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Experimental study of halo in isobar-analog states

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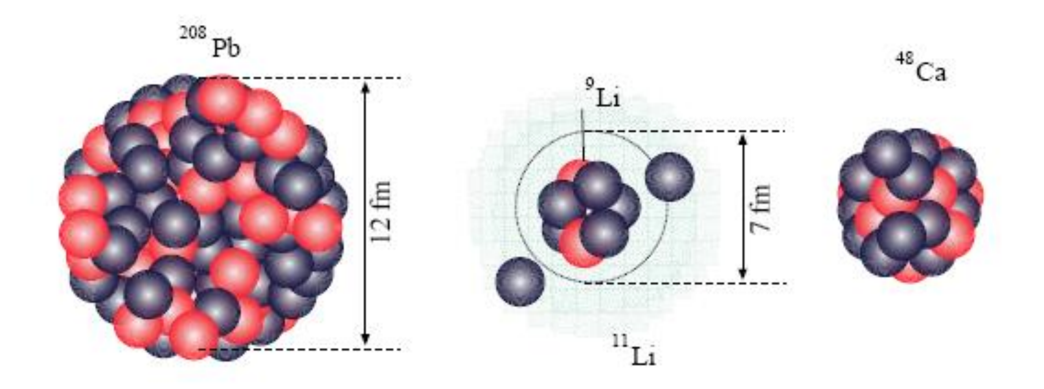
The discovery of the neutron halo is one of the most important achievements of nuclear physics at the end of the last century:

1) For the first time, nuclei with anomalously large sizes were found.
2) Neutron matter was first detected in an external field. Those. nuclei were synthesized, in which the symmetric nuclear matter (core) is spatially separated from neutrons. The term “exotic nuclei” itself was originally referred to these nuclei.

Neutron halo

5.1 fm 3.12 fm 3.19 fm



The main property of the halo is an increased radius of valence neutrons, 2 to 3 times the size of the core.

The halo was discovered in the ground states of the nuclei lying on the border of stability with the help of a new “tool” - beams of radioactive nuclei used to measure the total cross sections $\sigma \sim \pi R^2$.

Current overview on halo phenomena:

- **Neutron halos phenomenon extends far beyond what was known before:**
  1. **Halos exist not only in the drip-line nuclei but also in the stable ones.**
  2. **Halos can be formed not exclusively in the ground states but in the excited states as well.**
  3. **Halos can exist in particle unstable states.**

- **Three independent methods (Diffraction, Rainbow, ANC) of measuring the radii of particle unstable states were developed. More work is required.**

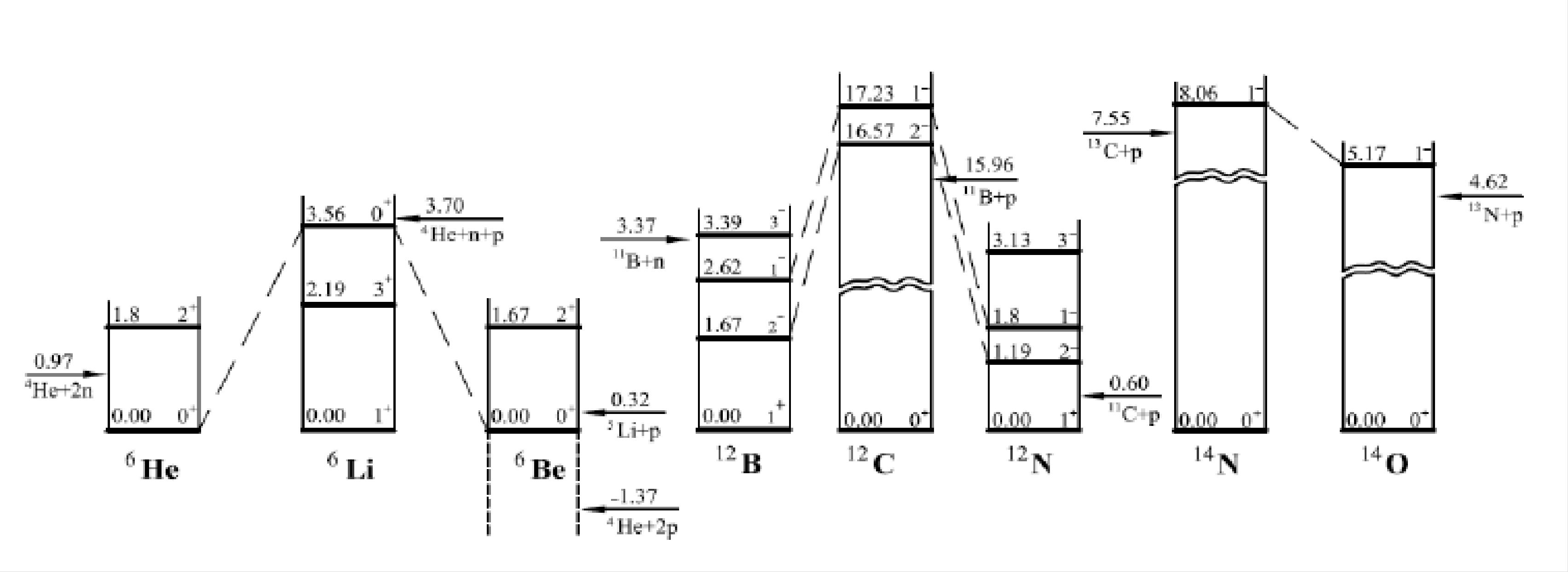
- **Signatures of neutron halos were observed in the excited states of:**
  1. **Some “non-exotic” nuclei ^{13}C $(1/2^+_1)$ and ^{9}Be $(1/2^+_1, 5/2^+_1)$**
  2. **Some drip-line nuclei: ^{11}Be $(5/2^+_1, 3/2^+_1)$, ^{12}Be (1^-_1), $^{14}Be(2^+_1)$**

- **New structures (like rotating halos) could appear.**

- **There is much more rare phenomena - proton halo. The Coulomb barrier prevents substantial proton separation from the core. Currently proton halo was observed in ^{8}B, ^{17}F, ^{13}N**

Halo in isobar-analog states

The purpose of this research is to search and study **nucleonic halo** in the **isobaric analog states (IASs)** of nuclei. Our group is one of the first who started works in this area. Isobaric invariance leads to the fact that the states of two neighboring nuclei obtained by replacing a neutron with a proton and having the same quantum numbers, including isospin, are analogous, i.e. they have in the first approximation the same structure and radii. In the case of isobaric analogs having halo, the situation is more complicated: replacing the neutron in the halo state with a proton does not necessarily lead to the appearance of a similar proton structure. The fact is that the appearance of a halo is determined by the proximity of the valence nucleon to the emission threshold, and it can be very different for a neutron and a proton.



Isobar-analog states of ^{6}He, ^{6}Li, ^{6}Be, ^{12}B, ^{12}C, ^{12}N, ^{14}N and ^{14}O nuclei
The arrows show the decay thresholds.

Modified diffraction model (MDM)

Diffraction radii are defined from positions of minima/maxima in angular distributions $d\sigma/d\Omega$

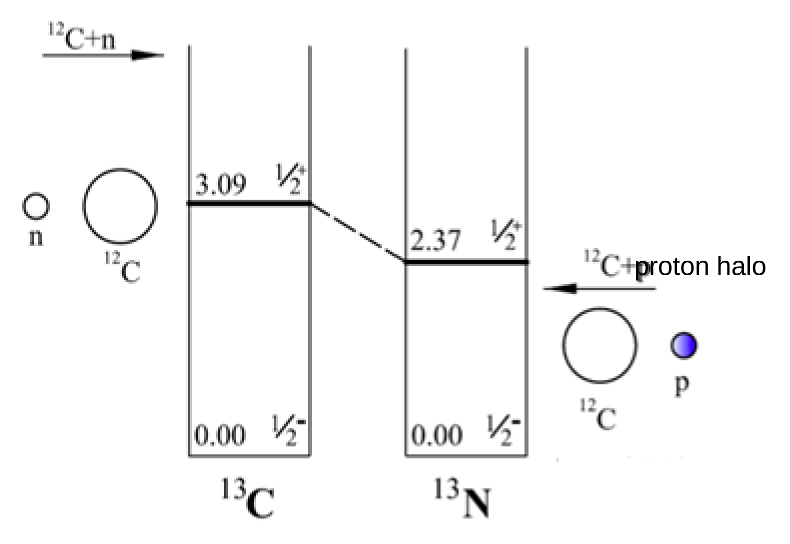
R_{dif} is the only parameter of the model. This parameter has dimension of length and could be directly connected with real (*rms*) nuclear radius

Model:

$$R_{rms}\,(exc.st.) = R_{rms}\,(gr.st.) + [R_{dif}\,(exc.st.) - R_{dif}\,(0)]$$

It has been known for a long time that the charge exchange reactions have much in common with the inelastic scattering *A.M. Lane, Nucl. Phys. 35, 676 (1962)*

MDM was successfully applied to (^{3}He,t) reactions

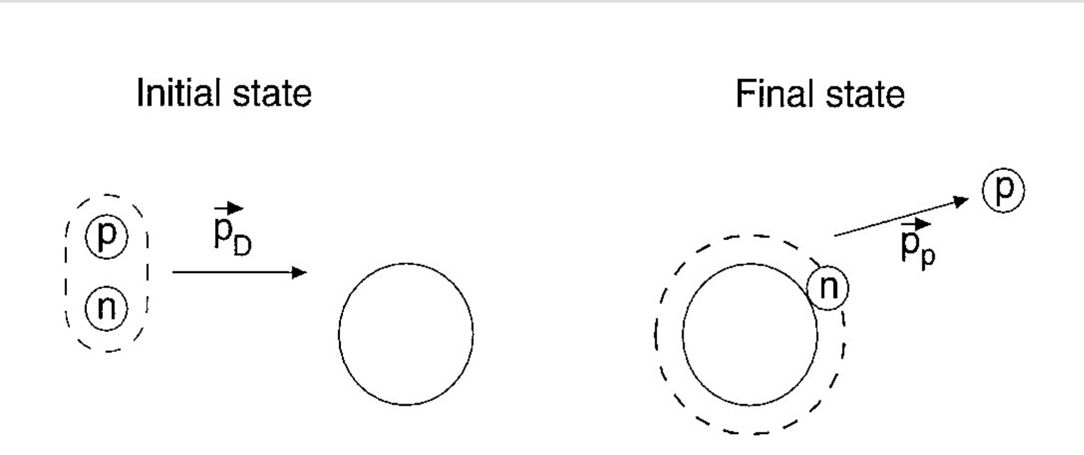


A. S. Demyanova et al., JETP Lett. 104, 526 (2016)
A.S. Demyanova et al., Phys. Atom. Nucl., 80, 831 (2017):
proton halo was observed for the 2.37-MeV state of ^{13}N nucleus

ANC method

of measuring the radii of the halo states

(d,p)-reaction



$$\frac{d\sigma_{exp}}{d\Omega} = (C^{B}_{Anl_B j_B})^2 (C^{d}_{pn})^2 R_{l_B j_B}$$

ANC

Transfer reactions are mainly peripheral

For peripheral reactions Asymptotic normalization coefficients (ANC) can be calculated with proper approximation

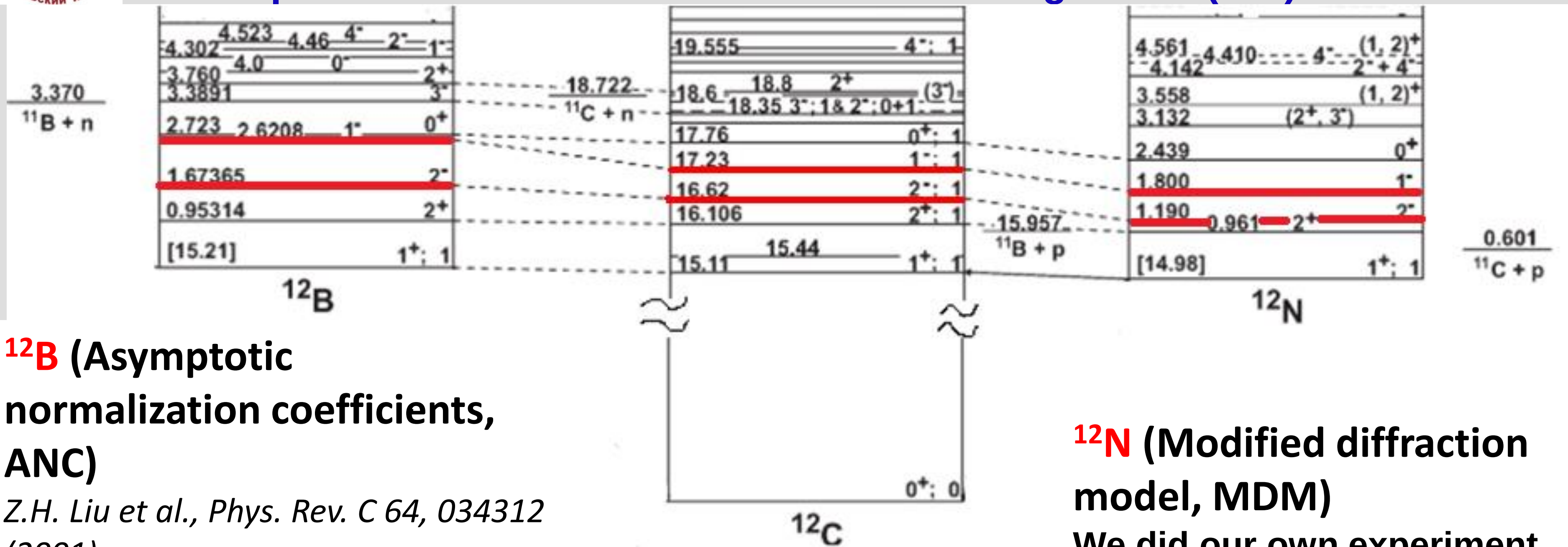
On base of ANC RMS radius of the last neutron can be calculated

L.D. Blokhintsev et al., Sov. J. Part. Nucl. 8, 485 (1977)
Z.H. Liu et al., Phys. Rev. C 64, 034312 (2001)
T.L.Belyaeva et al., Phys. Rev. C 90, 064610 (2014)

R(halo) may be extracted from ANC

Triplet $^{12}B - ^{12}C - ^{12}N$

We expect halo/halo like states in isobar-analog states (IAS) 2^- and 1^-



^{12}B (Asymptotic normalization coefficients, ANC)

Z.H. Liu et al., Phys. Rev. C 64, 034312 (2001)

Observation of halos in 2^- and 1^-,

R_h = 4.01 ± 0.61 and 5.64 ± 0.90 fm

ANC method was used for halo radius extraction on base of $^{11}B(d,p)^{12}B$, E_d = 11.8 MeV

We did our own experiment $^{11}B(d,p)^{12}B$, E_d = 21.5 MeV and applied ANC

T. L. Belyaeva et al., Phys. Rev. C 98, 034602 (2018).

^{12}C (Asymptotic normalization coefficients, ANC)

We did our own experiment $^{11}B(^3He,d)^{12}C$ at $E(^3He)$ = 25 MeV

ANC analysis: Increased radii (signs of halo)

A.S. Demyanova et al., Phys. Rev. C 102, 054612 (2020)

^{12}N (Modified diffraction model, MDM)

We did our own experiment $^{12}C(^3He,t)^{12}N$ at $E(^3He)$ = 40 MeV

MDM analysis: Increased radii (signs of halo)

A.S. Demyanova et al., JETP Letters, 111,409(2020)

We revealed that ^{12}B, ^{12}N, and ^{12}C in the IAS with T=1 and spin-parities 2– and 1– have increased radii and exhibit properties of neutron and proton halo states.

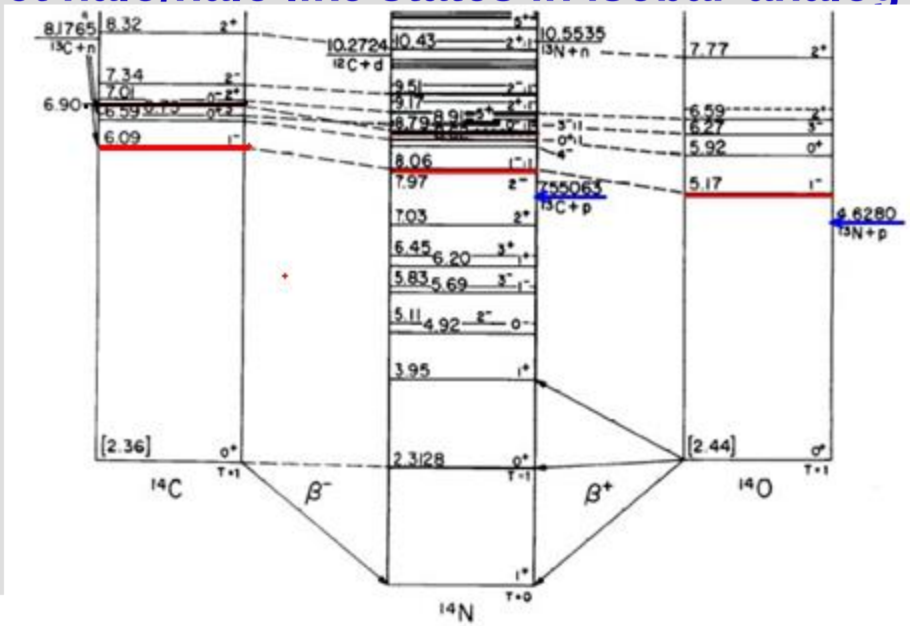
Triplet ^{12}B – ^{12}C – ^{12}N: overview of results

	^{12}B			^{12}C			^{12}N	
J_f^π	E_x (MeV)	$R_{\rm rms}$ (fm)	D_1 %	E_x (MeV)	$R_{\rm rms}$ (fm)	D_1 %	E_x (MeV)	$R_{\rm rms}$ (fm)
1^+	0.0	2.39 ± 0.02	11	15.11	2.40 ± 0.06	30	0.0	2.47 ± 0.07
								2.8 ± 0.4
2^-	1.67	2.73 ± 0.11	53	16.57	2.88 ± 0.13	47	1.19	2.8 ± 0.2
1^-	2.62	3.00 ± 0.11	62	17.23	2.94 ± 0.13	52	1.80	3.3 ± 0.2

D_1 – the probability of the last nucleon to be outside the range of the interaction
D_2 – the contribution of the asymptotic part of the wave function to the rms radius

Isospin triplet $^{14}C - {}^{14}N - {}^{14}O$

We expect halo/halo like states in isobar-analog states (IAS) 1^- T=1



^{14}C (ANC)

It was known

Z. H. Liu, Chin. Phys. Lett. 19, 1071 (2002).

Observation of halos in 1^- and 0^-

Increased radii: R_h = 4.57 and 5.78 fm

ANC method was used for halo radius extraction on base of $^{13}C(d,p)^{14}C$, E_d = 17.7 MeV

S. Yu. Mezhevych et al., Nucl. Phys. A 753, 13 (2005) - rms radius of valence neutron wave function was found to be 5.16 fm

^{14}N (ANC)

We analyzed existing exp data

Increased radius for 1^- state:

R_h = 5.9 ± 0.3 fm, D_1 = 42%, D_2 = 90%

the ANC analysis showed the signs of a proton halo in the 8.06-MeV 1^- state of ^{14}N. This result was obtained for the first time.

^{14}O (MDM)

We analyzed existing exp data

Increased radius for 1^- state: R_{rms} = 2.6 fm

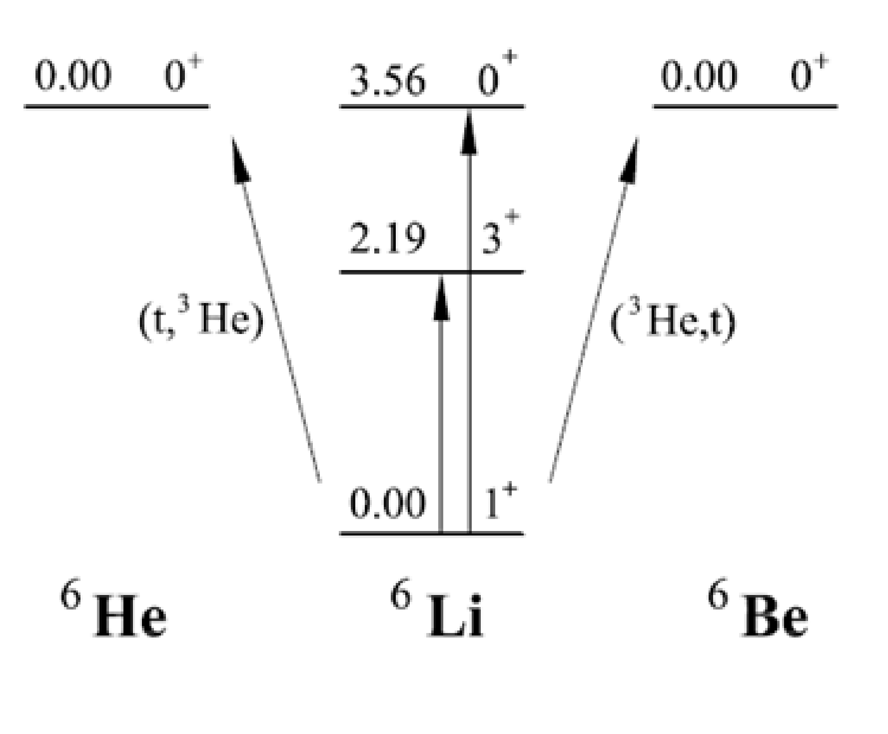
Theoretical analysis is in progress

Signs of halo?

Jetp Lett, vol. 112, iss. 8, pp. 463 – 470

New experiment will be done in 2020/2021 (JYFL, Finland)

Isospin triplet A=6 **^{6}He – ^{6}Li – ^{6}Be**



Among these triplet states, the neutron halo in ^{6}He is well known. A proton-neutron halo is predicted in the excited state of 0+, 3.56 MeV in ^{6}Li, which lies only 137 keV below the ^{6}Li →^{4}He + p + n threshold. Its radius is not known, but it is predicted by about 0.25 Fm larger than the radius of ^{6}He [Arai]. We can expect the appearance of a two-proton halo in the ground state of ^{6}Be. The table shows the known radii of states shown in Fig.

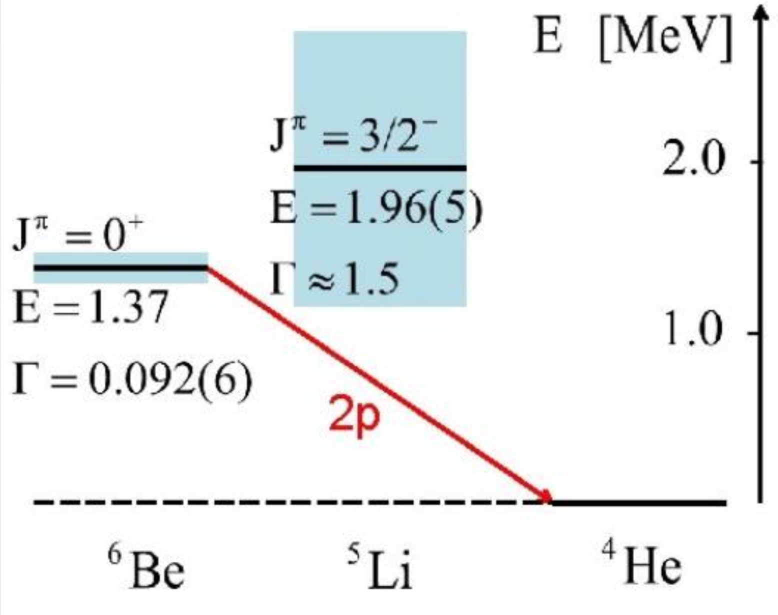
A S Demyanova et al. (2018),in The 3rd International Conference on Particle Physics and Astrophysics, KnE Energy & Physics, pages 1–9. DOI 10.18502/ken.v3i1.1715

Nucleus	E*, MeV	I^π	R_{rms}, fm
^{6}Li	0.00	1^+	2.36 ± 0.03
^{6}Li	3.56	0^+	**2.73 (prediction)**
^{6}He	0.00	0^+	**2.50 ± 0.05**

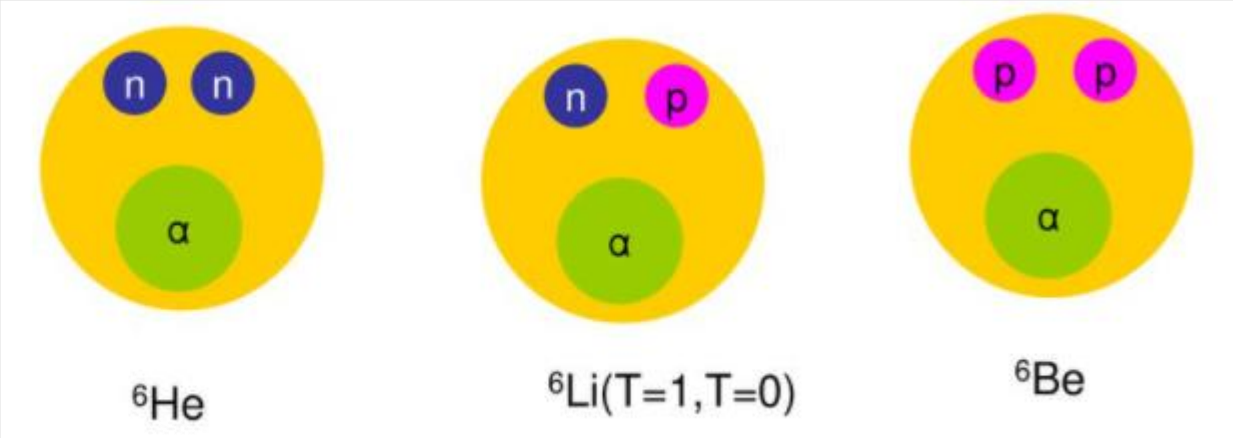
The resulting radius for the state 0^+, 3.56 MeV in ^{6}Li practically equals to the radius of the ground state of its ”Borromean” isobar analogue ^{6}He. It is equal 2.49 ± 0.16 fm.
It can be said preliminary that 0^+, 3.56 MeV state in ^{6}Li is ”Borromean” also and is neutron-proton halo.

^{6}Be nucleus

- The lightest and simplest 2p-emitters (democratic decay)
- The 1p-emission is suppressed



2n halo | tango halo | **2p halo?**



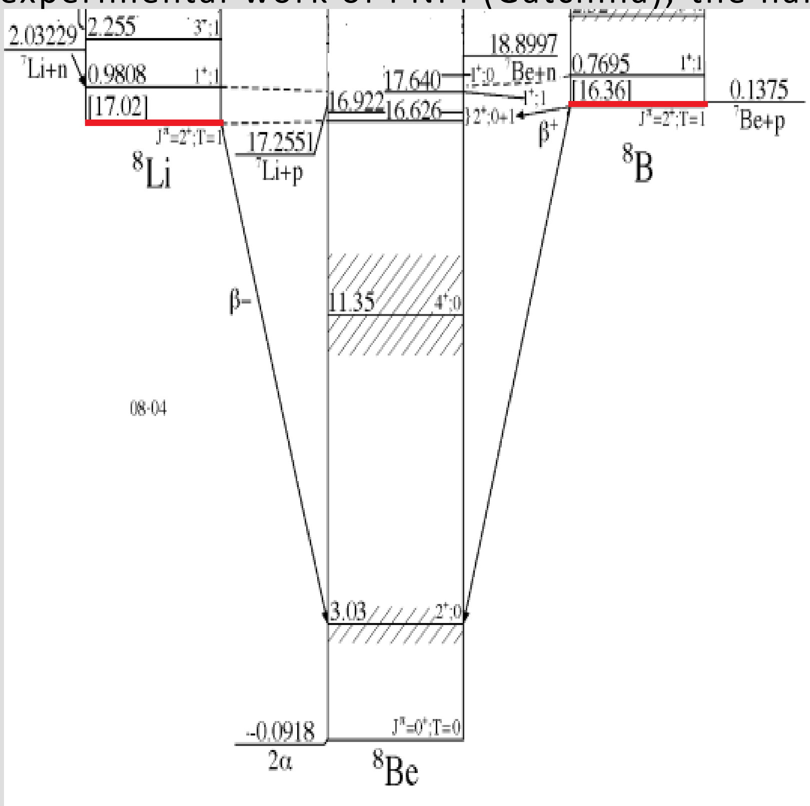
~2.5 fm | ~2.5 fm | Rough estimations **~ 2.5 fm**

New experiment on ^{6}Li(^{3}He,t)^{6}Be at 50-100 MeV

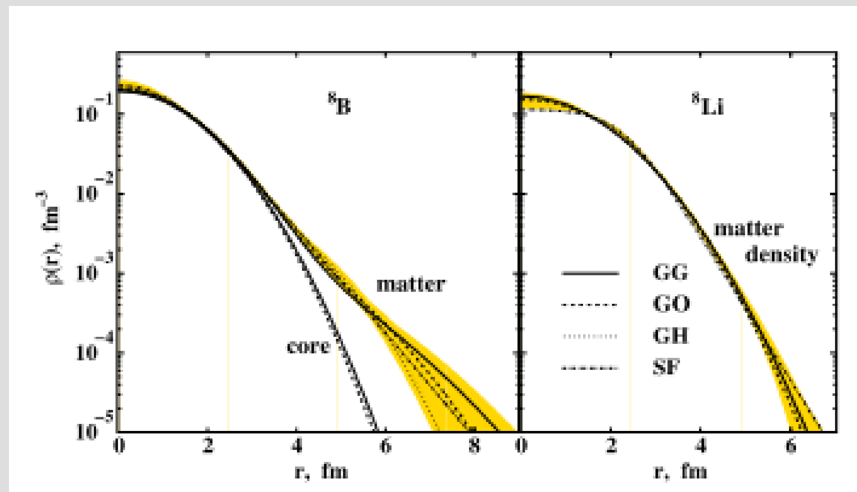
Where to do?
INP (KZ)? JYFL (FI)?

Multiplet A = 8

There are experimental and theoretical literature data on the single-proton halo in ^{8}B. Experimentally halo at g.s. ^{8}B was determined from increased quadrupole moment and total cross-sections. The question arises whether the presence of a neutron halo in the ^{8}Li mirror nucleus is possible. An article by Minamisono et al. find a halo in ^{8}B and the value of the quadrupole moment for ^{8}Li speaks of a thin neutron skin around the core. This is so far the only experimental work where the possibility of an exotic structure in ^{8}Li is considered. In the experimental work of PNPI (Gatchina), the halo in ^{8}B is confirmed and the halo in ^{8}Li is rejected.



The red indicates the state with a halo at ^{8}B and a possible exotic halo state at ^{8}Li.



The density distribution of the core and nucleus in ^{8}B and ^{8}Li

Conclusions

- Triplet A=12: similar radii were obtained for 2^- and 1^- states (T=1). Neutron halo was confirmed by ANC for ^{12}B. Possible proton halo in ^{12}C and ^{12}N.
- Triplet A=14: similar radii were obtained for 1^- state (T=1). Proton halo was observed in ^{14}N for the first time.
- Triplet A=6: It can be said preliminary that 0^+, 3.56 MeV state in ^6Li is ”Borromian” also and is neutron-proton halo. ^6Be analysis is in progress.
- ANC can be applied for resonance states

Collaboration

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