

ECOS NA

Task D1 High power thin-target technology

Task D2 SHE using high-intensity ion beams

FLRN, Dubna – activities (short summary)

– courtesy of Yu. Ts. Oganessian

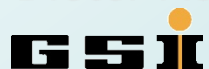
- **achievements**
- **SHE factory**

ECOS NA report on task 1 and 2

- **instrumentation**
 - **accelerators**
 - **separators**
- **outline**
- **ECOS goals**
- **ENSAR ECOS NA**
 - **tasks**
 - **deliverables**
 - **activities**

Discussion issues

Dieter Ackermann



Helmholtzzentrum für Schwerionenforschung GmbH



ENSAR

Erbismühle - Weilrod, Germany - May 13th - 16th, 2012

FUSHE2012

**ENSAR-ECOS
Workshop on Future
Super-Heavy
Element Strategy**

**EXPERIMENT
THEORY
INSTRUMENTATION**

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A. Wieloch (U. Cracow)
A. Yakushev (GSI)
V. Zagrebaev (JINR-FLNR)

FUSHE2012 will be a working meeting to discuss and develop the (near and far) future strategy for the field of Super-Heavy Elements.

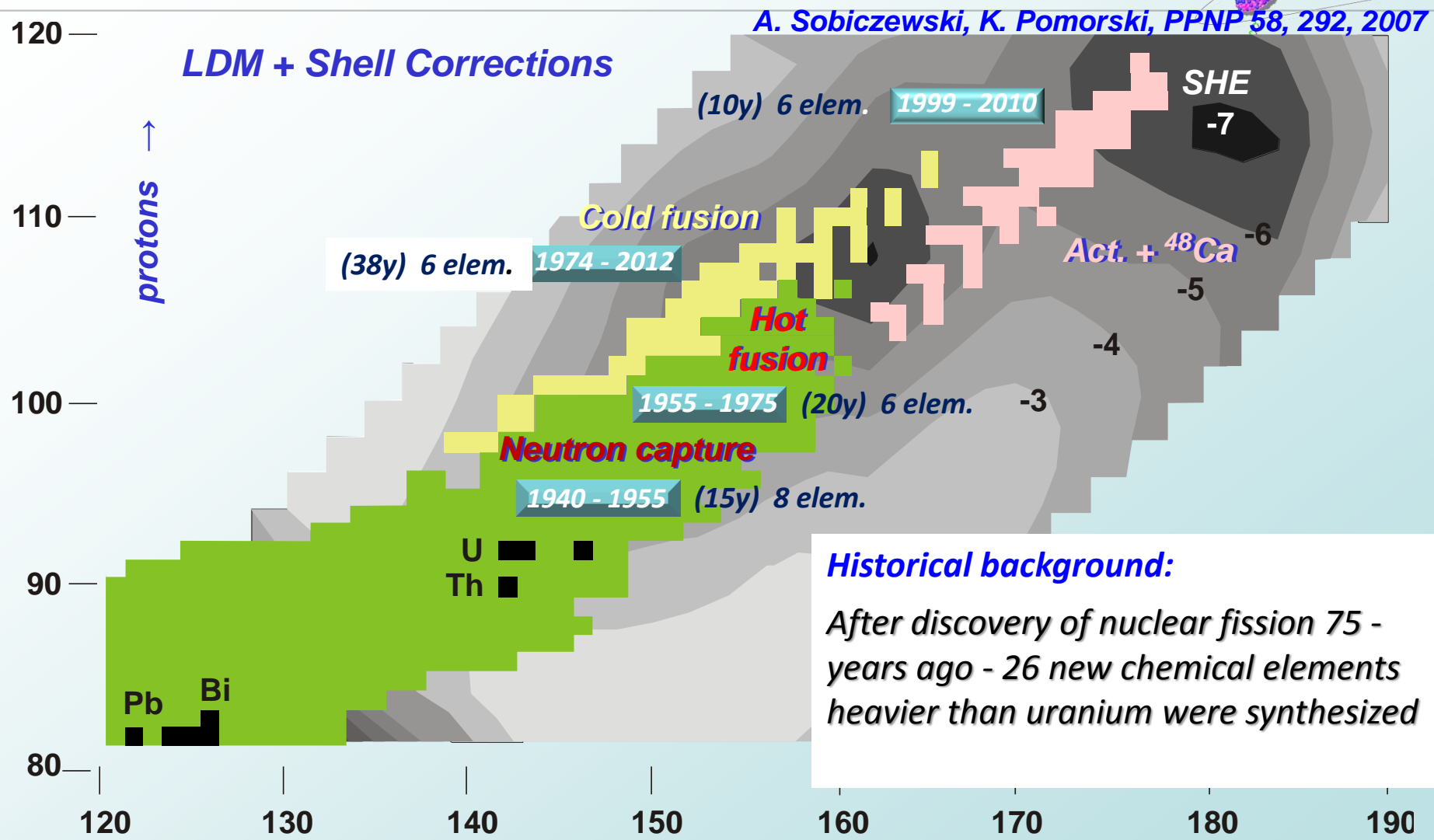
ORGANIZING COMMITTEE

D. Ackermann (chair – GSI)
D. Boilley (co-chair – GANIL)
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C. Stodel (scientific secretary – GANIL)
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B. Sulignano (IRFU-CEA)

CONTACT: fushe2012@ganil.fr WEB: <http://www.ensarfp7.eu/workshops/fushe2012/>

Reactions of Synthesis

courtesy of Yu. Ts. Oganessian



A. Sobiczewski, K. Pomorski, PPNP 58, 292, 2007

Yu/ Oganessian. XXII International Baldin Seminar, September 15-20, 2014, JINR, Dubna

Dieter Ackermann

ECOS-EURISOL Joint Town Meeting
Institute of Physics, Nuclear Energy, Cracow
EURISOL ENSEMBLE October 28-31, 2014

Orsay, October 28th 2014



Cold/hot fusion systematics

courtesy of Yu. Ts. Oganessian

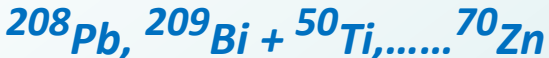
hot fusion

^{48}Ca -induced reactions

$$E_x = 35 - 45 \text{ MeV}$$

$$x = 3 - 4$$

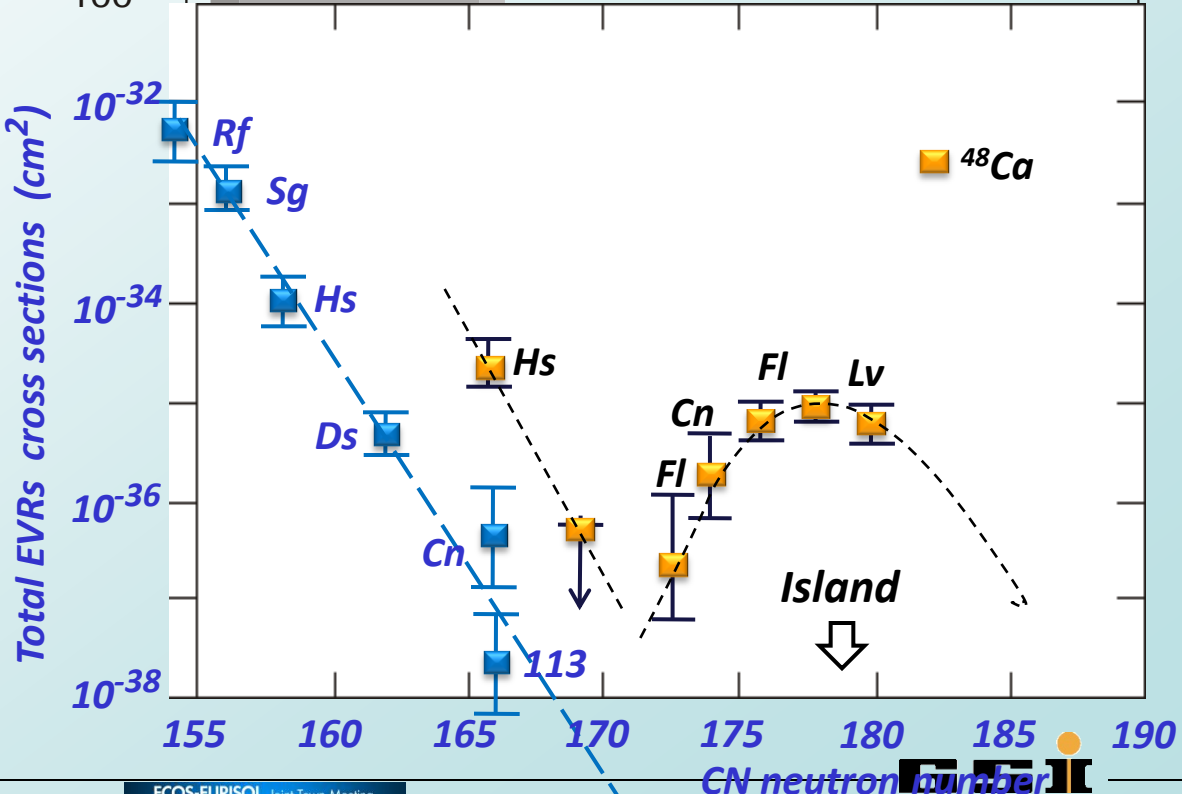
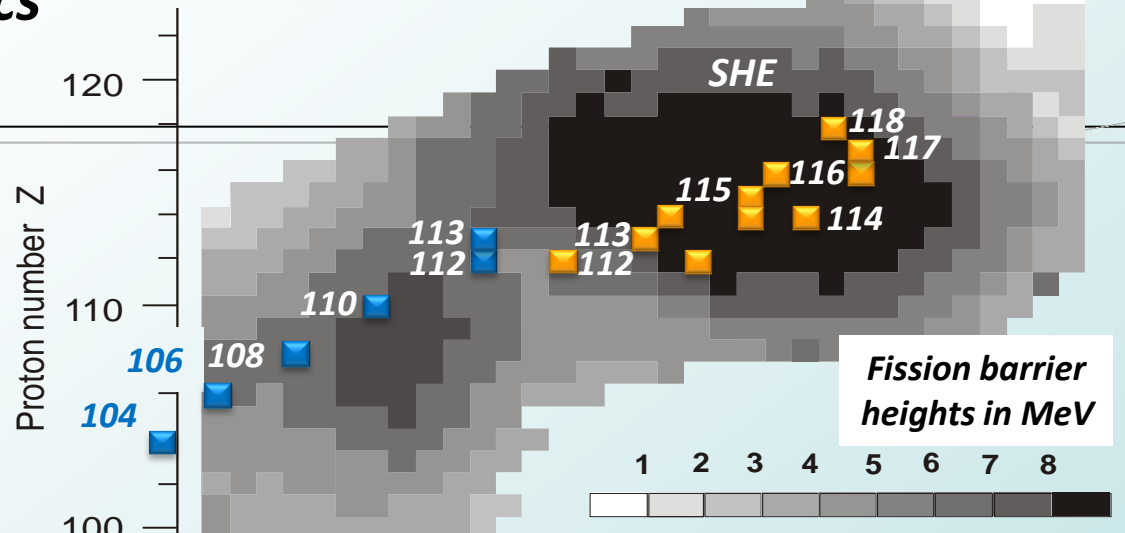
cold fusion



$$E_x = 12 - 15 \text{ MeV}$$

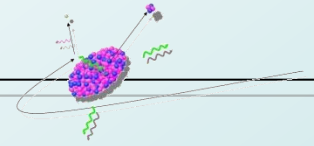
$$x = 1$$

P. Moller et al., PR., C79, 064304 (2009)



New accelerator and new Lab. in Dubna

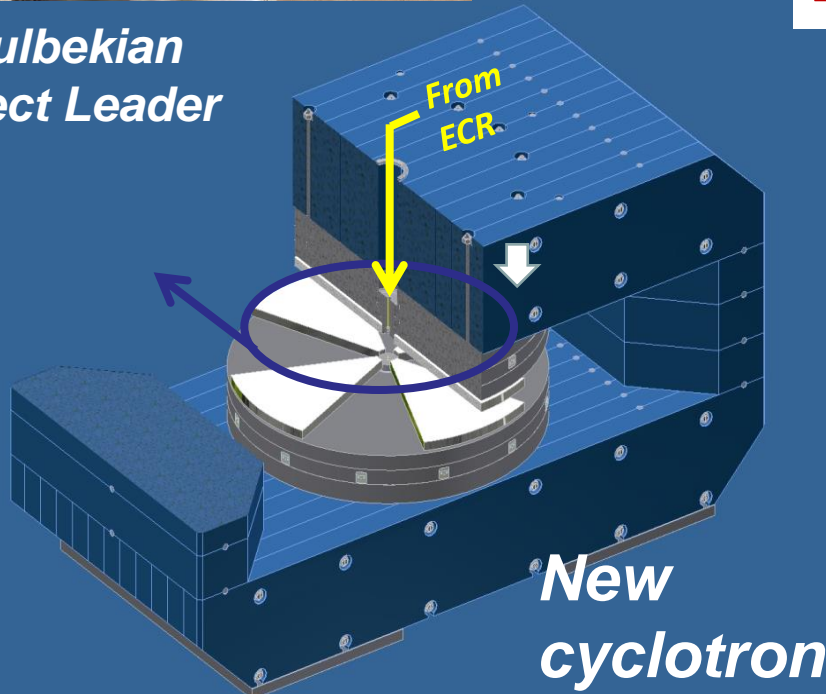
courtesy of Yu. Ts. Oganessian



today: $\sim 5 \cdot 10^{19}/y$ with Factory: $1.0 \cdot 10^{21}/y$



G. Gulbekian
Project Leader



beam dose

factor: ~ 20

Beam intensity

&

Beam time

$10-20 \mu A$

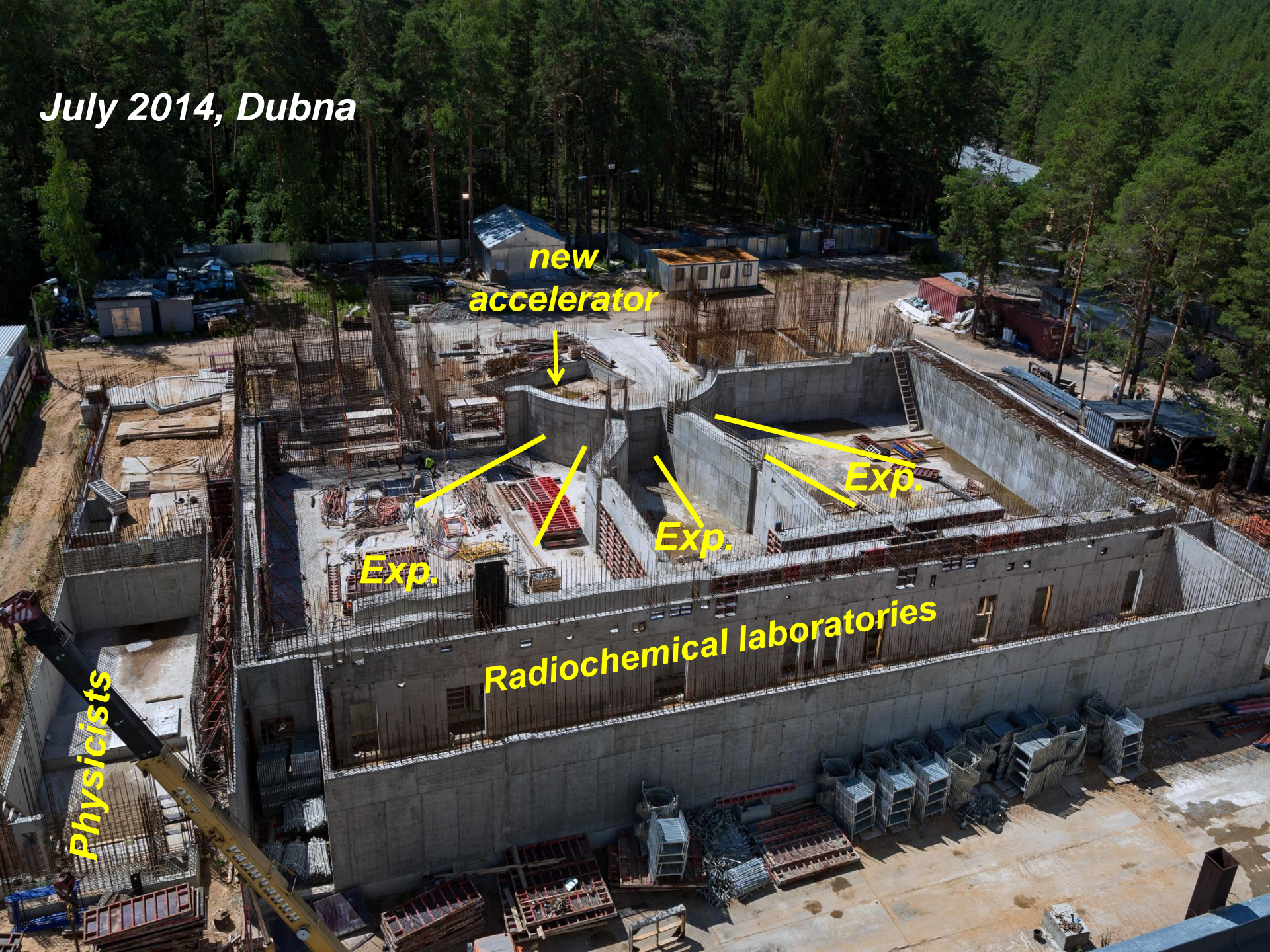


Factory



$\sim 7000 \text{ h/year}$

July 2014, Dubna



new
accelerator

Exp.

Exp.

Exp.


Radiochemical laboratories

Physicists

August 2014, Dubna




Yu/ Oganessian. XXII International Baldin Seminar, September 15-20, 2014, JINR, Dubna



**Novokramatorsk
Ukraine**

June 2014

Yu/ Oganessian. XXII International Baldin Seminar, September 15-20, 2014, JINR, Dubna



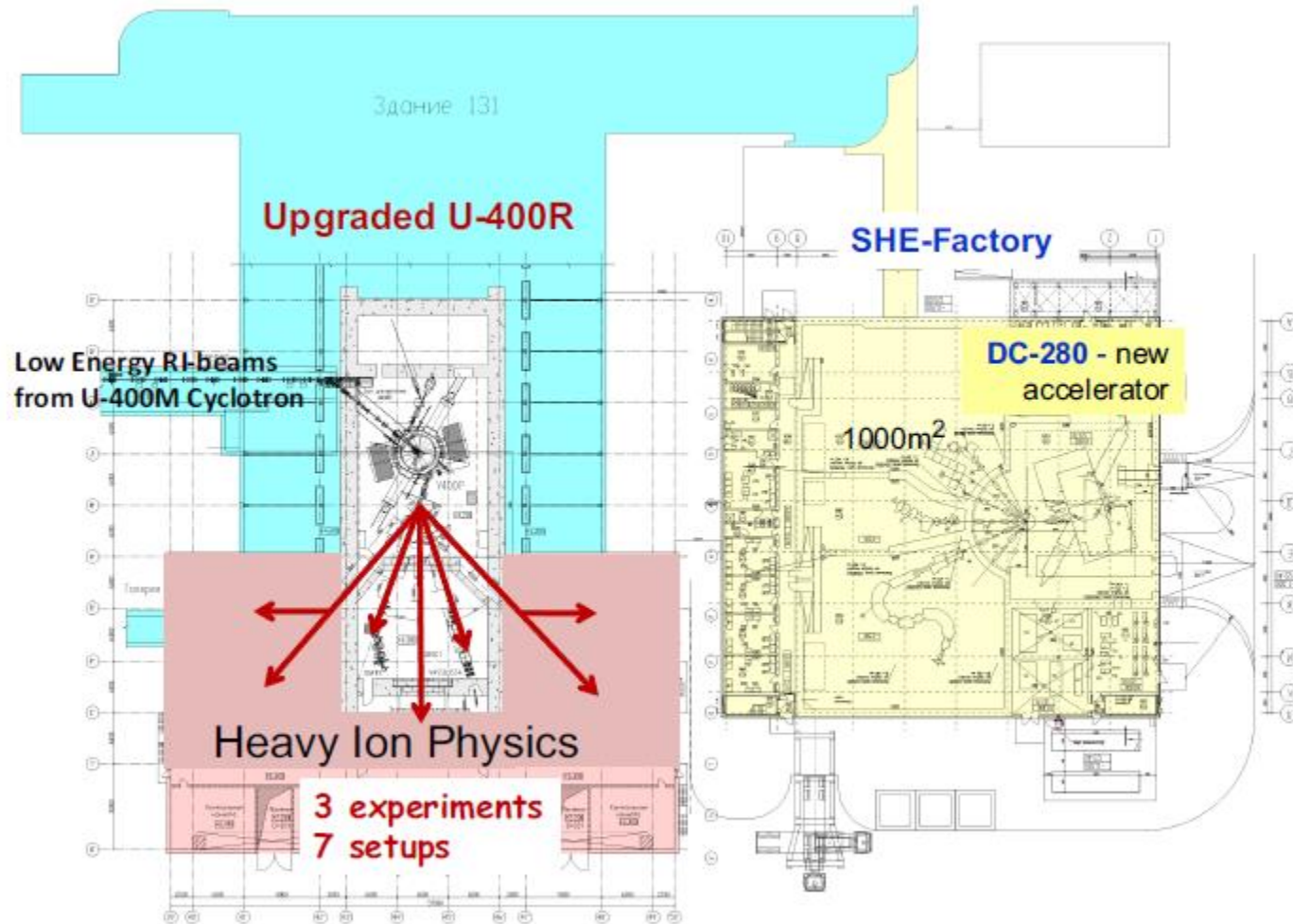
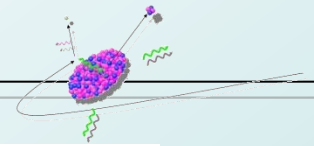
***Novokramatorsks
Ukraine***

August 2014

Yu/ Oganessian. XXII International Baldin Seminar, September 15-20, 2014, JINR, Dubna

SHE-factory at Dubna

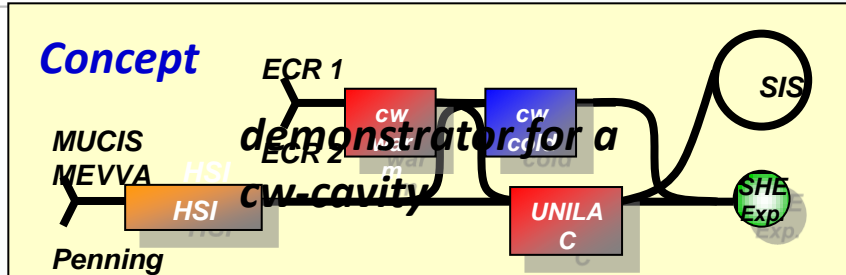
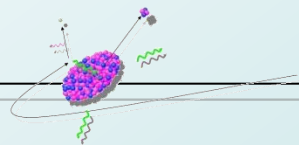
- integration in FLNR facility



Yuri Oganessian. "Synthesis of SH-nuclei" FUSHE 2012, May14, 2012, Weilrod, Germany

cw-accelerator project at GSI

- concept and "step-wise" realization



(presently under construction)

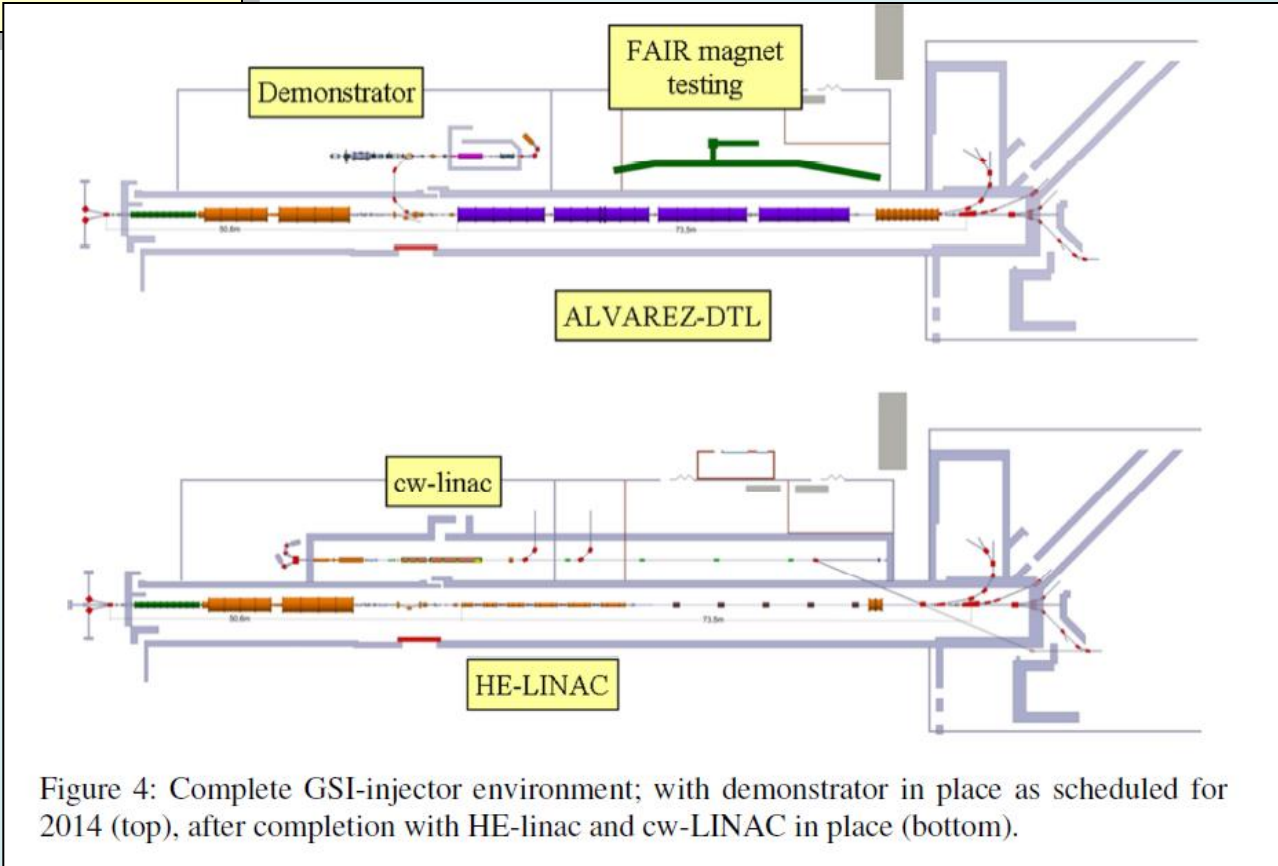
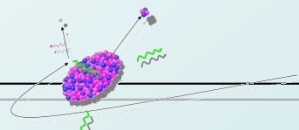


Figure 4: Complete GSI-injector environment; with demonstrator in place as scheduled for 2014 (top), after completion with HE-linac and cw-LINAC in place (bottom).

cw-accelerator project at GSI

- concept and "step-wise" realization

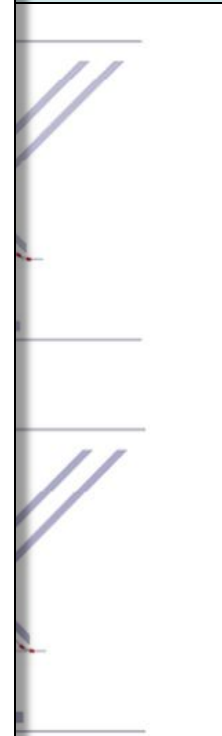
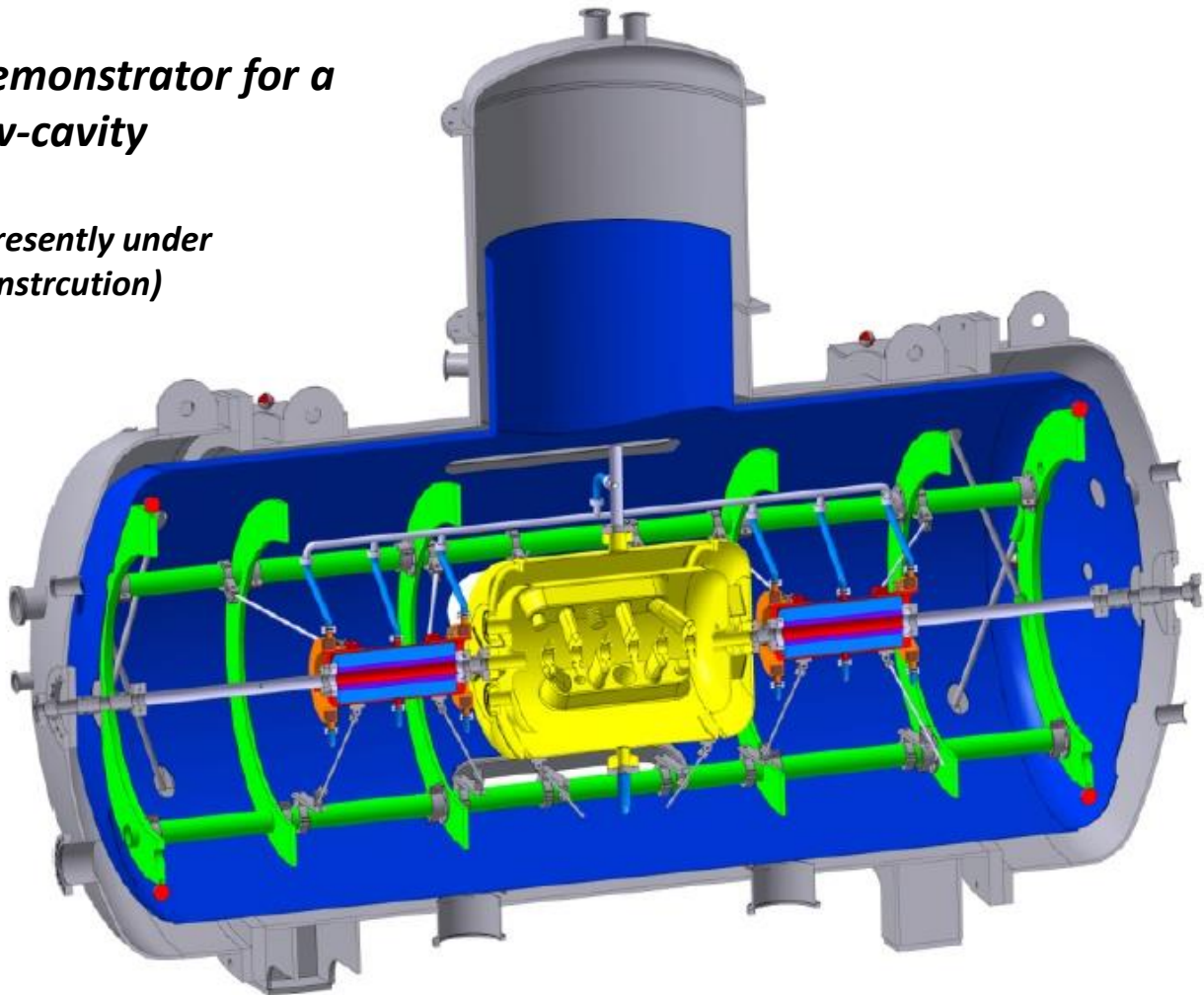


Concept

MUCIS
MEVVA
H
Penning

demonstrator for a
cw-cavity

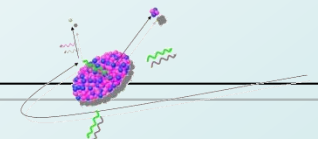
(presently under
constrcution)



cheduled for

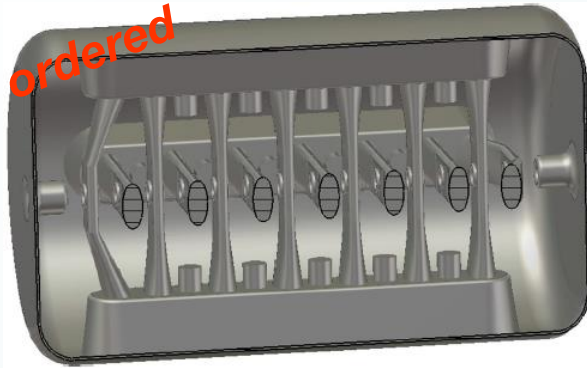
sc-216 MHz-CH-Prototype

- W. Barth at FUSHE 2012



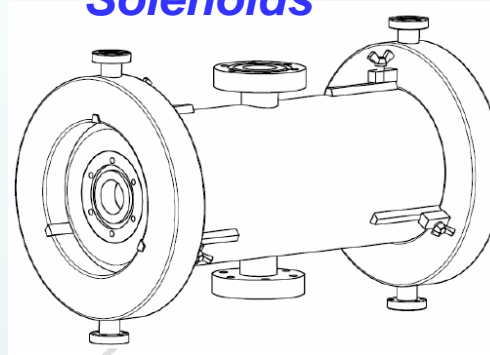
216 MHz-CH-cavity

(Goethe Univ. Frankfurt)



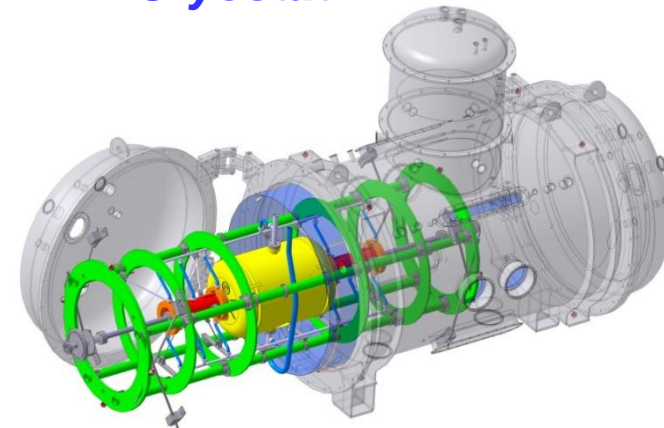
Parameter	Unit	CH-1
Beta		0.059
Frequency	MHz	217
Gap number		15
Total length	mm	690
Cavity diameter	mm	420
Cell length	mm	40.82
Aperture	mm	20
Effective gap voltage	kV	225
Voltage gain	MV	3.13
Accelerating gradient	MV/ m	5.1
E_p / E_a		6.5
B_p / E_a	mT/ (MV/m)	5.9
R/ Q	Ω	3540
Static tuner		9
Dynamic bellow tuner		3

Solenoids

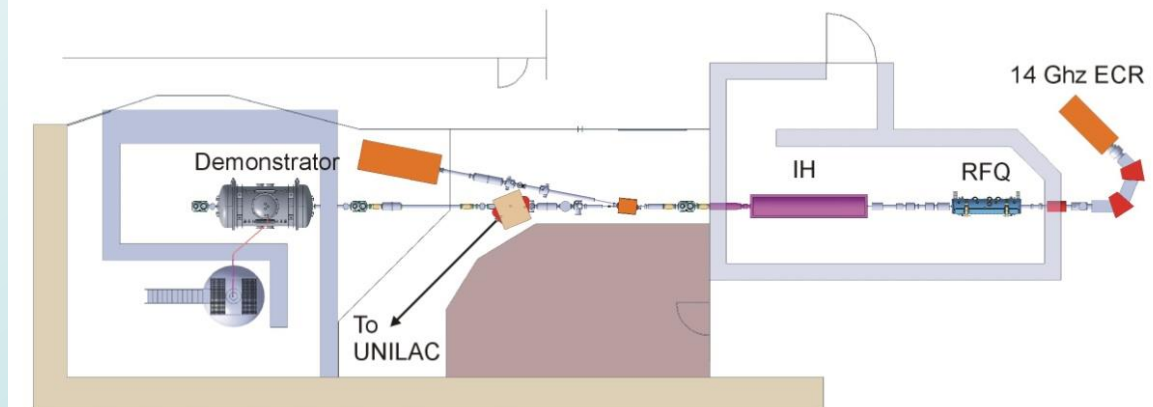


B_{max}	9,323T
$B*L$	2,635 Tm
L	0,28 m
Aperture	30 mm

Cryostat

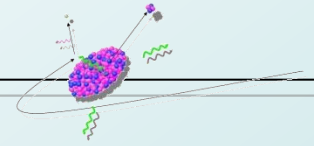


Demonstrator Project (HIM, GSI)



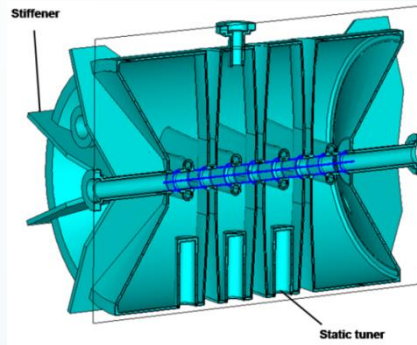
cw-accelerator project at GSI

- short CH-cavity and the advanced demonstrator



short CH-cavity

geometry

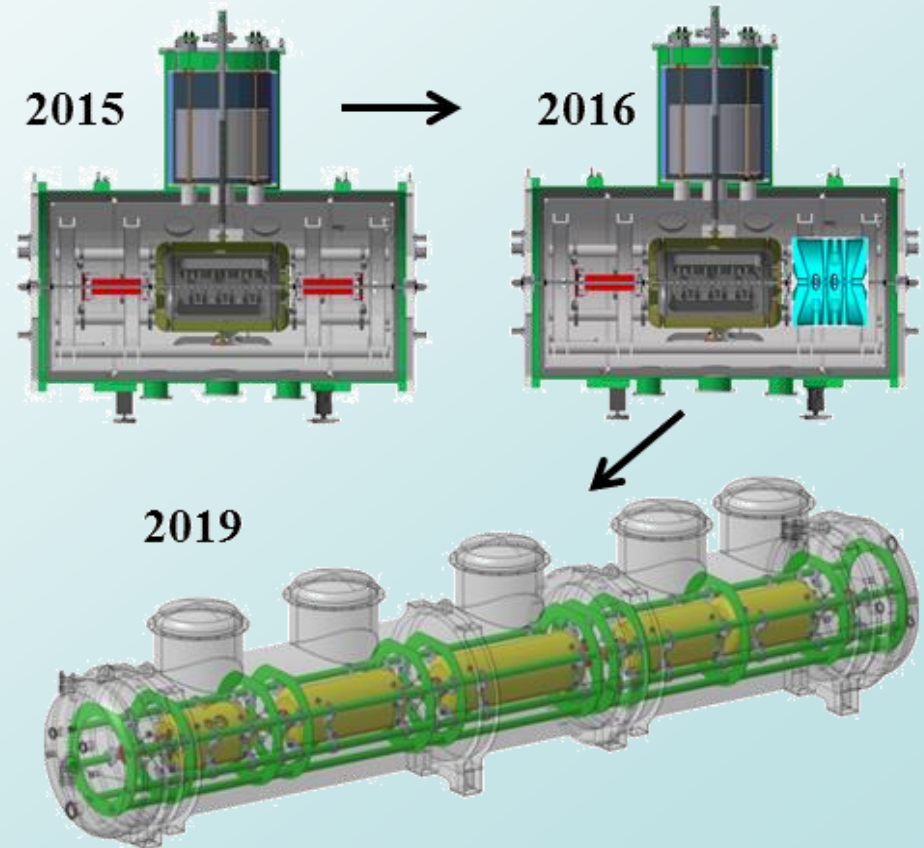


properties

Frequency	217	MHz
β	0.069	
Length ($8\beta\lambda/2$)	381.6	mm
Number gaps	8	
Inner tank diameter	438	mm
Aperture diameter	30	mm
Maximum inner length	560	mm
Wall thickness	$\approx 3.5-4$	mm
E_p/E_a	5.3	
B_p/E_a	6.5	mT/(MV/m)
E_a	>5	MV/m

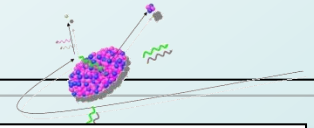
advanced demonstrator

implementation time line



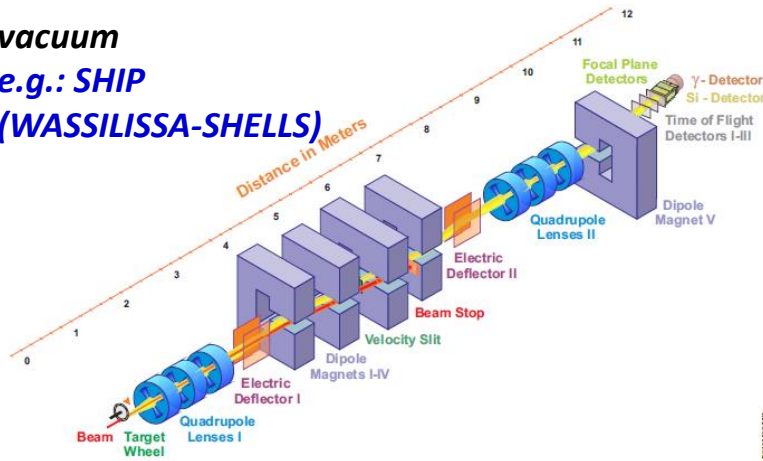
Separators

- present and (near) future devices

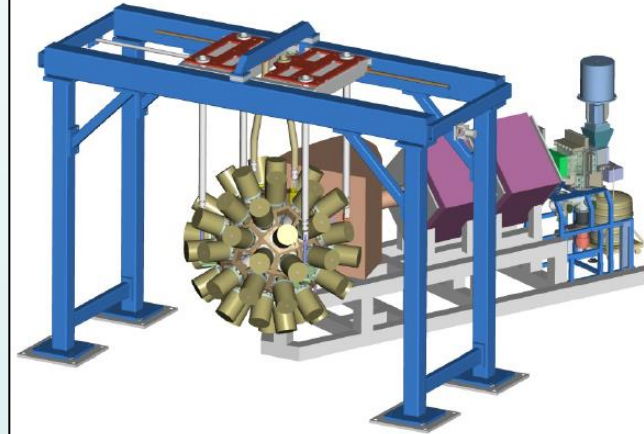


vacuum

**e.g.: SHIP
(WASSILISSA-SHELLS)**



gas-filled
**e.g.:RITU
(DGFS,
GARIS,
BGS...)**



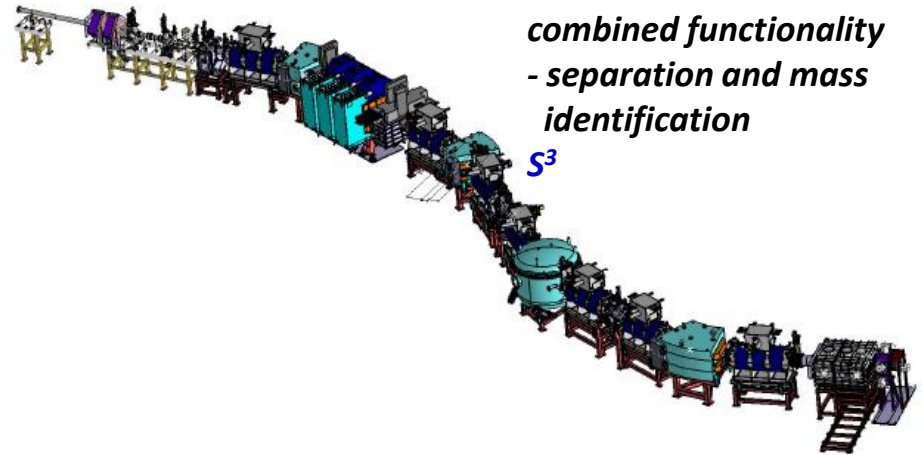
complementary configurations

- vacuum separators
 - velocity filters (SHIP, LISE)
 - mass spectrometers (FMA,RMS,..., EMMA, MARA)
- gas-filled separators
 - DGFRS, GARIS, TASCA, BGS, RITU, ...

instrumental/detection features

- comprehensive detection systems
 - decay spectroscopy (GREAT, TISISPEC, SHIP or FMA focal plane set-ups)
 - inbeam (JUROGAM, AGATA, GAMMASPERE, ...)
 - inbeam electrons (SAGE)
 - X-rays ...

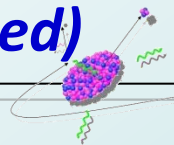
combined functionality
- separation and mass
identification



S^3

ENSAR ECOS NA Report

- excerpt from the FUSHE 2012 paper (to be published)



ECOS (European Collaboration On Stable ion beams)

ENSAR NA Report

Task 1 - High power thin-target technology

Task 2 - Synergies in Super Heavy Element Research

D. Ackermann^{1,†}, E. Litvinova², D. Boilley³, Ch. Stodel³, B. Avez⁴, W. Barth¹, M. Block^{1,5}, Ch. Düllmann⁶, S. Fritzsche⁶, P. Greenlees⁷, R.-D. Herzberg⁸, F.P. Heßberger^{1,5}, W. Loveland⁹, W. Nazarewicz¹⁰, V. Pershina¹¹, G. Pollaro¹¹, J. Roberto¹², P. Schwerdtfeger¹³, A. Türler^{14,15}, J. Uusitalo⁷, D. Vretenar¹⁶

¹ GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

² Western Michigan University, Kalamazoo, U.S.A.

³ GANIL, Caen, France

⁴ N.N., N.N., N.N.

⁵ HIM, Mainz, Germany

⁶ University of Mainz, Mainz, Germany

⁷ University of Jena, Jena, Germany

⁸ University of Jyväskylä, Jyväskylä, Finland

⁹ University of Liverpool, Liverpool, U.K.

¹⁰ Oregon State University, Corvallis, U.S.A.

¹¹ Michigan State University, East-Lansing, U.S.A.

¹² Universit di Torino and INFN, Torino, Italy

¹³ ORNL, Oakridge, U.S.A.

¹⁴ CTCP Massey University, Auckland, New Zealand

¹⁵ University of Bern, Bern, Switzerland

¹⁶ PSI, Villigen, Switzerland

[†] University of Zagreb, Zagreb, Croatia

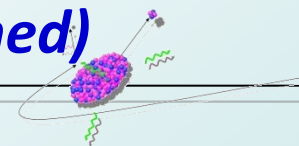


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CONTACT: fushe2012@ganil.fr WEB: <http://www.ensarfp7.eu/workshops/fushe2012/>





1. The ENSAR ECOS Network Activity

The ECOS (European COllaboration on Stable ion beams) working group has been appointed by NuPECC in 2004 with the following tasks:

- Describe and access the research perspectives with high intensity stable-ion beams.
- Categorise existing facilities and their possible upgrades.
- Identify the opportunities and specifications for a dedicated new facility in Europe.

The objectives of the proposed ECOS-Network are related to these two recommendations and they are twofold:

- (i) Bring together and coordinate the expertise that is available in the European countries in order to achieve the research and development activities in essential aspects related to the production and use of high-intensity heavy-ion beams (Task 1). The important aspect related to the development of high-power ion sources is the objective of JRA01-ARES with which the NA02-ECOS will have a significant synergy.

- (ii) Optimise resources and manpower for the upgrade and development of various stable-ion-beam facilities in Europe in order to optimise their scientific output (Tasks 2 and 3).

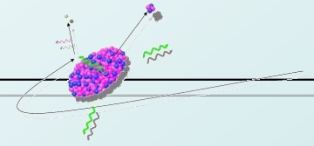
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B. Sulignano (IRFU-CEA)

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deliverables

D-NA02-1: Report on the development of high power thin-target technology with special emphasis on new techniques and methods that will allow increasing the primary beam intensity usable with such targets. (month 40)

D-NA02-2: Report on the research activities related to SHE s ,and on the achievement made in this research field (month 40)

D-NA02-3: Report on the collaborations and synergies between facilities providing stable Ions beam facilities in Europe initiated and driven by ECOS network (month 40)

actions

The report on task 1 and two is mainly based on the strategy discussion and in its results performed during the FUSHE 2012 workshop and follow up activities initiated by it. The FUSHE 2012 workshop was held in Weilrod, Germany, from May 13th 16th 2012 covered in with comprehensive program all subjects related to super-heavy element research including experimental, instrumental and theoretical questions (<http://www.ensarfp7.eu/projects/ecos/workshops-meetings/fushe2012>). The workshop was attended by about 90 participants from all institutions involved in SHE research worldwide. It was organized in 7 sessions with a strong emphasis on discussions including Theory, Experiment and Instrumentation in an integrated fashion in order to foster a constructive dialogue between theory and experiment. The sessions were organized as a combination of invited talks followed by a topical discussion for the subjects:

subjects discussed at FUSHE 2012

- SHE Synthesis
- Nuclear Structure of SHE
- Chemistry
- Atomic Physics and Alternative Approaches

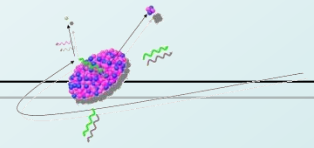
M. Leino (U. Jyväskylä)

E. Litvinova (scientific secretary – GSI)

G. Stodel (scientific secretary – GANIL)

Strategy and open questions

- visions and challenges (FUSHE 2012 paper)



- How many protons and neutrons can a nucleus hold together? What is the heaviest element that we can synthesize today and in the future? Where is the end of the periodic table in atomic number and mass?
- Can we develop a comprehensive theory of nuclei from the lightest to the heaviest? Are superheavy nuclei fundamentally different, and do they represent a new state of nuclear matter?
- What are the properties and boundaries of the predicted "island of stability" for superheavy elements? Does the stabilization emerge without large energy gaps?
- How can we produce superheavy nuclei that are more neutron rich?
- What is the physical and chemical behavior of elements with extreme numbers of neutrons, protons, and electrons?
- Can we understand the details of the fission process and competing decay modes?
- Can we understand and optimize the production mechanisms for superheavy nuclei: hot and cold fusion, multi-nucleon transfer, etc? Can we produce measurable quantities of superheavy elements?
- Do superheavy elements exist in the universe, and how are they produced? Are there remnants of long-lived superheavy elements on earth?

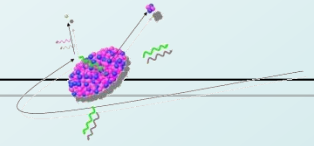
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FUSHE 2012 paper on SHE strategy

- outline



Exploring and Harvesting the Island of stability *Strategy for near and far future developments in superheavy element research*



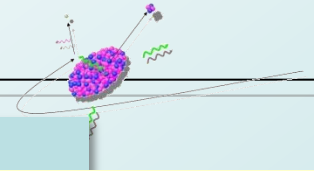
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W. Nazarewicz (U. Knoxville)
H. Nitsche (UC Berkeley/LBNL)
Yu. Ts. Oganessian (FLNR-JINR)
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Discussion issues

- contributions to this session and beyond ...



models

- self-consistent – macro-micro
- dynamic
- beyond mean field ...

stable beams

- high intensity accelerators – ECOS
 - cw-linac project GSI
 - LINAG at SPIRAL2
 - LINCE at Huelva ...

RIB facilities

- reaction mechanism studies
 - multi nucleon transfer
 - spin distribution
- nuclear structure of n-rich heavy species
 - isotonic/isotopic trends of single particle states
 - deformation, K-isomers

instrumentation

- accelerators, separators, detectors, ...

targets

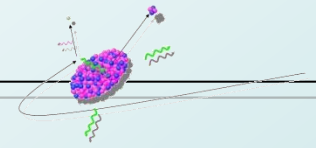
- stable (Pb, Bi, ...), actinides (^{243}Am , $^{\text{A}}\text{U}$, $^{242,244}\text{Pu}$, ^{248}Cm , ^{249}Cf , ^{249}Bk , ...)

alternative approaches

- traps
- lasers, ...

continuation in ENSAR2

- cw-accelerator – first beams(?)
 - GSI/HIM
 - LINAG at SPIRAL2
 - FLNR SHE-factory
 - LINCE (?)
 - ...
- possible synergies with RIB
 - ReA12 at FRIB
 - SPIRAL2, FAIR, EURISOL...?
- ...

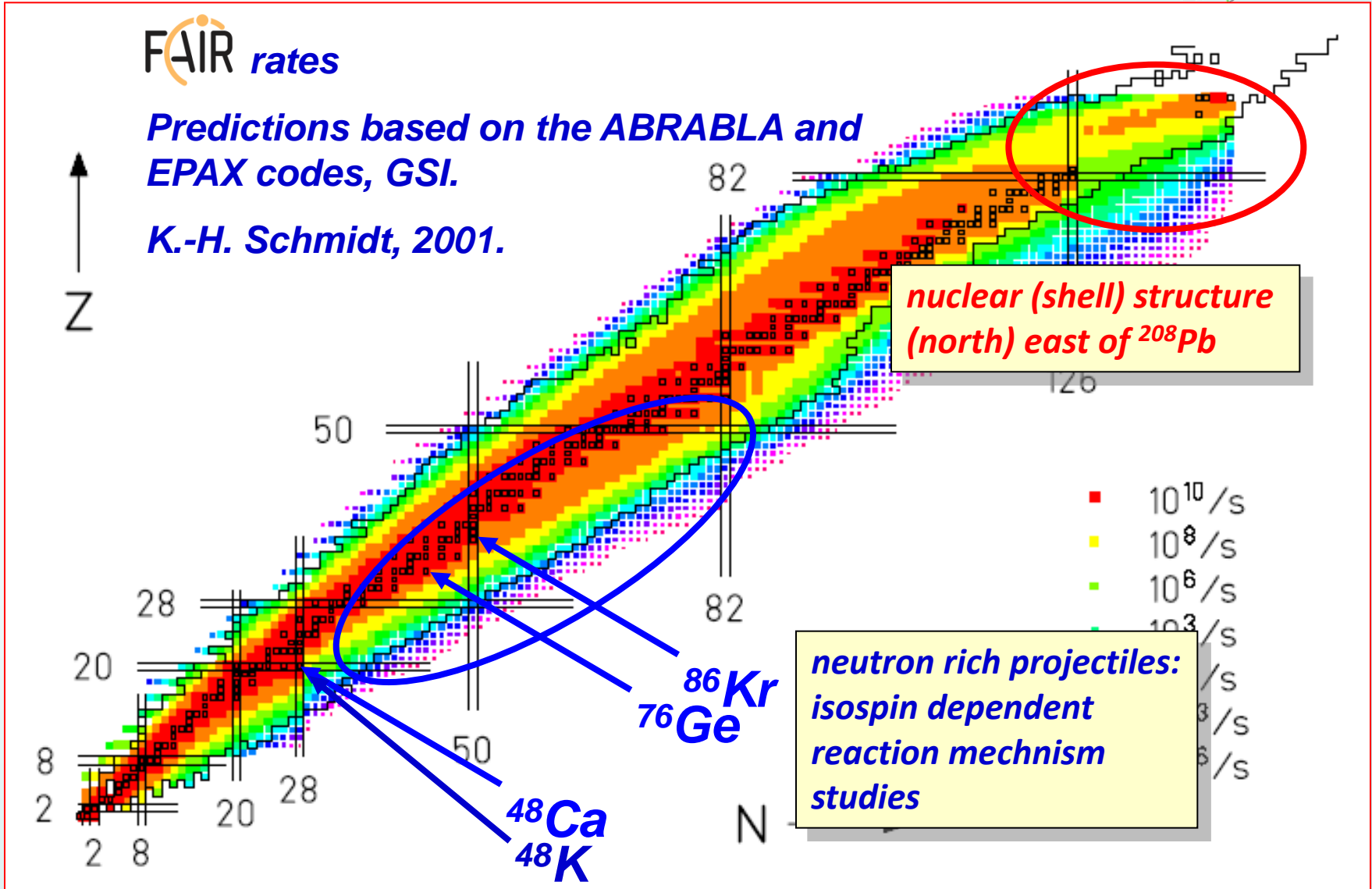
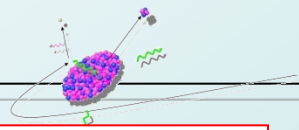


additional material on:

- *RIB*
- *alternative methods*
- *multinucleon transfer*
- *spindistribution*

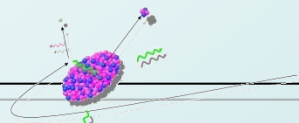
RIB reaction rates

- optimum rates from projectile fission and fragmentation



RIB reaction rates

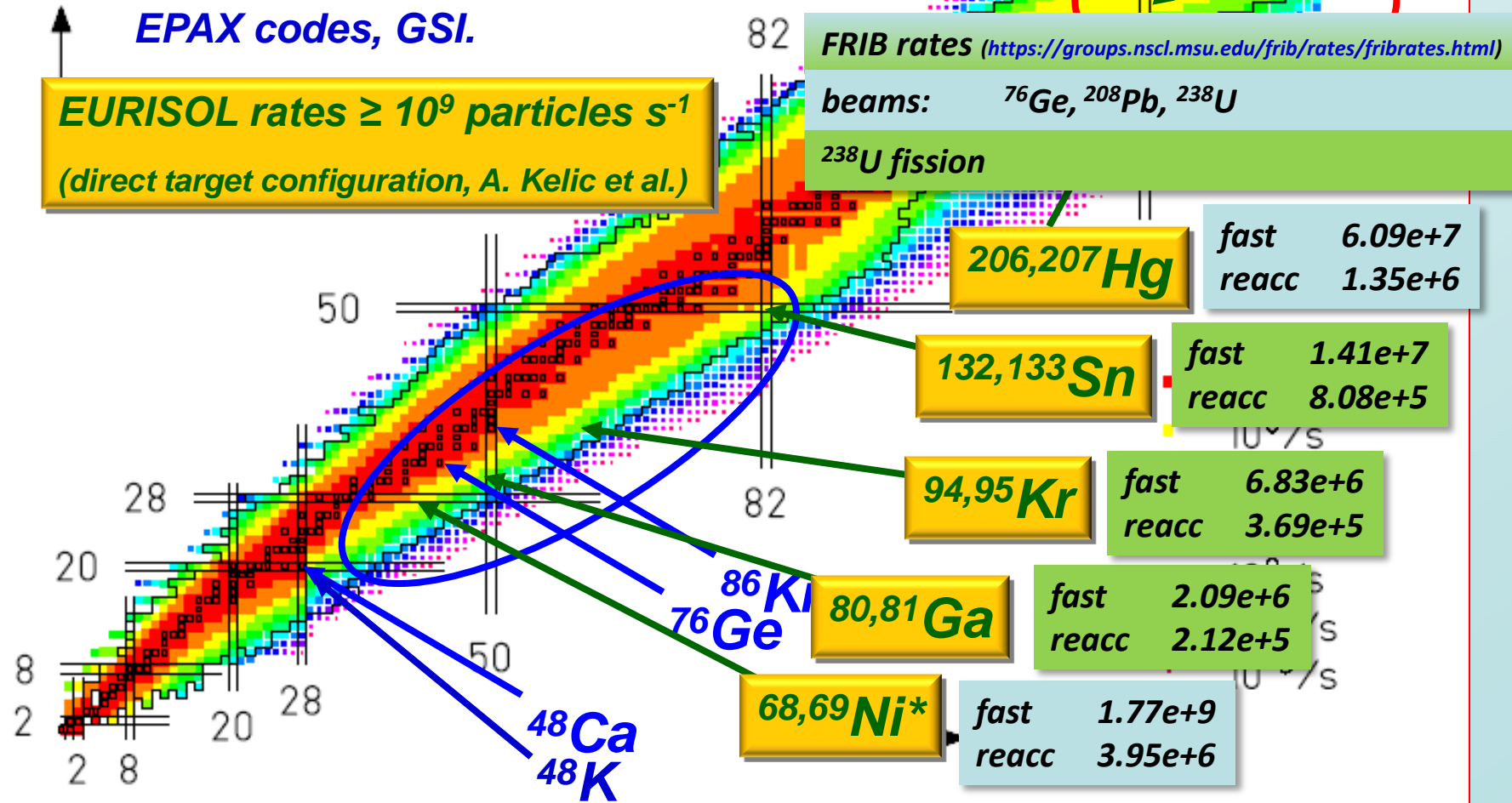
- optimum rates from projectile fission and fragmentation, and ISOL



FAIR rates

Predictions based on the ABRABLA and EPAX codes, GSI.

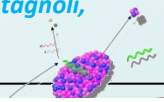
EURISOL rates $\geq 10^9$ particles s^{-1}
(direct target configuration, A. Kelic et al.)



Multi nucleon transfer as a tool to study n-rich species

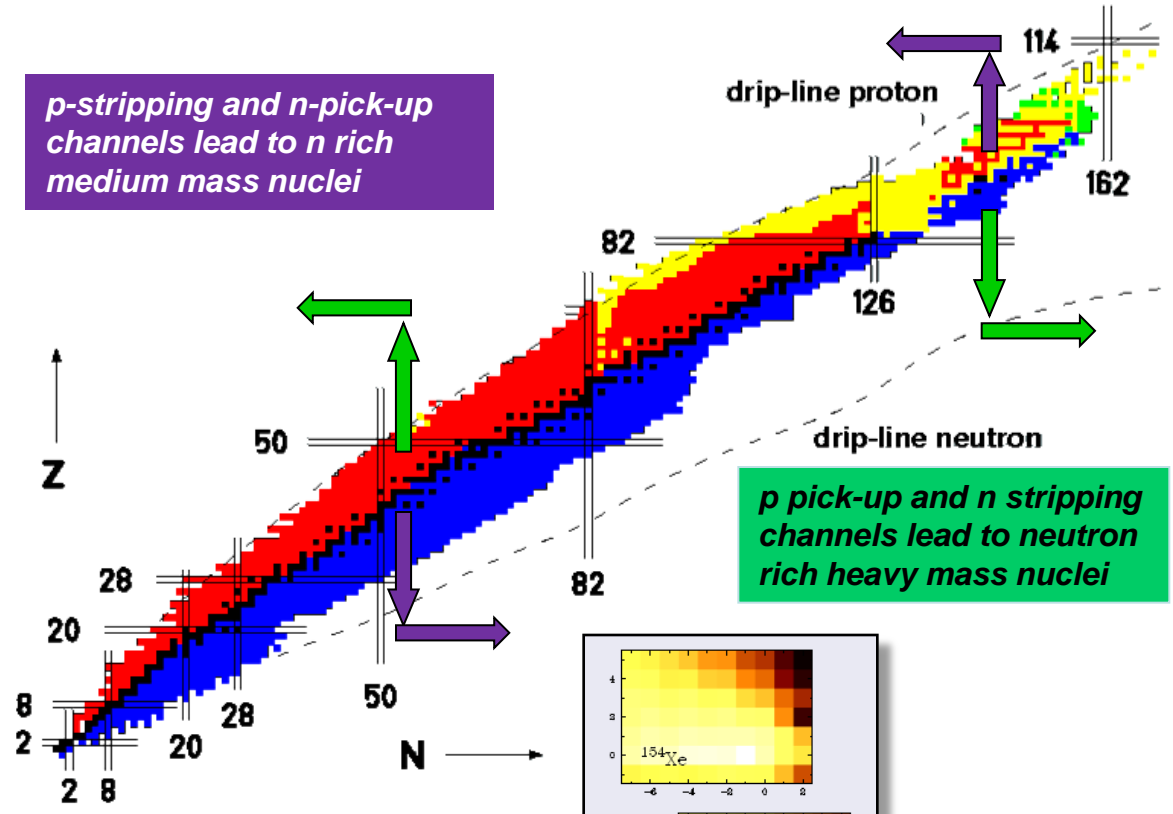
- Reaction dynamics

D. Ackermann, L. Corradi, E. Fioretto, D. Montanari, G. Montagnoli, G. Pllatolo, F. Scarlassara, A.M. Stefanini, S. Szilner

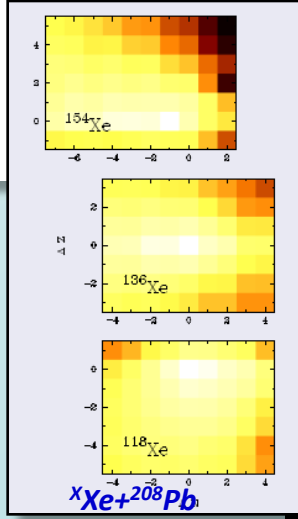
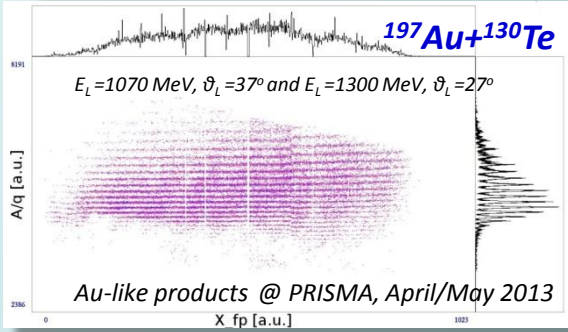


- investigation of transfer reaction dynamics**
- n* rich projectiles favor *p* pick-up/*n* stripping (light partner)
 - caution: *n* evaporation and (transfer induced) fission shifts towards stability
- instrumental requirements:**
- large acceptance magnetic (tracking) spectrometer (PRISMA/VAMOS type)
 - also in coincidence with particle and γ detector arrays
 - detection of the heavy partner
 - high spatial and energy resolution (PRISMA:
 - $\Delta x, \Delta y \approx 1\text{mm}$
 - $\Delta \theta_{in} \approx 1^\circ$
 - $\Delta E \approx 1\%$

p-stripping and *n*-pick-up channels lead to *n* rich medium mass nuclei



PRISMA@LNL



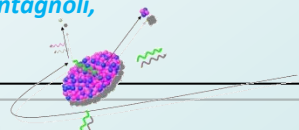
C.H. Dasso, G. Pollaro, A. Winther, PRL73 (1994) 1907;
L. Corradi, G. Pollaro, S. Szilner, J. of Phys. G 36 (2009) 113101



Multi nucleon transfer as a tool to study n-rich species

- research topics ...

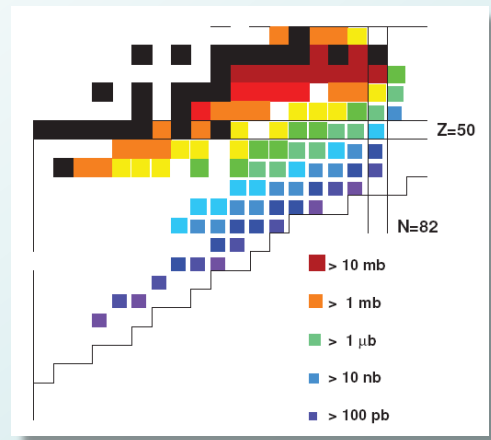
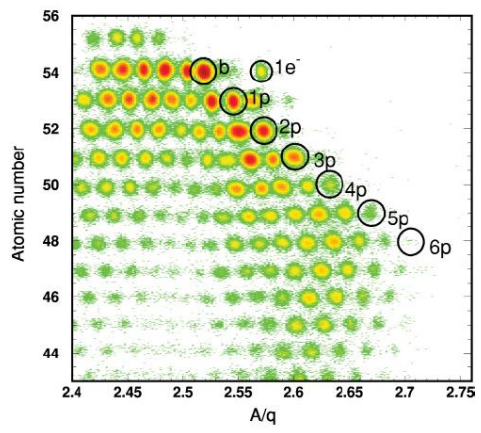
D. Ackermann, L. Corradi, E. Fioretto, D. Montanari, G. Montagnoli, G. Pllatolo, F. Scarlassara, A.M. Stefanini, S. Szilner



Fragmentation reactions of Xe isotopes at 1 A GeV on light targets

- competitive with fragmentation – where and to what extent?
- complementarity

J. Benlliure et al., Phys.Rev.C78 (2008) 054605



- production and nuclear structure of n-rich species (actinides, Z=82, N=126)

- population of high-A/high-Z in the tail of the transfer mass distribution

$^{136}\text{Xe} + ^{248}\text{Cm} \rightarrow$ Neutron-Rich Below-Target Nuclides

103	Li 252	Li 253	Li 254	Li 255	Li 256	Li 257	Li 258	Li 259	Li 260	Li 261	Li 262
	0.36s	1.46	0.57	13s	16.4	2.1	0.65s	3.9s	6.3s	30m	3.6s
102	No 250	No 251	No 252	No 253	No 254	No 255	No 256	No 257	No 258	No 259	No 260
	46	42	0.93	0.78	2.8s	1.7s	0.28	55s	3.1m	2.91s	24.5s
101	Md 247	Md 248	Md 249	Md 250	Md 251	Md 252	Md 253	Md 254	Md 255	Md 256	Md 257
	0.24	1.4	7s	7	19s	52s	4.0m	2.3m	-6m	10	28
100	Fm 246	Fm 247	Fm 248	Fm 249	Fm 250	Fm 251	Fm 252	Fm 253	Fm 254	Fm 255	Fm 256
	5.1s	43	29	38s	2.6m	1.8	30h	5.30h	25.39d	3.0d	3.24h
99	Es 245	Es 246	Es 247	Es 248	Es 249	Es 250	Es 251	Es 252	Es 253	Es 254	Es 255
	1.1m	7.7m	4.55m	27m	1.7h	2.22	8.6	33h	471.7d	20.47d	39.37h
98	Cf 244	Cf 245	Cf 246	Cf 247	Cf 248	Cf 249	Cf 250	Cf 251	Cf 252	Cf 253	Cf 254
	19.4d	43.6m	35.7h	3.11h	333.5d	350.8s	13.08h	898s	2.645s	17.81d	60.5d
97	Bk 243	Bk 244	Bk 245	Bk 246	Bk 247	Bk 248	Bk 249	Bk 250	Bk 251		
	4.5h	4.35h	4.90d	1.80d	1390s	23.7	39d	3.217h	55.6m		
96	Cm 242	Cm 243	Cm 244	Cm 245	Cm 246	Cm 247	Cm 248	Cm 249	Cm 250	Cm 251	
	162.94d	29.1d	18.10d	43.6m	35.7h	3.11h	3.40h	24.15m	-970s	16.8m	
95	Am 241	Am 242	Am 243	Am 244	Am 245	Am 246	Am 247				
	432.2a	141	16	7370h	26.10	2.65h	25	39			
94	Pu 240	Pu 241	Pu 242	Pu 243	Pu 244	Pu 245	Pu 246	Pu 247			
	6561a	14.35s	3.8.10 ⁻⁸ s	4.9591m	6.10 ⁻⁸ s	10.5h	10.85d	2.27d			
93	Np 239	Np 240	Np 241	Np 242	Np 243	Np 244					
	2.355d	7.32	65	13.9m	2.2	5.5	1.85m	2.29m			
92	U 238	U 239	U 240	U 242							
	29y	23.5m	14.1h	16.8m							

2 0.2 $^{136}\text{Xe} + ^{254}\text{Es}$

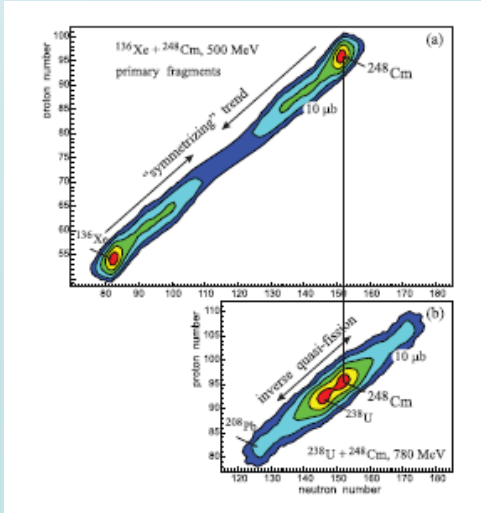
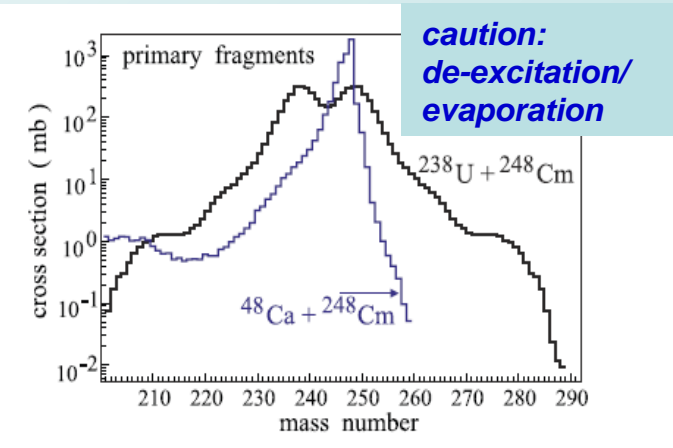
30 2 $^{136}\text{Xe} + ^{248}\text{Cm}$ Prediction by: K.E. Gregorich et al. PRC 35 (1987) 2117

cross section / μb

30 3 2 0.2 $^{136}\text{Xe} + ^{244}\text{Pu}$

100 20

GS I Darmstadt M. Schädel, IRIS10 GSI 1.3.2010 Nuclear Chemistry Group

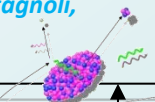


V.I. Zagrebaev and W. Greiner, Phys.Rev.C87 (2013) 034608

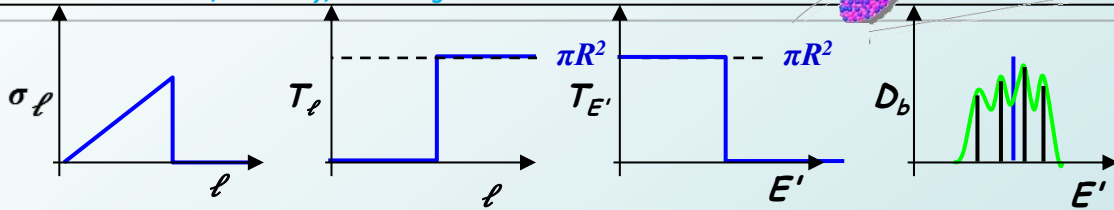
Fusion barrier distribution – alternative approach

- the CN spin distribution

D. Ackermann, L. Corradi, E. Fioretto, D. Montanari, G. Montagnoli, G. Pollarolo, F. Scarlassara, A.M. Stefanini, S. Szilner, A.Gade, Z. Kohley, W. Mittig



- D_b from 1st derivative of the transfer function
 T_ℓ equivalent to $E \cdot \sigma_{fus}$
- high spin part covers complete barrier distribution at one $E_{proj} \square V_b$ rather than many precise cross section measurements at small ΔE
 - n-rich projectiles for isospin dependent fusion barrier investigations
 - ...
- instrumental requirements:
- highly efficient ($\approx 80\%$ at $E_\gamma < 500$ keV)
 γ multiplicity array (CAESAR, DA-HD Crystalball, GASP...)
 - ER trigger
 - not evaporation channel selective
 → only separator
 - channel selective
 → e.g. Ge-detector (array) (GASP, AGATA, GREINA...)
 - separator
 - $E_{pro} \approx 5$ A MeV
 - $E_{ER} \approx 0.1-1$ A MeV
 - gas filled (TASCA, VAMOS, PRISMA)
 → $B\rho \geq 2.5$ Tm
 - vacuum type
 - v-filter (SHIP, LISE)
 - mass spectrometer (FMA/RMS...)
 - ...



$$\sigma_\ell(E) = T_\ell(E, \ell) (2\ell + 1) \pi \tilde{\lambda}^2$$

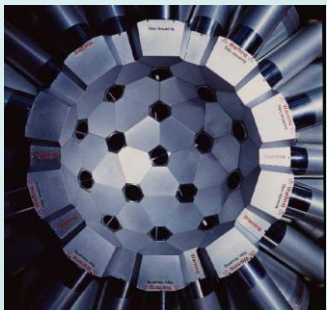
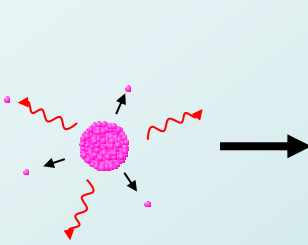
$$T_\ell(E, \ell) = \frac{\sigma_\ell(E)}{(2\ell + 1) \pi \tilde{\lambda}^2}$$

$$T_\ell \rightarrow T_{E'}$$

$$\ell \rightarrow E'$$

with $E' = E - \frac{\ell(\ell + 1)}{2\mu R_b^2}$

$$D_b = \frac{dT_{E'}}{dE'}$$



M_γ

γ multiplicity filter + ER trigger

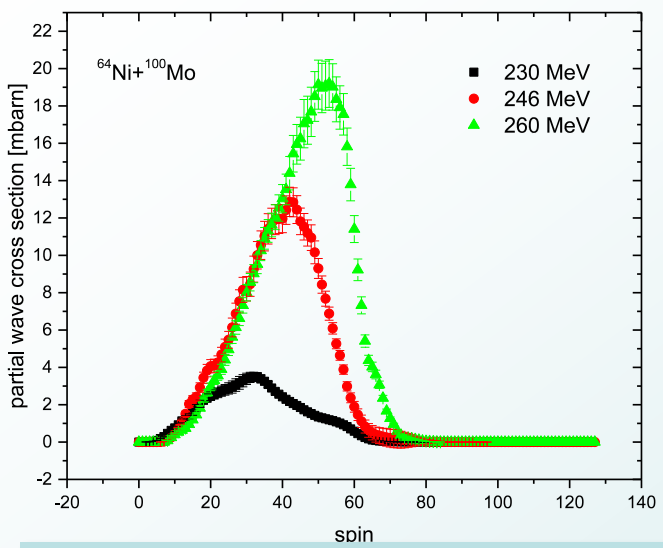
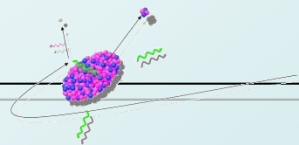
$$\ell_{CN} = (M_\gamma - M_{\gamma s}) \Delta \ell_\gamma + M_{\gamma s} \Delta \ell_\gamma + \sum_i \Delta \ell_i + \Delta \ell_{gs/m}$$

$i = p, n, \alpha$

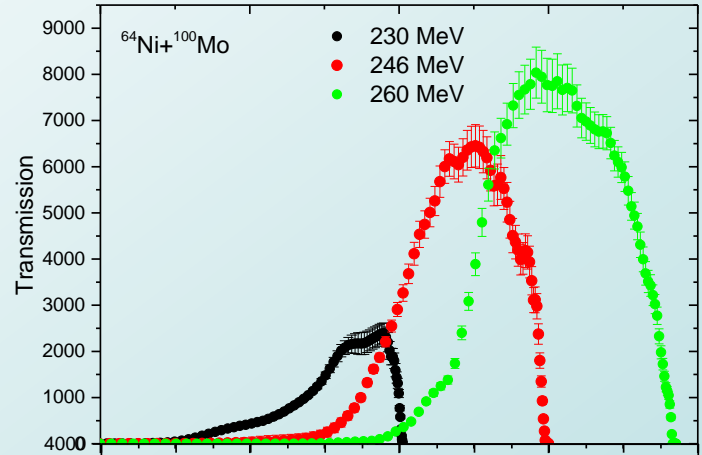
D. Ackermann et al., Eur.Phys.J. A 20 (2004) 151

Extraction of the barrier distribution for $^{64}\text{Ni}+^{100}\text{Mo}$

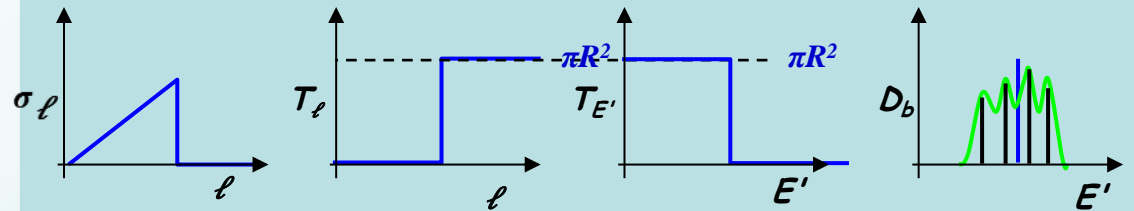
- analysis by Varinderjit Singh, Panjab University, India



spin $\ell \rightarrow E'$
 with $E' = E - \frac{\ell(\ell+1)}{2\mu R_b^2}$



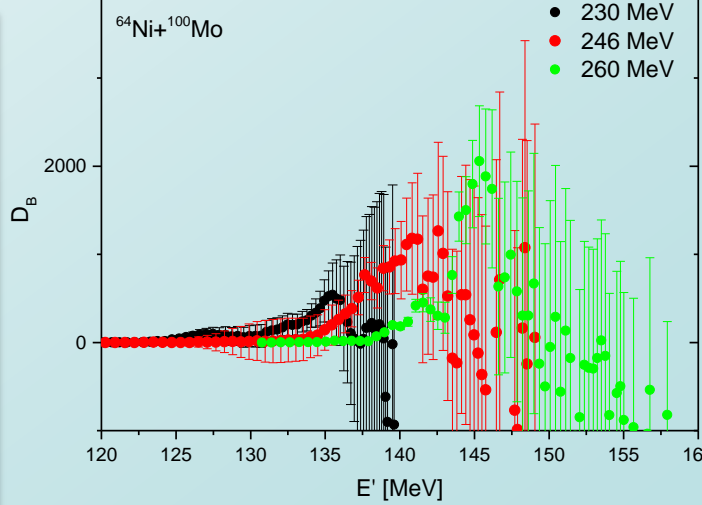
Step wise transformation σ_ℓ to D_b



• transmission function $T(E')$ ($T(\ell)$)

• barrier distribution

- covers large energy range E' for one E_{beam}
- sensitive only for fusion-evaporation
- fission cut-off leads to truncation at low $E' \leftrightarrow$ high ℓ

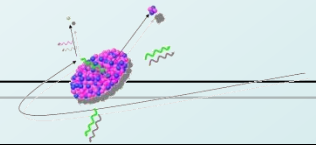


priliminary – analysis ongoing



Entrance channel effect on ER spin distribution

- G. Mohanto et al., Nucl. Phys. A 890–891 (2012) p. 62–76



Abstract

... **ER gated gamma-multiplicity** was measured for the reaction $^{30}\text{Si}+^{170}\text{Er}$

... measured multiplicity distribution was **compared ... $^{16}\text{O}+^{184}\text{W}$ and $^{19}\text{F}+^{181}\text{Ta}$ forming the same CN ... with **statistical model calculations** ... indicate an absence of higher spins in ERs for $^{30}\text{Si}+^{170}\text{Er}$... lowering of spin value is **attributed to non-compound fission**.**

HYRA + T.I.F.R. 4 π spin spectrometer at the IUAC, New Delhi

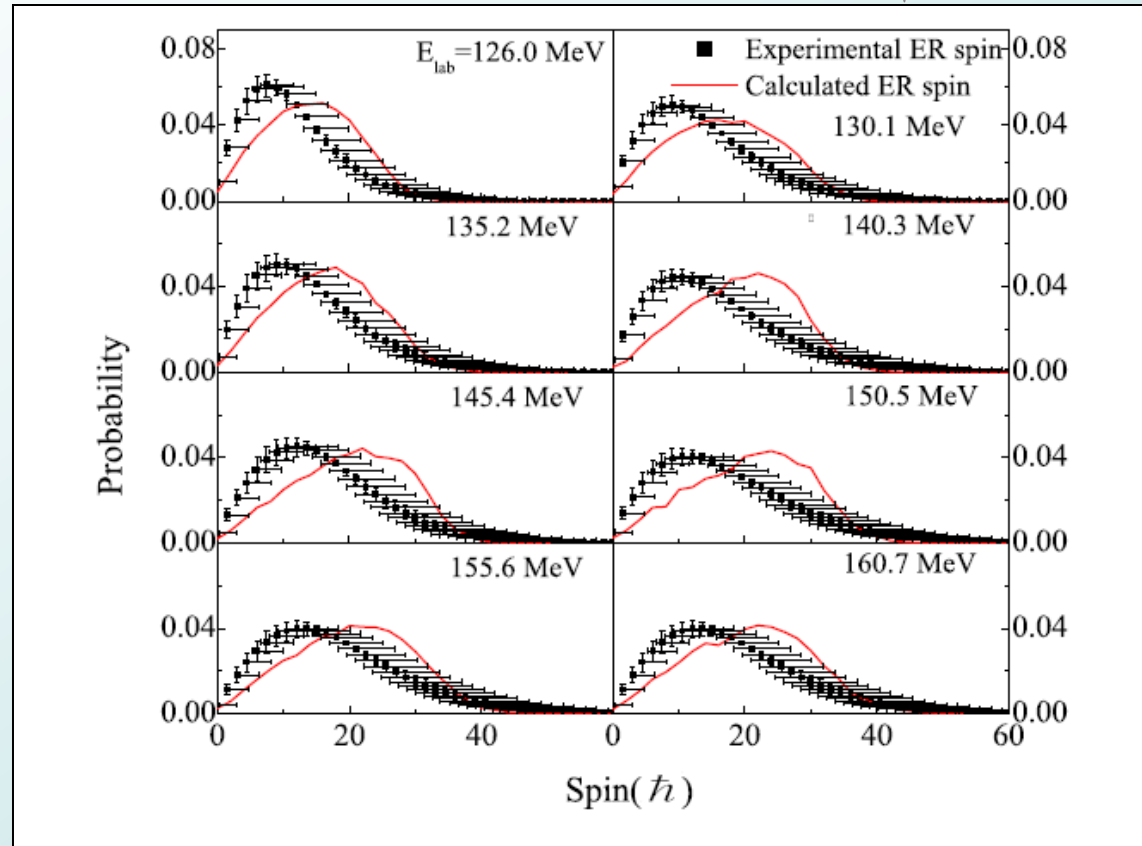


Fig. 11. Calculated and experimentally obtained ER spin distribution for the reaction $^{30}\text{Si}+^{170}\text{Er}$. The experimental ER spin is the spin remaining after particle evaporation. It is obtained by multiplying the gamma-multiplicity by $1.5\hbar$.