UCRL-PRES-235968

Nuclear Reactions used for Superheavy Element Research

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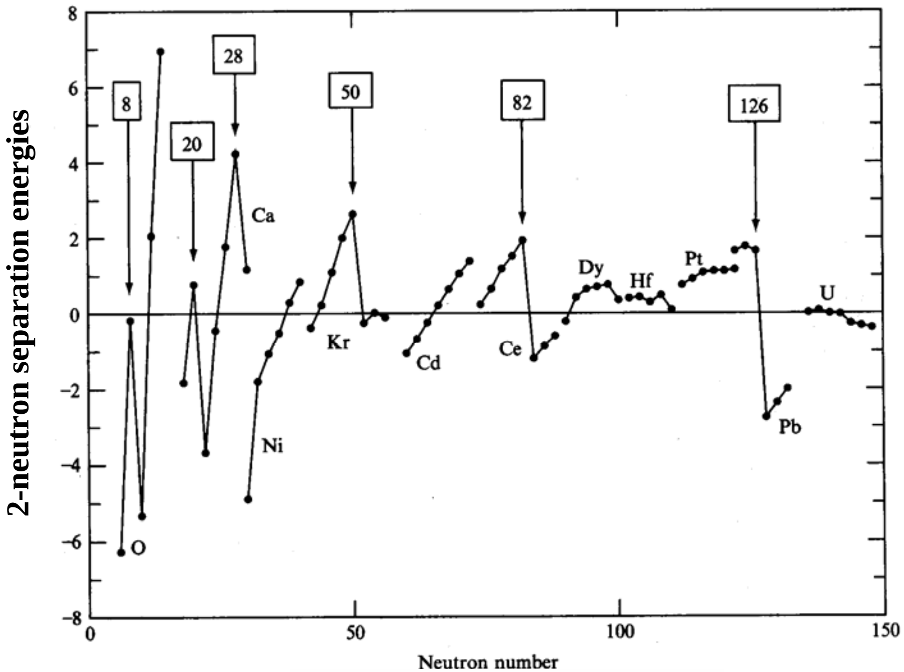
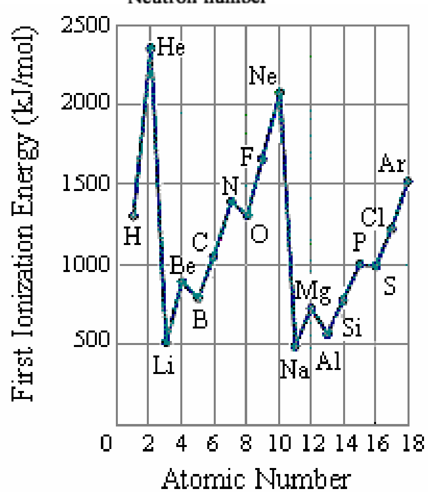
Introduction and Background

- Background on Superheavies
- Discussion of recent developments in SHE field
- Comparison of nuclear reactions
- Conclusions and future

The existence of certain "magic" numbers of neutrons or protons has been known for nuclei, prompting the development of the shell model and analogies to filled electronic orbits in chemistry





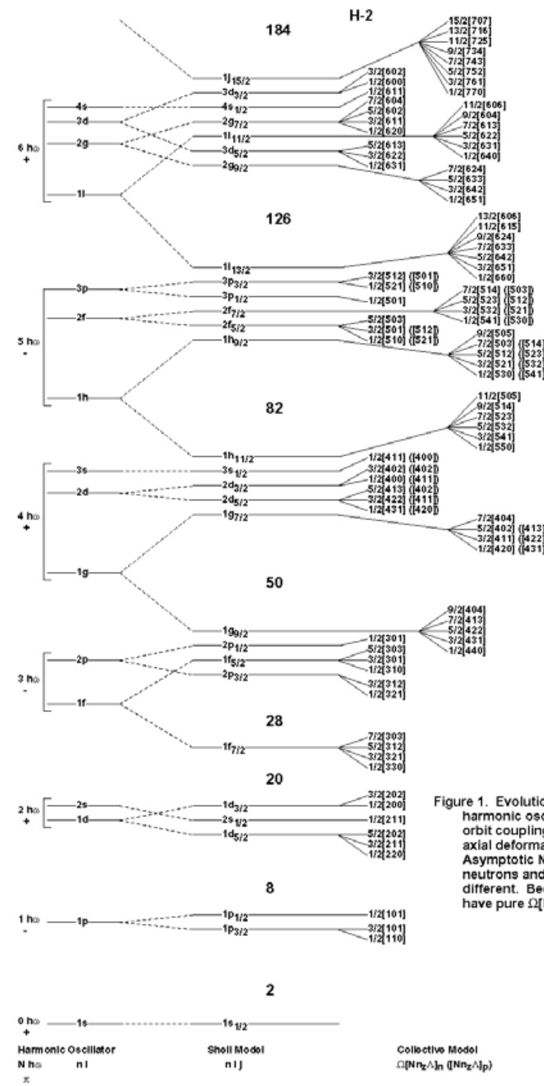
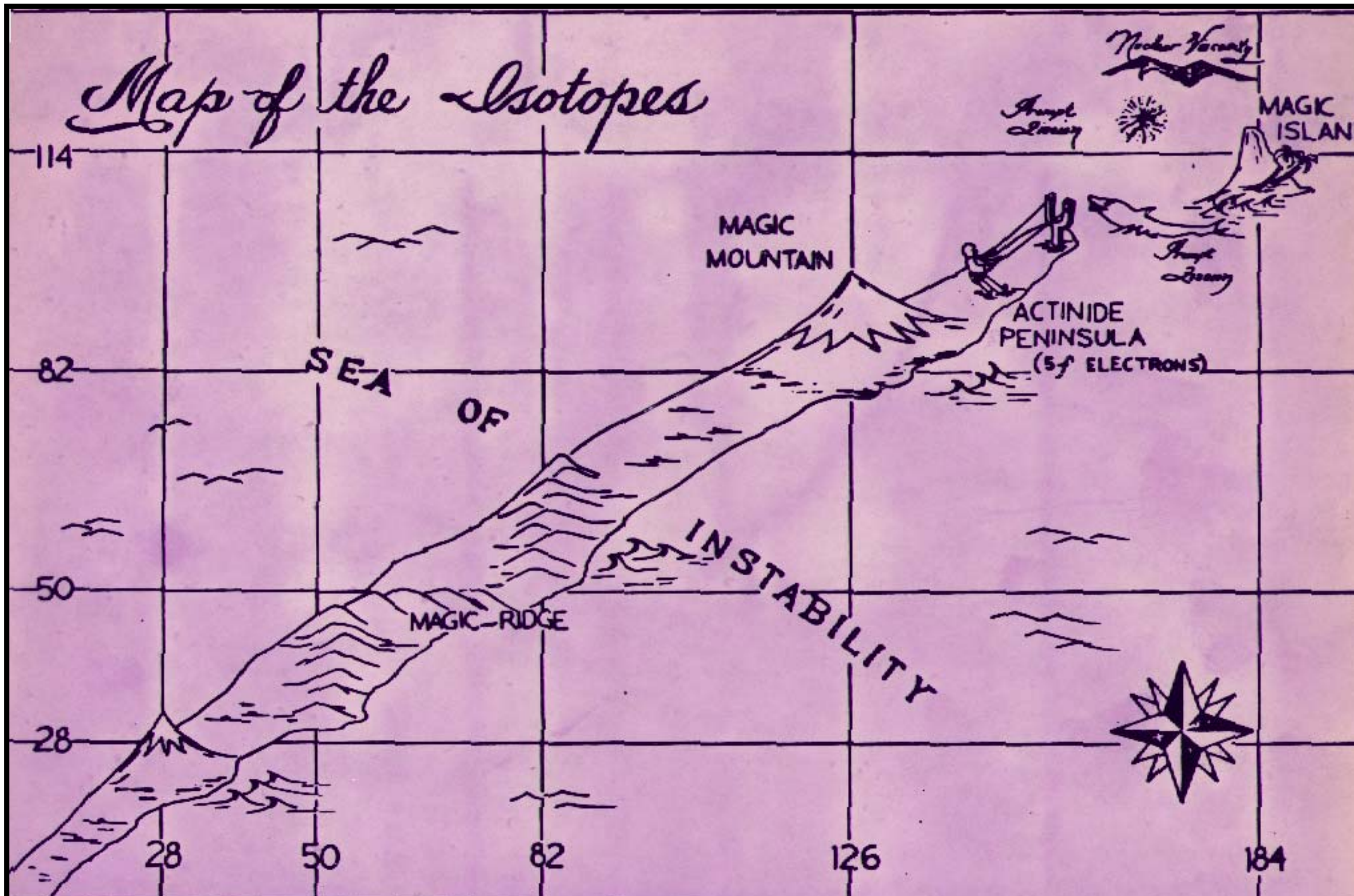


Figure 1. Evolution of nuclear models from the harmonic oscillator model, adding strong spin-orbit coupling to obtain the shell model, and axial deformation to give the collective model. Asymptotic Nilsson configurations are given for neutrons and, in parentheses, for protons when different. Because of mixing, very few states have pure $\Omega[Nn_z\Lambda]$ configurations.

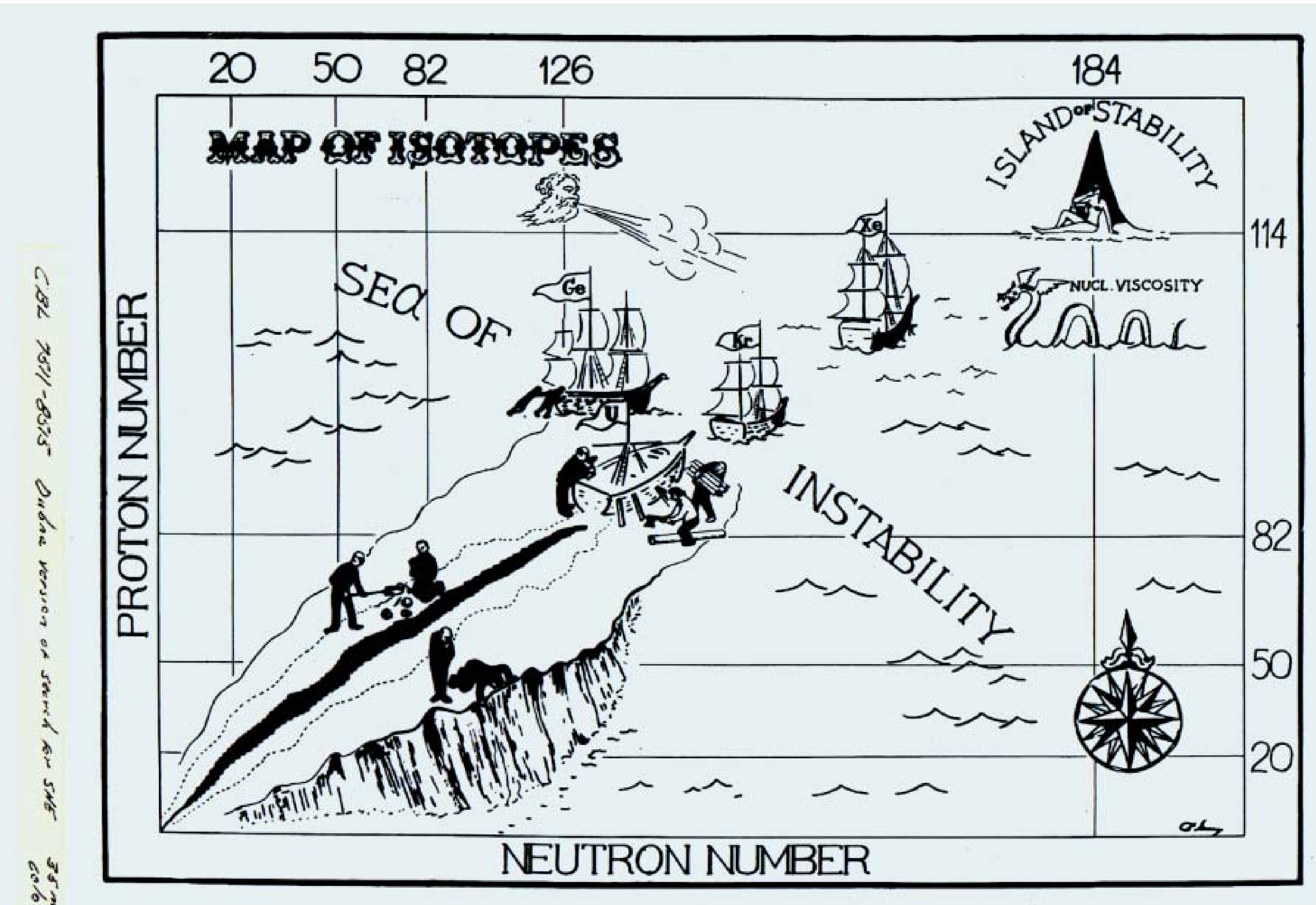
Nuclear theory at Berkeley, circa 1969

Proton number

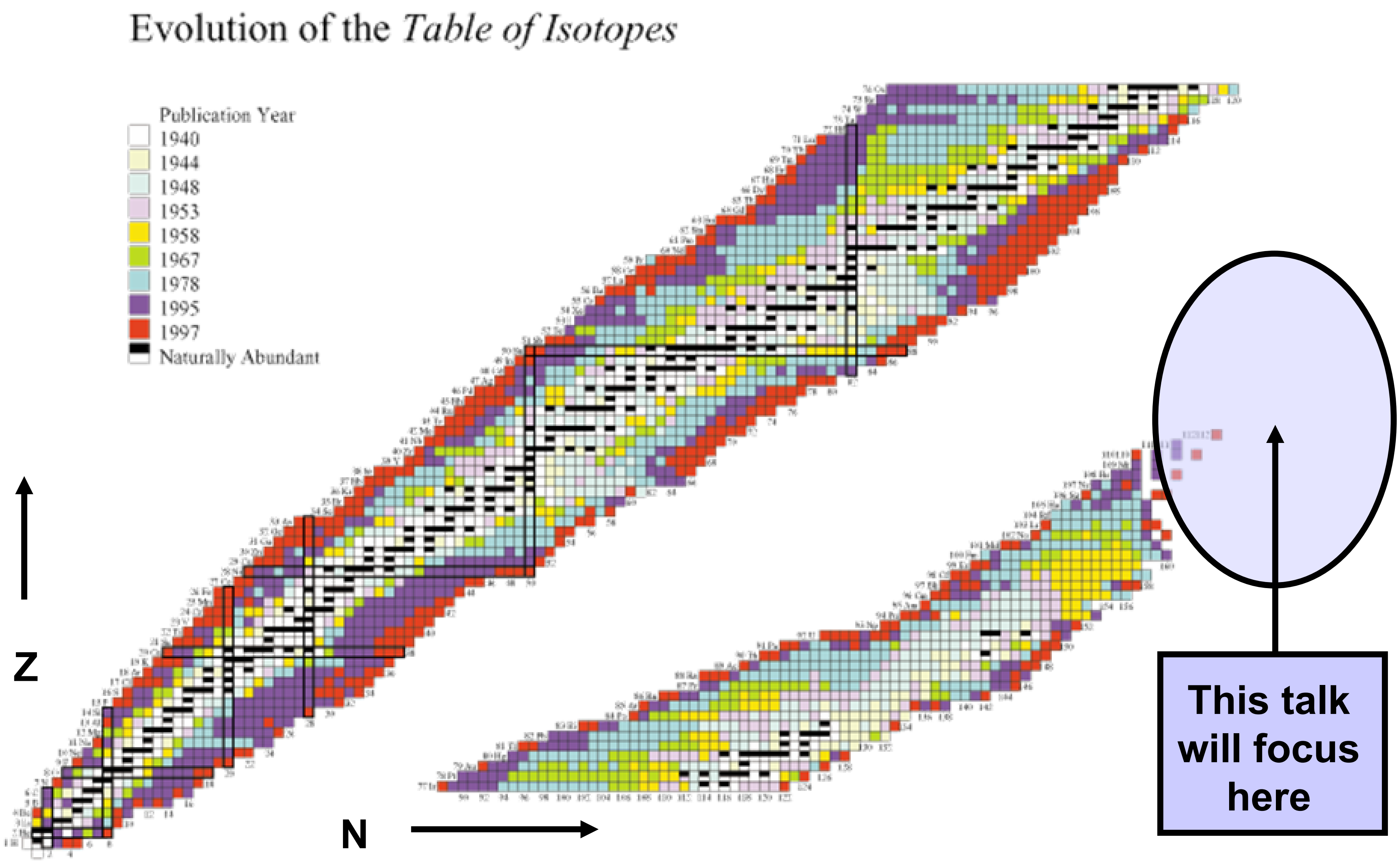


Neutron number

Nuclear theory in the Soviet Union, circa 1969



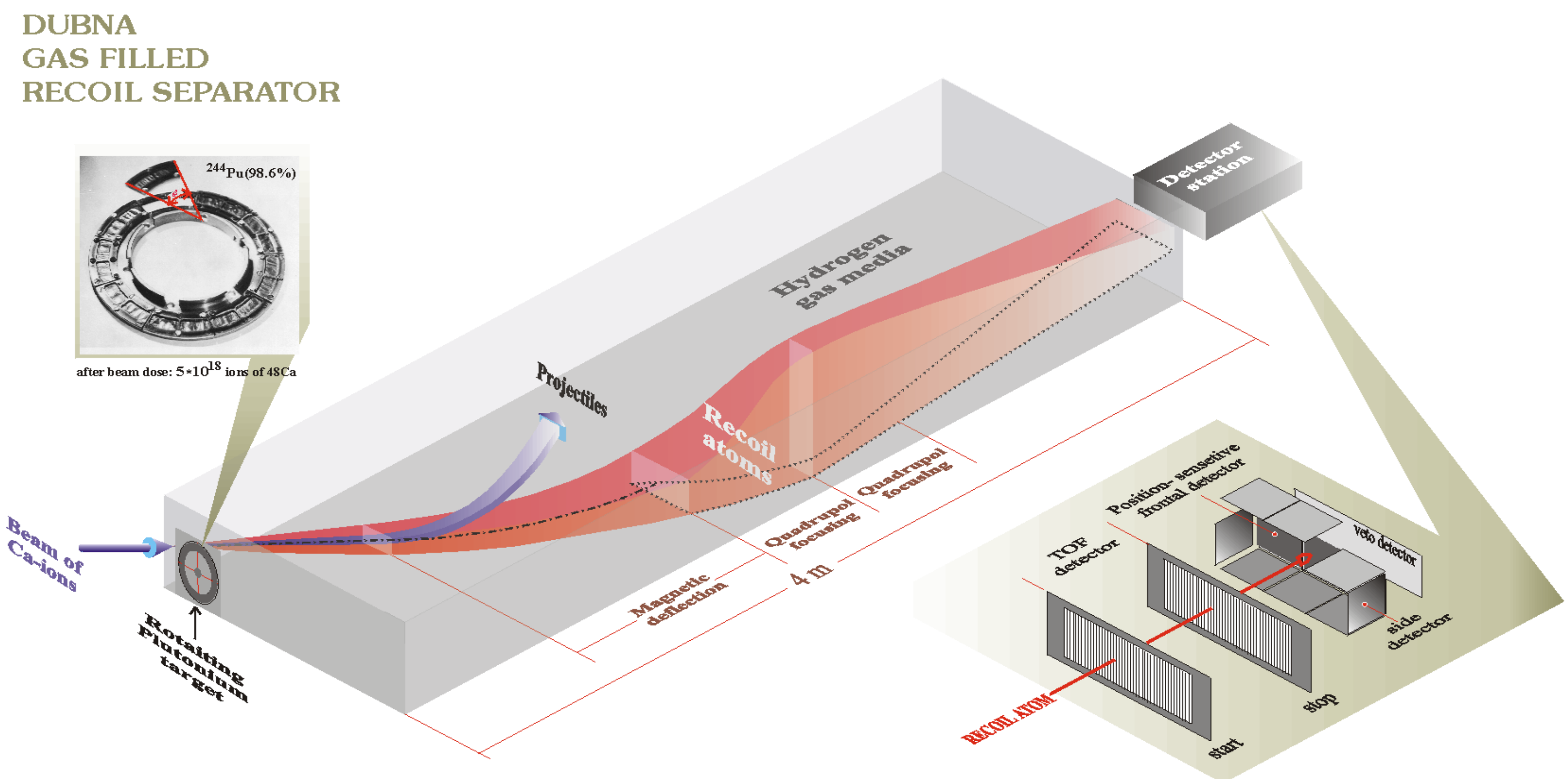
New isotope discovery has been rapid since the mid-1900's and routinely operating particle accelerators



Typical techniques for producing Heavy Elements or SHE

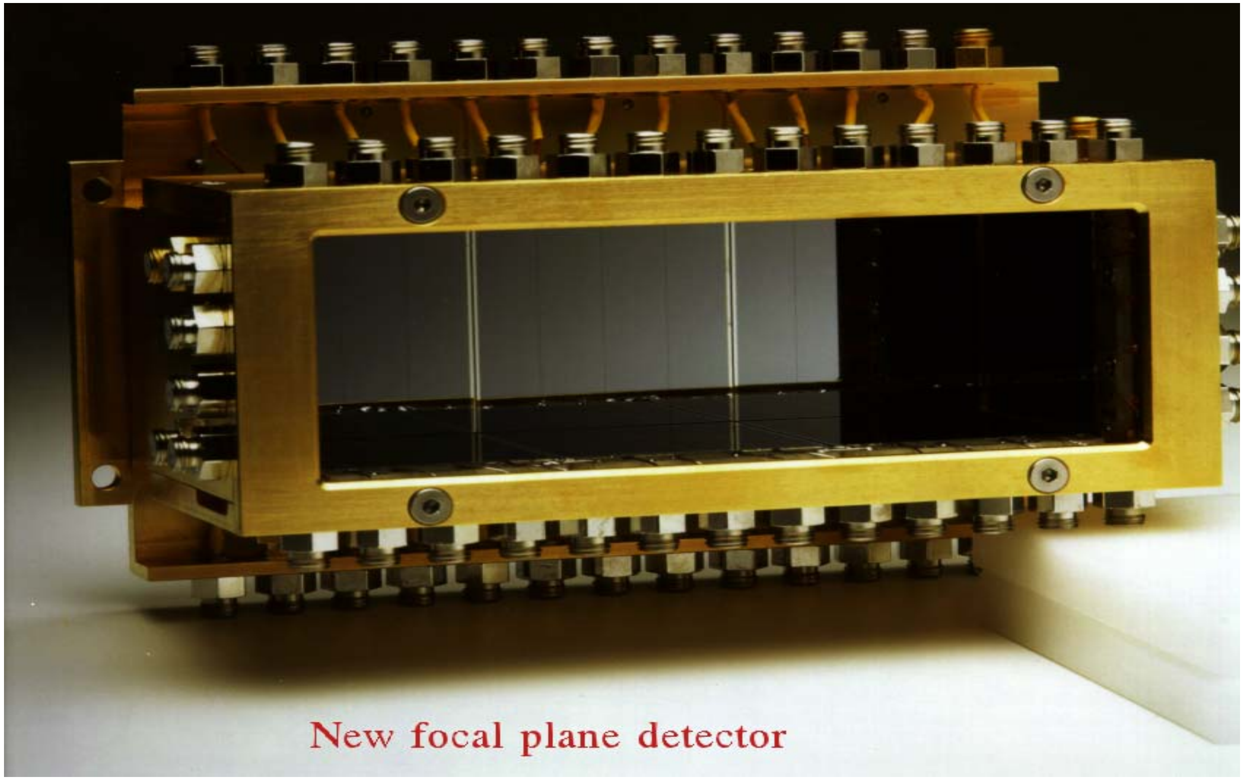
- **Most facilities use heavy ion accelerators to bombard targets and produce fusion/evaporation residues for further study, although transfer reactions are sometimes possible**
  - **"Cold Fusion" reactions (e.g. $^{70}Zn + {}^{208}Pb$)**
  - **"Hot Fusion" reactions (e.g. $^{48}Ca + {}^{243}Am$)**
- **Separation of "Goodies" from unwanted products**
  - **Separators like DGFS, BGS**
  - **Separators like VASSALISSA, SHIP**
  - **Advanced separators (MASHA …)**
  - **Fast and/or automated chemistry**
- **Detection and identification of "Goodies"**

The Dubna gas-filled separator uses a combination of chemistry and physics to suppress unwanted reaction products



Yuri Oganessian FLNR (JINR) June 14, 1999

The high-efficiency detector system

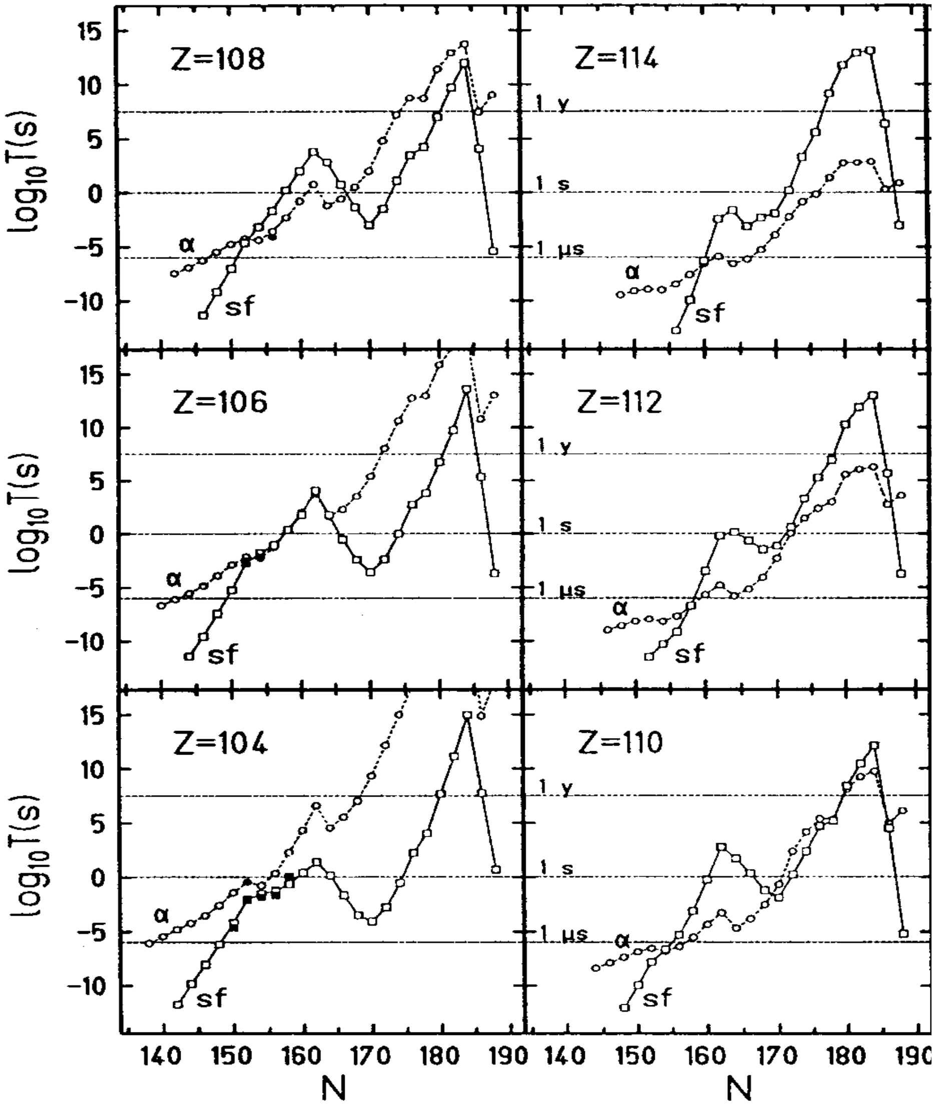


The addition of the top, bottom, and side detectors increased the geometry for counting α particles from 50% to 87%.

Veto detectors mounted behind the focal plane were used to identify and reject light charged particles passing through the separator.

The results of the predictions enabled us to plan experiments in this region

- With increasing nuclear charge, decay by alpha-emission becomes favored over decay by SF as one approaches the vicinity of the closed nuclear shells
- The signature of the decay of a superheavy nucleus is a series of alpha decays followed by a spontaneous fission
- The reaction of ^{48}Ca with ^{244}Pu results in a compound nucleus with Z=114 and N=178



Courtesy Yuri Oganessian

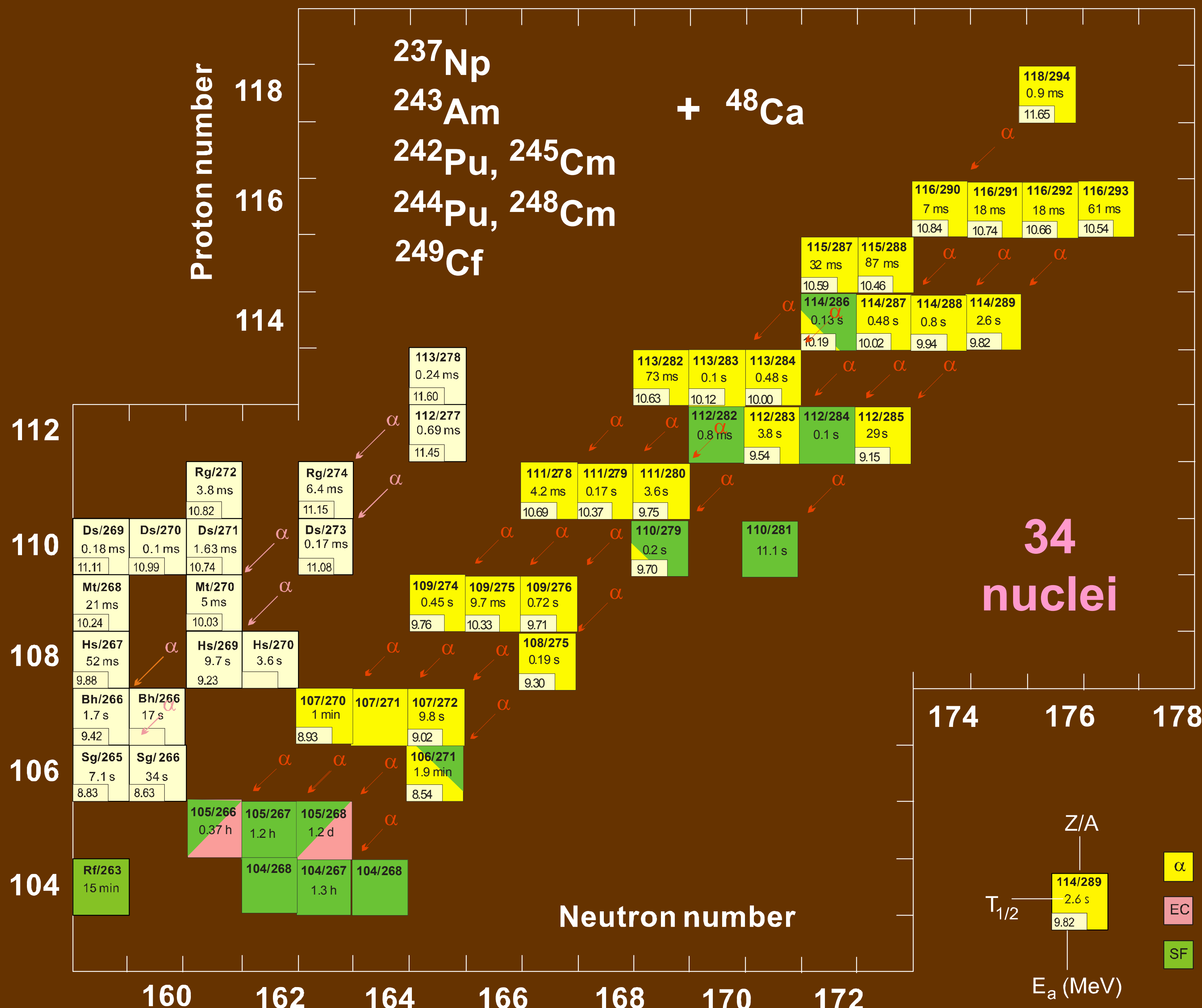
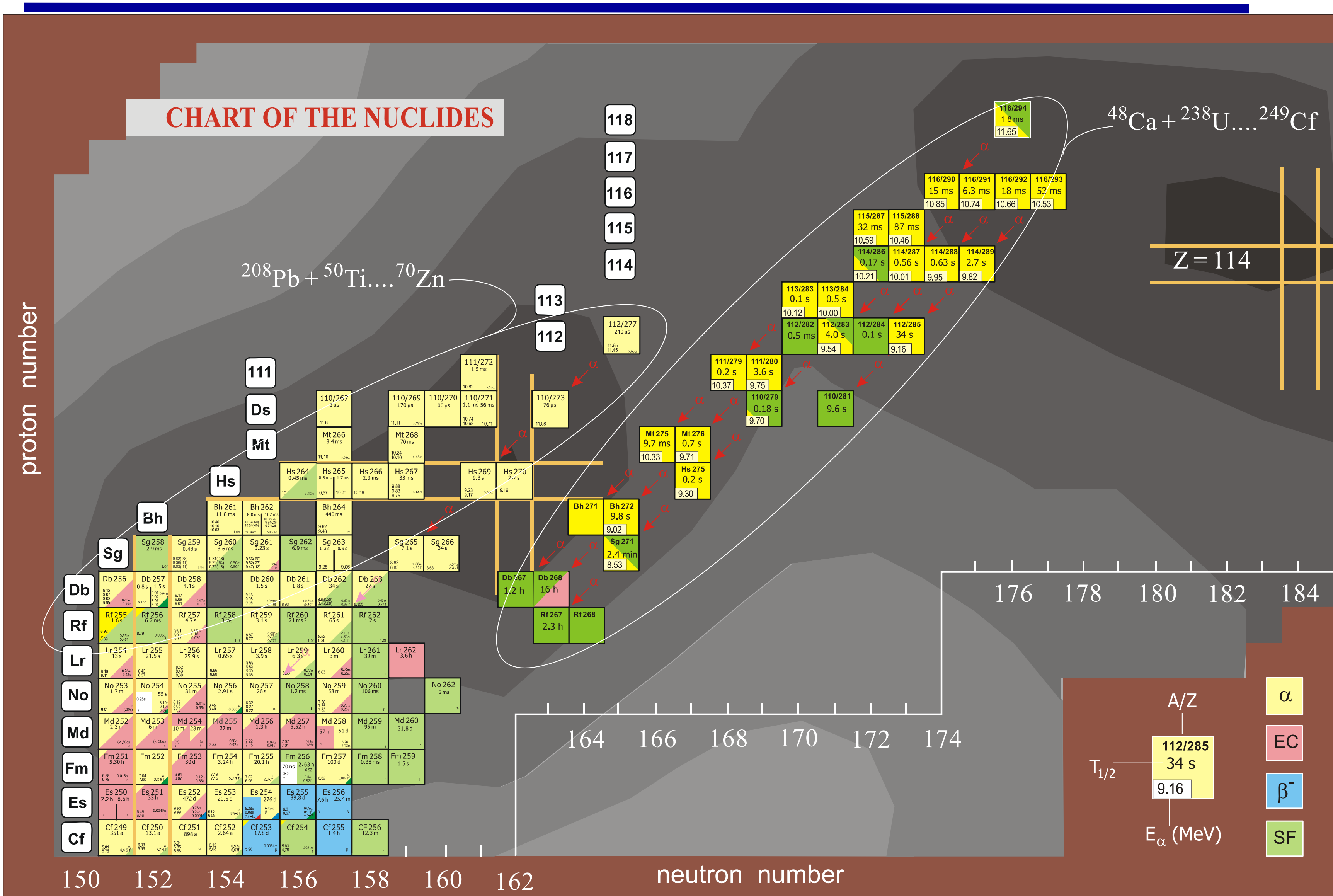


Chart of Nuclides about 2004



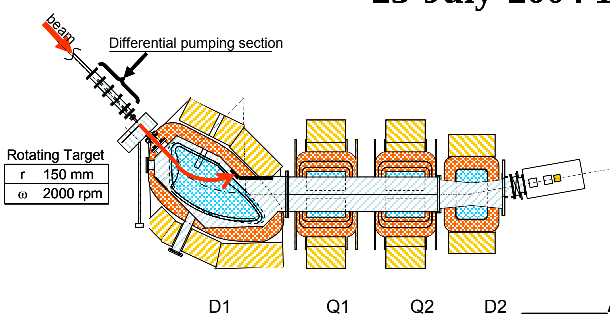
In the last few years, there have been some interesting advances in superheavy element research

- Experiments by Dubna/Livermore collaboration with DGFRS on elements 113, 114, 115, 116 and 118
  - Yu. Ts. Oganessian, et al., Phys. Rev. Lett. 83 (1999) 3154; Phys. Rev. C 69 (2004) 054607; Phys. Rev. C 69 (2004) 021601; and Phys. Rev. C 74 (2006) 044602.
- Experiments by RIKEN on element 113
  - K. Morita, et al., J. Phys. Soc. Japan 73 (2004) 2593.
- Experiments by PSI/Dubna collaboration on chemistry of element 112
  - R. Eichler, et al. in Proceedings of the IX International Conference on Nucleus Nucleus Collisions held Aug. 28 - Sep. 1, 2006 in Rio de Janiero, Brazil, Nucl. Phys. A. 787 (2007) 373c.
- Experiments by Dubna/Livermore collaboration on chemistry of Db – the decay descendent of element 115
  - S.N. Dmitriev, et al., Mend. Commun. 1 (2005) 1; Yu. Ts. Oganessian, et al., Phys. Rev. C 72 (2005) 034611 and N.J. Stoyer, et al. in Proceedings of the IX International Conference on Nucleus Nucleus Collisions held Aug. 28 - Sep. 1, 2006 in Rio de Janiero, Brazil, Nucl. Phys. A. 787 (2007) 388c.
- Experiments by Jyväskylä and ANL on detailed nuclear spectroscopy of ^{254}No
  - R.-D. Herzberg, et al., Nature 442 (2006) 896 and S.K. Tandel, et al., Phys. Rev. Lett. 97 (2006) 082502.
- Experiments by GSI on ^{48}Ca + ^{238}U → ^{283}112 – S. Hofmann, et al., EPJA 32 (2007) 251.

RIKEN cold fusion reaction to produce element 113

^{209}Bi + ^{70}Zn → ^{278}113 + n

GARIS



1st chain

23-July-2004 18:55 (JST)

36.75 MeV
TOF 44.61 ns
30.33 mm

^{278}113 CN

α: 11.68 MeV (PSD), 344 μs, 30.49 mm

^{274}111

α: 11.15 MeV, 6.149+5.003 (PSD+SSD), 9.260 ms, 30.40 mm

^{270}Mt

α: 10.03 MeV, 1.136+8.894(PSD+SSD), 7.163 ms, 29.79 mm

^{266}Bh

α: 9.08 MeV (PSD), 2.469 s, 30.91 mm

^{262}Db

s.f.: 204.05 MeV(PSD), 40.9 s, 30.25 mm

2nd chain

2-April-2005 2:18 (JST)

36.47 MeV
TOF 45.69 ns
30.08 mm

^{278}113 CN

α: 11.52 MeV (PSD), 4.93 ms, 30.16 mm

^{274}111

α: 0.88+10.43=11.31 MeV (PSD+SSD), 34.3 ms, 29.61 mm

^{270}Mt

α: 2.32 MeV (escape), 1.63 s, 29.45 mm

^{266}Bh

α: 9.77 MeV (PSD), 1.31 s, 29.65 mm

^{262}Db

s.f.: 192.32 MeV(PSD), 0.787 s, 30.47 mm

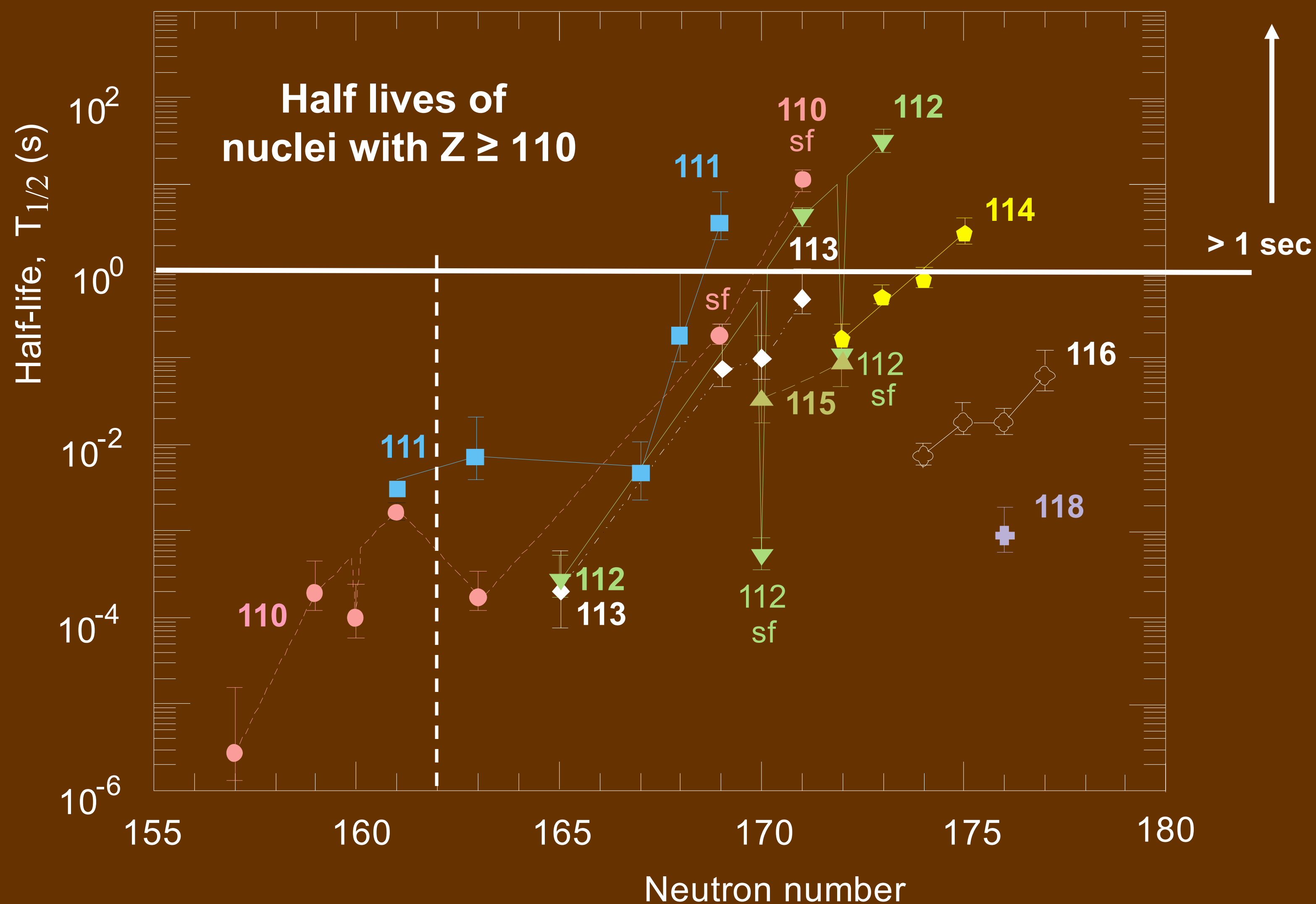
$\sigma = 78$ fb

preliminary

Chemistry will play a crucial role in exploring the "Island of Stability"

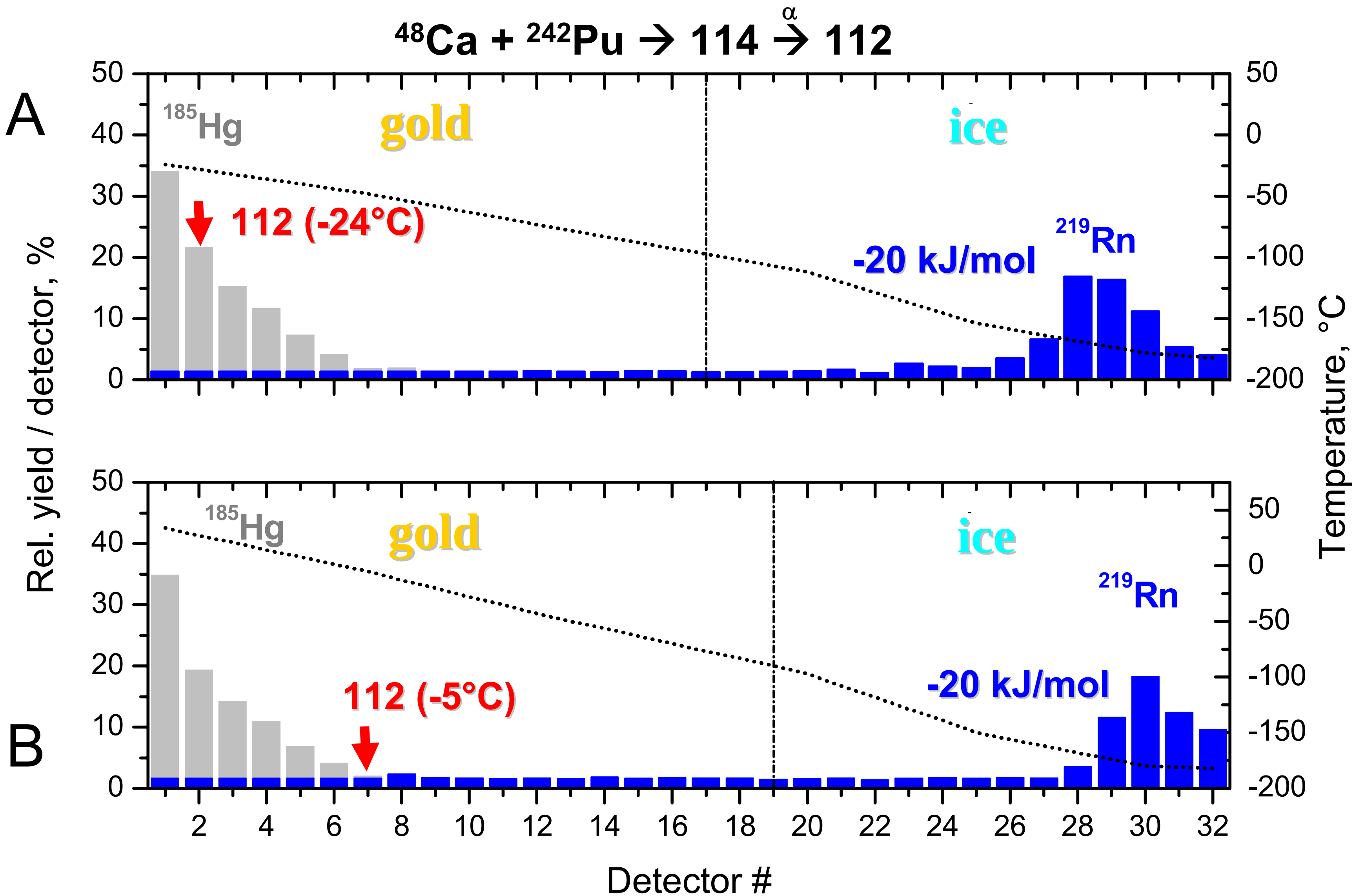
- Current experimental techniques are limited to investigation of nuclides with half-lives less than about 2 hours because random coincidence rate then dominates
- If lifetimes of isotopes nearer to the center of the "island of stability" are longer, not only will chemistry be possible, it will be *necessary* to isolate the new element and reduce counting backgrounds
- Relativistic effects already begin around Au, and will dominate the chemistry of superheavy elements, although some properties may be predictable already
- Long running times of these kind of experiments require as much automated chemistry as possible

Several long-lived nuclides are available for chemistry experiments



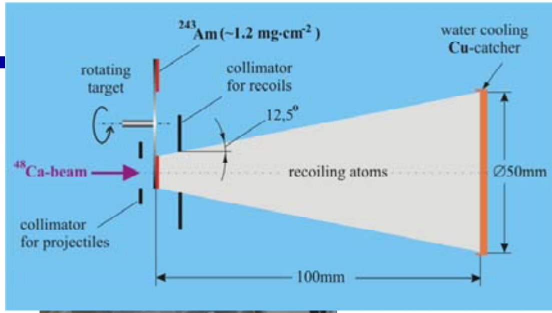
Courtesy R. Eichler

PSI/Dubna 112 experiments using COLD



In December 2005, we performed another chemical experiment to further define the chemical properties of the spontaneously-fissioning species

- Separations chemistries were developed by both JINR and LLNL groups to separate +4 and +5 groups as well as separate the +5 group into Nb-like and Ta-like fractions.
  - JINR separation scheme used anion exchange chromatography.
  - LLNL separation scheme used reverse phase chromatography.
- We used a similar set up as last time
  - We used the same reaction (^{48}Ca + $^{243}Am \rightarrow {}^{288}115$ + 3n reaction) with most irradiations about 40-hour long (2.5 – 6.9 $\times 10^{17}$ ions)
  - Reaction products were collected in a Cu block where the $^{288}115$ undergoes five alpha decays to ^{268}Db.
  - The surface (10 µm) of the Cu block was shaved and dissolved in aqua regia.
- Several tracers (^{177}Ta, ^{175}Hf, ^{92m}Nb, ^{89}Zr, ^{173}Lu), carriers (La, Ta, Hf, Nb, Zr), and NH_4OH were added.
  - Cu remained in solution, +3, +4 and +5 ions were carried with $La(OH)_3$ precipitate
- Precipitate was washed and dissolved in HCl; and NH_4OH was added and $La(OH)_3$ precipitated
- On alternate irradiations, each group performed a +4/+5 separation
  - LLNL chemists used a reverse phase column (details next), or
  - JINR chemists used an anion exchange column (details later).

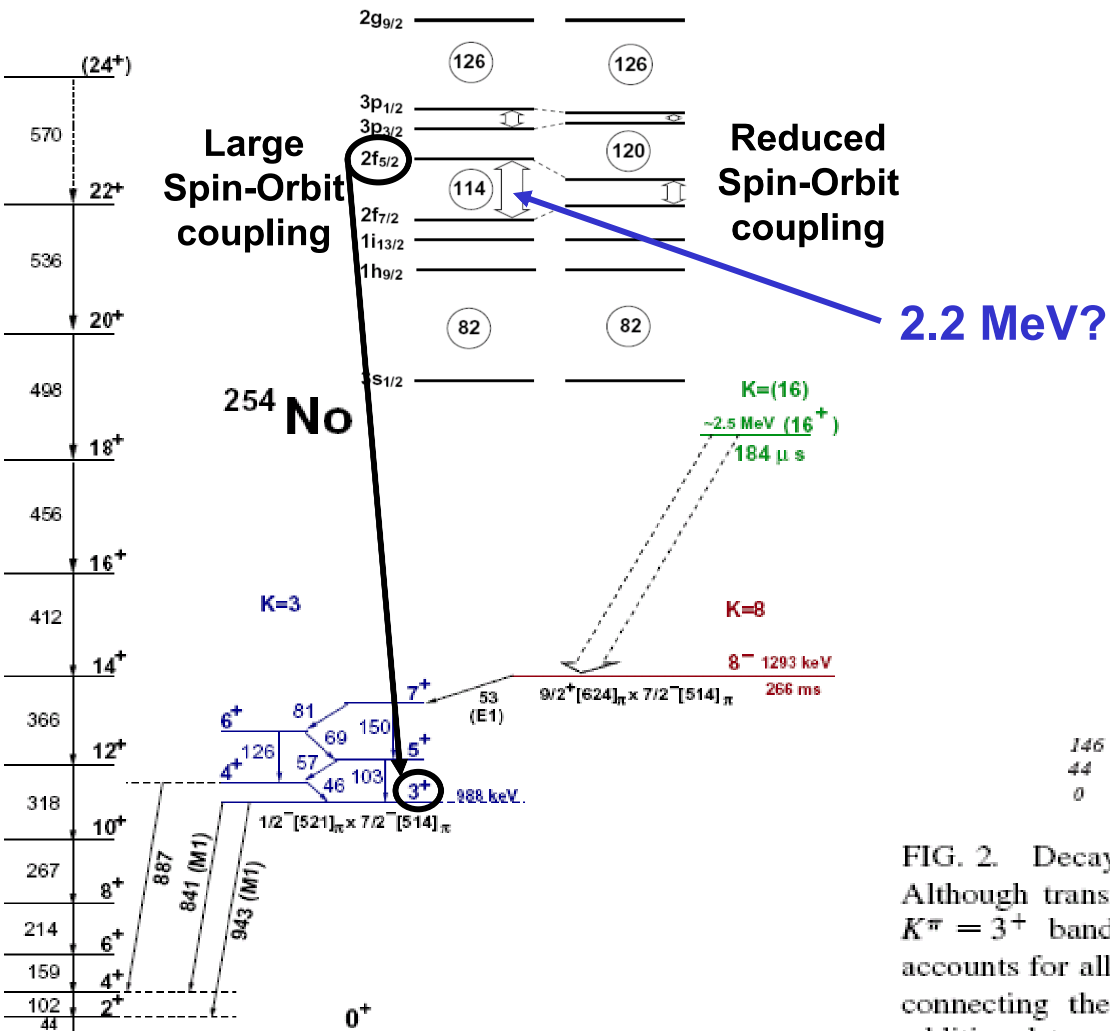


Chemistry results confirm the Db assignment and element 115 origin

Date	Beam Integral	Nb fraction	Ta fraction	Additional Information
10DEC2005	4.5×10^{17}	No SF	1 SF at 30 hrs – 2 FF 22+3 MeV + 6n	LLNL Chemistry – 96-hr counts Also Hf fraction (no SF in 48 hrs)
12DEC2005	5.2×10^{17}	1 SF at 27 hrs – 1 FF 51 MeV + 1 n		JINR Method I Chemistry – 96-hr count Also Group 4 fraction (no SF in 96 hrs)
14DEC2005	4.2×10^{17}	No SF	1 SF at 16 hrs – 2 FF 45+5 MeV + 2 n	LLNL Chemistry – 96-hr counts
16DEC2005	4.2×10^{17}	1 SF at 37 hrs – 2 FF 40+53 MeV + 3 n		JINR Method I Chemistry – 96-hr count Also Group 4 fraction (no SF in 96 hrs)
18DEC2005	4.2×10^{17}	No SF	No SF	JINR Method II Chemistry – 96-hr counts
20DEC2005	3.9×10^{17}	No SF	1 SF at 18 hrs – 2FF 66+8 MeV + 2 n	JINR Method II Chemistry – 96 hr counts
22DEC2005	4.4×10^{17}	No SF	No SF	JINR Method II Chemistry – 48-hr count for Nb fraction and 96-hr count for Ta fraction
24DEC2005	4.4×10^{17}	No SF	Two Ta fractions No SF	JINR Method II Chemistry – 96-hr count for Nb fraction, 48-hr count for one Ta fraction, and 1200-hr count for other Ta fraction

5 SF events were in Group 5 fractions, 3 of which were in Ta fractions. There were 0 SF events in Group 4 fractions or Nb fractions.

Jyväskylä/ANL work – single particle level from above the Z=114 “gap” identified using detailed nuclear spectroscopy



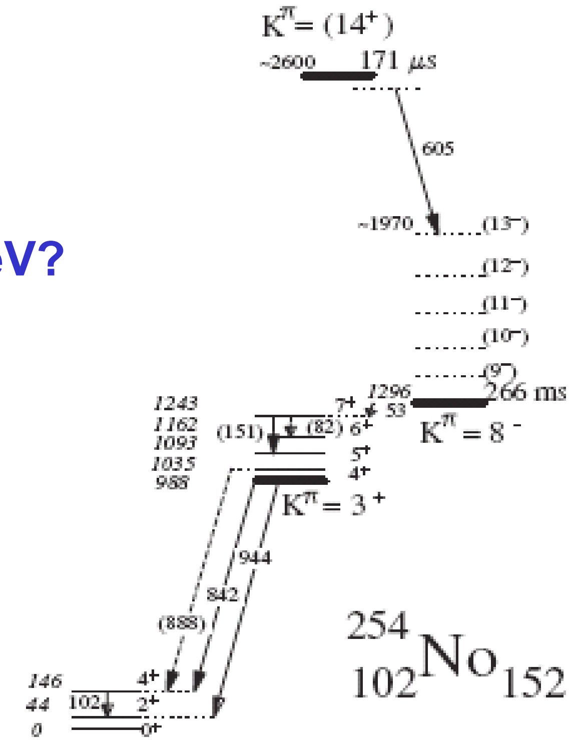


FIG. 2. Decay scheme proposed for the 2- and 4-qp isomers. Although transitions are not detected from every level of the $K^\pi = 3^+$ band, the levels are established via a model that accounts for all observed level spacings (see text). The pathway connecting the two isomers is speculative and may contain additional transitions. It is based on a model of the decay (see text) since γ rays within the $K^\pi = 8^-$ band were not detected.

Recent GSI results

Eur. Phys. J. A **32**, 251–260 (2007)
DOI 10.1140/epja/i2007-10373-x

THE EUROPEAN
PHYSICAL JOURNAL A

Regular Article – Nuclear Structure and Reactions

The reaction ^{48}Ca + ^{238}U $\longrightarrow$ ^{286}112* studied at the GSI-SHIP

S. Hofmann[1,2,a], D. Ackermann[1], S. Antalic[3], H.G. Burkhard[1], V.F. Comas[4], R. Dressler[5], Z. Gan[6], S. Heinz[1], J.A. Heredia[4], F.P. Heßberger[1], J. Khuyagbaatar[1], B. Kindler[1], I. Kojouharov[1], P. Kuusiniemi[7], M. Leino[8], B. Lommel[1], R. Mann[1], G. Münzenberg[1,b], K. Nishio[9], A.G. Popeko[10], S. Saro[3], H.J. Schött[1], B. Streicher[3], B. Sulignano[1], J. Uusitalo[8], M. Venhart[3], and A.V. Yeremin[10]

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Table 2. Properties of events assigned to the fusion reaction ^{48}Ca + ^{238}U $\rightarrow$ ^{286}112* at a mean excitation energy of 34.6 MeV.

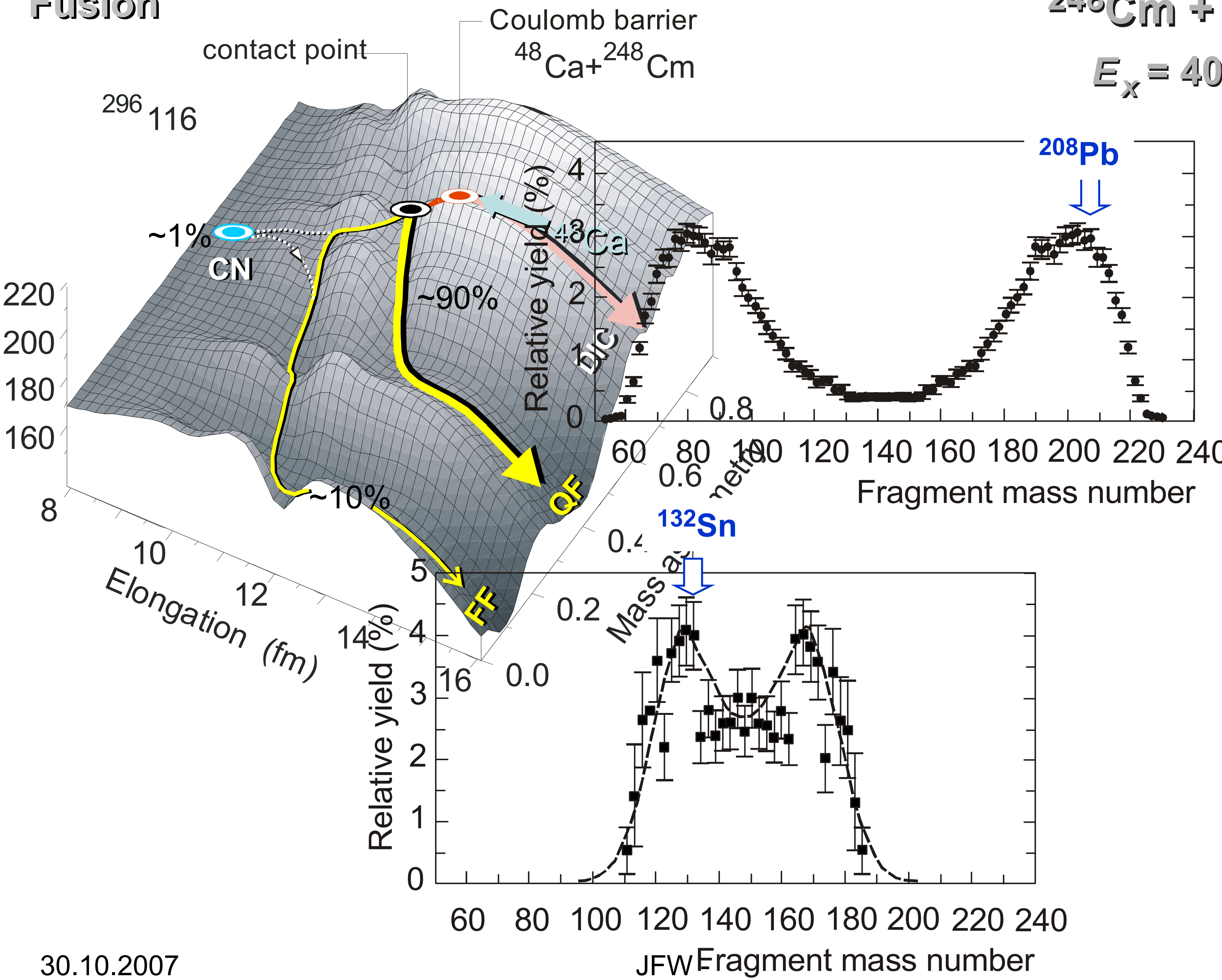
event no.	date time	t^a_{MP} /μs	E^b_{ct}(ER) /MeV	E^c_{raw} /MeV	$E^d_{ER}/E_\alpha/E_{SF}$ /MeV	A^e	n_γ	strip/box no.	y_{top} /mm	y_{bot} /mm	τ /s
ER1	08.05.2005	4,396	39.2	19.5	31.5	286	0	9	33.09	4.66	
SF	22:45 h	12,508		190.4+15.3	241±15		2	9/13	32.59	4.52	7.6
ER2	23.01.2007	2,081	39.1	25.2	34.3	293	0	14	3.16^f	33.23	
α	22:45 h	331		9.519	9.519±0.015		0	14	3.94	33.23	16.3
SF		17,848		199	224^{+45}_{-15}		2	14	4.32	32.27	0.397
ER3	26.01.2007	1,822	39.1	26.6	34.3	283	0	9	5.09	30.83	
SF	01:52 h	3,604		188	213^{+45}_{-15}		0	9	3.49	31.84	10.9
ER4	30.01.2007	1,902	39.1	24.8	34.3	281	0	6	27.01	7.63	
α	13:05 h	14,727		1.426+8.099	9.525±0.027		0	6/17	26.72	7.84	5.1
SF		12,999		170	195^{+45}_{-15}		0	6	27.31	7.63	0.118

[a] Macro beam pulse from 150 to 5,750 μs for event 1 and from 150 to 5,250 μs for events 2 to 4.
[b] E_{ct} is the kinetic energy of the ER calculated for reactions at the center of target.
[c] Energies in this column are based on calibration with α and ^{48}Ca beam particles.
[d] The energy E_{ER} is the calculated kinetic energy of ER before detector implantation.
[e] Uncertainty of atomic mass number determined from energy−TOF measurement is $\sigma = \pm 21$.
[f] This value was obtained using combined information from low and high energy branch (see discussion in the text).

Fusion

^{248}Cm + ^{48}Ca

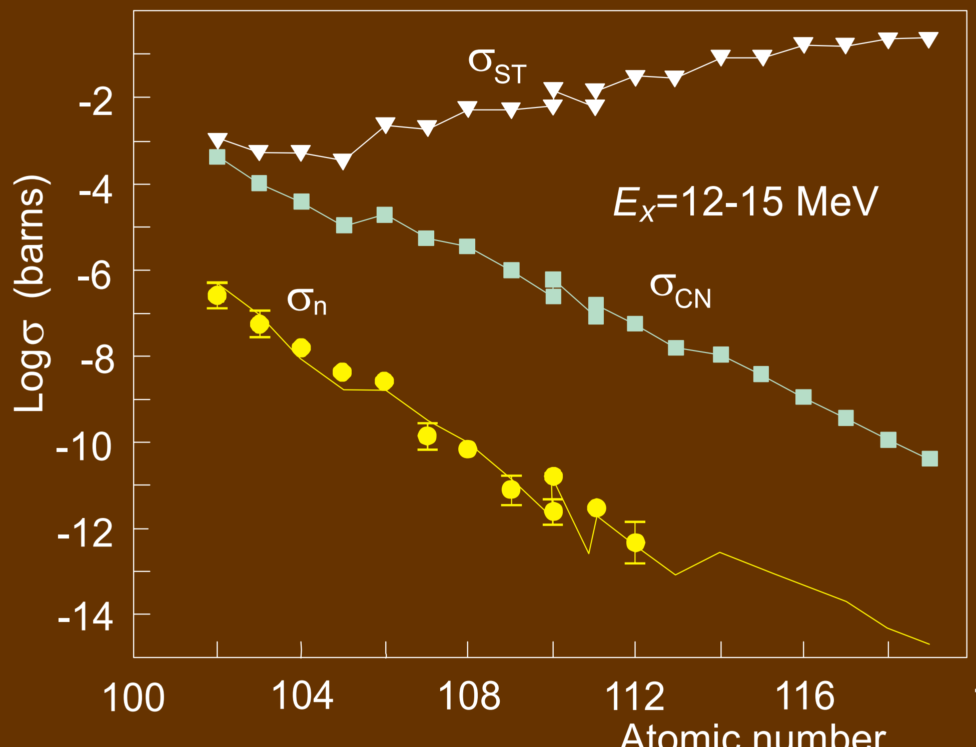
E_x = 40 MeV



Comparison of cold and hot fusion cross-sections

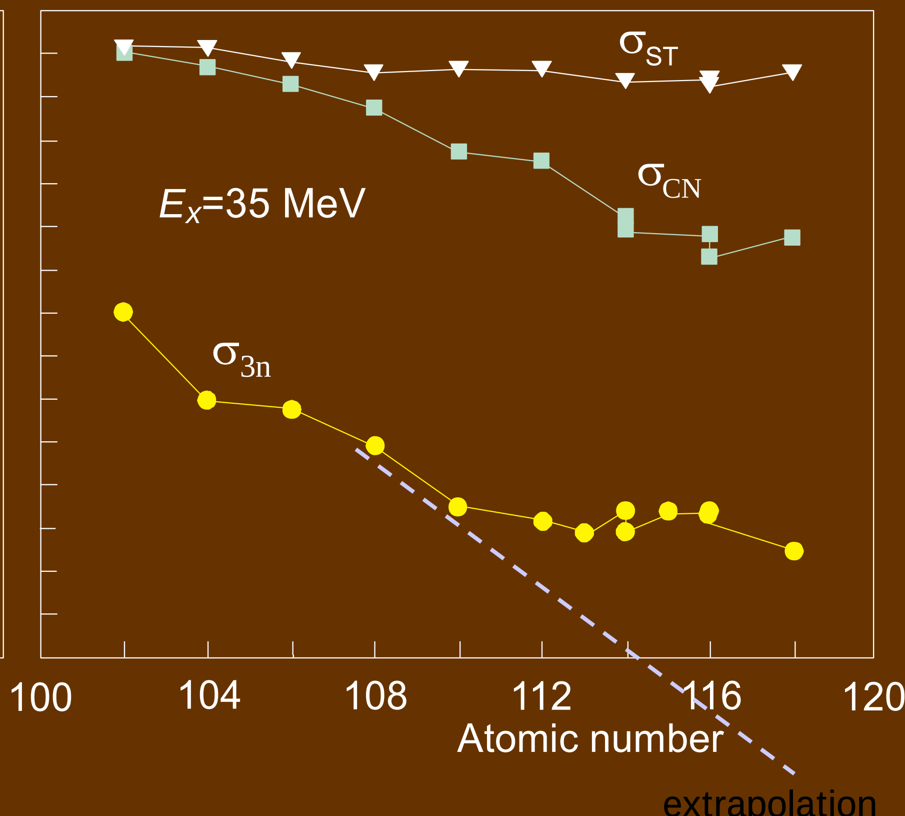
Cold fusion

W.J. Swiatecki, K. Siwek-Wilczynska and J. Wilczynski
Journ. Mod. Phys. E (2003)



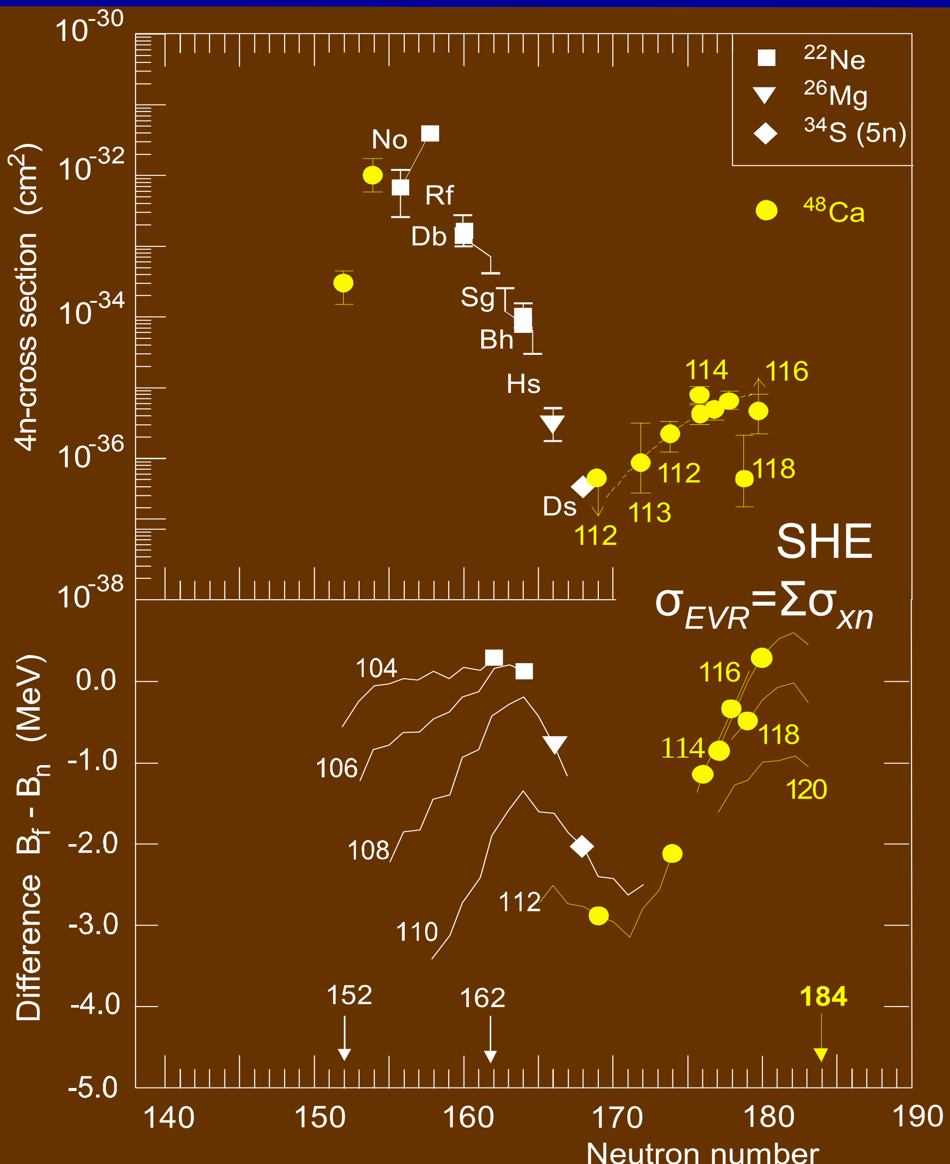
Hot fusion with ^{48}Ca

V.I. Zagrebaev, M.G. Itkis and Yu. Tz. Oganessian
Yad. Fis., 66 (2003)

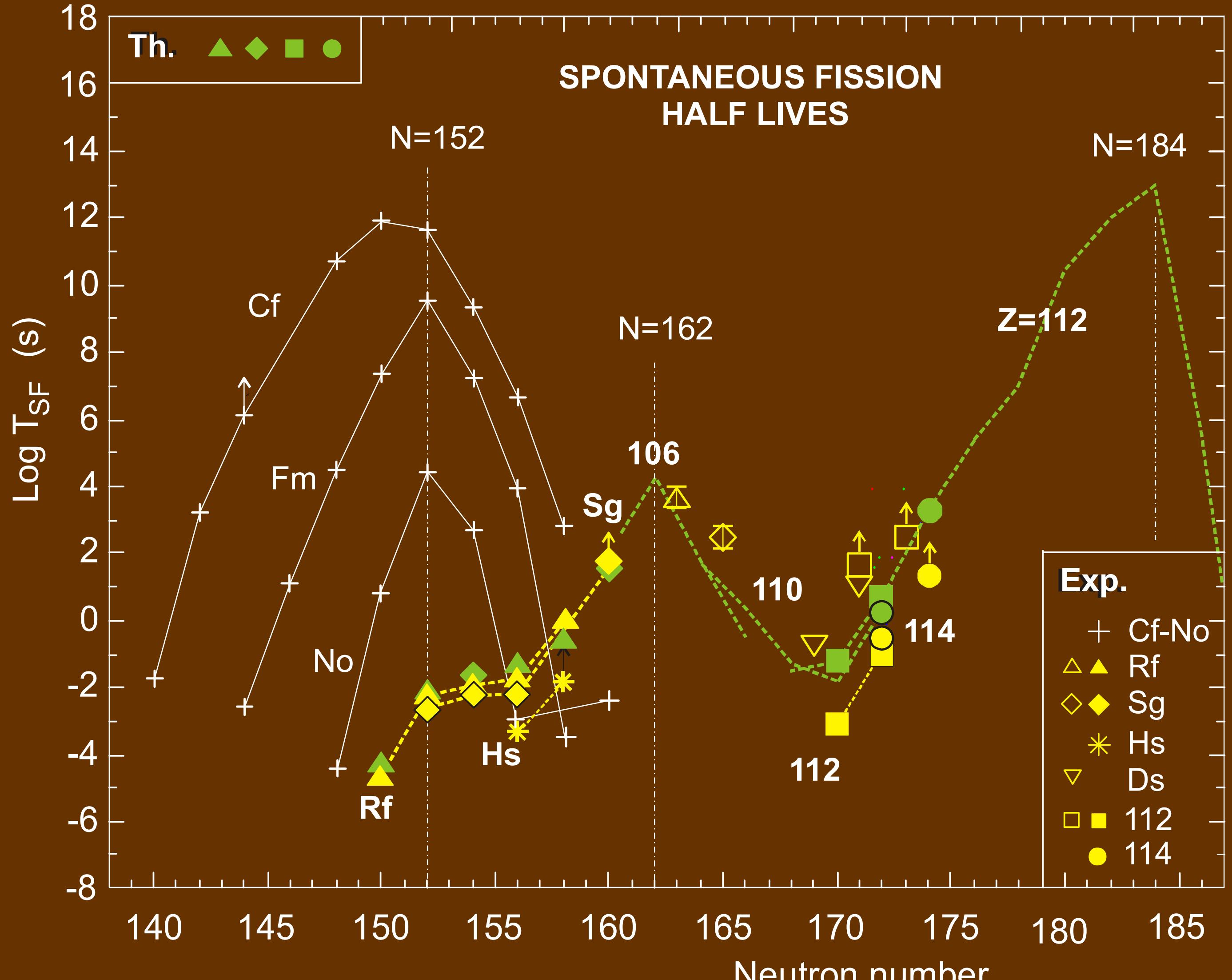


Comparison of 4n-evaporation cross-section with fission barrier

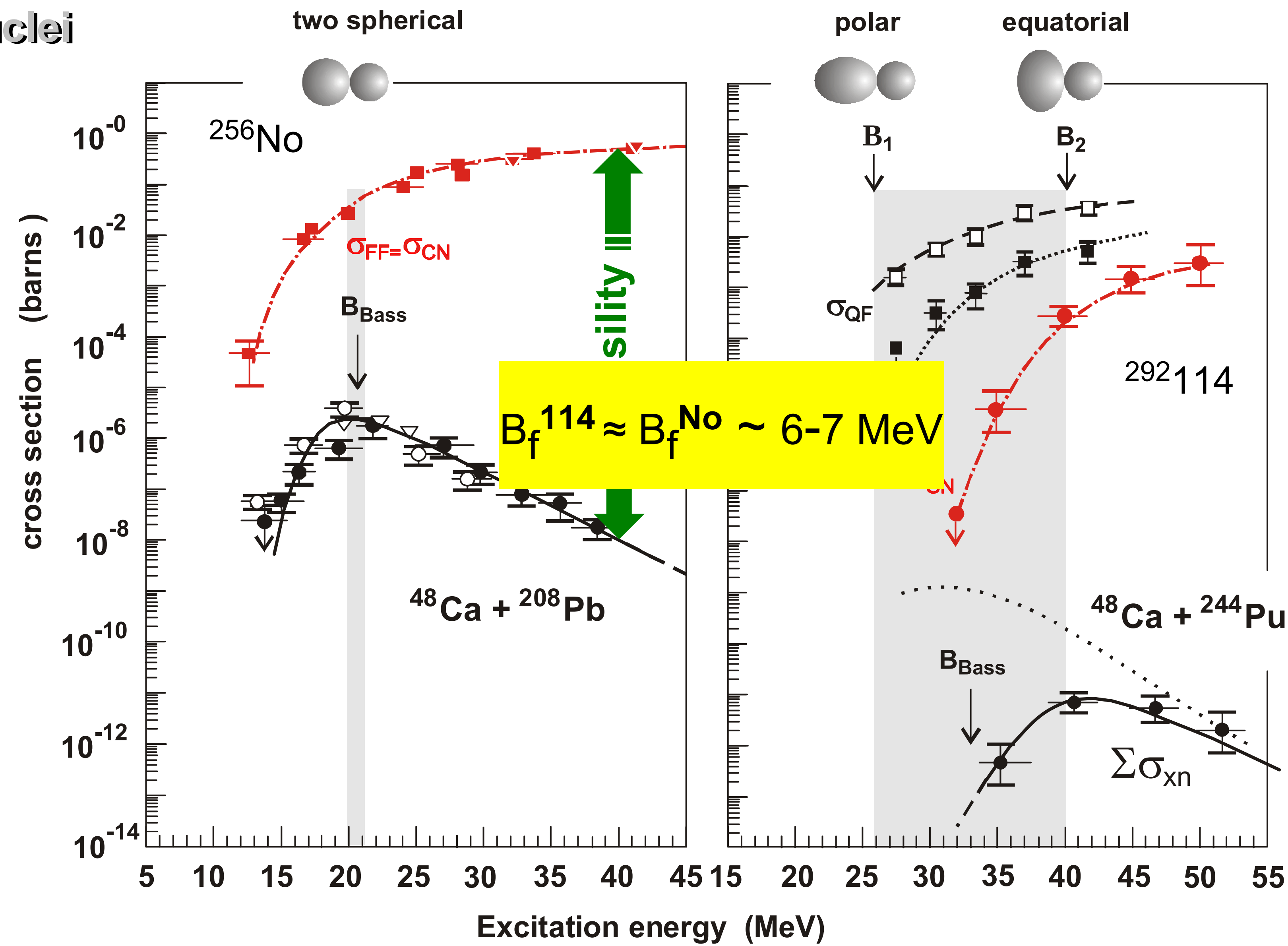
E_x=35-40 MeV
hot fusion



Spontaneous fission half-lives indicate shell closure



Survival of SH-nuclei



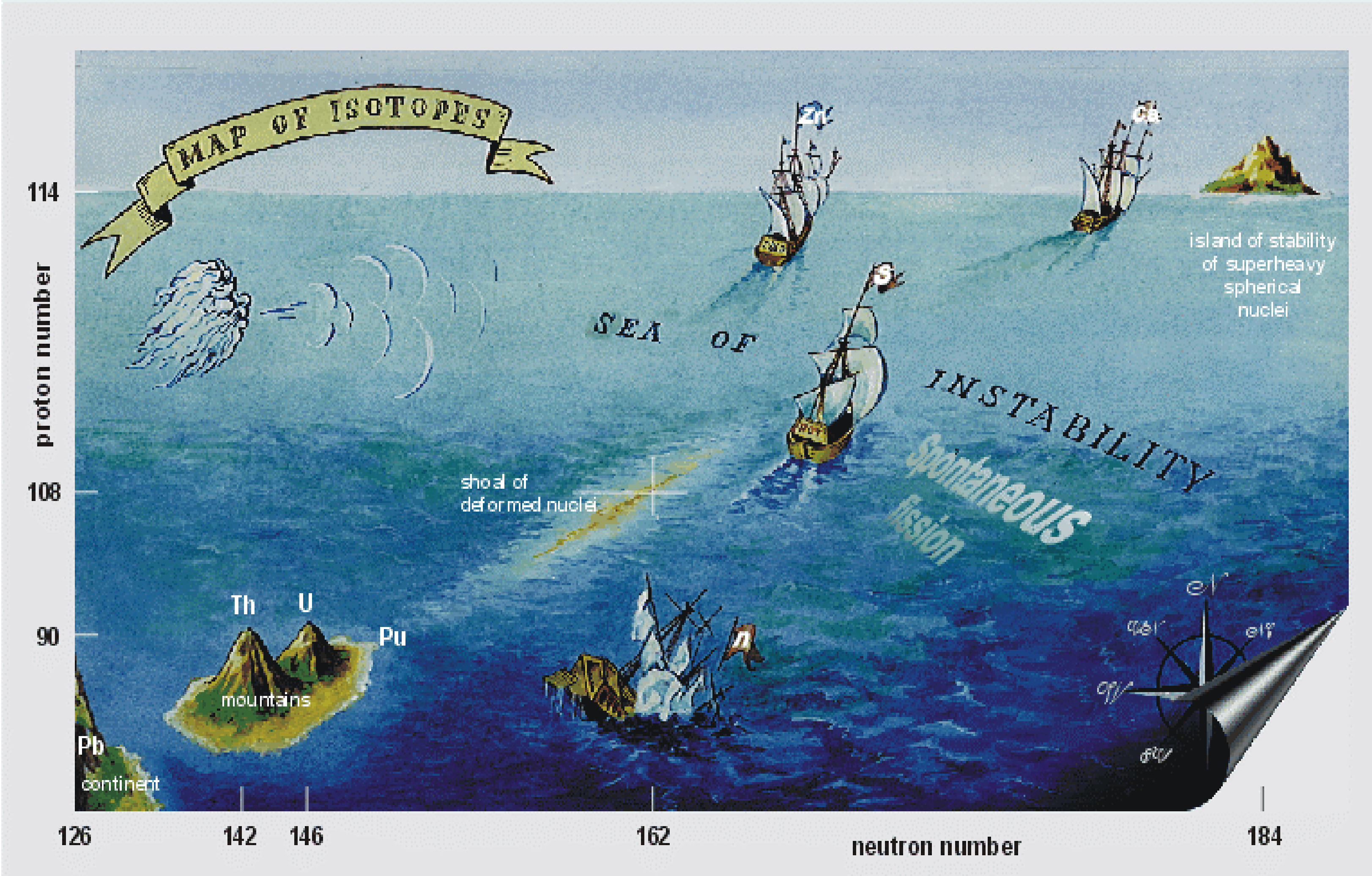
$B_f^{114} \approx B_f^{No} \sim$ 6-7 MeV

Yu. Oganessian. “Heaviest Nuclei from ^{48}Ca-induced Reactions” TAN-07, Davos, Sept. 23-27, 2007

Future

- ^{58}Fe + ^{244}Pu DGFRS experiment completed March 2007 with no observed element 120 decay sequences
- ^{48}Ca + ^{244}Pu chemistry experiment in Dubna (PSI/Dubna/LLNL) to investigate gas phase chemistry of element 112 (with first observed gas-phased chemistry of element 114!)
- MASHA mass measurement
- Fast automated chemistry (element 114)
- Reactions with RIBs
- …

We've only made it part way to the Island of Stability



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Participants in these experiments

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JINR -- Yu. Ts. Oganessian, V. K. Utyonkov, Yu. V. Lobanov, F. Sh. Abdullin, A. N. Polyakov, I. V. Shirokovsky, Yu. S. Tsyganov, G. G. Gulbekian, S. L. Bogomolov, B. N. Gikal, A. N. Mezentsev, S. Iliev, V. G. Subbotin, A. M. Sukhov, G. V. Buklanov, K. Subotic, M. G. Itkis