LONG RANGE PLANE WITH RADIACIVE BEAMS @ DUBNA

A. Fomichev
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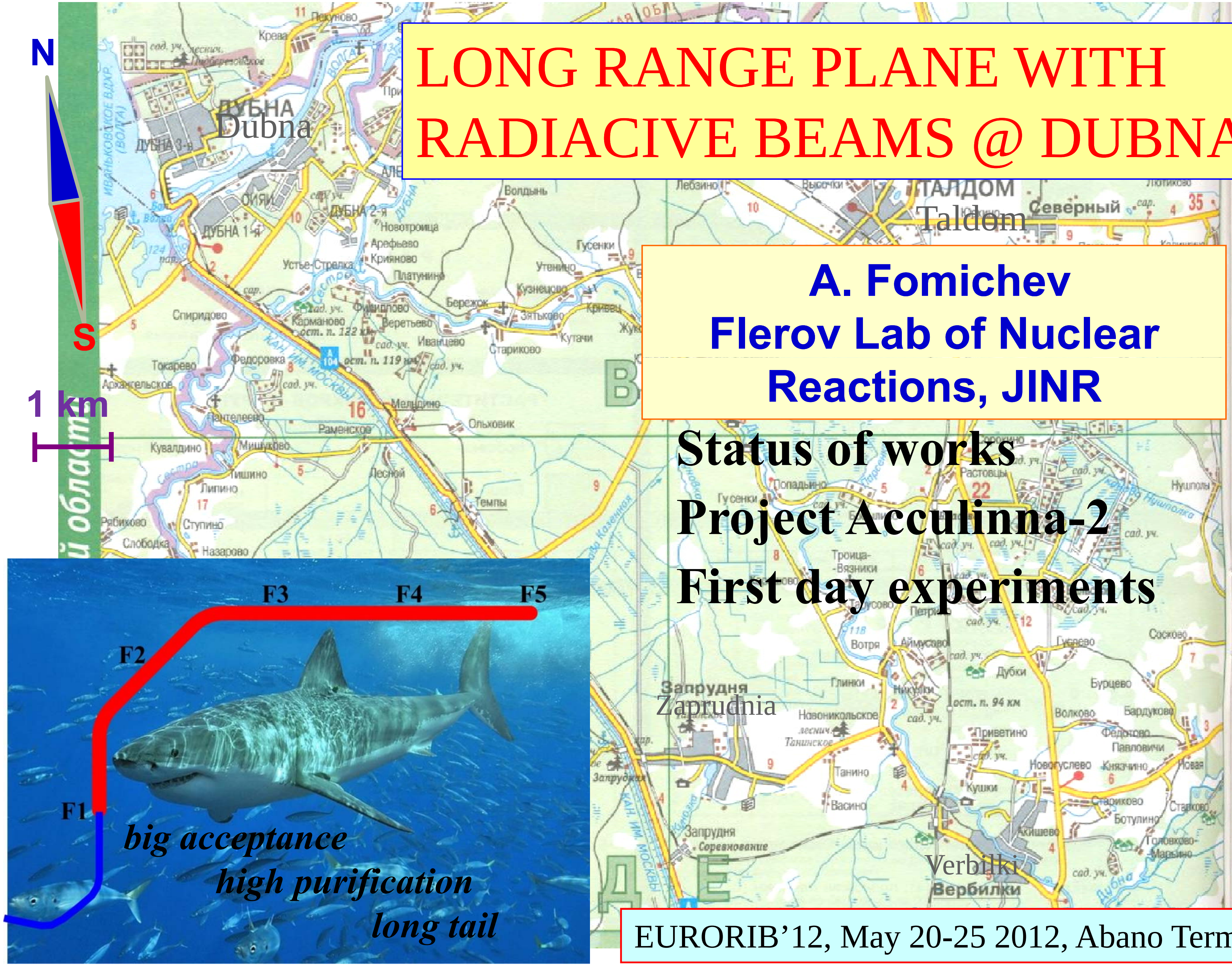
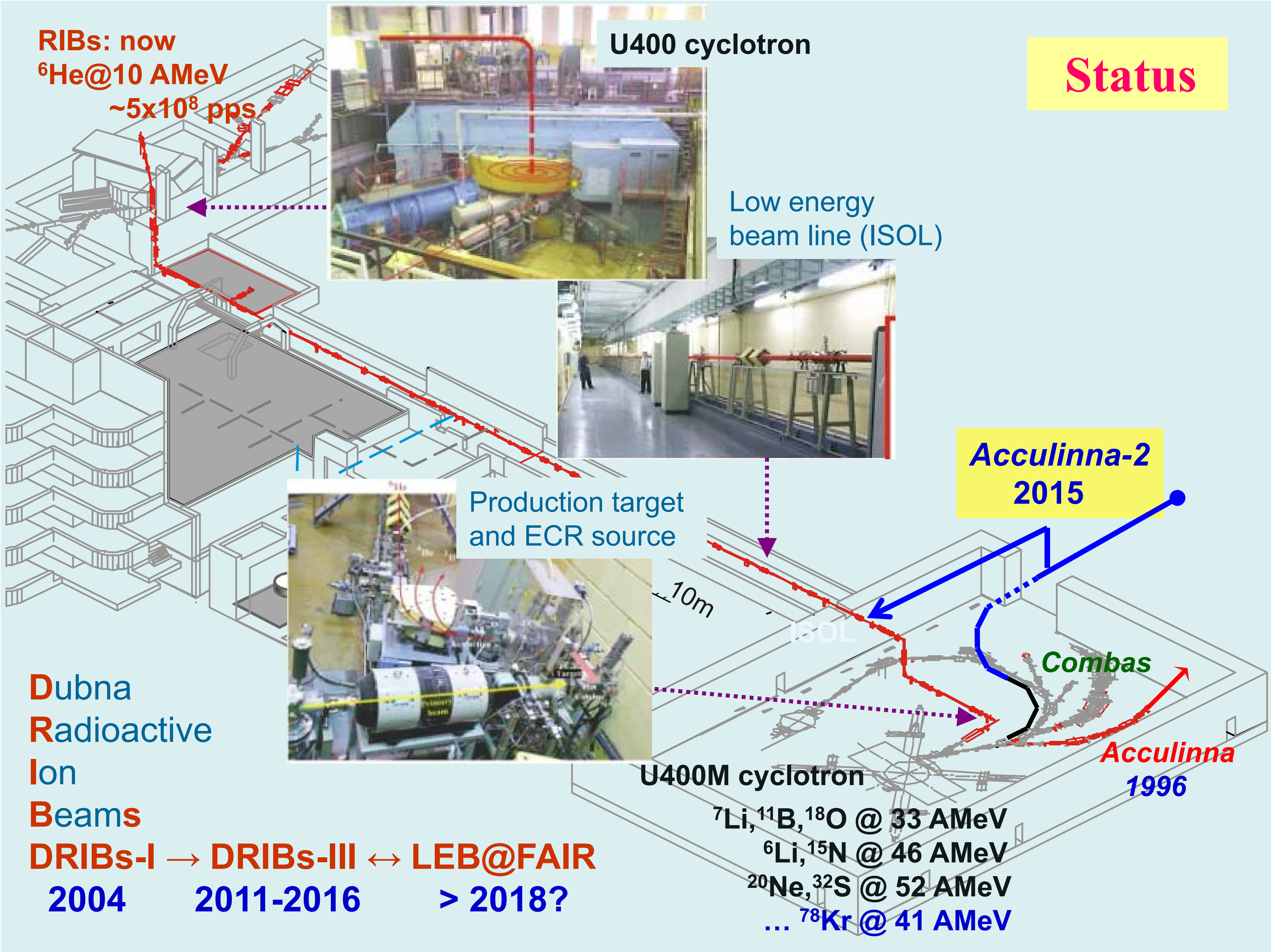
Status of works
Project Acculinna-2
First day experiments



EURORIB'12, May 20-25 2012, Abano Terme


Status
RIBs: now
6He@10 AMeV
~5x10^8 pps
U400 cyclotron
Low energy
beam line (ISOL)
Production target
and ECR source
Acculinna-2
2015
10m
ISOL
Combas
Acculinna
1996
U400M cyclotron
7Li, 11B, 18O @ 33 AMeV
6Li, 15N @ 46 AMeV
20Ne, 32S @ 52 AMeV
… 78Kr @ 41 AMeV
Dubna
Radioactive
Ion
Beams
DRIBs-I → DRIBs-III ↔ LEB@FAIR
2004 2011-2016 > 2018?

Main results of Acculinna group since 1997

1. A.M. Rodin et al, High resolution line for secondary radioactive beams at the U400M cyclotron, NIM B126 (1997) 236-241.
2. G.M. Ter-Akopian et al, Two-neutron exchange observed in the 6He+4He reaction. Search for the "di-neutron" configuration of 6He Phys. Lett. B426 (1998) 251-256
3. R. Wolski et al, Cluster structure of 6He studied by means of 6He+p reaction at 25 MeV/n energy, Phys. Lett. B467 (1999) 8-14.
4. A.A. Korsheninnikov et al, Superheavy Hydrogen 5H, Phys. Rev. Lett. 87 (2001) 092501-1-4.
5. S.V. Stepantsov et al, 24.5 A MeV 6He + p Elastic and Inelastic Scattering, Phys. Lett. 542B (2002) 35-42.
6. M.S. Golovkov et al, Evidences for resonance states in 5H, Phys. Lett. B566 (2003) 70-75.
7. A.A. Yukhimchuk et al, Tritium target for research in exotic neutron-excess nuclei, Nucl. Inst. Methods A513 (2003) 439-447.
8. S.I. Sidorchuk et al, Resonance states of hydrogen nuclei 4H and 5H obtained in transfer reactions with exotic beams, Nucl. Phys. A719 (2003) 229c-232c.
9. A.A. Korsheninnikov et al, Experimental Evidence for the Existence of 7H and for a Specific Structure of 8He, Phys.Rev. 90, 082501 (2003).
10. G.V. Rogachev et al, T=5/2 states in 9Li: Isobaric analog states of 9He, Phys.Rev. C 67, 041603 (2003).
11. A.M. Rodin et al, Status of ACCULINNA beam line, Nucl. Instrum. Methods Phys. Res. B204 (2003) 114-118.
12. M.S. Golovkov et al, Estimates of the 7H width and lower decay energy limit, Phys. Lett. B588 (2004) 163-171.
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15. S.V. Stepantsov et al, 5H and 5He nuclear systems studied by means of the 6He + 2H reaction, Nucl.Phys. A738 (2004) 436.
16. M.S. Golovkov et al, Observation of excited States in 5H, Phys. Rev. Lett. 93 (2004) 262501-1 - 4.
17. M.S. Golovkov et al, Correlation studies of the 5H spectrum, Physical Review C 72, 064612 (2005).
18. G.M.Ter-Akopian et al, Neutron excess nuclei of hydrogen and helium at ACCULINNA, Eur.Phys.J. Special Topics 150, 61 (2007).
19. M.S. Golovkov et al, New insight into the low-energy 9He spectrum, Phys.Rev. C 76, 021605 (2007).
20. S.A. Krupko et al, Complete and incomplete fusion of 6He and 6Li projectiles with medium mass targets at energy ~10 AMeV, CP1098, FUSION08: New Aspects of Heavy Ion Collisions Near the Coulomb Barrier. AIP, 2009, P.245–250.
21. A.S. Fomichev et al, The ACCULINNA-2 Collaboration. Fragment separator ACCULINNA-2. Letter of Intent, JINR Comm., Dubna, 2008.
22. M.S. Golovkov et al, The 8He and 10He spectra studied in the (t,p) reaction, Physics Letters B 672 (2009) 22–29.
23. L.V. Grigorenko et al, Soft dipole mode in 8He, Physics of Elementary Particles and Atomic Nuclei, Volume 40 (2009).
24. S.I. Sidorchuk et al, Study of the 6He structure in the reaction of quasifree scattering 4He(6He,2α). Nucl. Phys. A840 (2010) 1–18.
25. S. Mianowski et al, Imaging the decay of the 8He*. Acta Physica Polonica B, Vol. 41, p.449-456, 2010.
26. E.Yu. Nikolskii et al, Search for 7H in 2H+8He collisions. Physsical Review C 81, 064606 (2010).
27. A.S. Fomichev et al, Life time of 26S and a limit for its 2p decay energy. Int. Journal of Modern Phys. E Vol. 20, (2011) 1491–1508.
28. R.S. Slepnev et al, VME based data acquisition system for ACCULINNA fragment separator. E10, 11-2011-133, JINR, Dubna, 2011.
29. A.S. Fomichev et al, Isovector soft dipole mode in 6Be. Physics Letters B 708 (2012) 6-13.
30. S.I. Sidorchuk et al, Structure of 10He low-lying states uncovered by correlations. Physical Review Letters 108, 202502 (2012).

4n, ^{4,5,7}H, ^{5,6,7,8,9,10}He

^{6}Li, ^{6}Be, ^{17}Ne, ^{26,27}S

http://aculina.jinr.ru/publications.htm

STUDY OF COMPLETE AND INCOMPLETE FUSION FOR LOSELY BOUND PROJECTILES ^{6}He AND ^{6}Li ON ^{165}Ho AND ^{166}Er TARGETS

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[a] Flerov Laboratory of Nuclear rea

[b] The Henryk Niewodniczanski In

[c] CSNSM, IN2P3-CNRS, UMR86

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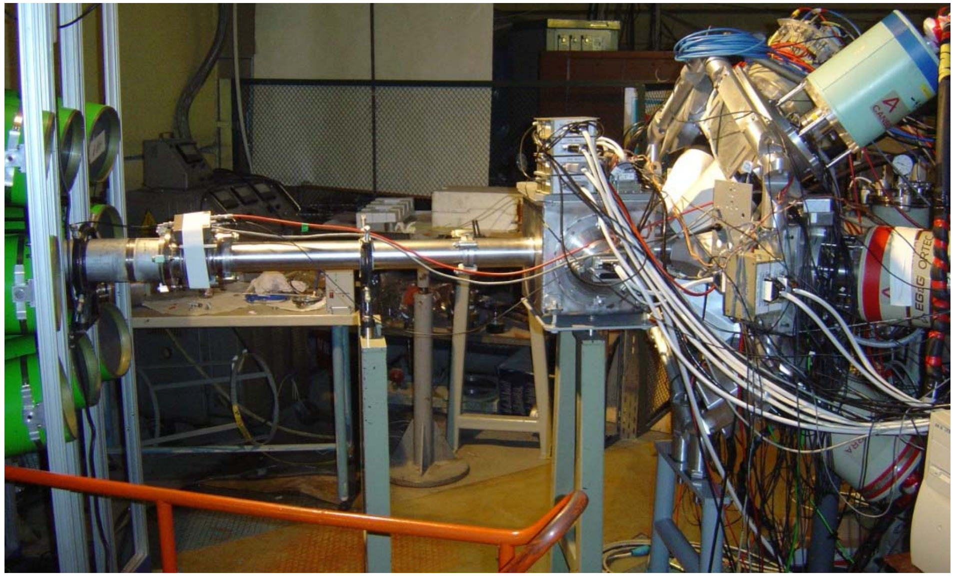
$$^{6}\mathrm{He} + {}^{166}\mathrm{Er} \rightarrow {}^{172}\mathrm{Yb}^{*} \rightarrow {}^{166}\mathrm{Yb} + 6n \quad \mathrm{(CF)}$$
$$\rightarrow {}^{170}\mathrm{Yb}^{*} + 2n \rightarrow {}^{166}\mathrm{Yb} + 4n \quad \mathrm{(ICF)}$$
$$\rightarrow {}^{168}\mathrm{Er}^{*} + \alpha \quad \mathrm{(ICF)}$$

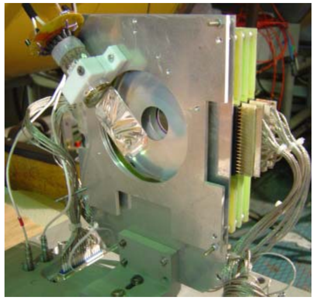
$$^{6}\mathrm{Li} + {}^{165}\mathrm{Ho} \rightarrow {}^{171}\mathrm{Yb}^{*} \rightarrow {}^{166}\mathrm{Yb} + 5n$$
$$\rightarrow {}^{169}\mathrm{Tm}^{*} + d$$
$$\rightarrow {}^{167}\mathrm{Er}^{*} + \alpha$$

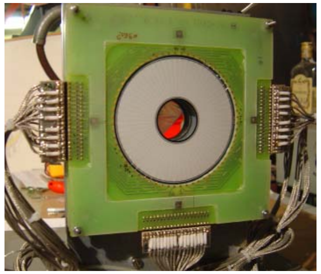
$$^{6}\mathrm{Li} + {}^{166}\mathrm{Er} \rightarrow {}^{170}\mathrm{Yb}^{*} + d \rightarrow {}^{166}\mathrm{Yb} + d4n$$
$$\rightarrow {}^{168}\mathrm{Tm}^{*} + \alpha$$
$$\rightarrow {}^{172}\mathrm{Lu}^{*} \rightarrow {}^{166}\mathrm{Yb} + p5n$$

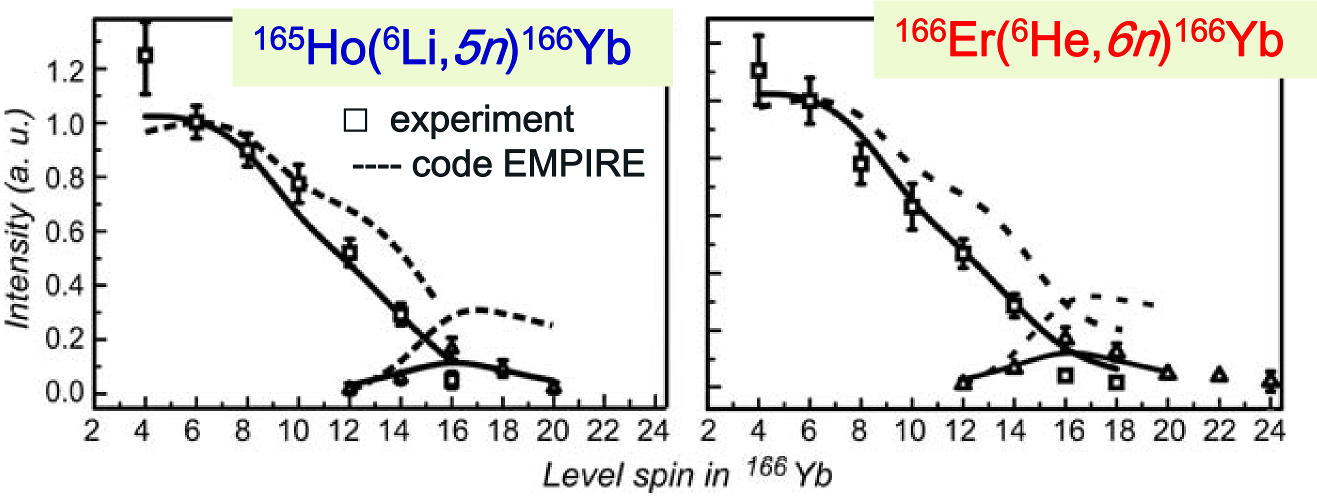
Complete fusion (CF) and incomplete fusion (ICF) re loosely bound ^{6}He and ^{6}Li projectiles bombarding ^{166}Er and MeV/nucleon. Experiments were carried out to test an approach exploiting the measured intensities of γ rays emitted at the transitions between the yrast-band levels of reaction products formed after the termination of neutron evaporation. Partial waves feeding the CF reactions ^{165}Ho(^{6}Li,5n)^{166}Yb and ^{166}Er(^{6}He,6n)^{166}Yb as well as ICF ^{165}Ho(^{6}Li,α3n)^{164}Er and ^{166}Er(^{6}He,α4n)^{164}Er reaction channels were revealed from the obtained γ-ray data. The method of exit channel identification via the triple coincidence (γ1–γ2–light charged particle) was employed for these reactions study.

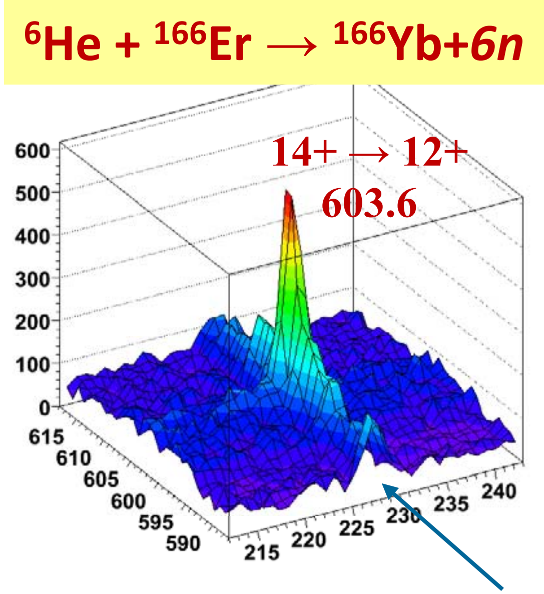
Physics of Particles and Nuclei Letters , V9, N5 (2012) 806-813

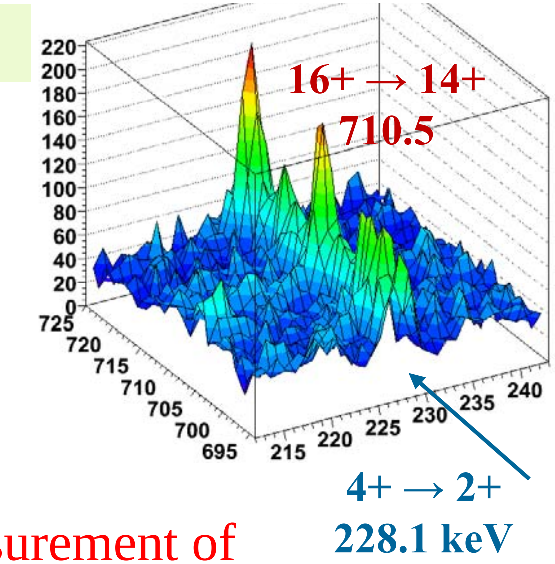








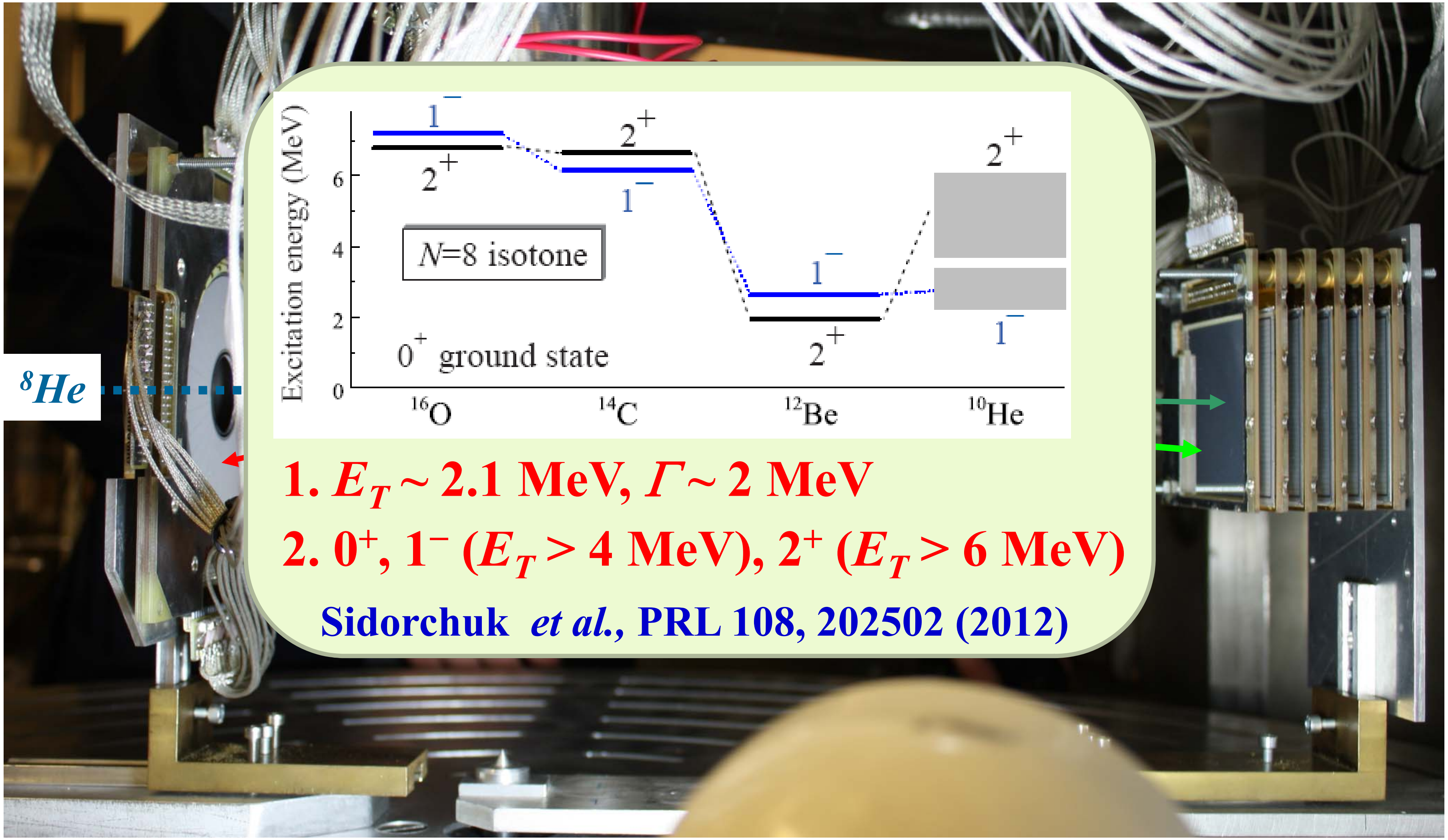




- Kinematically complete experiments including the measurement of gammas, neutrons and light charged particles were carried out
- This approach gives access to the partial wave distributions between the complete fusion and incomplete fusion reaction channels

^{10}He low-lying states structure uncovered by correlations

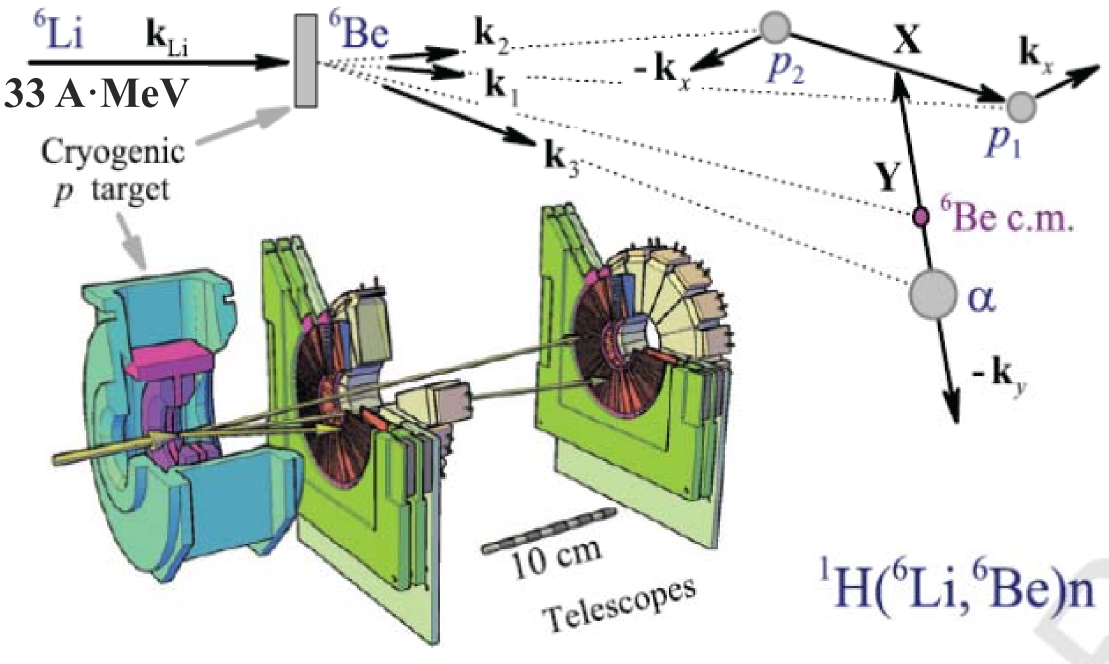
- ☞ ^{8}He beam: E= 23 A·MeV , I~1.5x10^{4} s^{-1} , 3 weeks exposition
- ☞ Tritium target: P=0.92 Atm, T=26K, Enrichment 99.7 %
- ☞ Zero degree geometry & kinematically complete measurements θ_{cm}=0-180°

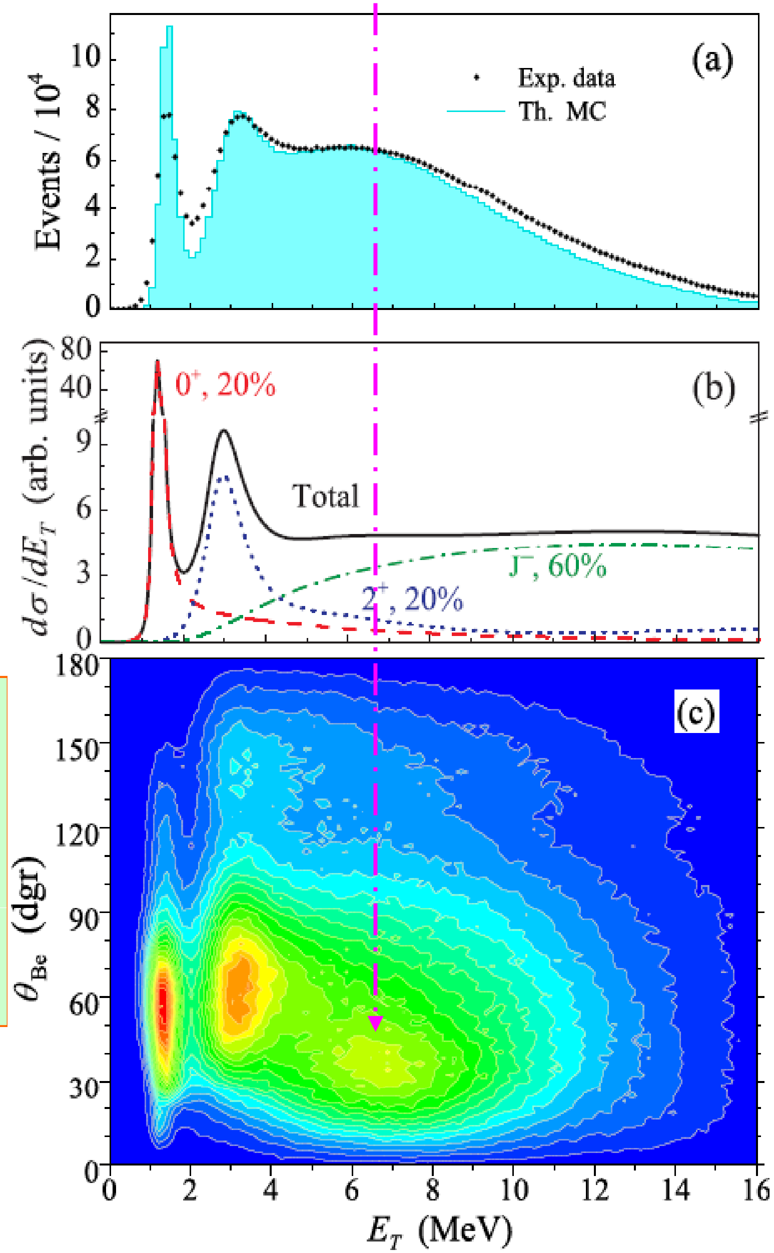


1. $E_T \sim 2.1$ MeV, $\Gamma \sim 2$ MeV
2. 0^+, 1^- ($E_T > 4$ MeV), 2^+ ($E_T > 6$ MeV)

Sidorchuk *et al.*, PRL 108, 202502 (2012)

^{6}Be: Isovector soft dipole mode (IVSDM)



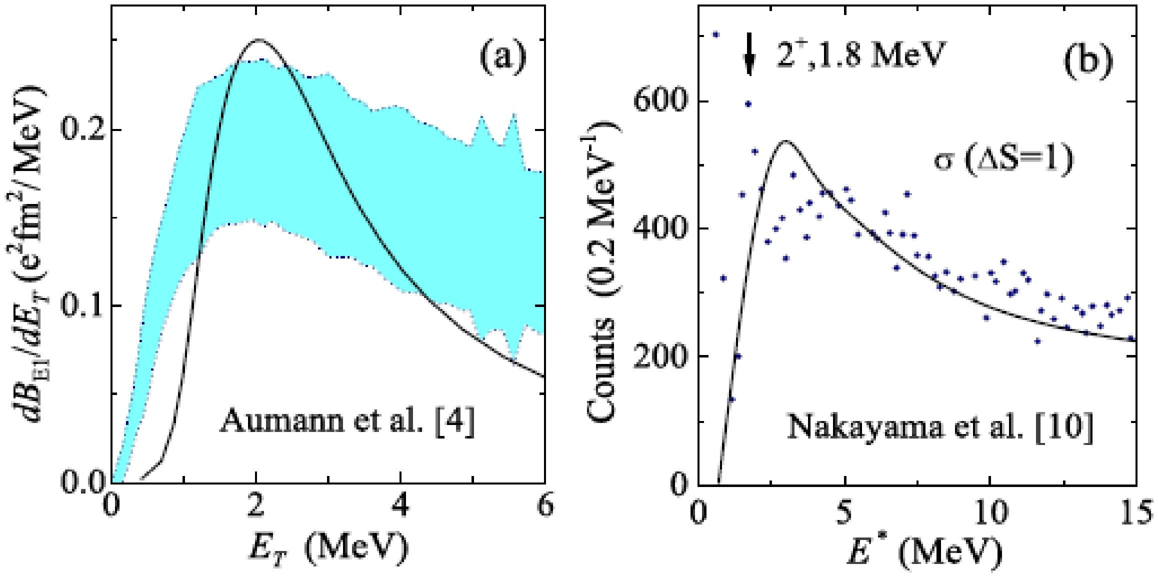


Experimental setup and kinematical diagram. ↑↑

Experimental energy spectrum of ^{6}Be (solid curve) and MC simulation (filled histogram) **(a)**. Theoretical input for MC simulation **(b)**. Contour plot of the spectrum in the (E_T, θ_{Be}) plane **(c)**. →

☻ High statistics (~10^7 events) and kinematically complete measurements by detecting α+*p*+*p* coincidences were obtained.

IVSDM in charge-exchange reactions



a) - Qualitative comparison of SDM calculations with ^{6}He data [T.Aumann, EPJ A26 (2005) 441]

b) - IVSDM calculations with ^{6}He data [S.Nakayama *et al.*, PRL 85 (2000) 262; ^{6}Li(^{7}Li, ^{7}Be)^{6}He]

There are several important issues:

☺ **The detailed correlation information about ^{6}Be 0+ g.s. at E_T = 1.37 MeV and the 2+ state at E_T = 3.05 MeV is extracted.**

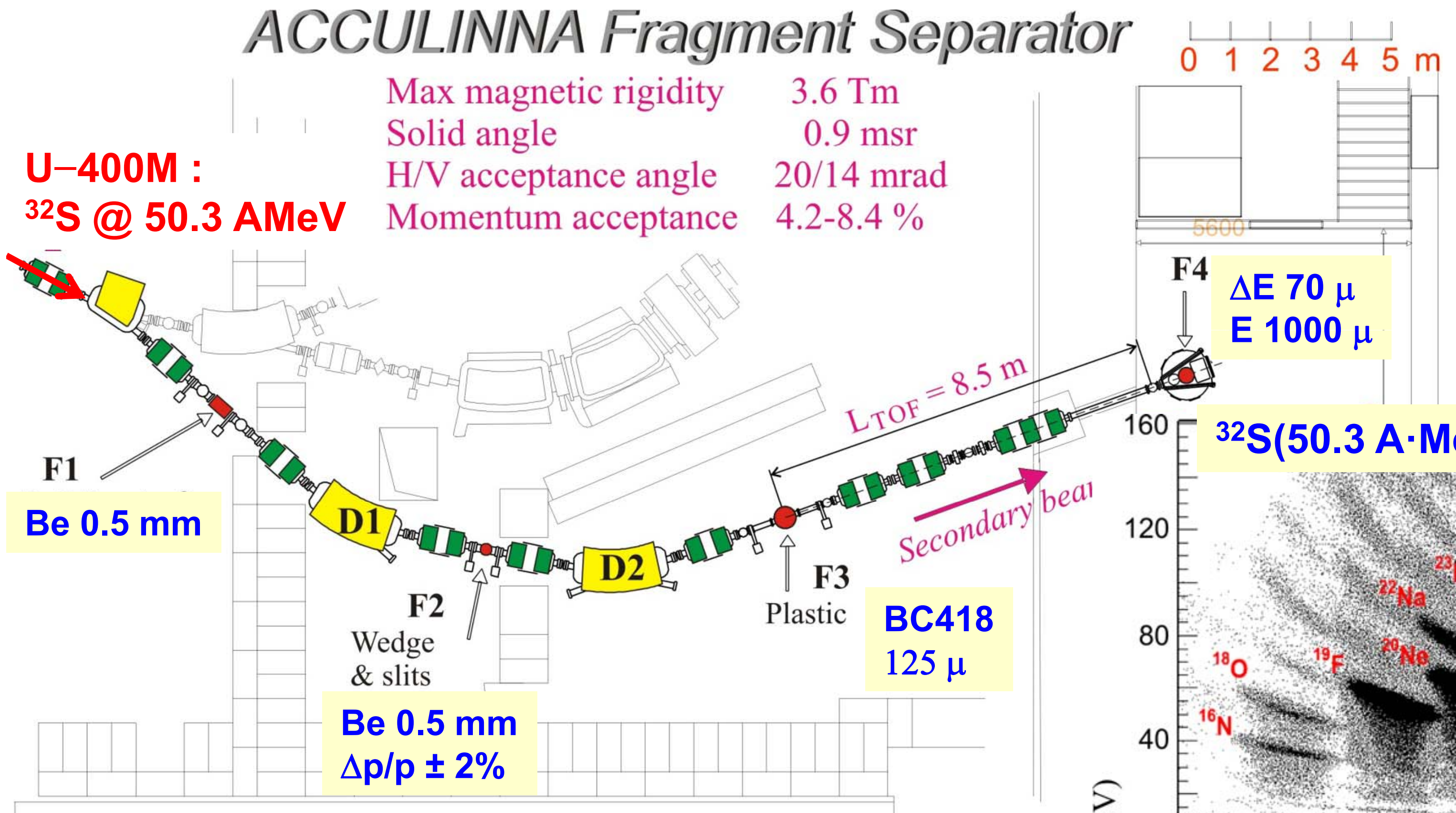
☺☺ **A broad structure extending from 4 to 16 MeV contains negative parity states (populated by Δ*L* = 1 angular momentum transfer).**

The continuum structure can be interpreted as a novel phenomenon:

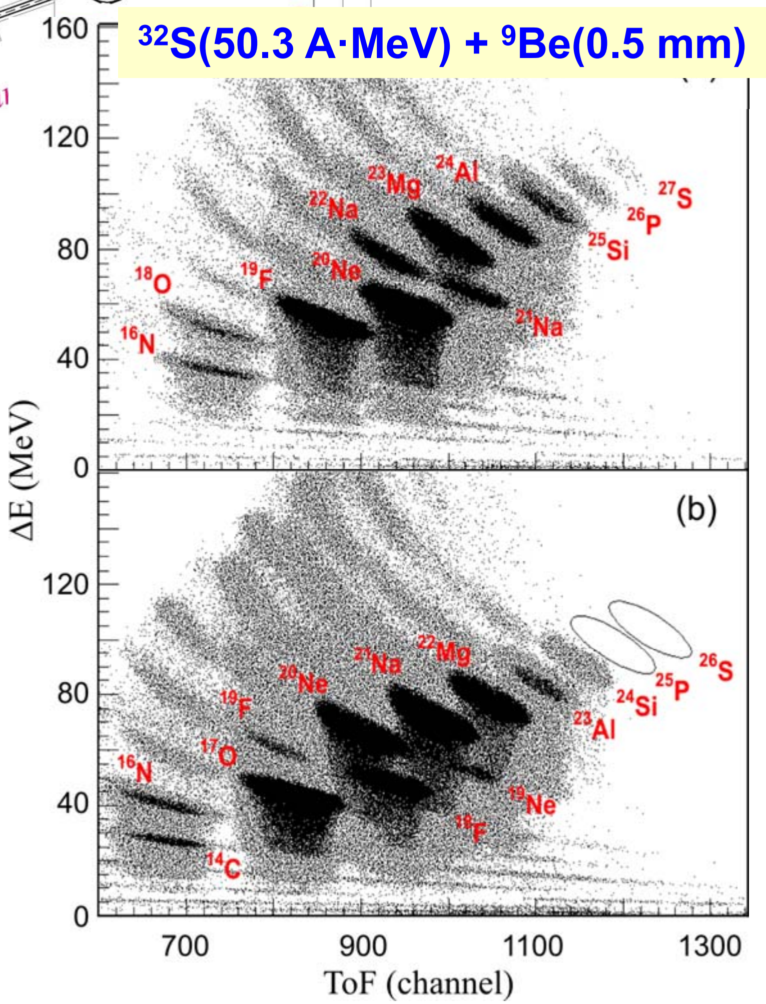
the isovector soft dipole mode associated with the ^{6}Li ground state

☻ ☻ **Our calculations provide very reasonable and consistent description of the three different sets of data: SDM in ^{6}He, IVSDM in ^{6}He and ^{6}Be branches.**

Fomichev et al. **Physics Letters B 708 (2012) 6-13.**



^{26}S: $T_{1/2}$-?



NNDC: $T_{1/2}$ ~ 10 ms

Acculinna: $ToF_{F1\text{-}F4}$ ~ 0.0003 ms

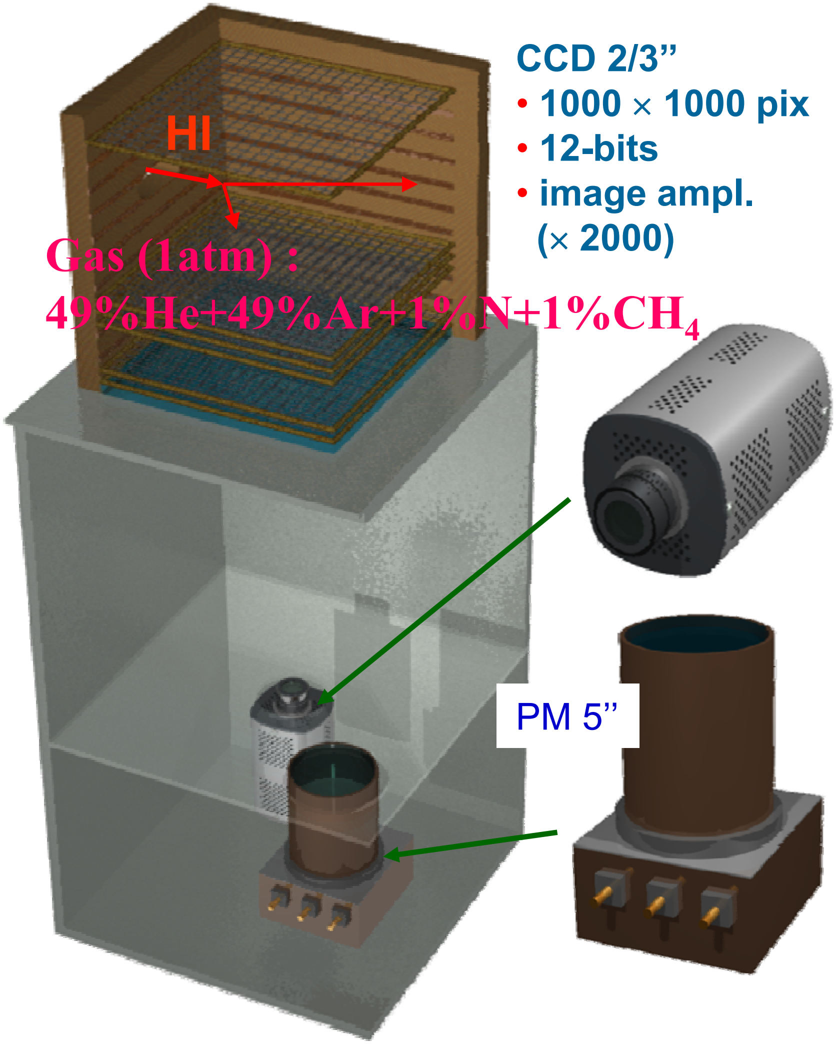
Experiment:

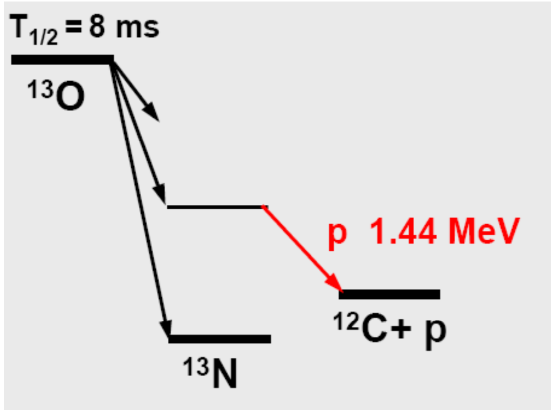
$T_{1/2} < 79$ ns, $Q_{2p} > 640$ keV

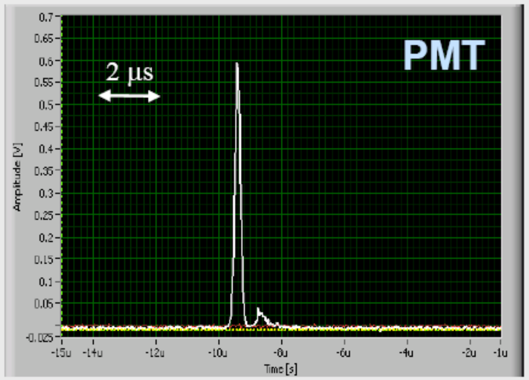
Fomichev A.S. et al., IJMP E20 (2011) 1491

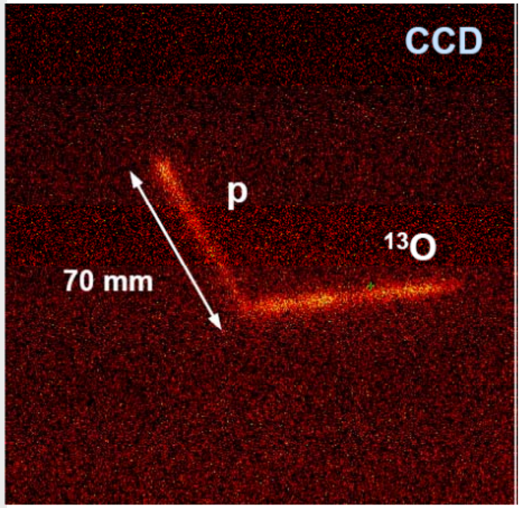
Optical Time Projection Chamber (OTPC) is an effective tool for the study of rare decay modes of exotic nuclei

$T_{1/2}$: 1-500 ms









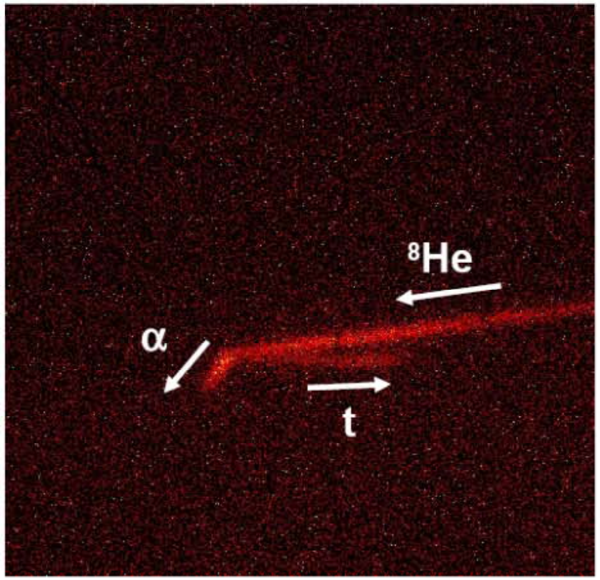
^{43}Cr, ^{45}Fe, ^{48}Ni @ MSU

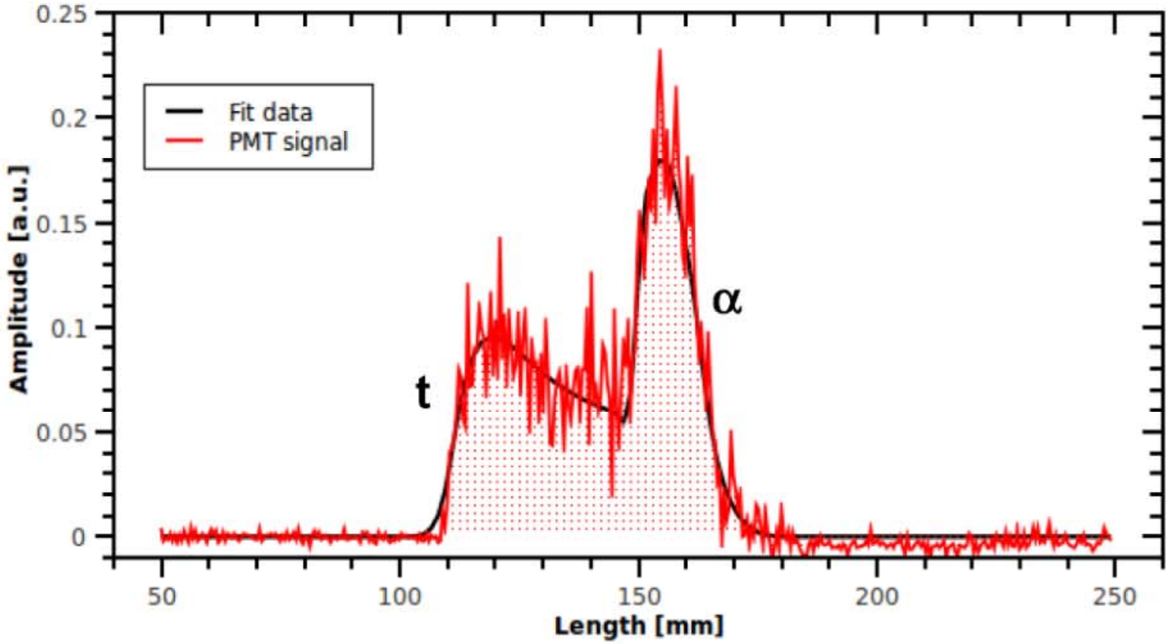
^{8}He, ^{14}Be, ^{27}S, tests @ FLNR

M. Ćwiok et al., IEEE TNS, 52 (2005) 2895

K. Miernik et al., NIM A581 (2007) 194

$^{8}He \rightarrow {}^{8}Li^{*}$: decay via $\alpha + t + n$, $^{7}Li + n$, $^{6}He + d$





Full kinematics

α:	t:	n:
L = (21 ± 2) mm	L = (66 ± 3) mm	E = (2.24 ± 0.30) MeV
E = (900 ± 50) keV	E = (1100 ± 50) keV	
Θ = (44 ± 8)°	Θ = (128 ± 8)°	Q = (4.24 ± 0.34) MeV
φ = (236 ± 5)°	φ = (3 ± 5)°	

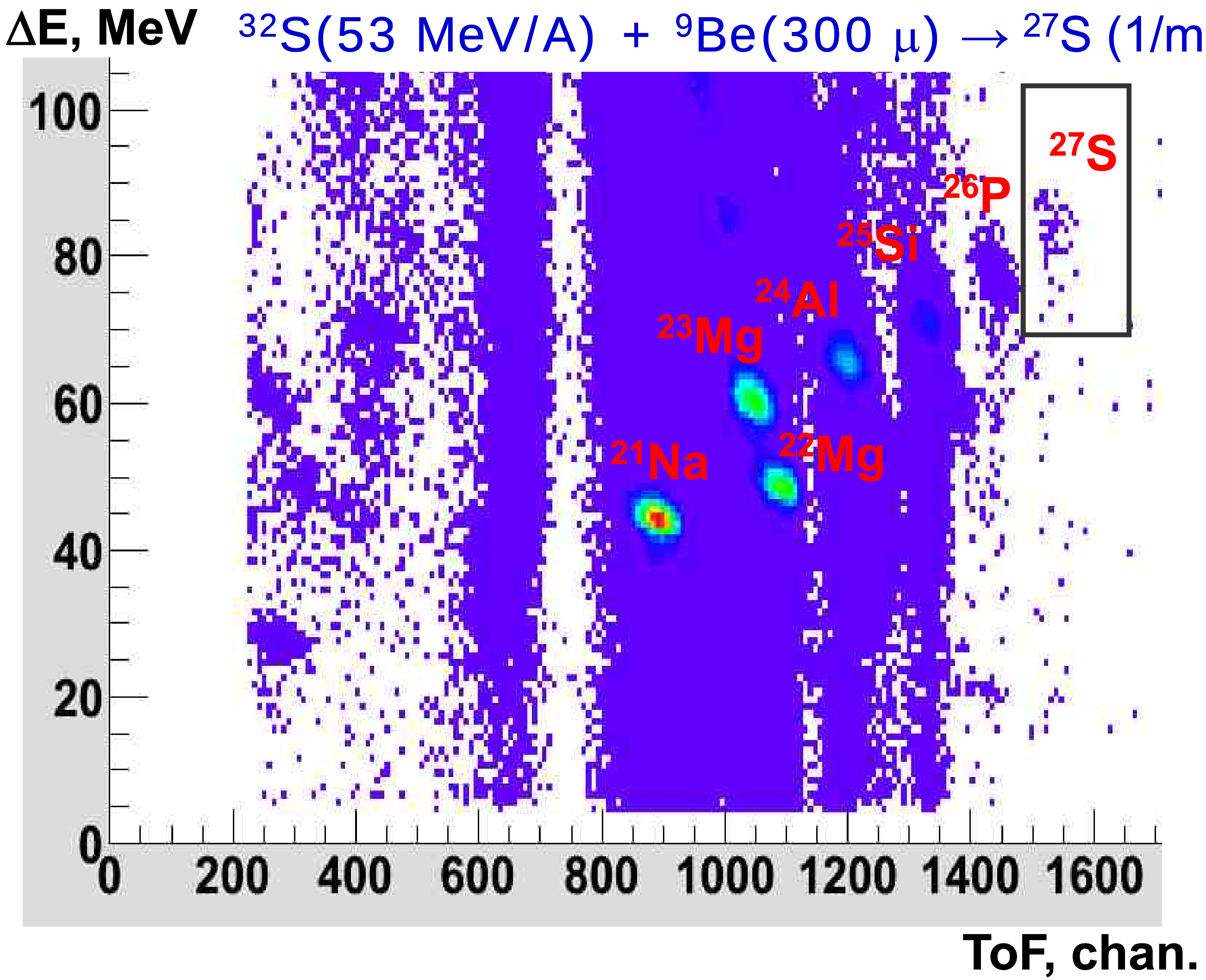
⇒ *New information about the mechanism of rare decays and the structure of exotic nucleus*

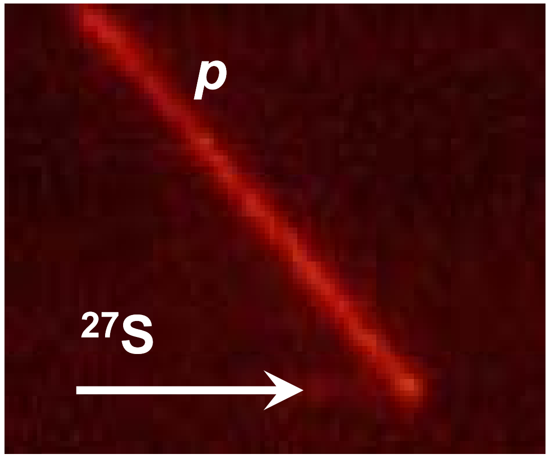
S. Mianowski et al., Acta Phys. Pol. B 41 (2010) 449

^{27}S study: β2p, β3p branch ratio search via OTPC

EPJ A12 (2001) 377: $T_{1/2}(^{27}S)$=15.5 ms; P(βp)=2.3%; P(β2p)=1.1%

^{32}S(53 MeV/A) + ^{9}Be(300 μ) → ^{27}S (1/min)





Analysis in progress

More statistics and better beam quality are obviously need (I_{27S}/I_{tot} ~ 0.02%)

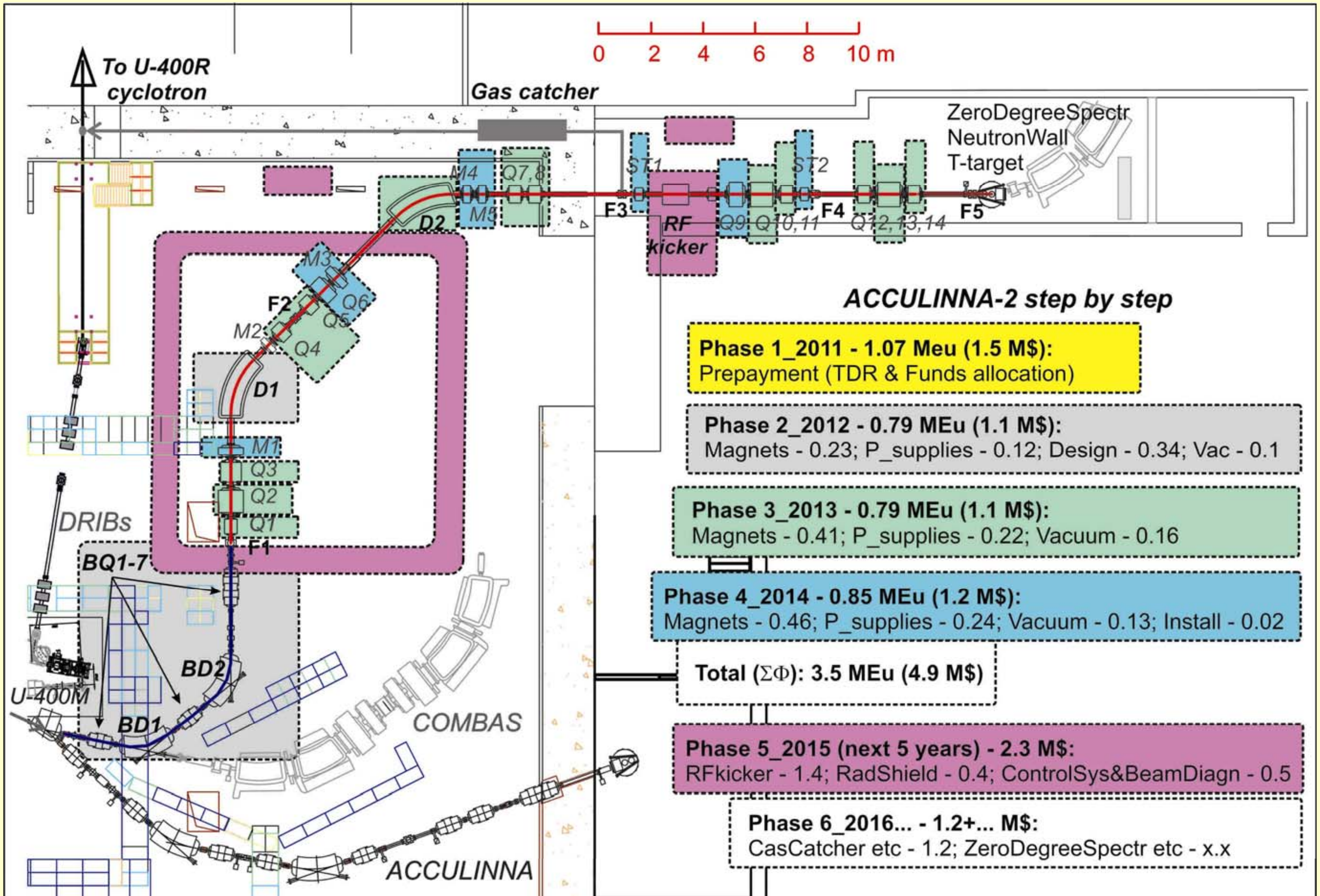
Acc-2 will provide a factor ~ 100 !!

Estimations for Acculinna-2 RIBs

HI	I, pμA	E, A·MeV	RIB	E, A·MeV	I, pps/pμA	Purity, %
^{7}Li	5	34	^{6}He	21.7	4.1×10^{7}	99
			^{6}He	6	2.1×10^{5}	99
			^{7}Be	22.4	5.9×10^{5}	70
^{11}B	5	33	^{8}He	21.9	8.6×10^{4}	99
			^{8}He	15.6	3.7×10^{4}	99
			^{8}B	15.8	2.2×10^{6}	28
^{15}N	2 => 5	47	^{11}Li	33.2	7.2×10^{3}	99
^{18}O	1.5 => 3	48	^{11}Li	31.3	7.4×10^{3}	81
			^{14}Be	34.6	1.6×10^{3}	99
			^{15}B	32.1	4.3×10^{5}	97
			^{16}C	28.8	2.8×10^{7}	99
^{20}Ne	1.5 => 5	54	^{13}O	24.2	1.5×10^{6}	10
			^{14}O	22.8	3.4×10^{7}	54
			^{17}Ne	29.0	5.4×10^{6}	69 vs 0.5
^{36}S	0.1 => 3	49	^{24}O	23.4	2.5×10^{3}	62
			^{14}Be	29.2	3.8×10^{3}	67
			^{17}C	25.0	1.1×10^{5}	78
			^{18}C	25.5	1.9×10^{4}	11
^{32}S	0.1 => 3	52	^{24}Si	11.3	7.2×10^{3}	31
			^{27}S	21.7	3.7×10^{2}	2 vs 0.02

Key stones for Acc2: acceptance, length, RF-kicker and HI RIBs

Scheme of ACCULINNA-2 setup at the existing building



In accordance with the Contract JINR – SigmaPhi № 500/1535 dated on 28.09.2011

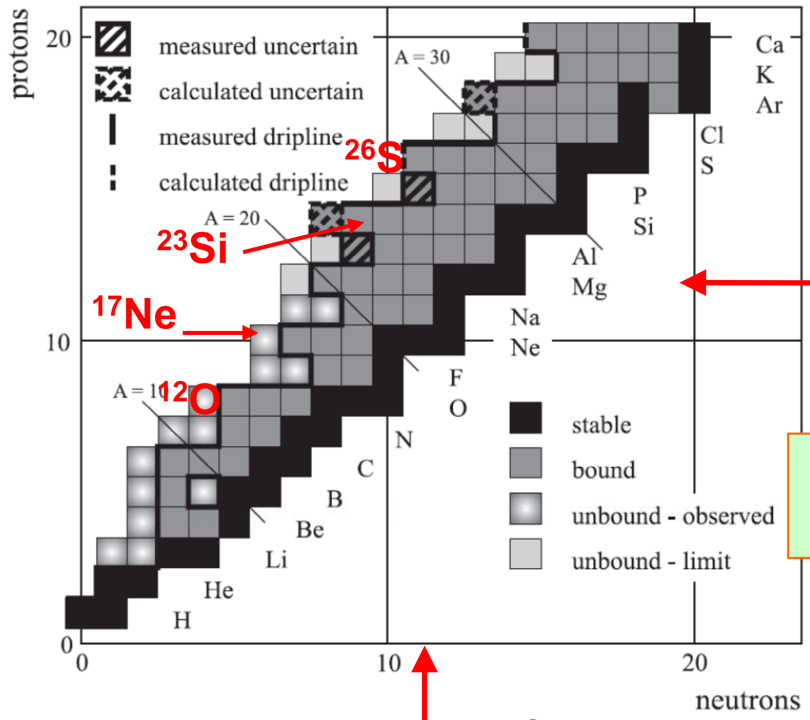
Characteristics of existing and new in–flight RIB separators

(ΔΩ and Δp/p are angular and momentum acceptances, Rp/Δp is the first-order momentum resolution when 1 mm object size is assumed)

	ACC / ACC-2 FLNR JINR	RIPS / BigRIBS RIKEN	A1900 MSU	FRS / SuperFRS GSI	LISE3 GANIL
ΔΩ, msr	0.9 / 5.8	5.0 / 8.0	8.0	0.32 / 5.0	1.0
Δp/p, %	± 2.5 / ± 3.0	± 3.0 / 6.0	± 5.5	± 2.0 / 5.0	± 5.0
Rp/Δp	1000 / 2000	1500 / 3300	2915	8600 / 3050	2200
Bρ, Tm	3.2 / 3.9	5.76 / 9.0	6.0	18 / 18	3.2 - 4.3
Length, m	21 / 38	27 / 77	35	74 / 140	19(42)
E, AMeV	10÷40 / 6÷60	50÷90 / 350	110÷160	220÷1000/1500	40÷80
Additional RIB Filter	No / RF-kicker	RF-kicker / S-form	S-form & RF- kicker	S-form	Wien Filter

ACCULINNA-2 will looks like improved RIPS operating at low energy domain E_{RIB}~6-60 AMeV and with Z_{RIB}=1-36

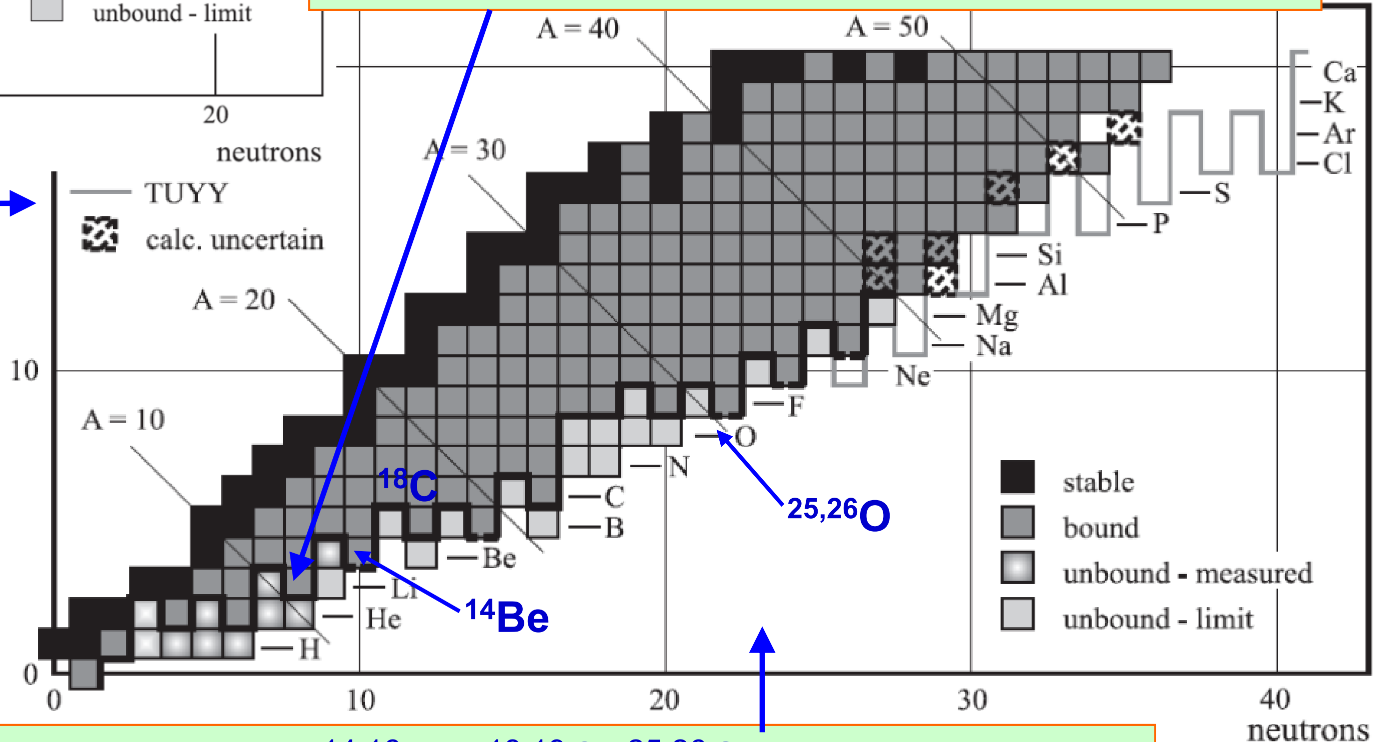
Road map for DRIBs-III



one, two and three proton decays of ^{12}O, ^{16,17}Ne, ^{26,27}S using the modern technique (OTPC, vertex method, zero-degree geometry etc)

Reactions of complete and incomplete fusion near Coulomb barrier; fusion-fission etc.

Exotic branches of beta-decay for neutron and proton reach nuclei in vicinity of the drip lines (^{8}He, ^{11}Li, ^{23}Si etc)



structure of neutron rich nuclei ^{14,16}Be, ^{18,19}C, ^{25,26}O etc with the use of cryogenic tritium target and ^{36}S & ^{48}Ca intensive primary beams

The start up research program beginning 2015

1. **Neutron haloes.**
Detailed study of the excitation spectra of ^{13}Be, ^{14}Be, ^{16}Be and heavy carbon nuclei ^{19}C, ^{20}C, ^{21}C via transfer reactions in complete kinematic measurements.

2. **Nuclei close to the doubly magic ^{24}O.**
Transfer reactions (t,p), (d,p), (p,^{2}He), (d,^{3}He) and charge-exchange reactions (d,2p), (t,^{3}He) are suitable for these experiments. The required RIBs ($^{21-24}$O and ^{26}F) with 1×10^{3} – 3×10^{5} s^{-1} will provide the measurements of resonant states for the ^{24}O, ^{25}O and ^{26}O isotopes.

3. **Proton drip-line nuclei in vicinity of atomic numbers Z = 10 – 20.**
No dedicated search has been performed yet for the neighbor nuclei with even Z: ^{21}Mg, ^{26}S, ^{30}Ar and ^{34}Ca.
The rp-process waiting point associated with the magic ^{15}O nucleus calls for the importance of a measurement of the ^{15}O(α,γ) reaction rate. The two-proton capture processes namely, the ^{15}O(2p,γ)^{17}Ne(3/2−) was underestimated by several orders of magnitude in the treatment of the rp-process waiting points.

4. **Complete and incomplete fusion reactions and fusion-fission near B_C**
^{6,8}He, ^{9}Li, ^{12}Be (5-7 AMeV) + Ho, Au, Pb, Bi, U

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Welcome for collaboration ! Thanks for attention !!