Opportunities for PARIS @ FLNR JINR Dubna

Yuri Penionzhkevich, Yuri Sobolev, Flerov Laboratory JINR Dubna

FLNR's basic directions of research:

- **Heavy and superheavy nuclei**
- **Light exotic nuclei**
- **Radiation effects and physical groundwork of nanotechnology**
- **Accelerator technologies**

U-400 ACCELERATOR COMPLEX

NUCLEAR SPECTROSCOPY AND REACTION'S MECHANISMS

Commissioned: 1978
Modernized: 1996
Reconstruction: 2020-2023 (plan)

Tasks:

Stand-alone mode:
- Synthesis of superheavy elements (SHE)
- Chemistry of SHE
- Nuclear & laser spectroscopy
- Nuclear reactions: fusion, fusion-fission & quasi-fission, multi-nucleon transfer reactions
- Applied research

Post-accelerator mode:
- Reactions with exotic nuclei
- Structure of light exotic nuclei

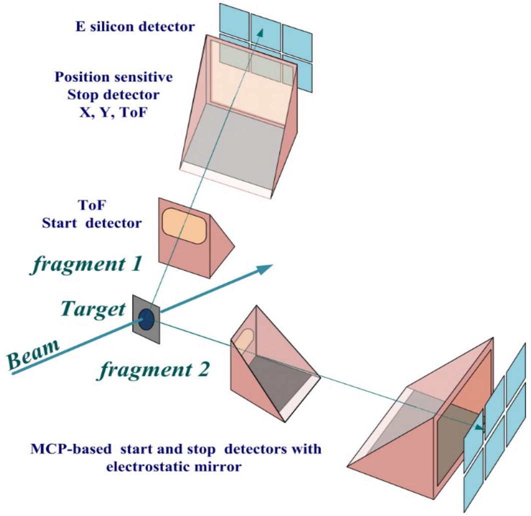
Ion	Ion energies [MeV/A]	Output intensity [pps]
16O2+	5.7; 7.9	3×1013
18O3+	7.8; 10.5; 15.8	2.6×1013
40Ar4+	3.8; 5.1	1×1013
48Ca5+	3.7; 5.3	7.2×1012
48Ca9+	8.9; 11; 17.7	6×1012
50Ti5+	3.6; 5.1	2.4×1012
58Fe6+	3.8; 5.4	4.2×1012
84Kr8+	3.1; 4.4	1.8×1012
136Xe14+	3.3; 4.6; 6.9	4.8×1011
160Gd19+	5.5	6×1010
209Bi19+	3.4	6×1010

Main parameters	
Energy range	3÷21 MeV/A
K factor max.	650
Pole diameter	4 m
Magnet weight	2100 t
Magnet power	850 kW
Vacuum	10-7 Torr

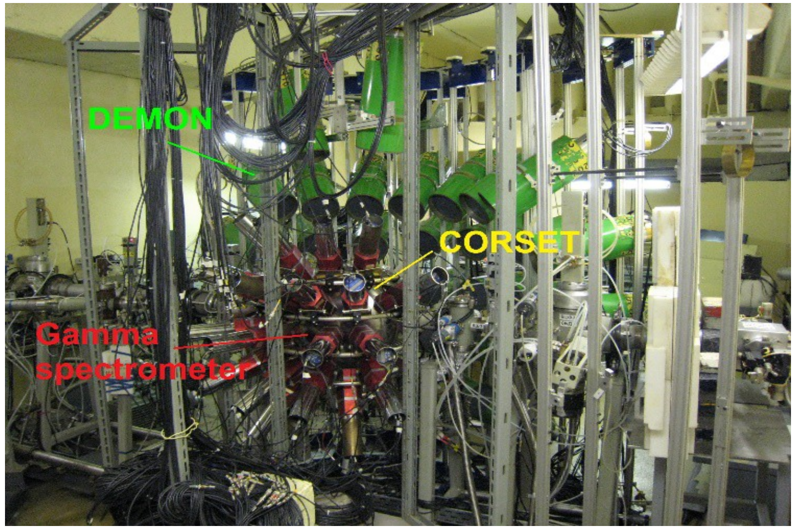
…etups:
- …GFRS-I)
- …Spectroscopy (SHELS)
- Radio-chemical setups
- Double-arm time-of-flight spectrometer (CORSET)
- Magnetic Analyzer of High Resolution (MAVR)

DOUBLE-ARM TIME-OF-FLIGHT SPECTROMETER (CORSET)

Study of the mechanisms of heavy-ion-induced reactions (fusion-fission, quasifission and deep inelastic processes)

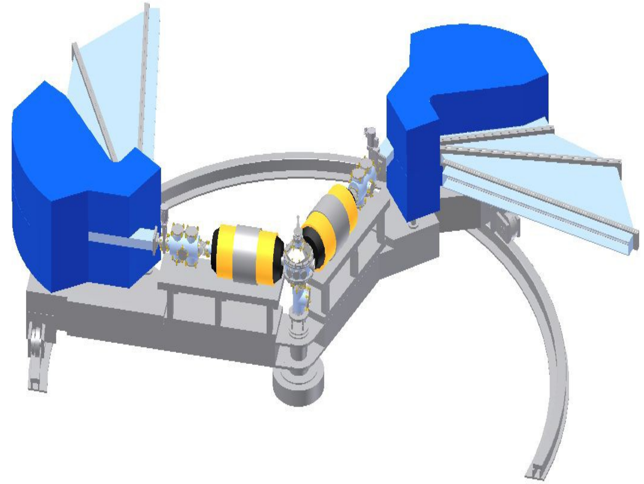


Time resolution	150-180 ps
ToF base	10-30 cm
ToF arm rotation range	15°-165°
Solid angle	100 -200 msr
Angular resolution	0.3°
Mass resolution	2-4 u
Energy resolution	1%



MAGNETIC ANALYZER OF HIGH RESOLUTION (MAVR)

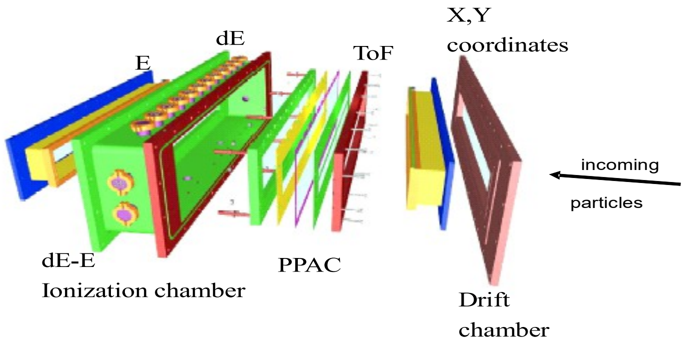
Configuration: QQDD



Main parameters

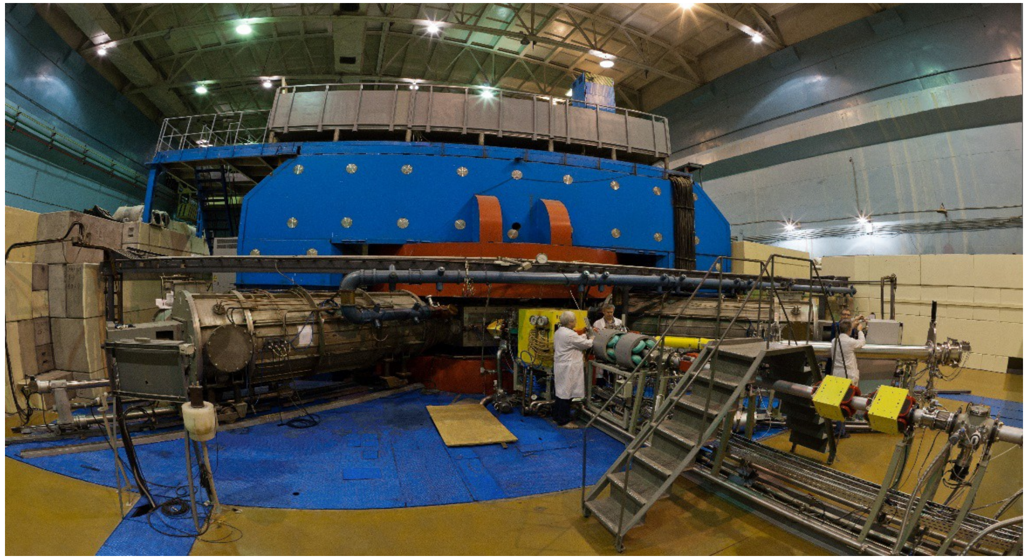
dispersion in the focal plane	1.9 cm/%
$\Delta p/p$	10 %
$B\rho$	1.5 Tm
Solid angle	30 msr
Energy resolution $\Delta E/E$	5 10-4

Focal plane detector system



separation, detection and identification of nuclear reaction products in wide range of masses (5÷150) and charges (1÷60)

U-400M ACCELERATOR COMPLEX



Commissioned: 1991
Modernized: 1996
Reconstruction: 2019 (plan)

Tasks:

Stand-alone mode:

- Properties and structure of light exotic nuclei
- Reactions with exotic nuclei
- Decay properties of nuclei at drip lines
- Mass & laser spectroscopy of heavy nuclei
- Applied research

Driving accelerator mode:

- Production of beams of radioactive nuclei

Main parameters	
Energy range	5÷10 & 25÷55 MeV/A
K factor max.	550
Pole diameter	4 m
Magnet weight	2300 t
Magnet power	1000 kW
Vacuum	10-7 Torr

Beams (examples)

Beam	E [MeV/A]	Output intensity [pps]
7Li	**35**	**6×1013**
11B	**32**	**4×1012**
15N	**50**	**2×1012**
40Ar	40	1×1012
84Kr	27	2×1010
132Xe	25	1×109
48Ca	4.5-9	3×1012
84Kr	4.5-9	1×1011
132Xe	4.5-9	1×1010
209Bi	4.5-9	1×1010

Experimental setups (high-energy mode):

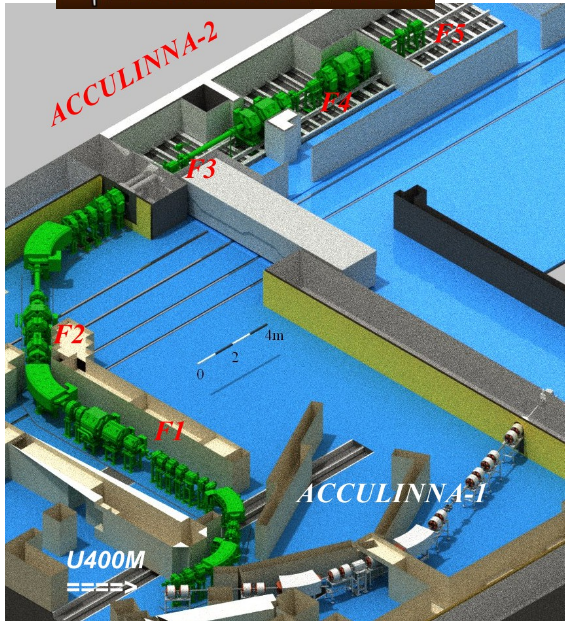
- ACCULINNA-1 fragment separator
- ACCULINNA-2 fragment separator
- COMBAS fragment separator

Experimental setups (low-energy mode):

- Mass Analyzer of SuperHeavy Atoms (MASHA)
- Gas-cell based Laser ionization Setup (GaLS)
- Correlation setup for the reaction products registration (CORSAR)

FRAGMENT SEPARATORS ACCULINNA-I, II

Experiments with radioactive beams with Z≤36

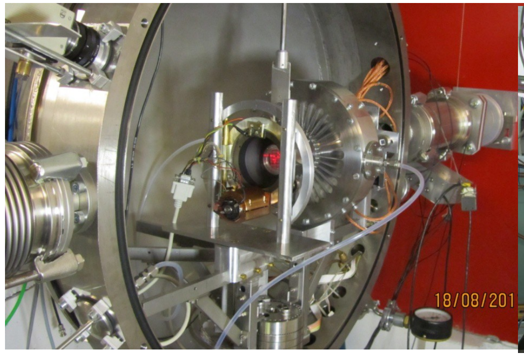


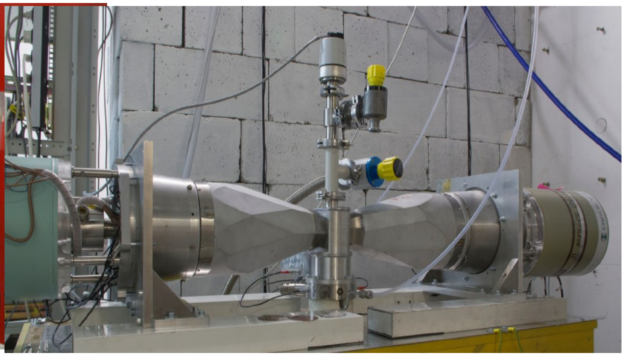
http://aculina.jinr.ru/acc-2.php

RIB*	Intensity, pps (at 1 pμA)	Energy, MeV/A
6He	4x107	22
6He	1x107	13
8He	8x104	23
11Li	7x103	33
14Be	2x103	35
15B	4x105	32
16C	2x107	29
18C	1x104	25
24O	2x103	23
8B	2x106	16
13O	1x106	24
17Ne	2x106	30
24Si	7x103	12
28S	1x103	38

* - expected RIB's characteristics at ACCULINNA-2; RIB's intensities for ACCULINNA-1 are lower by factor of ~20.

CORRELATION SETUP FOR THE REACTION PRODUCTS REGISTRATION (CORSAR)





Main parameters	
transportation of reaction products	aerosol jet and magnetic tape
cross section limit	10 μb
half-life limit	5 sec
registration	β-γ-γ coincidence method

Purpose:
identification and investigation of the properties of neutron-rich heavy nuclei in the region of nuclei near *N* = 126

FRAGMENT SEPARATOR COMBAS

Main parameters

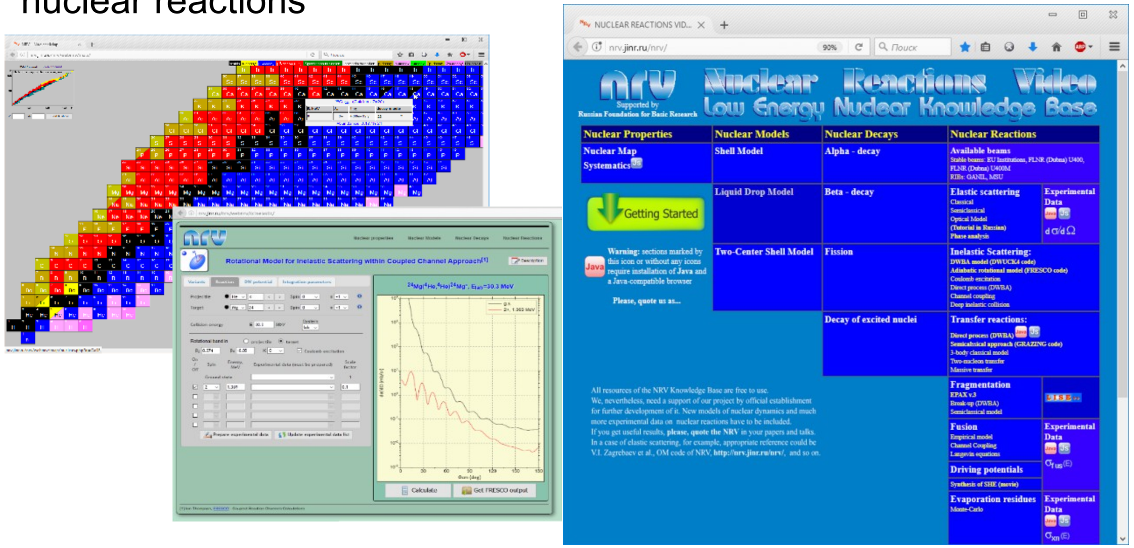
Bρmax, Tm	4.5
Solid angle(maximum), msr	6.4
Momentum acceptance (maximum), %	20
Momentum dispersion (in the linear approximation), cm/%	1.53
Momentum resolution, FWHM	4360
Full length of the channel, m	14.5

KNOWLEDGE BASE ON LOW-ENERGY NUCLEAR PHYSICS

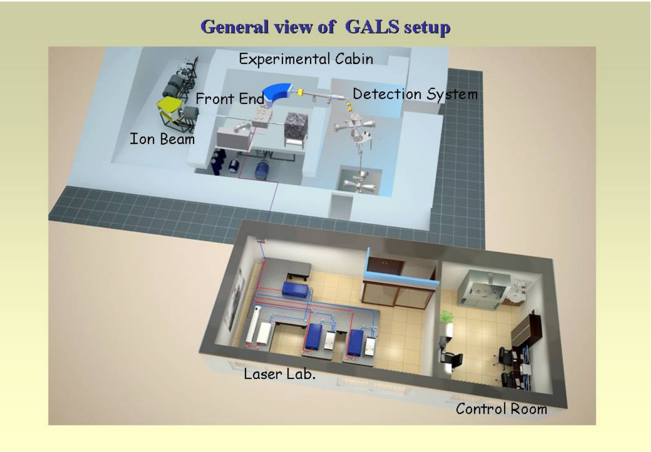
http://nrv.jinr.ru

Unified system of:

- Numerous modern algorithms of nuclear dynamics;
- Databases on nuclear properties and cross sections of nuclear reactions



GAS-CELL BASED LASER IONIZATION SETUP (GaLS)



synthesis and study of properties of heavy neutron-rich nuclei produced in multinucleon transfer reactions

Laser system specifications:

Type	Output power Main&harmonic, W, (2nd),{3rd, 4th}	Puls frequency, Hz	Puls length, ns	Wave length, nm
Dye laser	**3, (0.3)**	**104**	**10-30**	**213-850**
Ti:Sapphir	*2, (0.2), {0.04}*	*104*	*30-50*	*680-960*
Nd-YAG	**(80-100), {20-40}**	**104**	**10-50**	**532**
Matisse system				
Ring dye	0.8-6	cw	cw	540-900
Ti:Sapphir	0.8-6.5	cw	cw	700-1000

Mass-separator specifications:

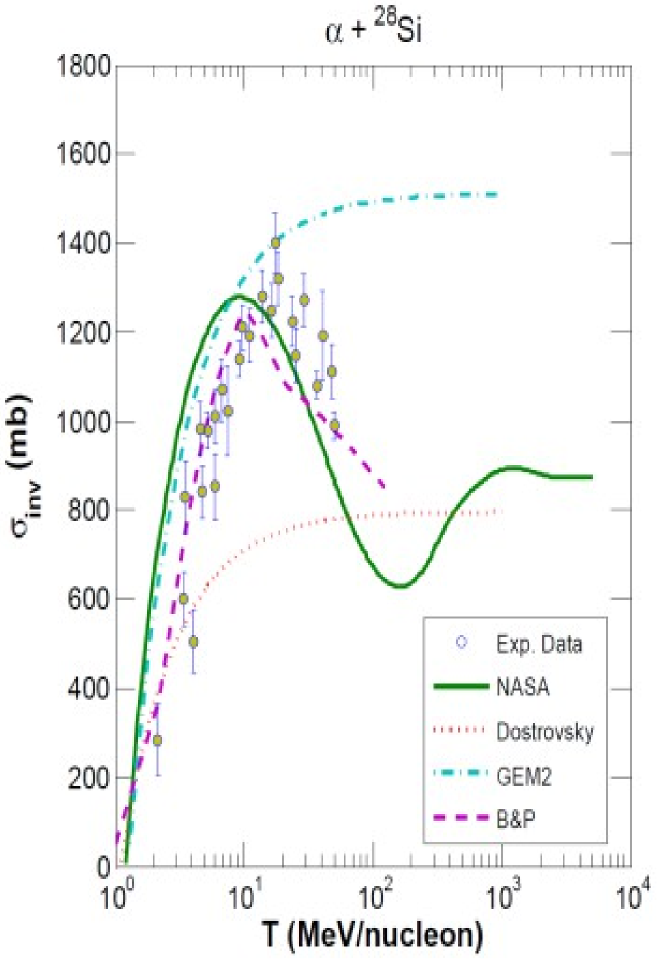
Bending radius	1 m
Bending angle	90o
Rigidity of about	0.5 T.m
Dipole gap	60 mm
Mass resolution	1400
Focal plane length:	~1 m
Weight:	1800 kg

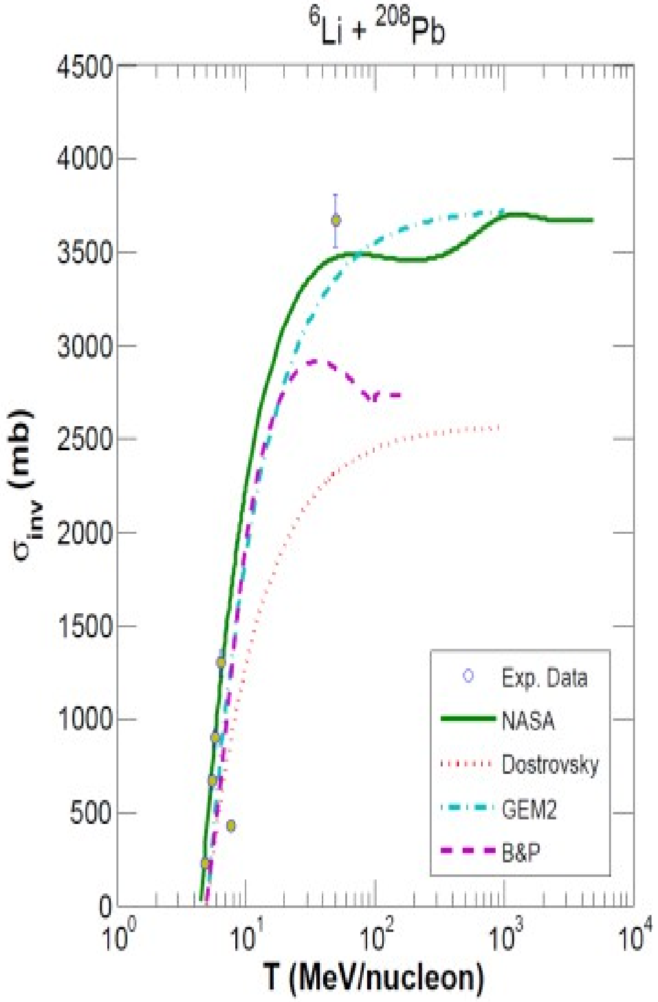
Motivation to measure σR(*E*)

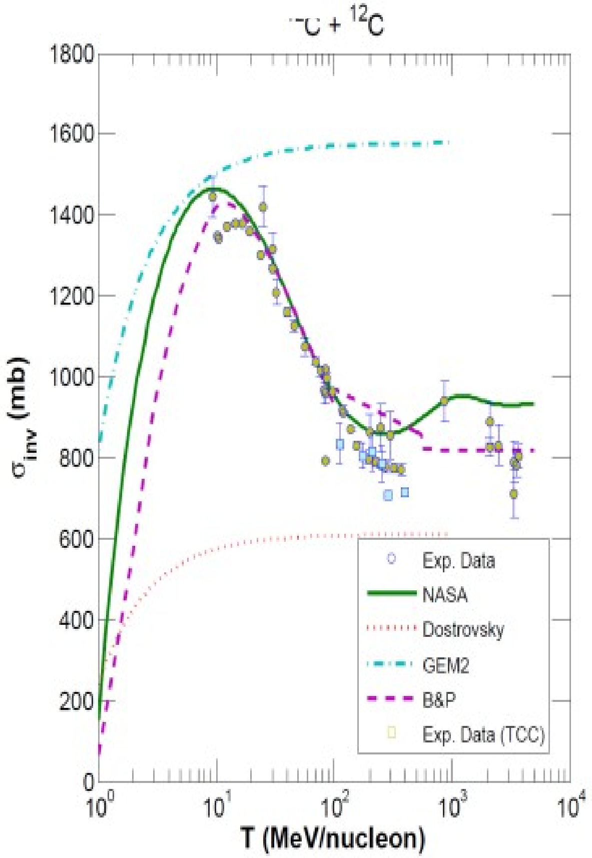
Total Reaction Cross Sections in CEM and MCNP6 at Intermediate Energies

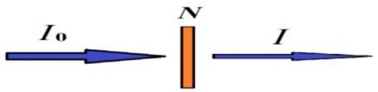
Leslie M. Kerby[a,b], Stepan G. Mashnik[a]

[a]Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[b]University of Idaho, Moscow, ID 83844, USA









$$I = I_0 e^{-\sigma_R(E_\alpha)N}$$ $\sigma_R(E)N \ll 1$ $\sigma_R(E)N = (I_0 - I) / I_0$

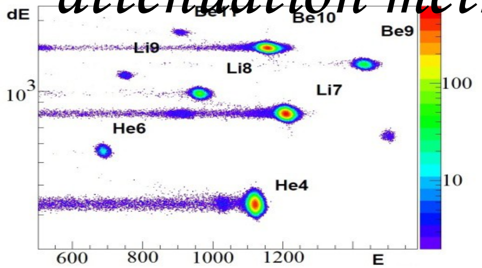
TRCS are including $\forall$ INELASTIC processes

1- simultaneous measurement of ***I0*** ensembles of beam particles which hit target и ***I*** passed without interaction **"attenuation method"**
2- simultaneous measurement of ***I0*** ensembles of beam particles and the corresponding reaction events (***I0- I***) **"transmission method"**

[*T.J. Gooding, Proton Total Reaction Cross Sections at 34 MeV, Nucl. Phys. Vol.* ***12****, Issue 3, 2 July 1959, P. 241–248;*] и Айсберга [*R. M. Eisberg, Proton total reaction cross sections at 62 MeV, Florida Optical Model Conference Report, (1959);*] **"attenuation method"**

[*E.J. Burge, The total proton reaction cross section of carbon from 10—68 MeV by a new method, Nucl. Phys. Vol.* ***13****, Issue 4, 2 November 1959, P. 511–515* **"transmission method"**

- *attenuation method*



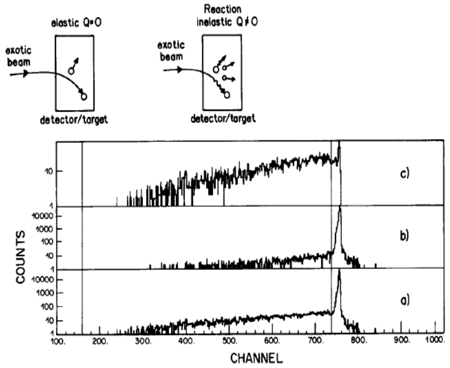


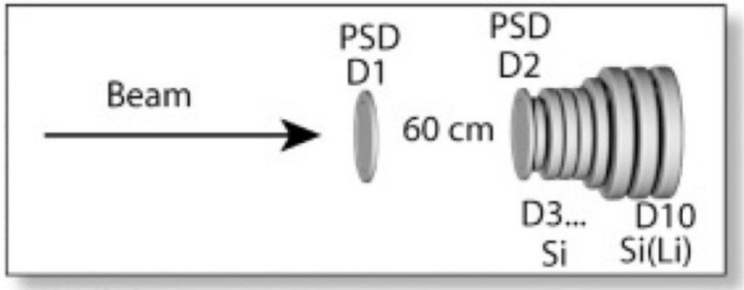
Fig. 2. Upper: scheme of the direct method. The reaction probability is the number of inelastic events divided by the total number of events. Lower: ET^2 spectrum. (a) Unconditioned detector/target spectrum; (b) anticoincidence spectrum with 4π γ-array; (c) coincidence spectrum with 4π γ-array. The two vertical lines delimit the region considered as reaction events.

- *transmission method :*

PHYSICAL REVIEW C **74**, 014605 (2006)

Reaction and proton-removal cross sections of ^{6}Li, ^{7}Be, ^{10}B, ^{9,10,11}C, ^{12}N, ^{13,15}O, and ^{17}Ne on Si at 15 to 53 MeV/nucleon

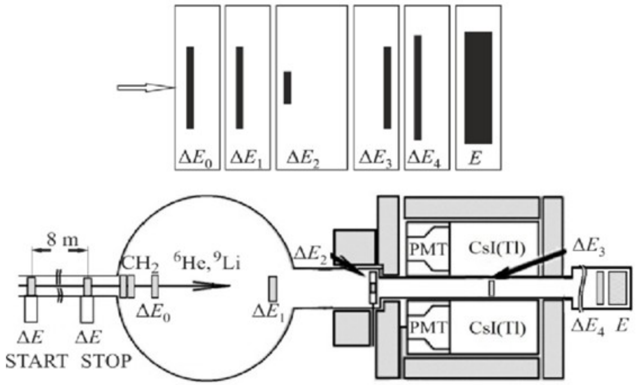
R. E. Warner
Oberlin College, Oberlin, Ohio 44074, USA



Eurasian Journal of Physics and Functional Materials
2017, **1**(1), 12-18

Study of enhancement of total cross sections of reactions with ^{6}He, ^{6,9}Li nuclei

Yu. E. Penionzhkevich [*1,2], Yu. G. Sobolev [1], V. V. Samarin [1,3], M. A. Naumenko [1]



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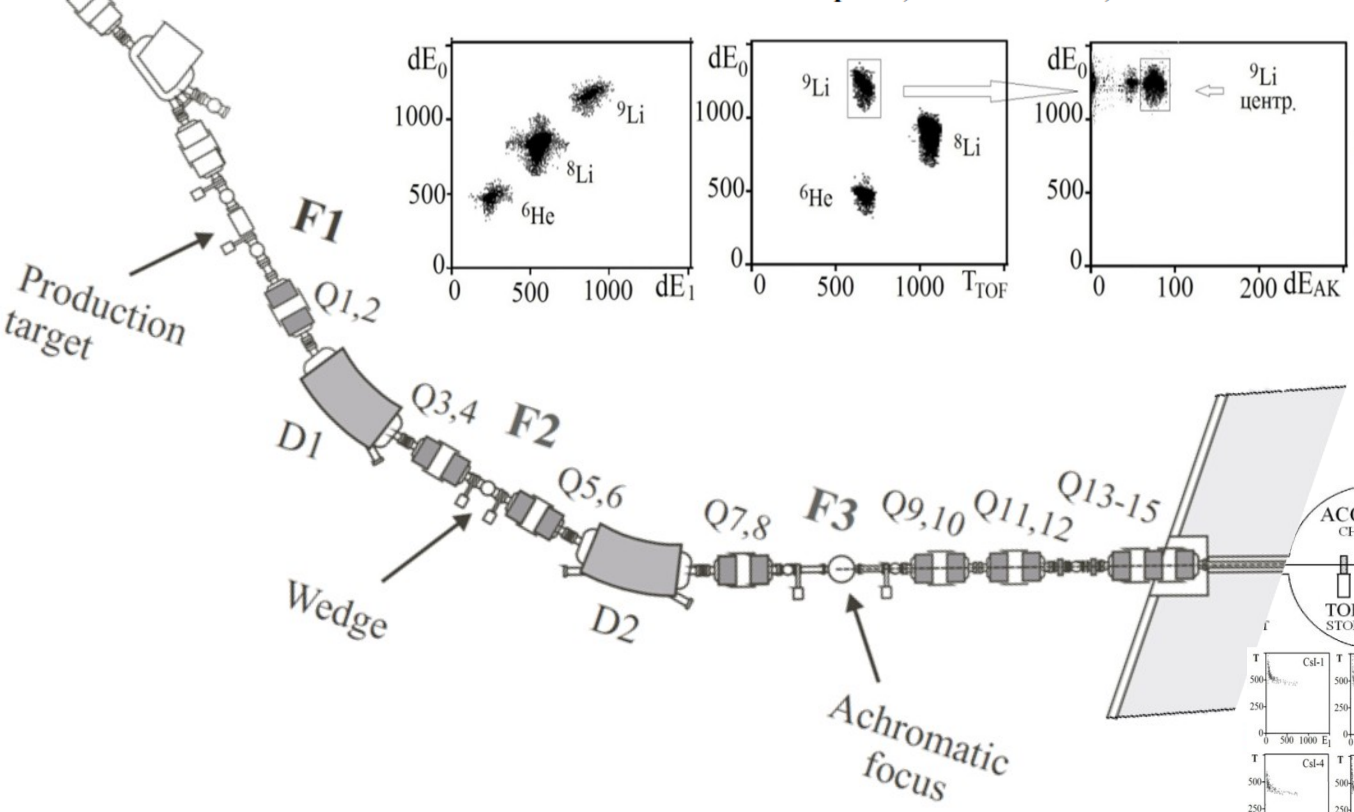
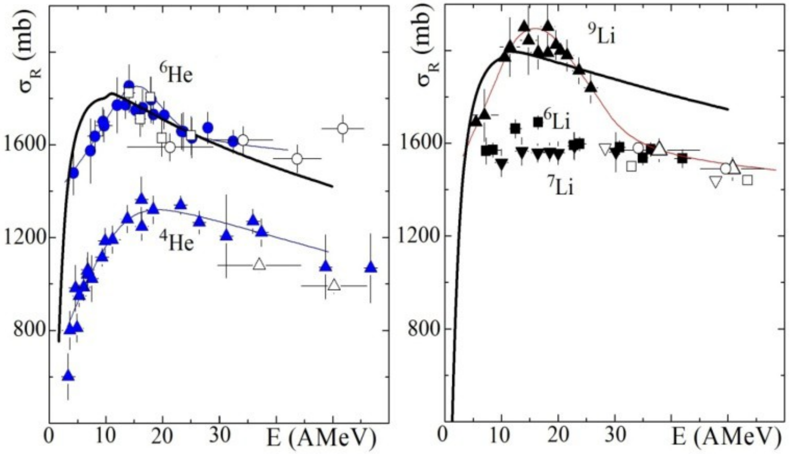
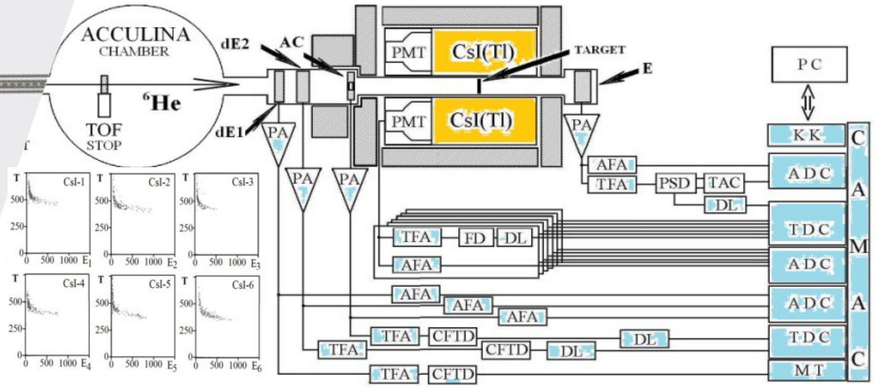
Original Russian Text © Yu.G. Sobolev, Yu.E. Penionzhkevich, D. Aznabaev, E.V. Zemlyanaya, M.P. Ivanov, G.D. Kabdrakhimova, A.M. Kabyshev, A.G. Knyazev, A. Kugler, N.A. Lashmanov, K.V. Lukyanov, A. Maj, V.A. Maslov, K. Mendibayev, N.K. Skobelev, R.S. Slepnev, V.V. Smirnov, D. Testov, 2017, published in Fizika Elementarnykh Chastits i Atomnogo Yadra, 2017, Vol. 48, No. 6.

Experimental Study of the Energy Dependence of the Total Cross Section for the $^6He + {}^{nat}Si$ and $^9Li + {}^{nat}Si$ Reactions

Yu. G. Sobolev[a, b, *], Yu. E. Penionzhkevich[a, c], D. Aznabaev[a, d], E. V. Zemlyanaya[a], M. P. Ivanov[a], G. D. Kabdrakhimova[e], A. M. Kabyshev[e], A. G. Knyazev[a], A. Kugler[f], N. A. Lashmanov[a], K. V. Lukyanov[a], A. Maj[g], V. A. Maslov[a, b], K. Mendibayev[a, d], N. K. Skobelev[a], R. S. Slepnev[a], V. V. Smirnov[a], and D. Testov[a]

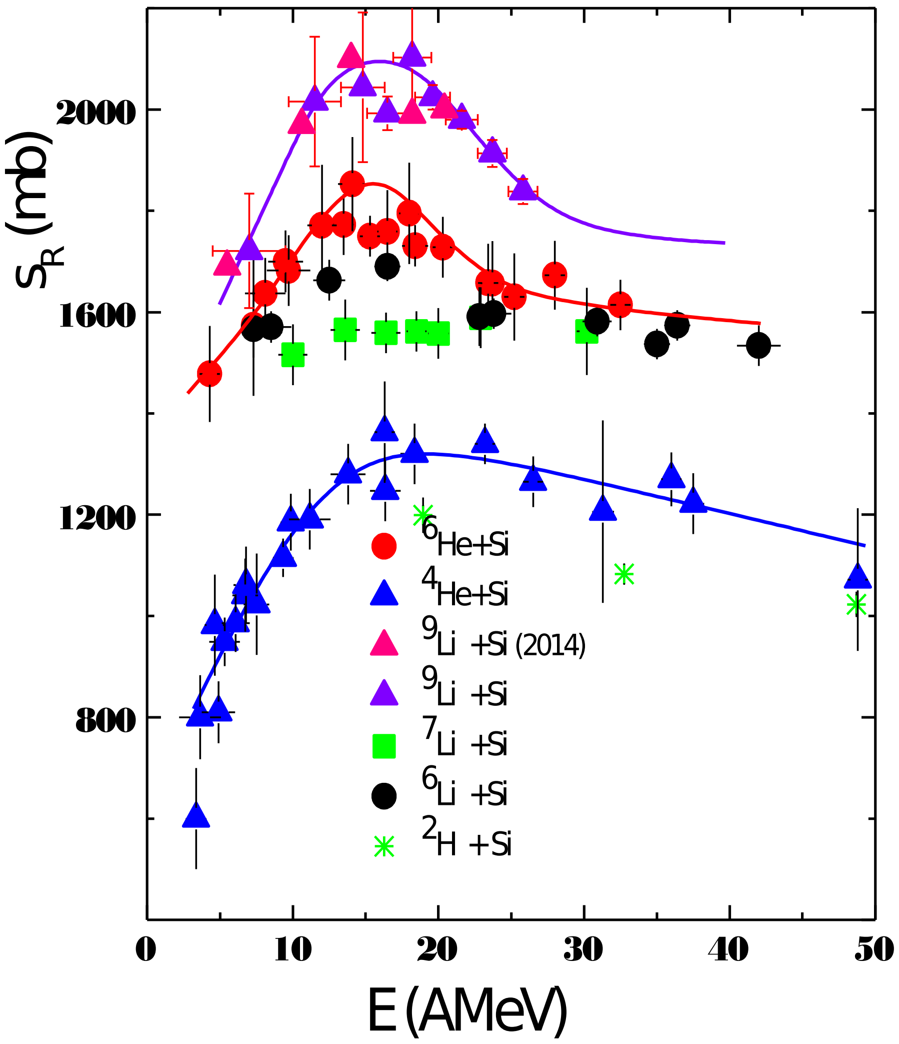






PECULIARITIES IN TOTAL CROSS SECTION OF REACTION WITH WEAKLY BOUND NUCLEI 6He, 6Li, 9Li WITH Si

Results and resume:



Two peculiarities of σR(E) can be observed:

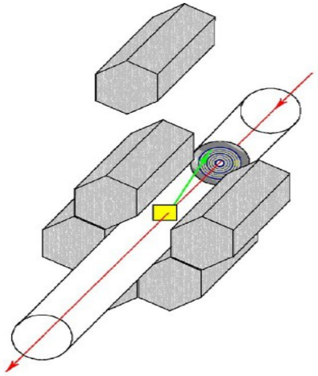
1 peculiarity is *the increased cross section for 6He+Si with respect to 4He+Si in the whole studied energy range.*

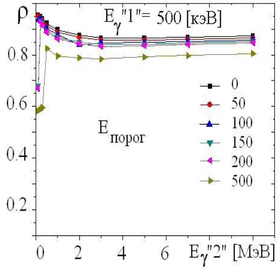
2 peculiarity is *the local increase of σR values in the form of a bump in a limited energy range 10÷30 AMeV for the case of 9Li+Si*.

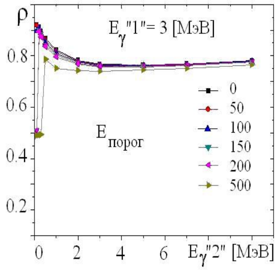
The 1 peculiarity may be explained by the larger size of the 6He nucleus, while the 2 peculiarity may be a manifestation of the dynamic effects associated rearrangement of external weakly bound nucleons or their clusters in the 9Li.

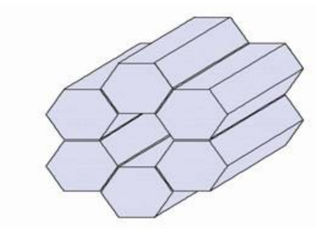
28Si		29Si		30Si		31Si	
Eγ [keV]	Iγ %	Eγ [keV]	Iγ %	Eγ [keV]	Iγ %	Eγ [keV]	Iγ %
1778,97	100	1273,36	100	2235,23	100	0752,22	100
2838,29	100	2028,09	100	1263,13	100	1694,87	100
3200,7	100	2425,73	100	1534,12	100	2316,80	100
4496,92	100	1595,5	100	1552,36	100	2787,9	100
4910,8	100	2806,3	100	1732,7	100	1438,5	100
5107,6	100	2712,8	100	2595,39	100	2780,56	100
5600,4	100	2051,9	79	4810,0	100	3629,90	100
6877,0	100	1038,90	21	3498,33	98	1564,2	22
5098,8	39	1152,57	17,6	1311,80	89,7	0662,19	18

Modified transmission technique based on: 6CsI(Tl) or 8CeBr3 or 12CsI(Tl)&4CeBr3 4π γ-spectrometers









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NUCLEAR EXPERIMENTAL TECHNIQUE

A Setup for Measuring Total Cross Sections of Nuclear Reactions

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Received December 20, 2011

Abstract—An experimental technique and a setup for measuring the energy dependence of the total cross sections of nuclear reactions with stable and radioactive nuclear beams at kinetic energies approaching the Coulomb barriers are described. The modified transmission method, complemented with γ-ray detection in the 4π geometry and pulse-shape discrimination of particles by a semiconductor detector, is used.

356

RESPONSE FUNCTION INVESTIGATION OF 4π γ-SPECTROMETER "MULTI" BY GEANT4 MONTE-CARLO CODE

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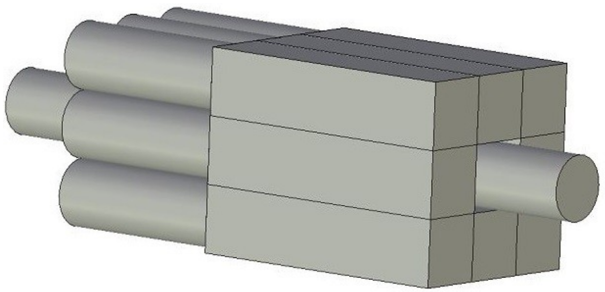
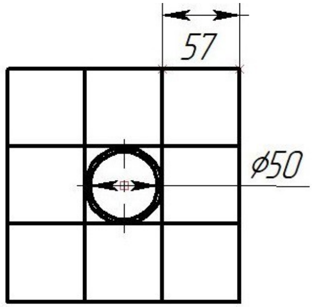
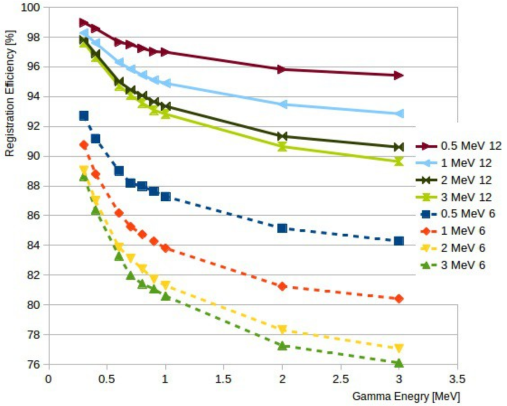
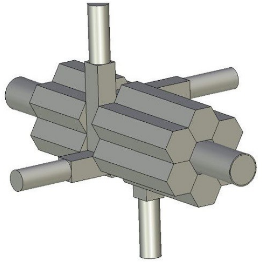
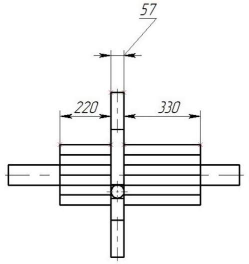
Monte Carlo simulations were performed to estimate properties of improved 4π γ- spectrometer "MULTI" designed for registration of prompt gamma from nuclear reactions. Results are compared to previous version of spectrometer and data obtained during on-beam measurements.

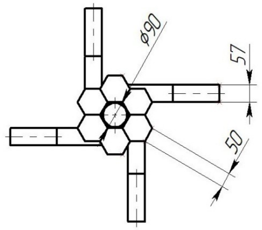


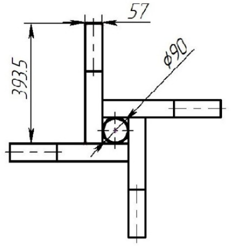






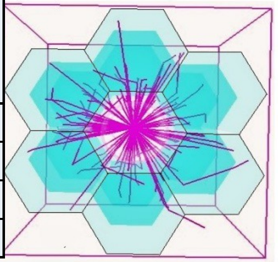


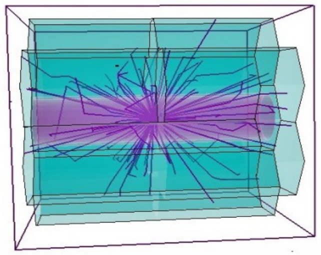




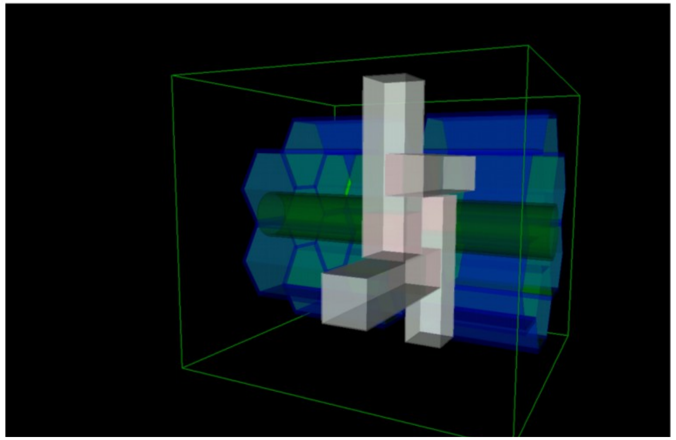
Measured efficiency P(Mγ) for Eγ=1173 keV

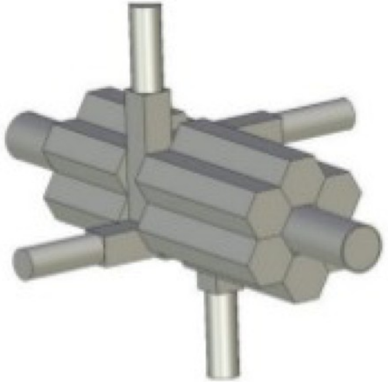
E thr	Mγ=1	Mγ=2	Mγ=3	Mγ=4	Mγ=5
150 keV	48%	73%	86%	92%	99%
200 keV	46%	71%	84%	91%	99%
250 keV	44%	69%	82%	90%	99%



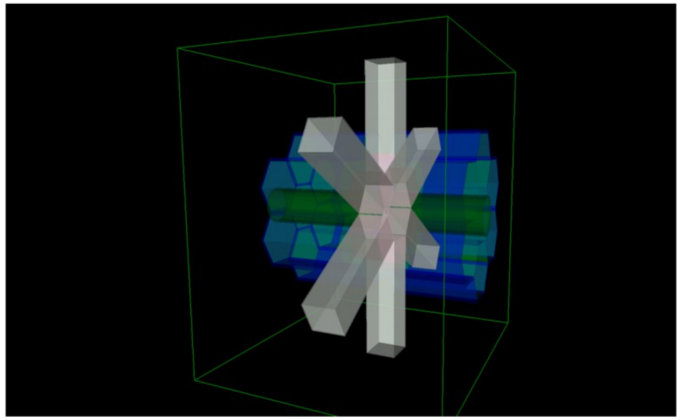


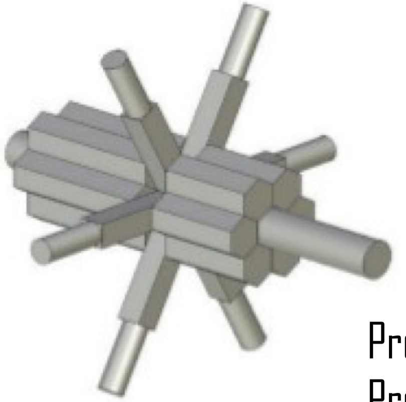
Monte Carlo simulation of 12 × CsI(Tl) & 4 × CeBr3 and 12 × CsI(Tl) & 6 × CeBr3 4π γ -spectrometers





Probability of registering gamma in coincidence in any of CsI crystals = 5,5 +/- 0,01 %
Probability of registering gamma in coincidence in CeBr3 crystal = 9,6 +/- 0,01 %
Overall probability of registering a gamma in coincidence = **94,95 +/- 0,25 %**





Probability of registering gamma in coincidence in any of CsI crystals = 5,5 +/- 0,01 %
Probability of registering gamma in coincidence in CeBr3 crystal = 4,8 +/- 0,01 %
Overall probability of registering a gamma in coincidence = **89,55+/- 0,25 %**

THANK YOU

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IX International Symposium on Exotic Nuclei

Russia, Petrozavodsk
September 10-15, 2018

PETROZAVODSK 2018 EXON

Organized by: **FLNR JINR (Dubna), RIKEN (Wako-shi),**
GANIL (Caen), GSI (Darmstadt),
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Symposium will be held in Petrozavodsk, the capital city of the Republic of Karelia

We hope that taking place in such an exotic region the Symposium will contribute to the success of productive work on exotic nuclei and will promote the collaboration of physicists from different countries.

The Symposium will be devoted to the investigation of nuclei in extreme states and, in particular, at the limits of nuclear stability (from very light neutron- and proton-rich up to superheavy nuclei).

The Topics to be discussed are:

- ***Properties of light exotic nuclei***
- ***Superheavy elements. Synthesis and properties***
- ***Rare processes and decays***
- ***Radioactive beams. Production and research programs***
- ***Experimental facilities and future projects***