Excited nuclear states with abnormally radii (size isomers)

A.A. Ogloblin

Kurchatov Institute, Moscow, Russia

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Isomers in nuclear physics

- Traditional isomers: excited states with abnormally large time of life
- Fission isomers
- Shape isomers
- Hipothetic density isomers?
- Size isomers

Predictions:

* Neutron halos in excited states

A.*I. Baz', Threshold states (1959)*

T.Otsuka et al., Halo in 1/2+, 3.09 MeV state of ^{13}C (1993)

* Dilute alpha-cluster states

A.*Tohsaki et al., Alpha particle condensation (2001)*

The radii of these short-lived particle-unstable states cannot be measured in traditional ways

Only non-direct methods (electron scattering form factors, CC, DWBA) existed until recently

New direct methods should be developed

Proposed methods: MDM, NR, ANC

Modified diffraction model (MDM) of inelastic scattering

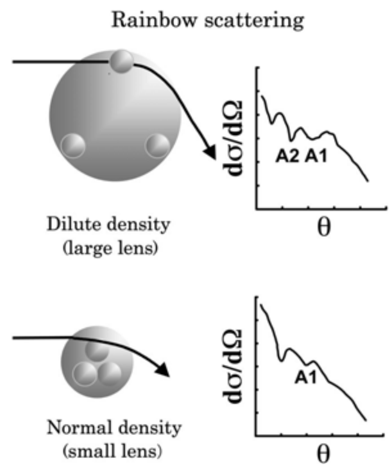
A.N. Danilov et al., (2009)

$R^*rms = R_{0.0} + [R^*(dif) – R_{0.0}(dif)]$

R(dif) are determined from positions of diffraction min/max in angular distributions

Inelastic nuclear rainbow (NR) scattering

S.Okhubo, Y.Hirabayashi, (2007)
A.S. Demyanova et al., (2008)



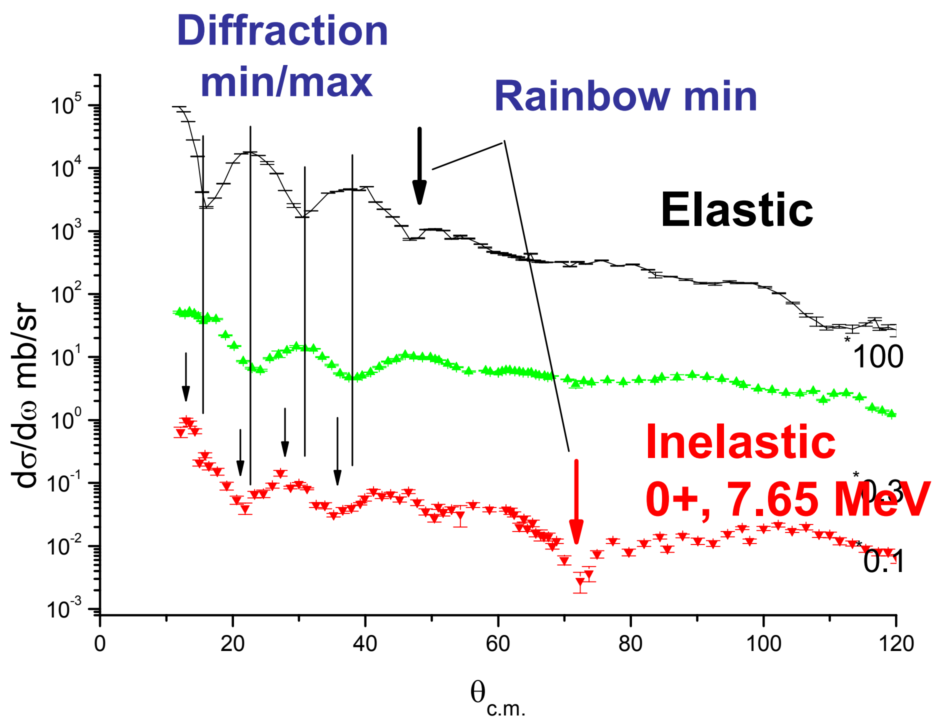
Shift of Airy minima
Radii are detetmined from empirical relation
$\Theta(Airy) \sim A^{2/3}_t \sim R^2_t$

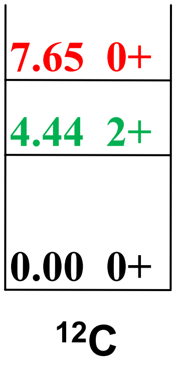
Asymptotic normalization coefficients (ANC) from transfer reactions, e.g., (d,p)

L.D. Blokhintsev, A. Muhametdzanov
Z.H. Liu et al., (2001)

Spectroscopic factors may be substituted by ANC
R(halo) may be extracted from ANC

$^{12}C + \alpha$ scattering, E = 60 MeV





Inelastic 2+, 4.44 MeV
no shifts

Shifts of inelastic min/max relatively elastic ones

Diffraction radii → left, rainbow (Airy) → right

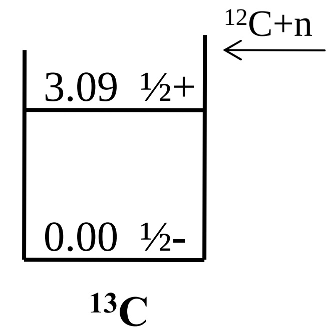
signatures of the RMS radii change

R(0.00) = 2.34 fm → R(7.65) = 2.89 ± 0.04 fm (MDM)

R(7.65) = (1.2 – 1.3) R(0.00) NR-method

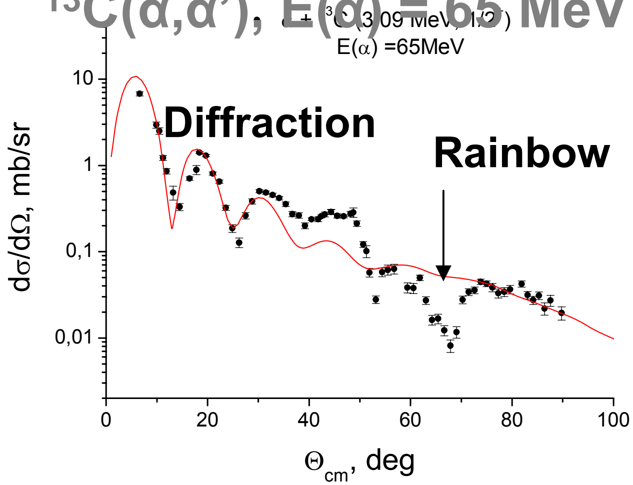
(averaged over 6 - 8 values of E(α) from 60 to 380 MeV)

Size isomer in ^{13}C: neutron halo in 1/2+, 3.09 MeV excited state

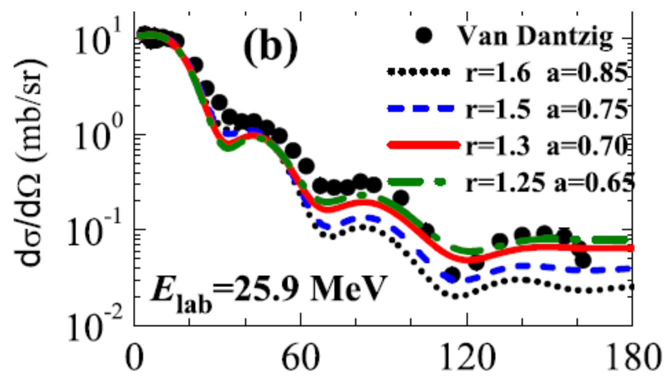


Radius was extracted from inelastic scattering (MDM and NR) and (d,p)-reaction (ANC)

$^{13}C(\alpha,\alpha')$, E(α) = 65 MeV



$^{12}C(d,p)$



Method	Rhalo	Rrms, fm
MDM	6.44 ± 0.40	2.83 ± 0.09
ANC	5.72 ± 0.16	2.72 ± 0.10
NR	≥ 5.6	≥ 2.7
Theory		2.68
$R(^{12}C)+\hbar(\mu\varepsilon)^{-1/2}$	5.8	

All three methods gave similar results in agreement with theory.

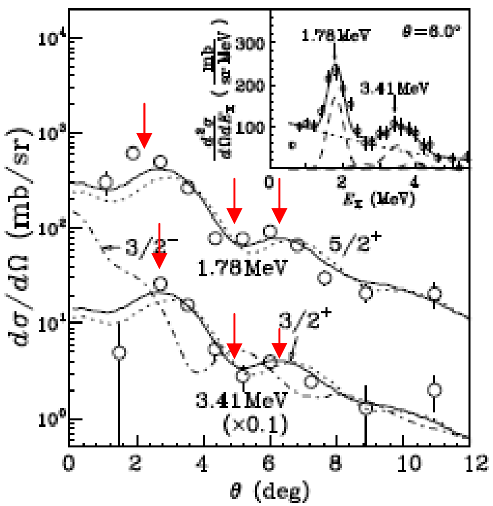
1. Validity of models
2. Evidence of halo

Radii of ^{11}Be excited states

The ground state 1/2+ of ^{11}Be is a standard of a neutron halo. It is the basis of a rotational band whose members have equal radii (*from ^{11}Be + C inelastic scattering*). ANC-analysis of ^{10}Be(d,p) –reaction (*Belyaeva et al*)

^{11}Be + C, 67MeV*A

N.Fukuda et al



^{11}Be radii

Rdif, fm, MDM

1/2+ 5.60 ± 0.07

5/2+ 5.72 ± 0.17

3/2+ 5.77 ± 0.15

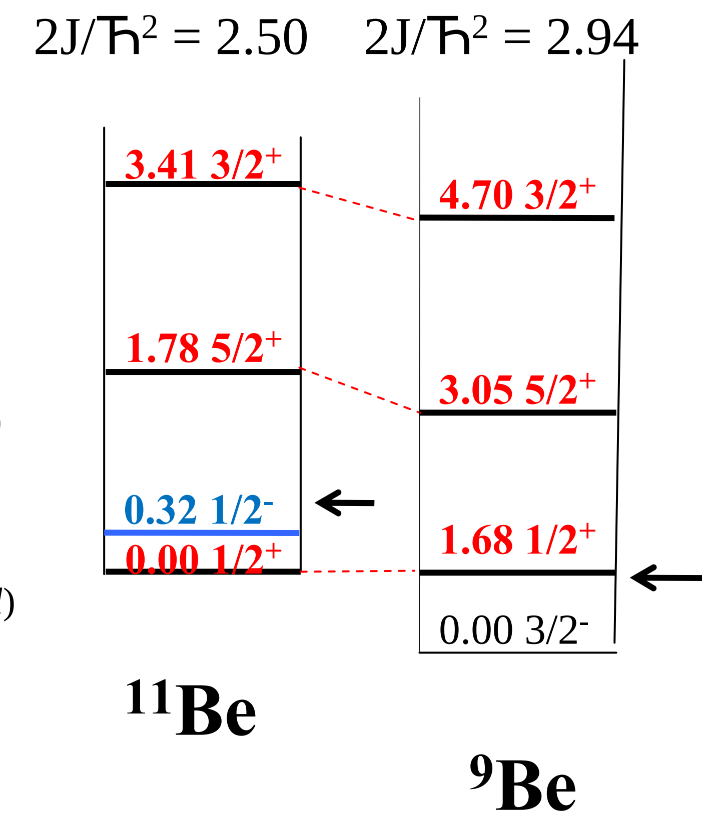
Rhalo, fm, ANC

1/2+ 8.0 ± 0.2 (*Belyaeva et al*)

7.98 ± 076 (*Tanihata et al)*

1/2$^-$ 4.65 ± 0.20 (*Belyaeva et al*)

(Radius is1.7 times smaller than that of the ground state and 1.5 times larger than those of normal states)

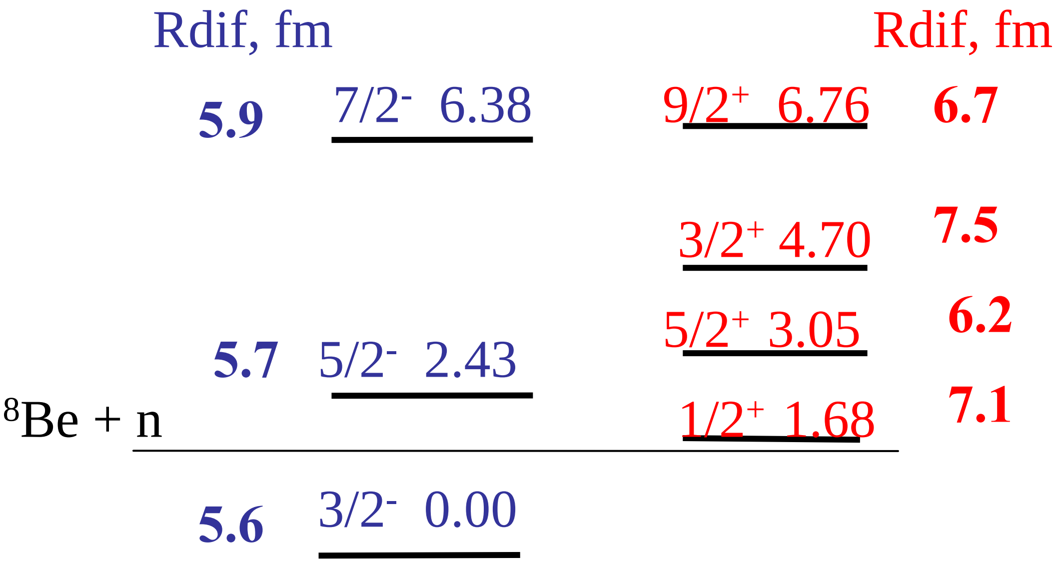


Halo structures conserve in the states in continuum

0.32 NeV, 1/2$^-$ state is size isomer with reduced radius

Rotational size isomers in ^{9}Be

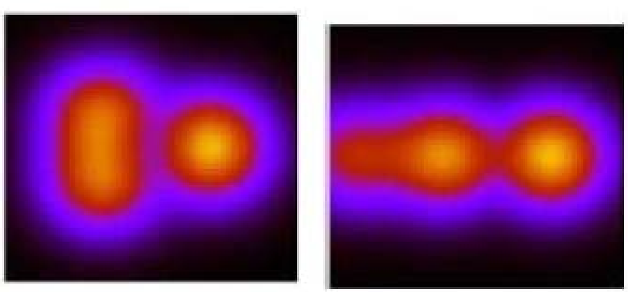
^{9}Be(α,α’), E(α) = 30 MeV, *Kurchatov – Tsukuba*, MDM analysis



π-band **σ-band**

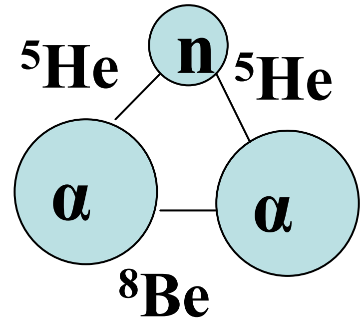
$2J/\hbar^2 = 1.90$ $2J/\hbar^2 = 2.59$

AMD predictions by Kato *et al*



^{5}He + α ^{8}Be + n

Borromean structure of ^{9}Be



Radii enhancement for *σ-band* states

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Neutron halo in continuum

Correlation between radii and moments of inertia

Halo type size isomers

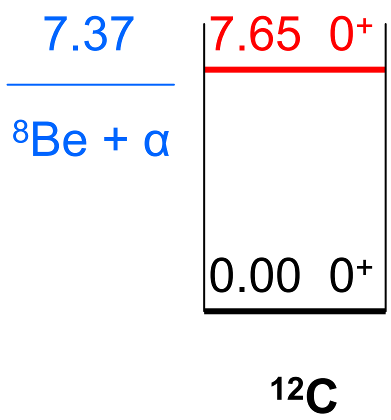
Neutron halos in excited states of ^{9}Be, ^{11}Be, ^{12}B, ^{13}C, ^{14}Be were observed in inelastic scattering and (d,p) - reactions

Halos located in continuum were identified (^{9}Be, ^{11}Be)

Rotation of states with halos was observed (^{9}Be, ^{11}Be)

Reduction of halo radius in excited state was observed ($1/2^{-}$, ^{11}Be)

0^+_2, 7.65 MeV "Hoyle" state in ^{12}C is a key object for testing modern cluster theories



* Hoyle state is responsible for existence in Universe of elements heavier than Helium
* Not consistent with shell model. Exotic cluster structure was predicted.
* Abnormally large radius?
* Excited states based on the Hoyle state?
* Does the Hoyle state rotate?
* Prototype of alpha condensate?

RMS Radii of Hoyle state. Test of cluster theories

1	2	3	4	5	6	7	8	9	10 EXP
4.31	3.83	3.53	3.47	3.38	3.22	3.27	2.90	2.4	2.89±0.04

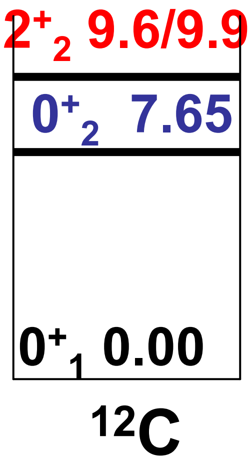
α-condens.

FMD

AMD
Kanada-Enjo

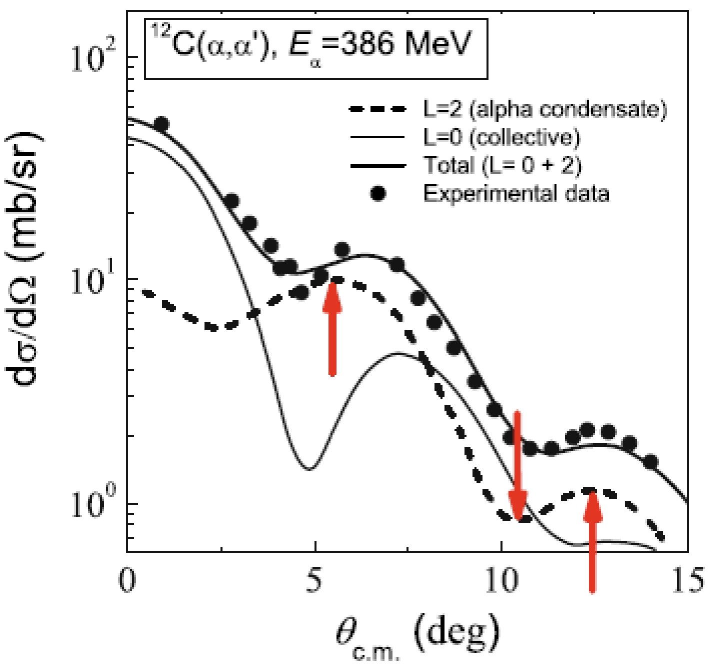
Lattice

Radius of 2^+_2 state of ^{12}C from diffraction α-scattering

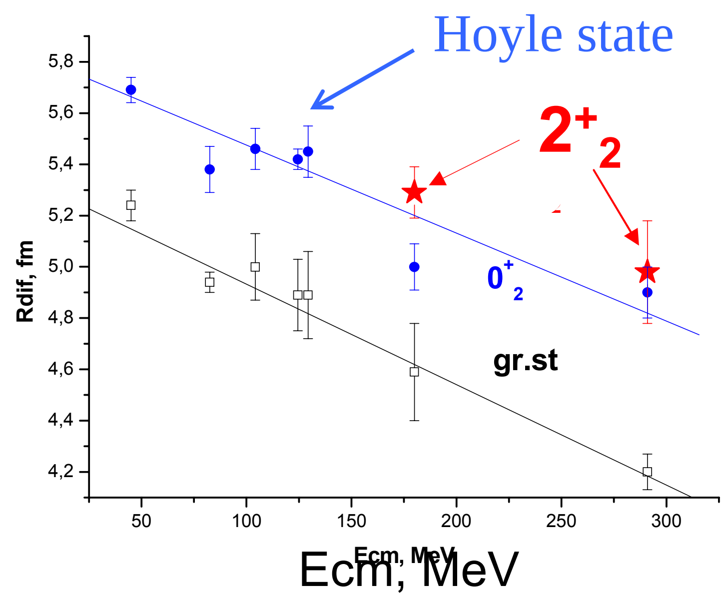


Prediction of condensate model (*T.Yamada, P.Schuck*):
A giant state Rrms = 6.12 fm

E(α) = 386 MeV



Energy dependence of Rdif



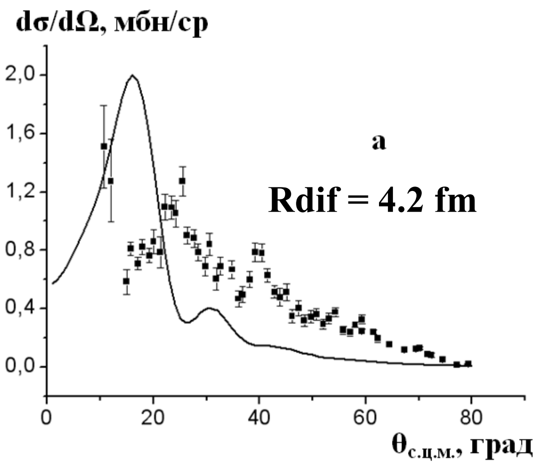
From MDM analysis:
$R(2^+_2)_{RMS}$ = 3.07 ± 0.13 fm
≈ R_{RMS}(Hoyle)

From moment of inertia:
$R(2^+_2)_{RMS}$ = 2.7 fm
Member of Hoyle rotational band

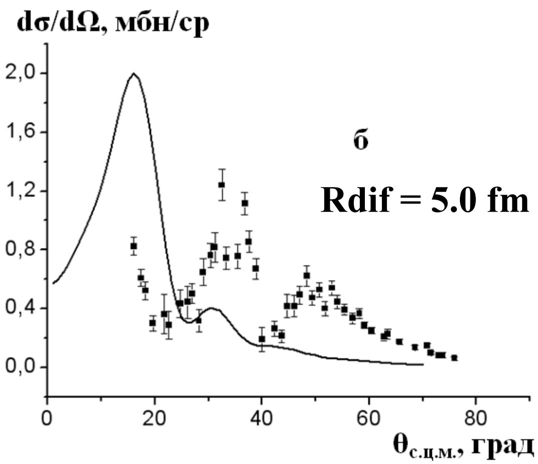
4^+_2 state in ^{12}C. Hoyle state rotational band

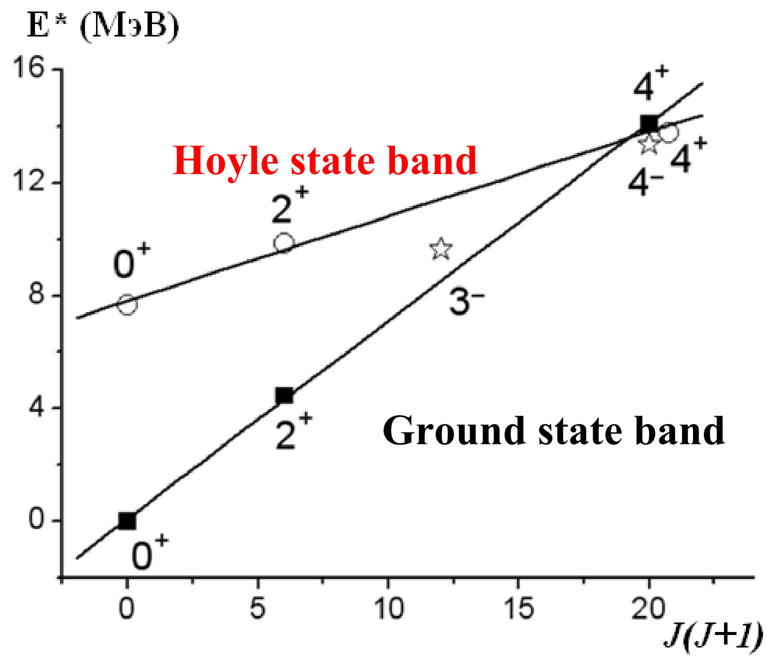
4^+_2 state was claimed at 13.3 MeV (*Freer et al*) and 13.75 MeV (*Ogloblin et al*)

E* = 14.08 MeV, 4+



E* = 13.75 MeV, 4+?





Differential (α,α') cross-sections at 110 MeV

Hoyle state band: 7.65 – 9.84/9.6 – 13.75/13.3 MeV (enhanced radii)

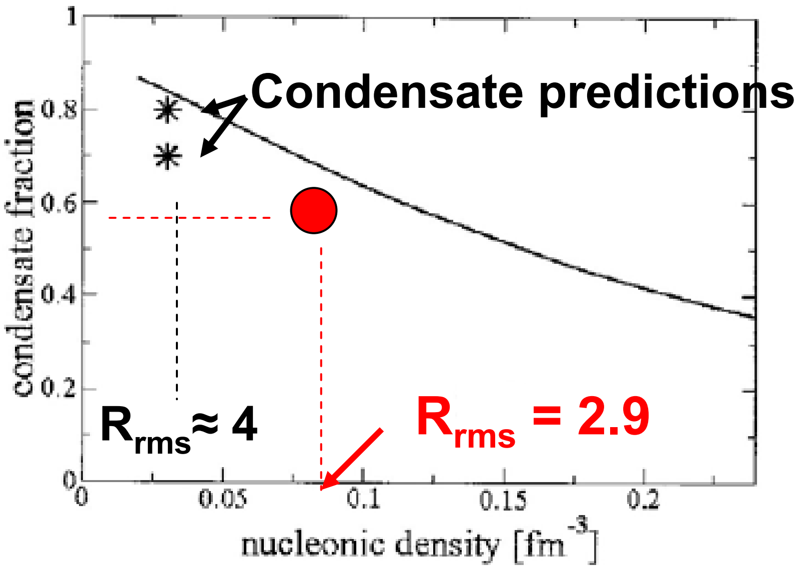
Negative parity branch (3-, 4-, 5-) of ground state band?
However, Rrms (3-) = 2.88 ± 0.11 fm → larger than Rrms (0+) = 2.34 fm

Does alpha condensate exist in the Hoyle state?

Rrms = 2.89 ± 0.04 fm ≈ 1.25 R(0.00), smaller than predicted

S-state occupation probability (condensate fraction) was measured from $^4He(^{12}C,\alpha)^{12}C^*$ reaction (*T.L.Belyaeva et al., Phys.Rev. C 82, 054618 (2010)*)

$W_\alpha(L = 0) = 0.6$, close to predictions (W = 0.7 – 0.8)

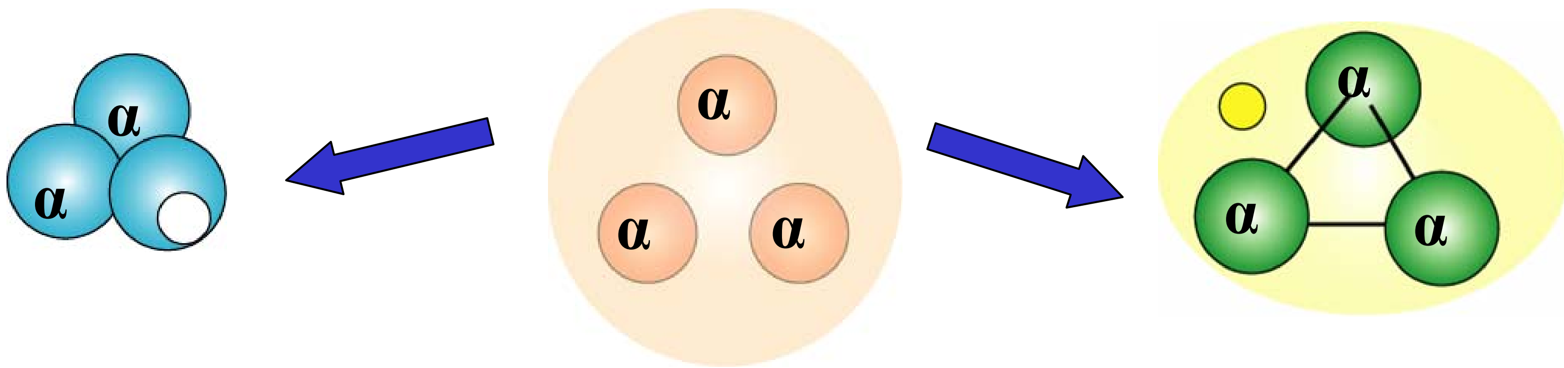


"Ghost" of α-condensate

Exotic cluster structure in a boson-fermion mixture

(A ≠ 4n nuclei)

T. Kawabata
Y. Kanada-En'yo



^{11}B | ^{12}C | ^{13}C

One alpha-particle is replaced with a triton.

One neutron is added

Search for analogs of the Hoyle state

Inelastic α-scattering was studied at 65 and 90 MeV
MDM – analysis of high – lying states was done

Size isomers were found in ^{11}B and ^{13}C

^{11}B

A. Danilov, this conference

- **8.56 MeV, 3/2^{-} state was determined as the analog of the Hoyle**
- Predicted "giant" state at E* = 12.5 MeV (Rrms ~ 6 fm) was not observed
- Several rotational bands including the analogous one to the Hoyle state band were observed

^{13}C

A. Demyanova, this conference

- **8.86 MeV state is an analog of the Hoyle state**
- A puzzle of 9.90 MeV state ?

Diffraction min/max shift to large angles

Rainbow minimum shifts to small angles

⬇

Some evidence for reduced radius

Is the 9.90 MeV state a compact size isomer?

Conclusions & perspectives

Nuclear excited states with abnormally enhanced radii (size isomers) were observed

Two main classes:

- **States with neutron halo (in ^{9}Be, ^{11}Be, ^{13}C)**
- **Cluster states (in ^{11}B, ^{12}C, ^{13}C)**

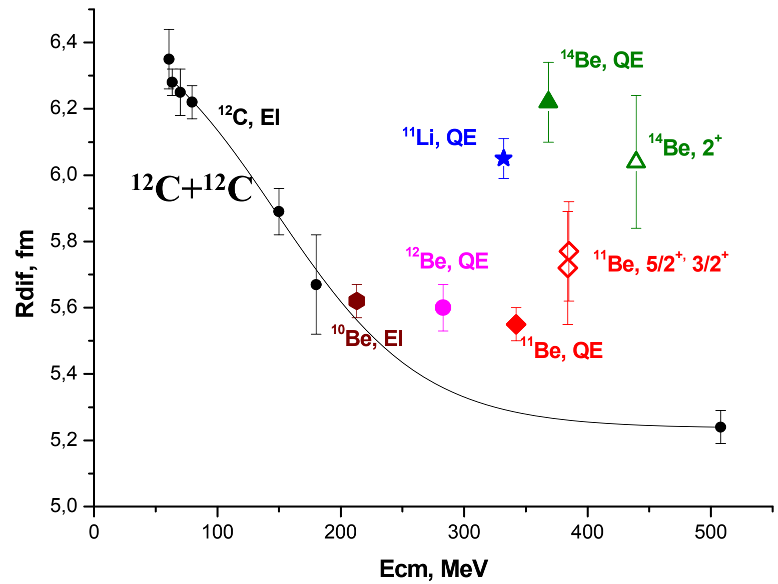
Some new exotic structures were observed

Possible observation of a state with reduced radius (in ^{13}C)

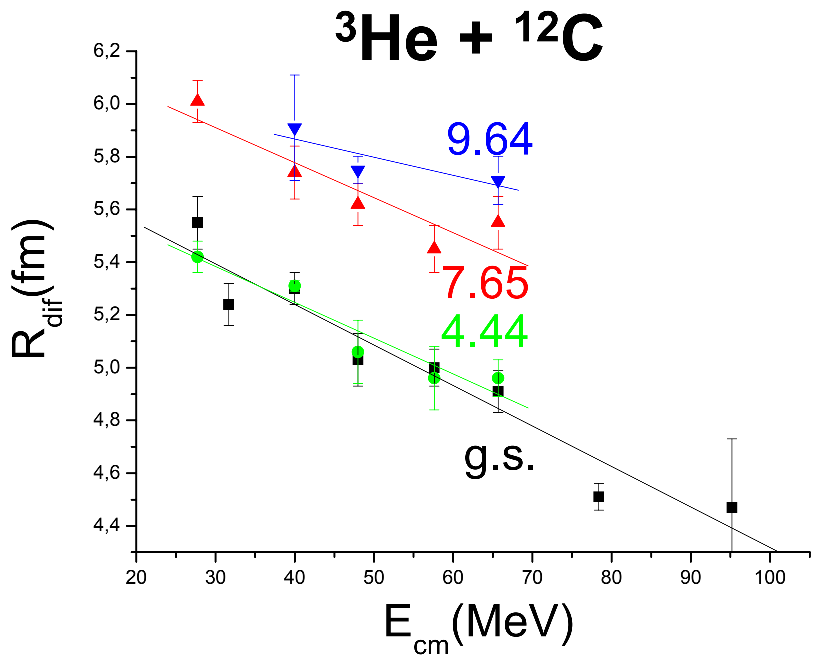
All these findings were done with stable beams and in stable nuclei. Search of size isomers in drip-line nuclei may open wide perspectives

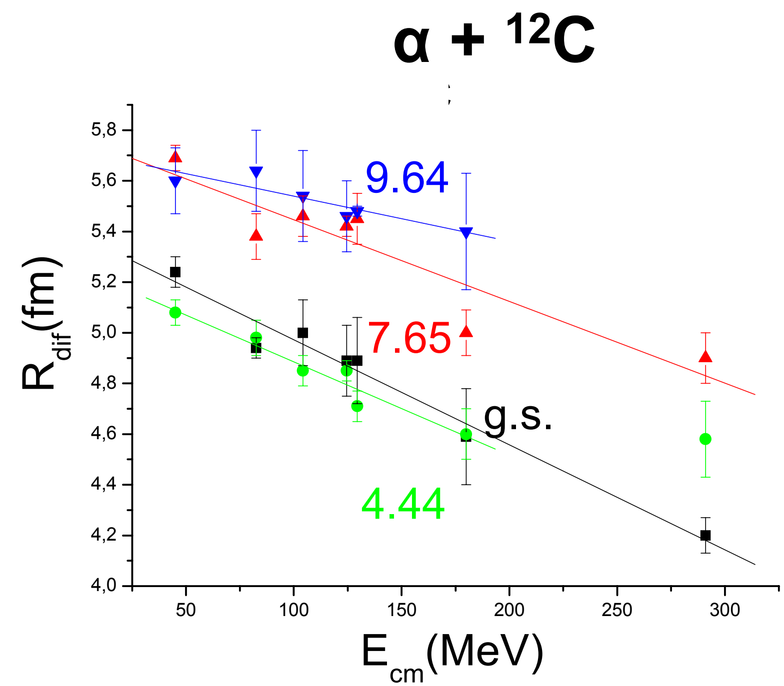
First application of MDM to experiments with radioactive beams

Diffraction radii from RIB scattering on ^{12}C



Diffraction radii from ^{3}He, α + ^{12}C scattering





	^{3}He	α	^{6}Li	^{12}C	d
R(7.65) – R(0.00)	0.56 ± 0.06	0.57 ± 0.03	0.58 ± 0.06	0.47 ± 0.05	0.29 ± 0.07

R(7.65) = 2.89 ± 0.04 fm ≈ 1.25 R(0.00)

NUCLEAR SIZE ISOMERS

Ogloblin A.A.
National Research Center "Kurchatov Institute", Moscow, Russia
E-mail: ogloblina@bk.ru

Isomerism is a well-known phenomenon in nuclear physics. Besides widely spread "normal" isomers (excited states with much larger time-of-life comparatively that of the corresponding ground states) there are known shape and fission isomers. The recently developed methods of measuring the radii of nuclei in their short-lived states led to the observation of the effect of size isomerism, that is, significant enhancement of nuclear radii in some excited states relatively those in the corresponding ground ones. Two classes of size isomers were identified: some alpha-cluster states (e.g., the famous Hoyle state (0^+, E^* = 7.65 MeV) in ^{12}C and its analogs in the neighbor nuclei) and the excited states with neutron halos. These findings resulted in critical reconsideration of many settled ideas about nuclear structure.