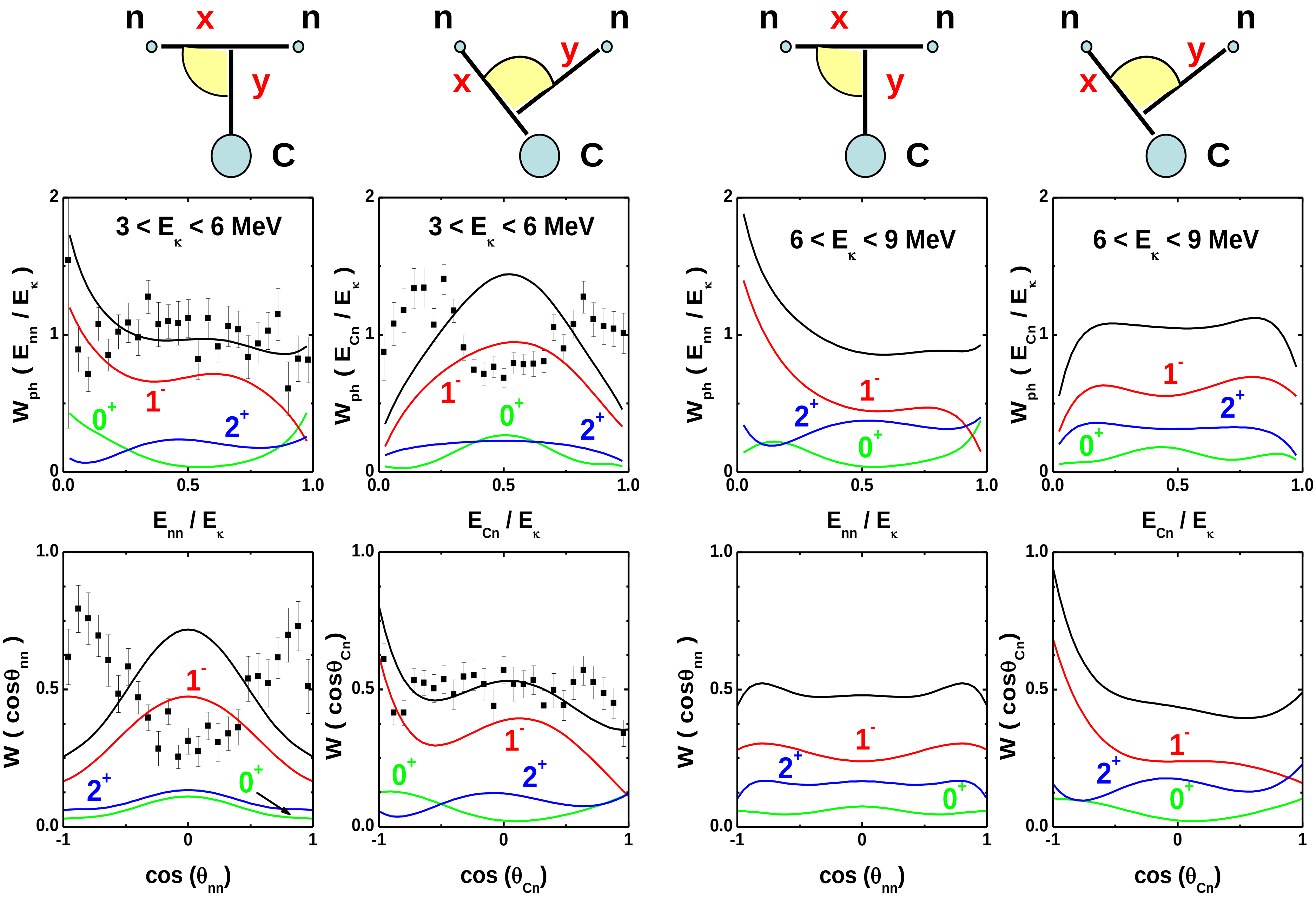
Energy and angular fragment correlations







L.V. Chulkov et al., **Nucl. Phys. A759, 23 (2005)**


n
x
n
y
C
3 < E$_\kappa$ < 6 MeV
6 < E$_\kappa$ < 9 MeV
W$_{ph}$ (E$_{nn}$ / E$_\kappa$)
W$_{ph}$ (E$_{Cn}$ / E$_\kappa$)
E$_{nn}$ / E$_\kappa$
E$_{Cn}$ / E$_\kappa$
W (cosθ$_{nn}$)
W (cosθ$_{Cn}$)
cos (θ$_{nn}$)
cos (θ$_{Cn}$)
1$^-$
0$^+$
2$^+$
0.0
0.5
1.0
0
1
2
-1

CONCLUSIONS

☐ The field of exotic nuclei due to the impressive advance in experimental methods is one of the fastest developing subjects in nuclear physics. Research on unstable nuclei has achieved significant progress over the last few decades.

☐ The dramatic evolution of nuclear shell structure have been revealed for nuclei with large isospin asymmetries. New forms of nuclear matter such as the neutron halo not encountered in normal stable nuclei have been observed.

☐ Development of new experimental techniques for production and /or detection of radioactive beams is the way to unexplored

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