LXXV Международная конференция «ЯДРО-2025. Физика атомного ядра и элементарных частиц. Ядерно-физические технологии»

Experimental studies of $^{10}B(^{7}Li,^{6}Li)^{11}B$ and $^{10}B(^{7}Li,^{6}He)^{11}C$ transfer reactions

Yu.G. Sobolev[1]*, S.S. Stukalov[1], Yu.E. Penionzhkevich[1], N. Burtebayev[2], A.N. Danilov[3], A.S. Demyanova[3], S. V. Dmitriev[3], J. L. Ferreira[4], S. A. Goncharov[5], Yu.B. Gurov[1], J. Lubian[4], M. Nassurlla[2], V. I. Starastsin[3]

[1]Joint Institute for Nuclear Research, Dubna, Moscow oblast, 141980 Russia

[2] Institute of Nuclear Physics, Almaty, 050032 Republic of Kazakhstan

[3]National Research Centre Kurchatov Institute, Moscow, 123098 Russia

[4]Instituto de Fisica Universidade Federal Fluminense Niteri 24210-340 R.J. Brazil

[5]LomonosovMoscow State University, Moscow, 119991 Russia

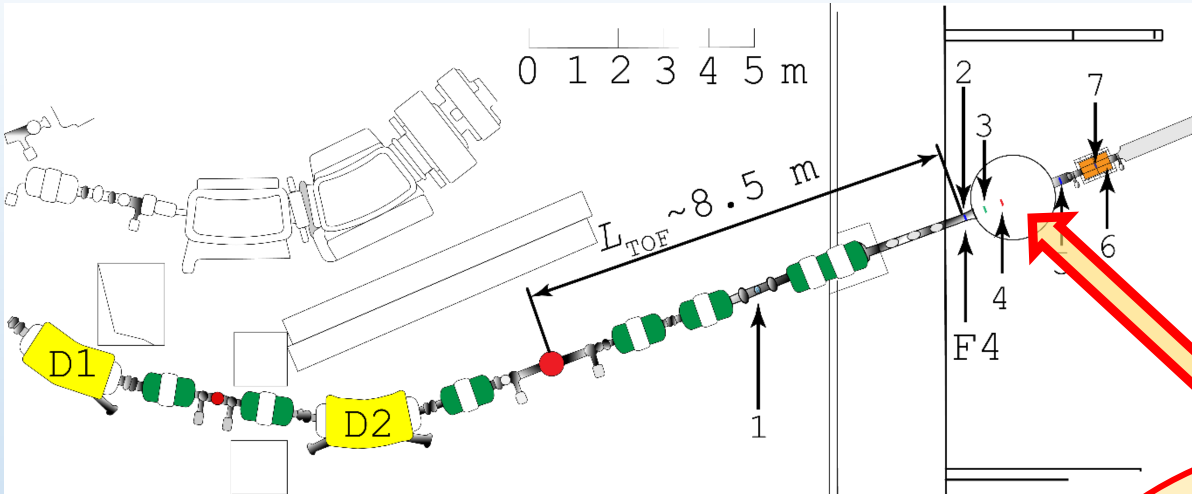
*E-mail: sobolev@jinr.ru

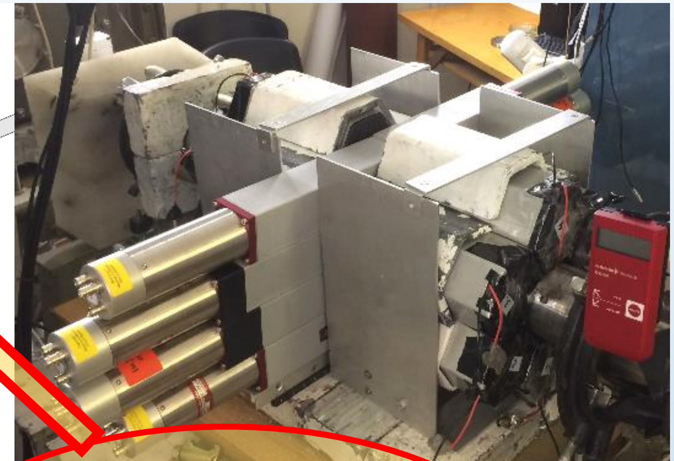
Motivation: The peculiarity of $\sigma_R(E)$ in ^{6}He,^{6,9}Li+^{28}Si

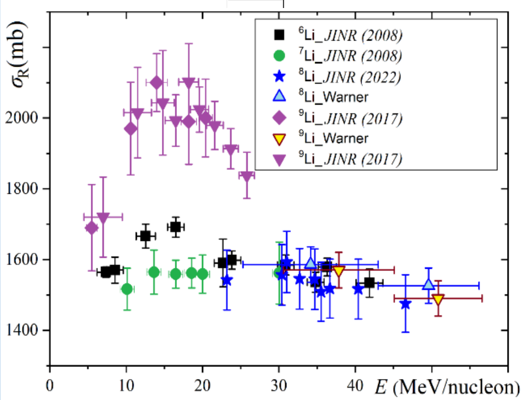
$\sigma_R(E)$ measurements by the 4π-method

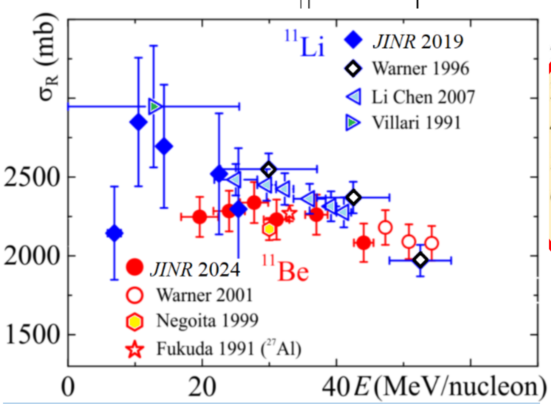
$\sigma_R(E)$ ^{4,6,8}He,^{6,7,8,9,11}Li,^{10,11,12}Be+^{28}Si

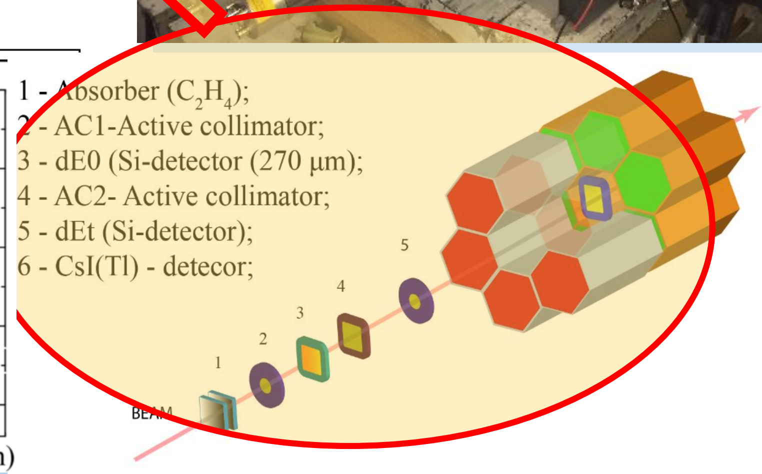
Experiments at fragment-separator ACCULINNA@JINR











$\sigma_R(E)$ of ^{4,6,8}He,^{6,7,8,9,11}Li,^{10,11,12}Be+^{28}Si have been measured at the region E_{LAB}~5÷30AMeV.

The peculiarity of $\sigma_R(E)$ in ^{6,8}He,^{6,9}Li,^{12}Be+^{28}Si were observed:

Local excess of $\sigma_R(E)$ "bamp" at E=[10÷20 AMeV] for ^{6,8}He,^{6,9}Li,^{12}Be+Si reactions were observed.

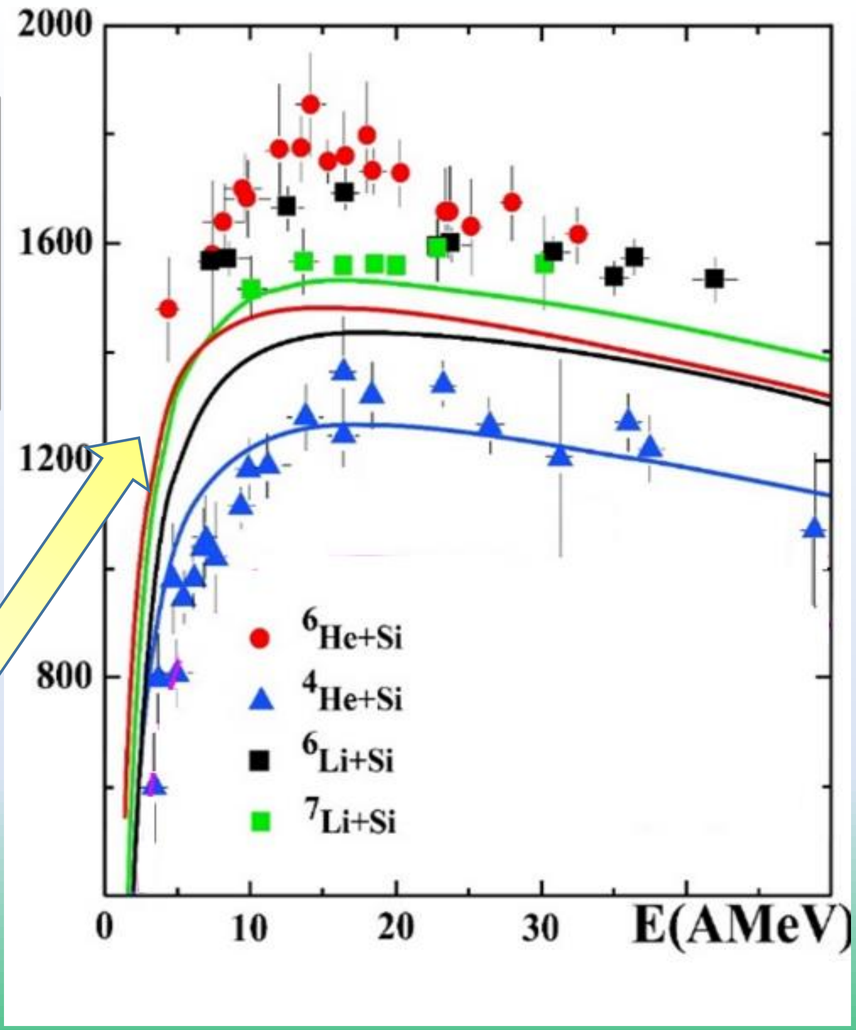
Motivation to study $^6Li_{g.s.}$ spatial properties

An argument to study the spatial properties of $^6Li_{g.s.}$ is in a peculiarities of $\sigma_R(E)$ ^{6}He,^{6}Li+^{28}Si reactions at E_{LAB} = (7—20) AMeV.
The values of σ_R(^{6}He,^{6}Li+^{28}Si) exceed the values of σ_R(^{7}Li+^{28}Si).

The values of σ_R(**^{6}He,^{6}Li**+^{28}Si) exceed the σ_R of empirical Kox model.

The values of σ_R(**^{4}He,^{7}Li**+^{28}Si) are close to the $\sigma_R(E)$ predictions of Kox model systematics

^{4}He, ^{6}He, ^{7}Li data from:
Bull. RAS **69** (11), p.1605, (2005);
^{6}Li data from:
Bull. RAS **72** (3), p.356, (2008).



The experimental data on the spatial structure of the ground state of $^6Li_{g.s.}$ remain insufficient and contradictory:

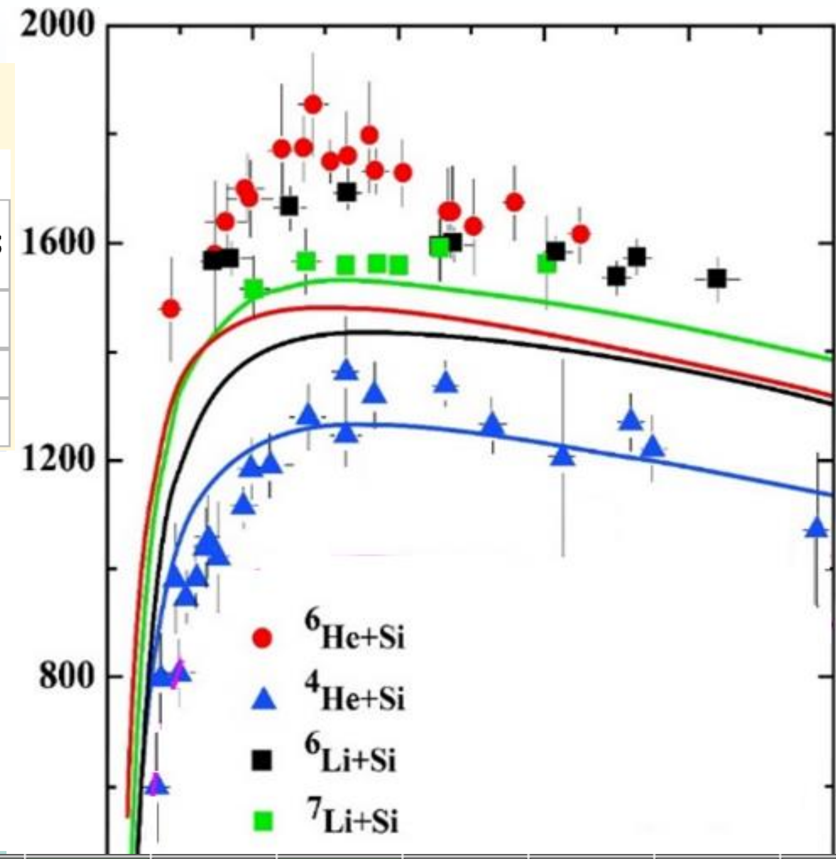
The experimental values of the material radius of $^6Li_{g.s.}$ vary significantly, ranging from R_{rms}= 2.09±0.02 fm [I. Tanihata *et al.*, Phys.Rev.Lett. **55** 2676, (1985)]
to R_{rms}= 2.45±0.07 fm [A.V. Dobrovolsky, *et al.*, Nucl.Phys. **A 766**, pp..1–24, (2006)].

Motivation to study $^{6}Li_{g.s.}$ spatial properties

$\beta_2(Q_{mom})$

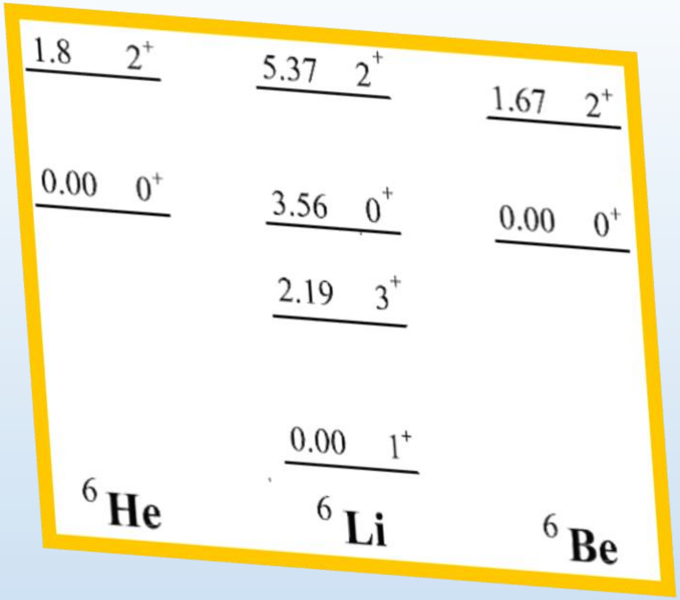
Parameter	*Data 1*	*Data 2*
Q-moment (barn) for 1^+ state at E = 0.000 MeV:	-0.00083 ± 0.00008	-0.00083 ± 0.00008
$\beta_2(Q_{mom})$:	**+0.023 ± 0.003**	**-0.045 ± 0.006**
NSR Reference:	1984Su09	1984Su09
Journal Reference:	CPL 112 1 (84)	CPL 112 1 (84)

sign unknown:	positive:	negative:
$0 \le \|\beta_2\| < 0.2$	$0 < \beta_2 < +0.2$	$0 > \beta_2 > -0.2$
$0.2 \le \|\beta_2\| < 0.3$	$+0.2 \le \beta_2 < +0.3$	$-0.2 \ge \beta_2 > -0.3$
$0.3 \le \|\beta_2\| < 0.4$	$+0.3 \le \beta_2 < +0.4$	$-0.3 \ge \beta_2 > -0.4$
$0.4 \le \|\beta_2\| < 0.5$	$+0.4 \le \beta_2 < +0.5$	$-0.4 \ge \beta_2 > -0.5$
$\|\beta_2\| > 0.5$	$\beta_2 > +0.5$	$\beta_2 < -0.5$



Z=8	^{12}O	^{13}O	^{14}O	^{15}O	***^{16}O***	***^{17}O***	***^{18}O***	^{19}O	^{20}O	^{21}O	^{22}O	^{23}O	^{24}O	^{25}O	^{26}O
^{10}N	^{11}N	^{12}N	^{13}N	***^{14}N***	***^{15}N***	^{16}N	^{17}N	^{18}N	^{19}N	^{20}N	^{21}N	^{22}N	^{23}N	^{24}N	^{25}N
^{9}C	^{10}C	^{11}C	***^{12}C***	***^{13}C***	***^{14}C***	^{15}C	^{16}C	^{17}C	^{18}C	^{19}C	^{20}C	^{21}C	^{22}C		
^{8}B	^{9}B	***^{10}B***	***^{11}B***	^{12}B	^{13}B	^{14}B	^{15}B	^{16}B	^{17}B	^{18}B	^{19}B				
^{7}Be	^{8}Be	***^{9}Be***	^{10}Be	^{11}Be	^{12}Be	^{13}Be	^{14}Be	^{15}Be	^{16}Be						
^{6}Li	***^{7}Li***	***^{8}Li***	***^{9}Li***	^{10}Li	***^{11}Li***	^{12}Li									
^{5}He	***^{6}He***	^{7}He	***^{8}He***	^{9}He	^{10}He										

Motivation to study $^6Li^*(3.56MeV)$ spatial properties



[K. Arai et al., Phys.Rev.C 51(5), (1995)]:

R_{rms} ($^6He_{g.s.}$)= 2.51fm,

R_{rms} ($^6Li_{g.s.}$)= 2.44fm,

R_{rms}($^6Li^*$(3,56MeV)) = 2.73fm

ISOBARIC TRIPLET ^{6}He - ^{6}Li - ^{6}Be

One of the issues in the study of exotic nuclei is the question of preserving the properties of the halo in excited isobaric analog states (IAS).

The **most accessible** experiments for this are those with beams of stable ^{6}Li nuclei included in the isobaric triplet A=6 (^{6}He-^{6}Li-^{6}Be)

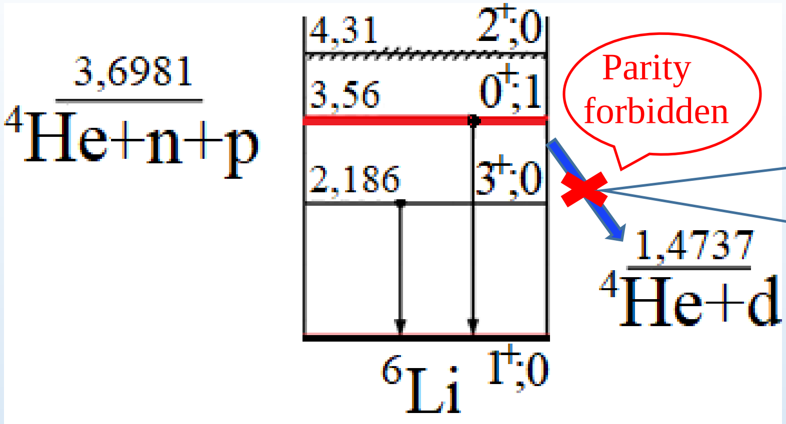
Experimental data on the spatial structure of excited ^{6}Li IAS are **significantly limited**.

Data analysis based on data from various experiments showed [A. S. Demyanova, *et al*., ICPPA 2017, KnE Energy (2018)]:

R_{rms} ($^6He_{g.s.}$) ≈ R_{rms}($^6Li^*$(3,56)) ≈ **2.49±0.16fm**.

One of the newes theoretical studies of the properties of isobaric triplet A=6 are calculations within the **ab initio** NCSM (no-core shell model) [D.M. Rodkin, Yu.M. Tchuvil'sky, "Sizes of the Neutron–Proton Halo in Nucleon-Stable States of the ^{6}Li Nucleus", JETP Lett., 118(3), 153 (2023)]. **NCSM ab initio calculations showed that the radius of $^6Li_{g.s.}$ coincides within the error limits with the radius of the $^6Li^*$(3,56) state.**

Motivation:



As the spin-parity of the deuteron is 1^+, the decay of the 0^+ ^{6}Li state into the α+ d channel is only possible if the continuum final state is $J^\pi = 0^-$; thus this process violates parity.

The structure of ^{6}Li can be roughly represented as two subsystems: the "core" of ^{4}He and the **(*p*-*n*)** pair forming a "*p*-*n*" shell.

The excited level ^{6}Li*(0^+,T=1,*E*=3.56 MeV) is the IAS of ^{6}He$_{g.s.}$ and ***due to the* isospin symmetry of the strong interaction*, the*** ^{6}Li*(0^+,T=1,*E*=3.56 MeV) ***state* should have similar spatial and spin characteristics of the wave function *, the same as the ground state of the ^{6}He*.**

If the ground state of ^{6}He has a *2n*-halo of the "Boromian" type, then the state ^{6}Li*(3.56) should have a similar ***n-p*** structure, which has received a number of names in various publications: **"n-p halo" or "tango-halo"** [I. N. Izosimov, Phys. At. Nucl. 80(5), 867, (2017)].

Motivation: *for studying $^6Li_{g.s.}$ and $^6Li^*$(3.56MeV) spatial properties in 1-step reactions:*

Most studies focusing on the structure of ^{6}Li*(E=3.56 MeV) have examined multi-step reaction channels like (t,p), charge-exchange reactions like ^{1}H(^{6}He,^{6}Li)n, etc.

The analysis of multistep reaction channels, unlike one-step processes (nucleon-stripping and nucleon-pickup reactions) requires consideration of a greater number of possible combinations, which complicates obtaining definitive results.

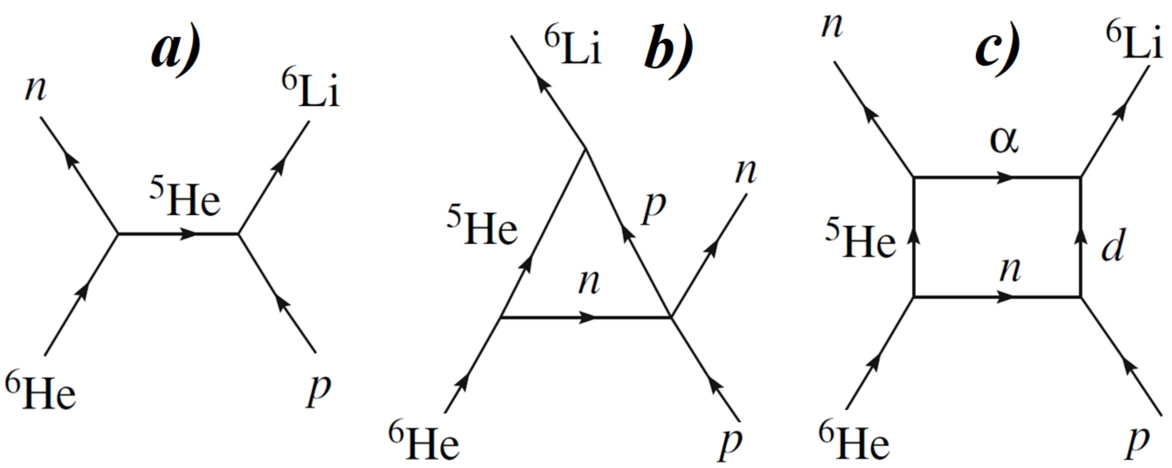
ЯДЕРНАЯ ФИЗИКА, 2013, том 76, № 12, с. 1542–1548

ЯДРА

ПРОСТРАНСТВЕННАЯ ПЕРИФЕРИЯ ИЗОТОПОВ ЛИТИЯ

© 2013 г. Л. И. Галанина*, Н. С. Зеленская

$p(^6\mathrm{He},n)^6\mathrm{Li}(0^+)$ direct reaction diagrams:



a – ^{5}He stripping;

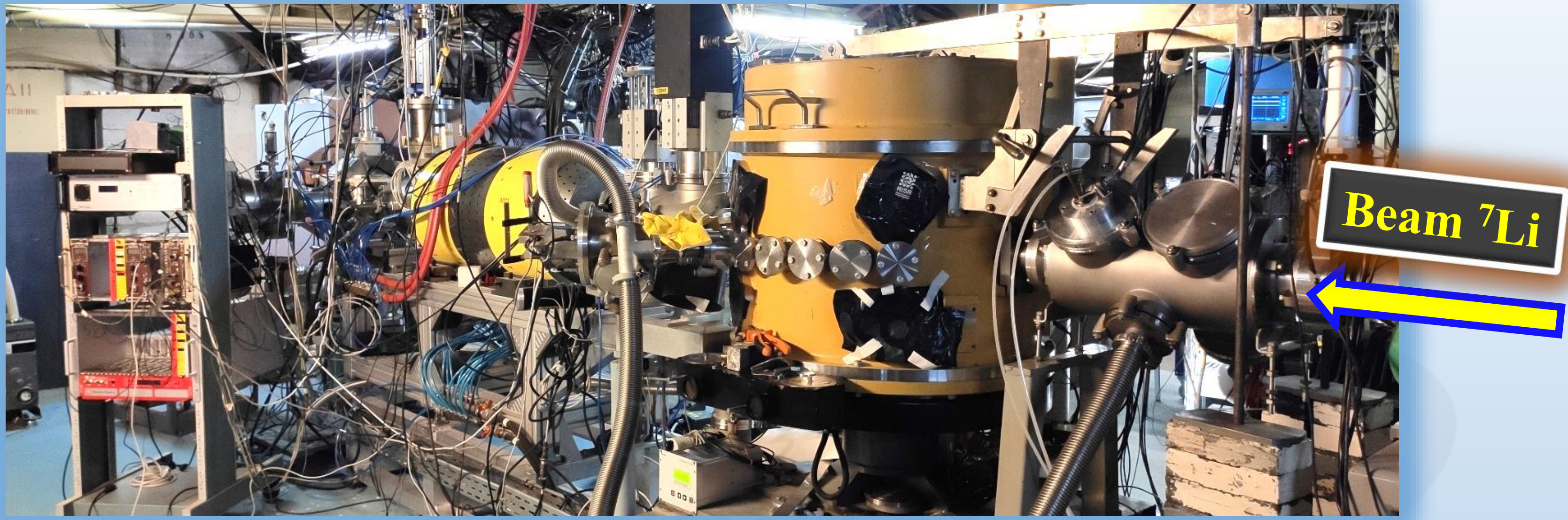
b – exchange of a virtual neutron with a proton;

c – sequential transmission of neutron and α–particle.

experiment: *study $^{6}He_{g.s.}$, $^{6}Li_{g.s.}$ and $^{6}Li^{*}$(3.56MeV) spatial properties in 1-step reactions:*

Measurement of differential cross sections of reaction products

$^{10}B+^{7}Li$ (E_{lab}=58 MeV)



The experiment was carried out on the U-400 @ FLNR JINR, Dubna.

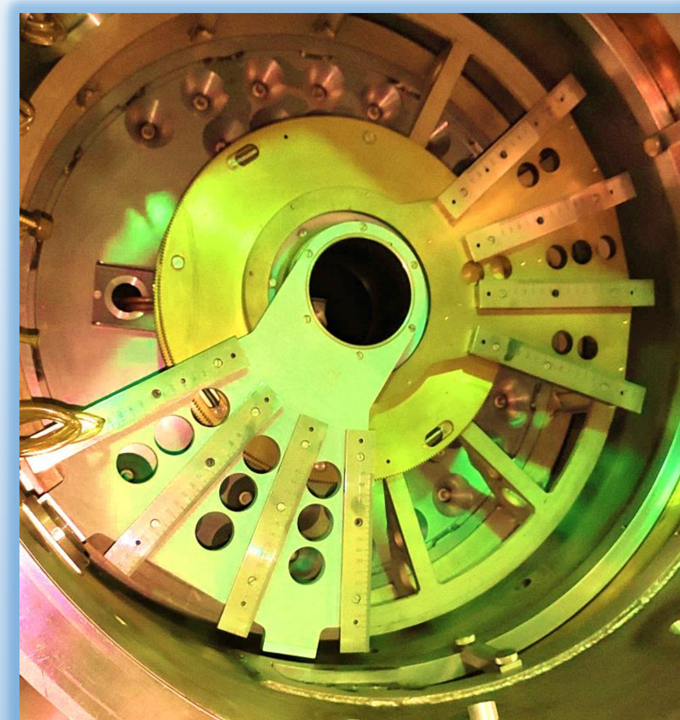
The aim of the experiment was to measure the differential cross sections dσ/dΩ of :

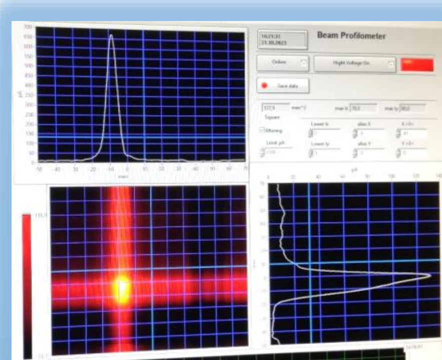
1) elastic scattering: $^{10}B(^{7}Li, ^{7}Li)^{11}B$;
2) n -transfer reaction: $^{10}B(^{7}Li, ^{6}Li)^{11}B$, $^{10}B(^{7}Li, ^{6}Li^{*}(3{,}56MeV))^{11}B$
3) p -transfer reaction: $^{10}B(^{7}Li, ^{6}He)^{11}C$

and other reaction channels.

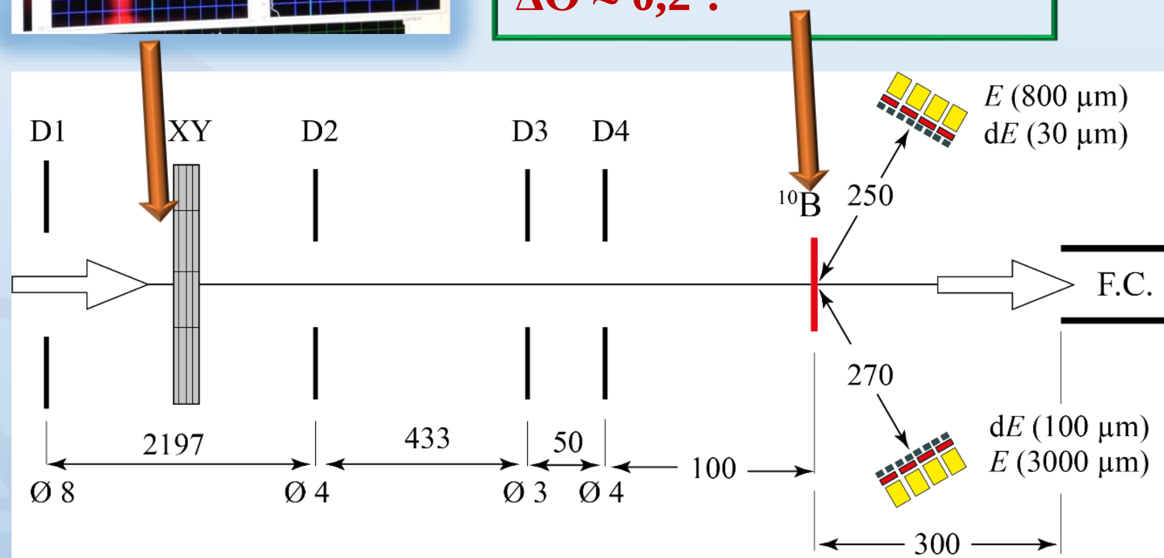
Details of the experiment:

study $^{6}He_{g.s.}$, $^{6}Li_{g.s.}$ and $^{6}Li^{*}$(3.56MeV) spatial properties in 1-step reactions:





Beam spot on the target position: Ø = 3,6 mm.
Beam angular aperture: ΔΘ ≈ 0,2°.



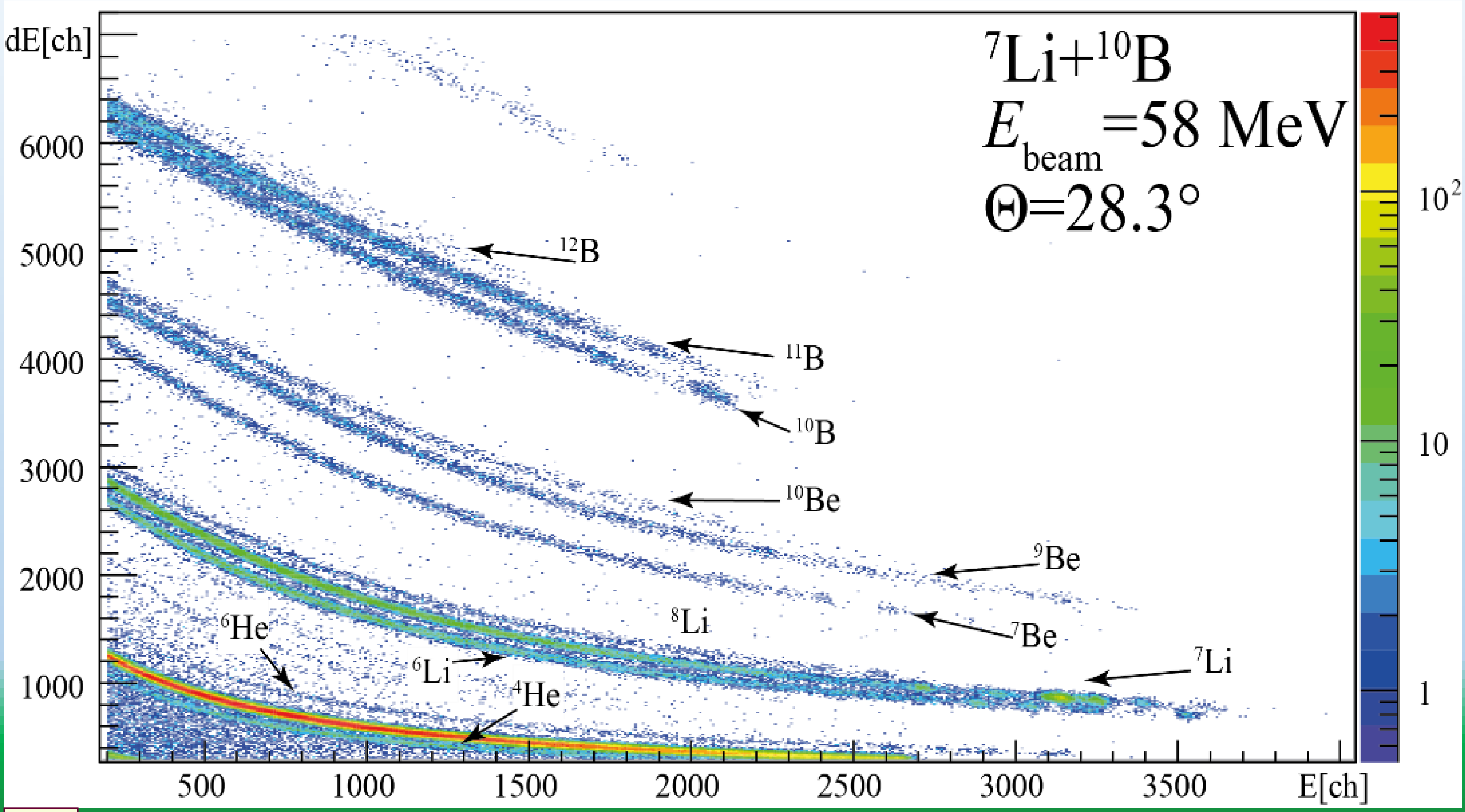
The measurements were carried out in a scattering chamber using two assemblies of semiconductor detectors. Each assembly includes 4 ΔE–E telescopes.

Left: 4 telescopes (ΔE=30μm, E=800μm) with angular step $\Theta=1^0$, angular capture of each detector $\Delta\Theta=\pm0.5^0$. The distance to the target is - 25 см. The range of measured angles - $17^o<\Theta<50^o$.

Right: 4 telescopes (ΔE=100μm, E=3000μm) with angular step $\Theta=3^0$, angular capture of each detector $\Delta\Theta=\pm1^0$. The distance to the target is - 27 см. The range of measured angles - $7^o<\Theta<30^o$.

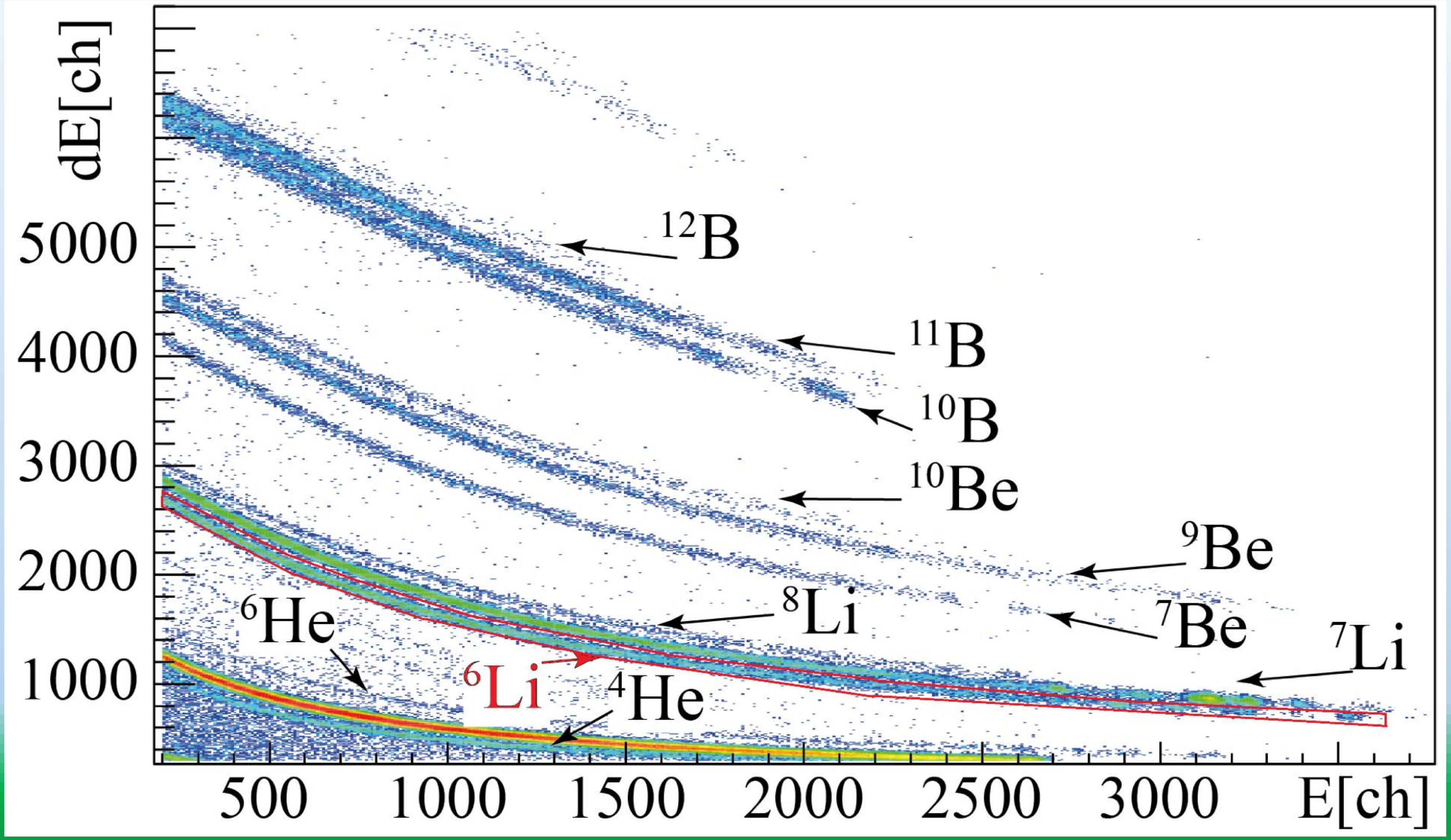
Experiment:

- The energy resolution of the d*E* and *E* telescope detectors was no worse than ΔE_{FWHM} **= 60 keV**, which ensured the identification of particles in d*E*–*E* telescopes from hydrogen isotopes to boron isotopes.



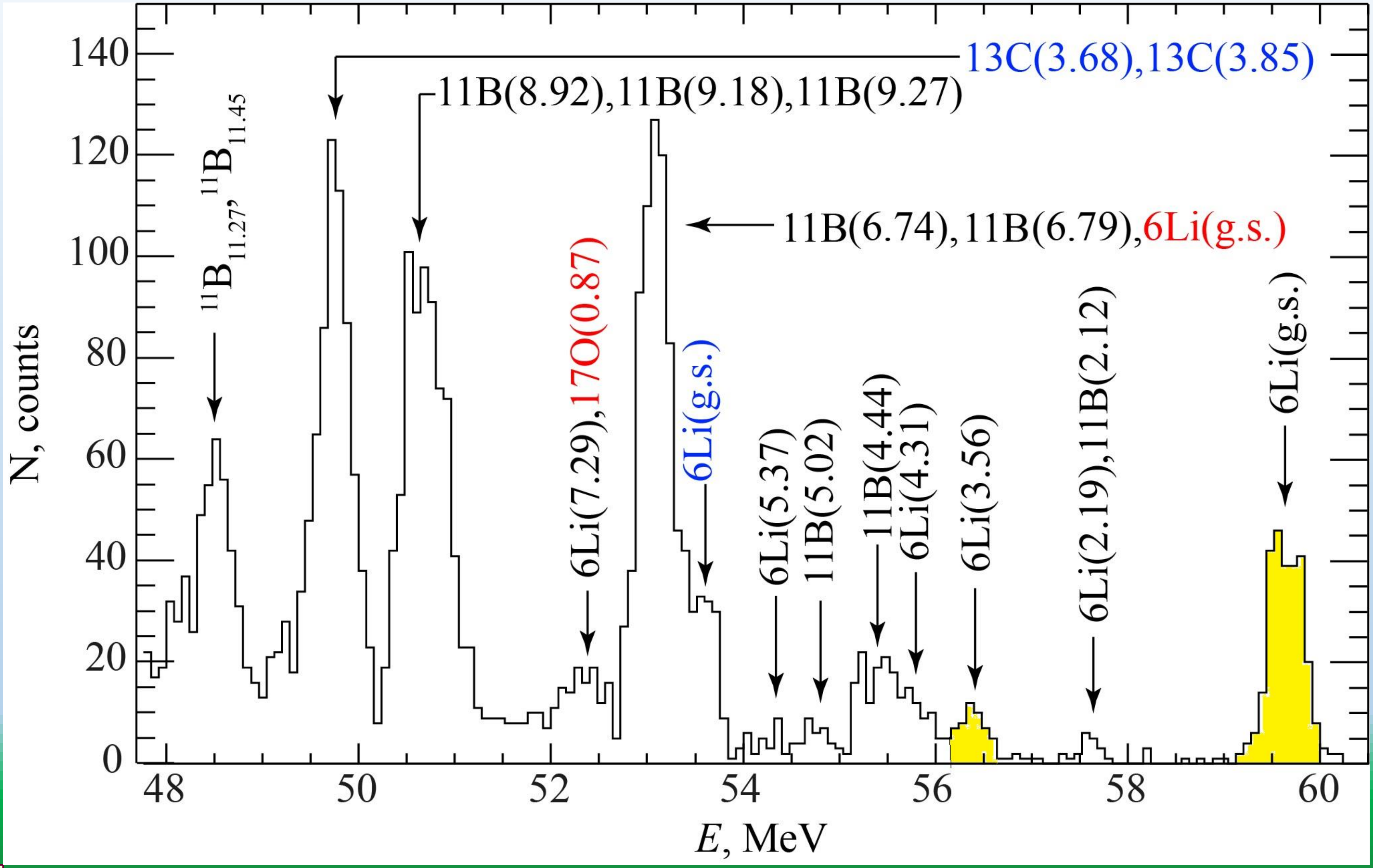
Experiment:

- The energy resolution of the d*E* and *E* telescope detectors was no worse than **ΔE_{FWHM} = 60 keV**, which ensured the identification of particles in d*E*–*E* telescopes from hydrogen isotopes to boron isotopes.



Experiment: *study $^{6}Li_{g.s.}$ and $^{6}Li^{*}$(3.56MeV) spatial properties in 1-step reactions:*

Energy (d*E*+*E*) spectrum ^{6}Li, $\Theta_{LAB} = 10^{0}$:



Experiment: *study $^6Li_{g.s.}$ and $^6Li^*$(3.56MeV) spatial properties in 1-step reactions:*

(Preliminary results)

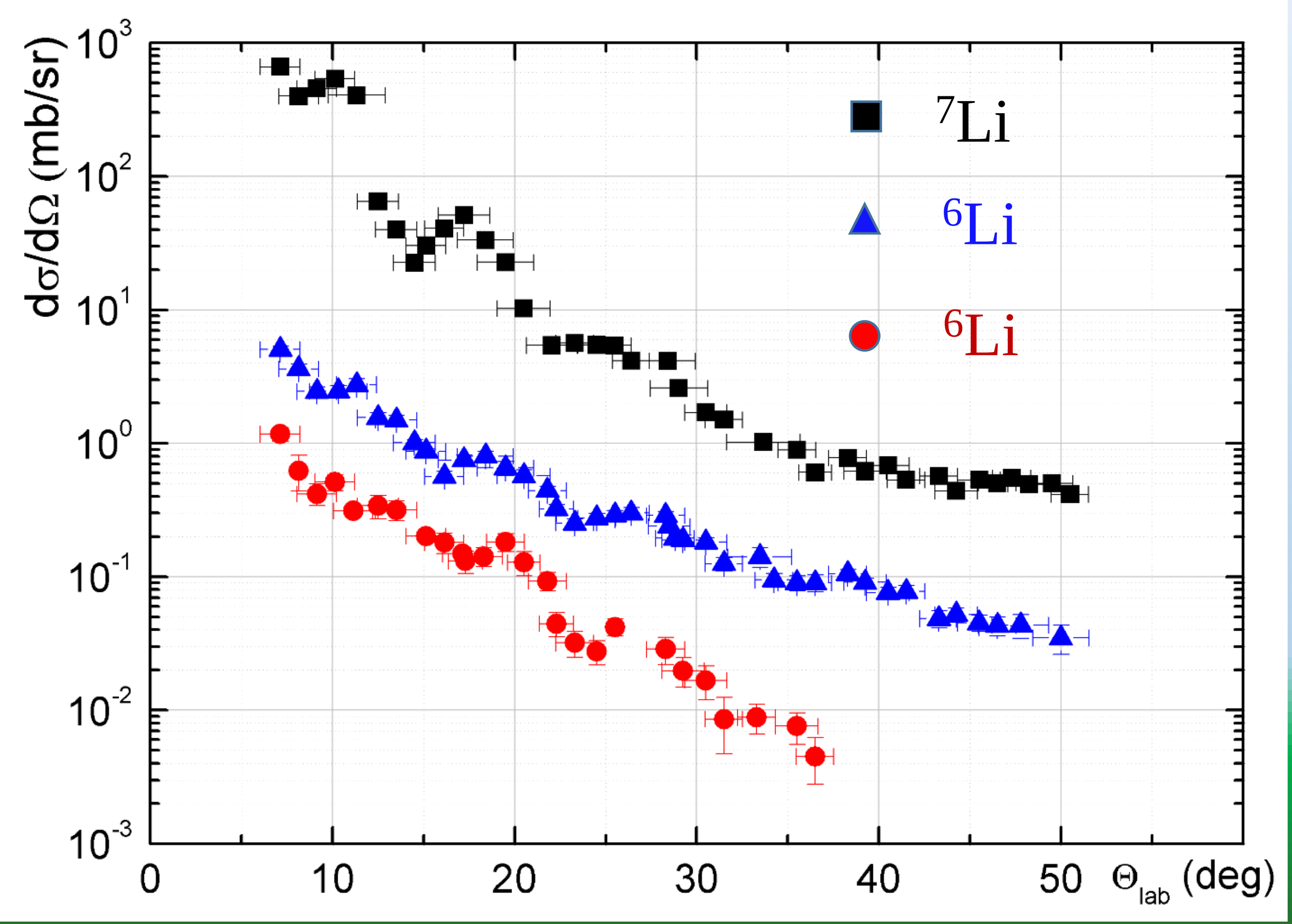
The angular distributions of differential cross sections $d\sigma/d\Omega$:

elastic scattering $^7Li+^{10}B$ ■ - black squares

And one-nucleon transfer reactions $^{11}B(^7Li,^6Li)^{10}B$:

to ground state $^6Li(J^\pi=1^+; E=0.0$ MeV;T=0) ▲ - blue triangles

to excited state ^6Li ($J^\pi=0^+$; E=3.56 MeV; T=1) ● - red circles.

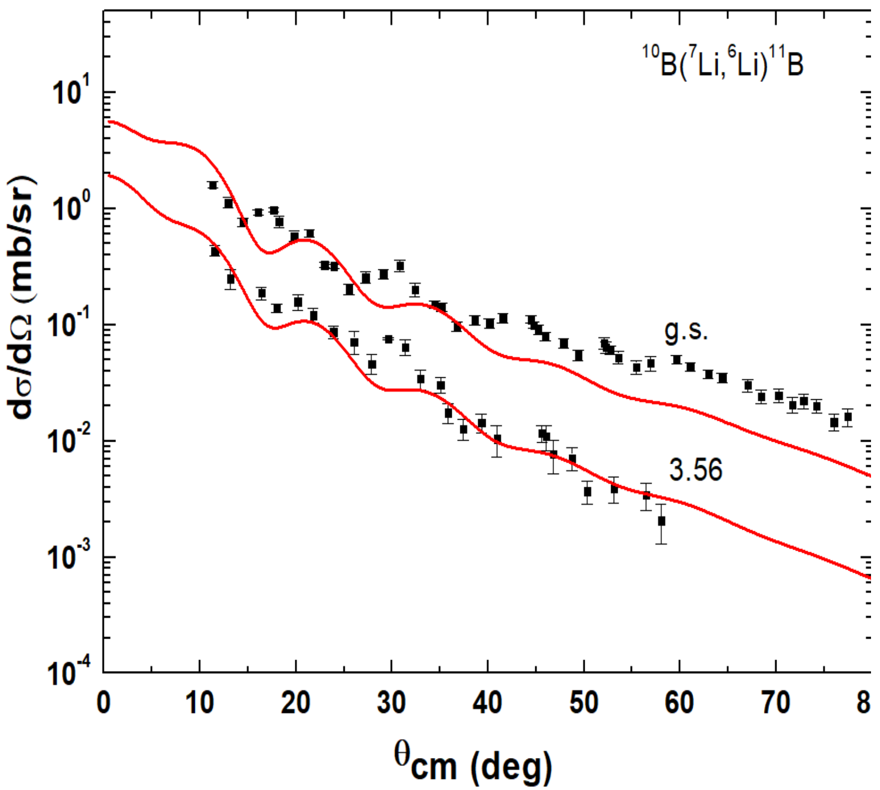


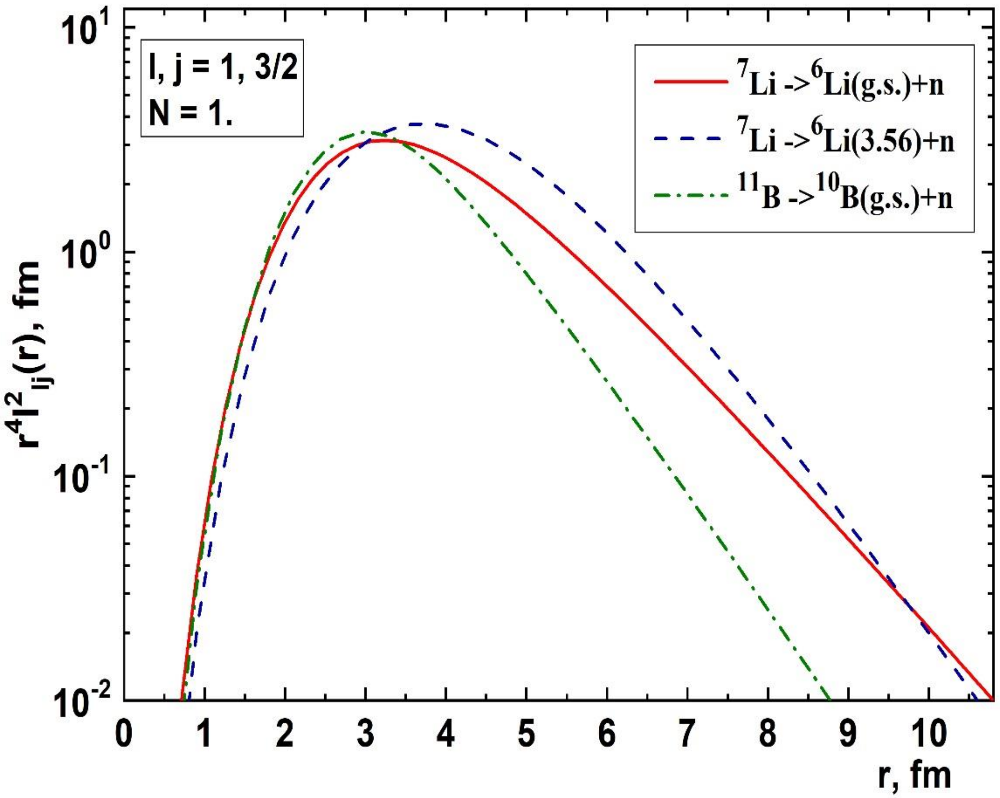
Analysis: *study $^6Li_{g.s.}$ and $^6Li^*$(3.56MeV) spatial properties in 1-step reactions:*

arXiv:2408.09231v2 [nucl-ex] 9 Oct 2024

The “Finite Range Distorted Wave Born Approximation” (FRDWBA) analysis of the differential cross section of the $^{10}B(^7Li,^6Li)^{11}B$ for the $^6Li_{g.s.}$ and $^6Li^*$(3.56 MeV) transition was performed.

Phenomenological approach based on solving an approximate equation for the reaction form factor was used to determine its radial dependence and empirical values of asymptotic normalization coefficient (ANC).

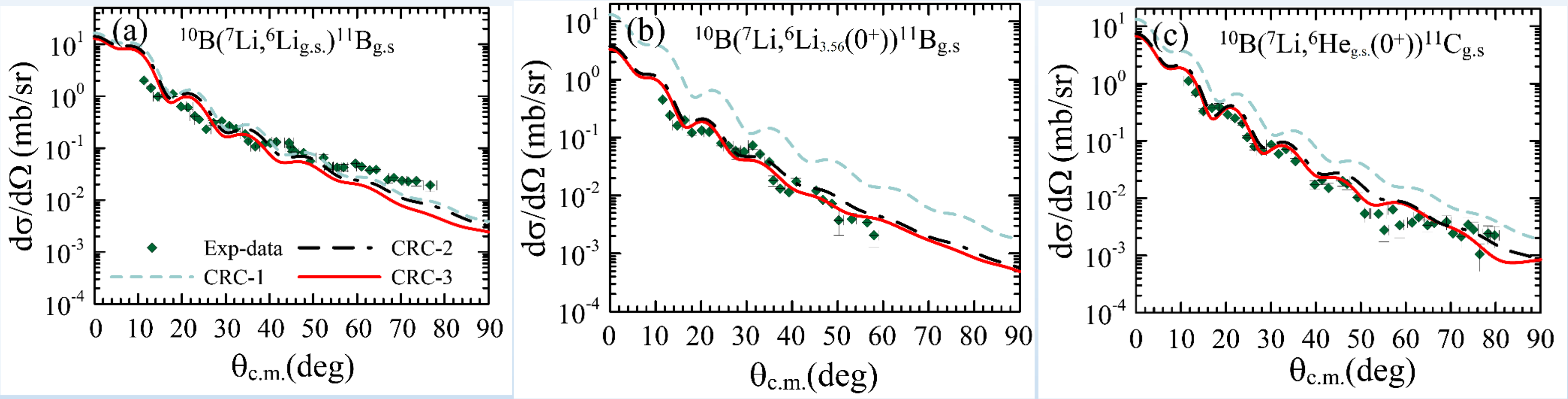




The radial dependences $r^4 I_{lj}^2(r)$ for three form factors

Analysis: *study $^{6}Li_{g.s.}$ and $^{6}Li^{*}$(3.56MeV) spatial properties in 1-step reactions:*

The "Finite Range Distorted Wave Born Approximation" (FRDWBA) analysis of the differential cross section of the $^{10}B(^{7}Li,^{6}Li)^{11}B$ for the $^{6}Li_{g.s.}$ and $^{6}Li^{*}$(3.56 MeV) transition was performed.



Conclusions:

- ^{7}Li elastic scattering and 1n-transfer reaction ^{10}B(^{7}Li,^{6}Li)^{11}B E(^{7}Li)=58MeV have been measured at U-400 @FLNR JINR, Dubna.
- The angular distribution for reaction ^{10}B(^{7}Li,^{6}Li)^{11}B with excitation state ^{6}Li*($J^{\pi}=0^{+}$,T=1,E=3.56MeV) **is presented for the first time**.
- The "Finite Range Distorted Wave Born Approximation" (FRDWBA) analysis of the differential cross section of the ^{10}B(^{7}Li,^{6}Li)^{11}B for the ^{6}Li$_{g.s.}$ and ^{6}Li*(3.56 MeV) transition was performed.
- Phenomenological approach based on solving an approximate equation for the reaction form factor was used to determine its radial dependence and empirical values of asymptotic normalization coefficient (ANC). The obtained values of ANC for the ^{6}Li$_{g.s.}$ and ^{6}Li*(3.56 MeV) states are in agreement with the literature ones.
- Comparison of the radial dependences of form factors shows that **the wave function of the ^{6}Li*($J^{\pi}=0^{+}$,T=1,E=3.56MeV) state has increased spatial dimension compared to the ^{6}Li$_{g.s.}$**.
- This result is an **argument in favor of a halo existence in ^{6}Li*(3.56 MeV)** state, while the question of a halo in ^{6}Li$_{g.s.}$ still leaves open.

arXiv:2408.09231v2 [nucl-ex]

Study of ^{7}Li+^{10}B elastic scattering and the lithium-induced reaction of one-nucleon transfers ^{10}B(^{7}Li,^{6}Li)^{11}B*

Sergey Stukalov,[1] Yuri Sobolev,[1,2,†] Yuri Penionzhkevich,[1,3] Nassurlla Burtebayev,[4,5] Sergey Goncharov,[6,‡] Yuri Gurov,[1,3] Andrey Danilov,[2] Alla Demyanova,[2] Sergey Dmitriev,[2] Maulen Nassurlla,[4,5] Viktar Starastsin,[2,3] Alexey Shakhov,[1] Semyon Raidun,[2] and Nguyen Hoai Chau[1,7]

ISSN 1063-7788, Physics of Atomic Nuclei, 2024, Vol. 87, No. 2, pp. 16 21. © Pleiades Publishing, Ltd., 2024.

NUCLEI
Experiment

Study of the ^{6}Li 0^{+} Excited State

S. S. Stukalov[1)], Yu. G. Sobolev[1),2)], Yu. E. Penionzhkevich[1)], N. Burtebayev[3)], S. A. Goncharov[4)], Yu. B. Gurov[1)], A. N. Danilov[2)], A. S. Demyanova[2)*], S. V. Dmitriev[2)], M. Nassurlla[3)], V. I. Starastsin[2)], A. V. Shakhov[1)], and S. K. Raidun[2)]

ISSN 1062-8738, Bulletin of the Russian Academy of Sciences: Physics, 2025, Vol. 89, No. 8, pp. 1236–1240. © Pleiades Publishing, Ltd., 2025.

Microscopic Analysis of Elastic Scattering and Transfer Reactions in the ^{7}Li + ^{10}B Collision at a Beam Energy of 58 MeV

E. V. Zemlyanaya[a, b, *], K. V. Luk'yanov[a, b], V. K. Luk'yanov[a], Yu. E. Penionzhkevich[a, c], Yu. G. Sobolev[a], and S. S. Stukalov[a]

Experimental studies of $^{10}B(^{7}Li,^{6}Li)^{11}B$ and $^{10}B(^{7}Li,^{6}He)^{11}C$ transfer reactions

Thank you