Searching for collinear tripartition of heavy nuclei – status and prospects

Collaboration

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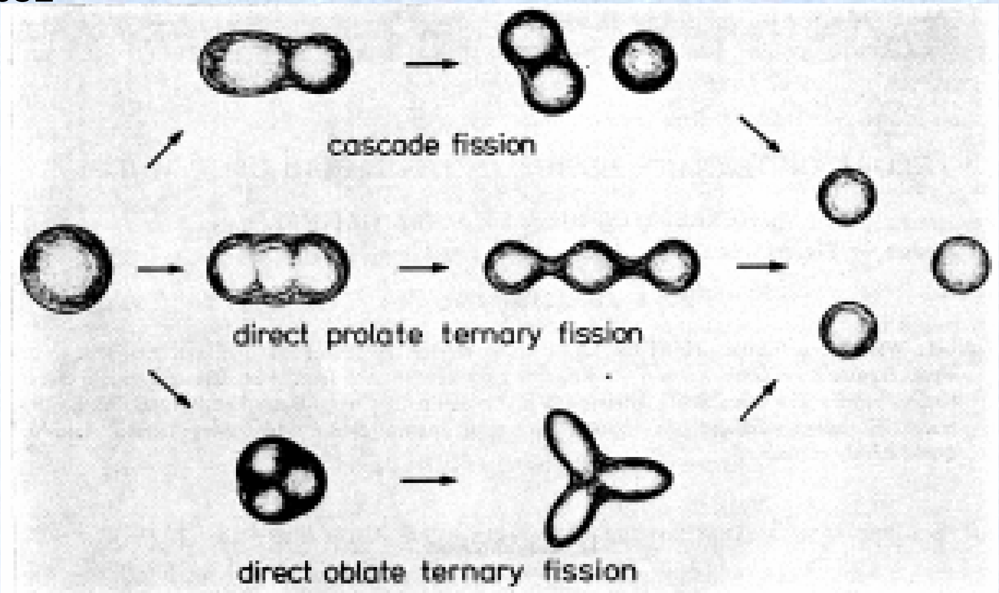
- Joint Institute for Nuclear Research, Dubna, Russia
- Department of Physics of University of Jyväskylä, Jyväskylä, Finland
- Khlopin-Radium-Institute, St. Petersburg, Russia
- Institute for Nuclear Research RAN, Moscow, Russia
- Hahn-Meitner Institute, Berlin, Germany
- Technical University, Darmstadt, Germany

Our major CCT publications since 1998

1. Ю.В. Пятков и др., Препринт ОИЯИ Р15-98-263, Дубна, 1998
2. Yu. V. Pyatkov et al., Proc. Int. Conf. “50Years of Shells”, 21-24 April 1999, Dubna , p. 301
3. Yu.V. Pyatkov et al., Proc. Int. Symp. On Exotic Nuclei (EXON-2001), Baikal Lake, July 24-28, 2001, p. 181
4. Yu.V. Pyatkov et al., Physics of Atomic Nuclei, Vol. 66, No. 9, 2003, p. 1631
5. D.V. Kamanin et al., Physics of Atomic Nuclei, Vol. 66, No. 9, 2003, p. 1655
6. Yu.V. Pyatkov et al., preprint JINR E-15-2004-65, Dubna, 2004
7. W. Trzaska et al., Proc. Seminar on Fission Pont d’Oye V, Belgium, 16-19 September 2003, p.102
8. Yu.V. Pyatkov et al., Proc. Int. Symp. On Exotic Nuclei (EXON-2004), Peterhof, July 5-12, 2004, p.351
9. Yu.V. Pyatkov et al., preprint JINR E-15-2005-99, Dubna, 2005

1.H. Diehl and W. Greiner, Nucl. Phys. A 229 (1974) 29
2.D. N. Poenaru, R.A. Cheghescu and W. Greiner, Proc. Symp. On Nuclear Clusters, Rauischholzhaussen, Germany, 5-9 August 2002, p.283
3.Yu. V. Pyatkov, D. V. Kamanin, A. A. Alexandrov, I. A. Alexandriova, S.V. Khlebnokov, S.V. Mitrofanov, V. V. Pashkevich, Yu. E. Penionzhkevich, Yu.V. Ryabov, E.A. Sokol, V. G. Tishchenko, A. N. Tjukavkin, A. V. Unzhakova and S.R. Yamaletdinov, Physics of Atomic Nuclei, 66 (2003) 1631



L. Rosen and A. M. Hudson, Phys. Rev. (1950) 533	233U (nth, f)
M.L. Muga et al., Phys. Rev. Lett. 11 (1963) 129	252Cf (sf)
18 (1967) 404	233,235U (nth, f)
Phys. Rev. 161 (1967) 1266	239,241Pu (nth, f)
II Int. Symp. On Physics and Chemistry of Fission, IAEA-SM-211/99, 1969	
E.P. Steinberg et al., Phys. Rev. C1 (1970) 2046	criticism (scattering)
Roy J.C. et al., Can. J. Phys. 39 (1961) 315	I
R.W. Stoenner et al., Phys. Rev. 142 (1966) 716	I radio-chemical methods
G. Kugler et al., Phys. Rev. C3 (1971) 849	I
P. Schall et al., Phys. Let. B, 191 (1987) 339	252Cf (sf)
A.V. Kravtsov and G.E. Soljakin Phys. Rev. C 60 (1999) 017601-1	252Cf (sf)

Fig1

How to find and verify the effect?

collinear fragments

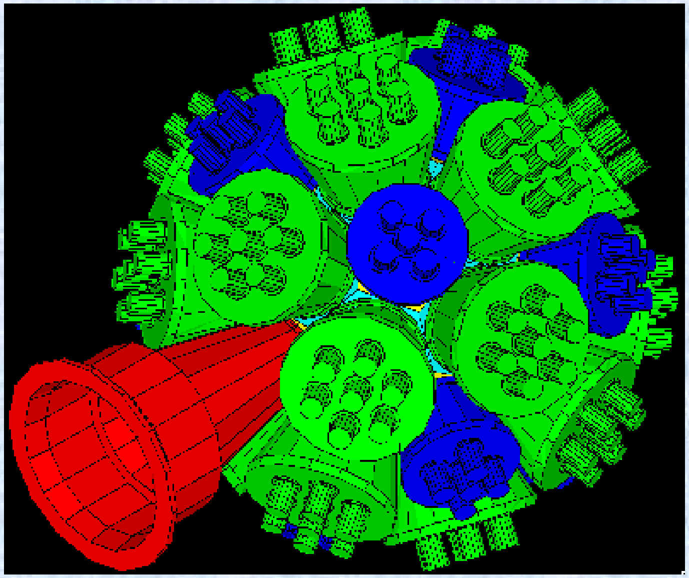
+

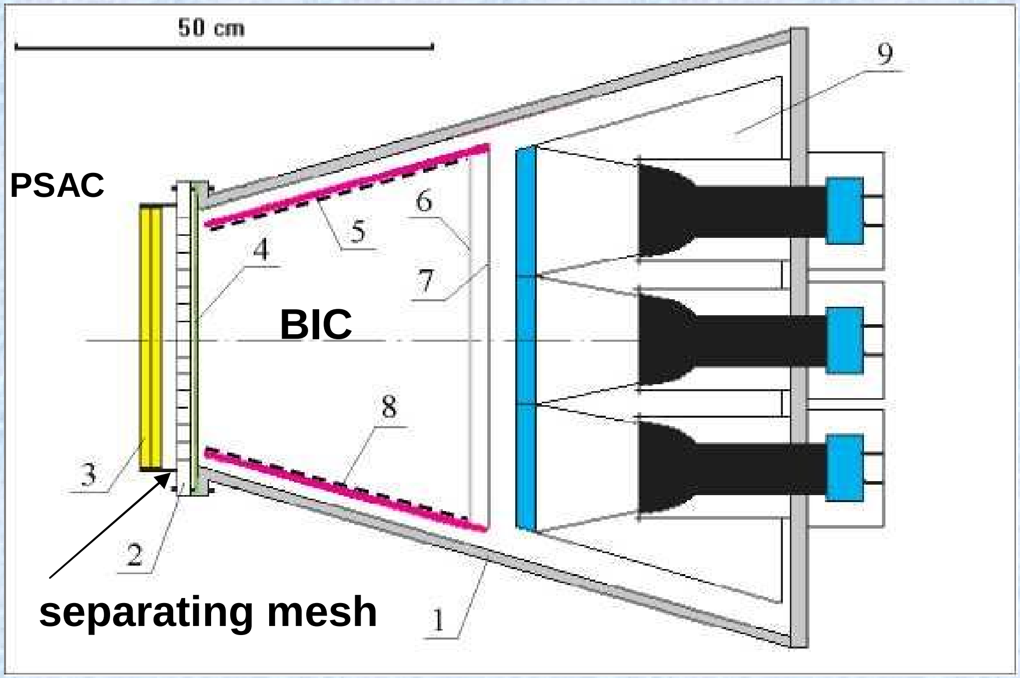
missing mass

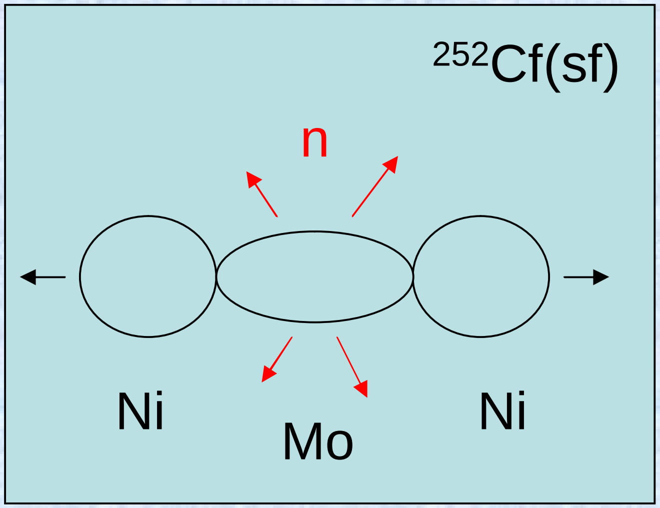
Direct registration of all decay partners

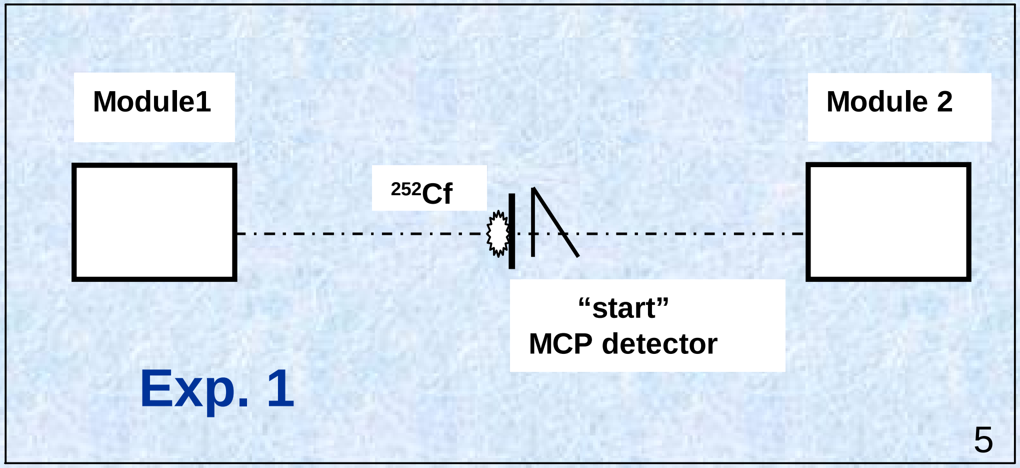
- **Sophisticated analysis**
  - Momentum and velocity gating
- **Independent experiments using different measurement techniques**
  - Modified FOBOS spectrometerat Flerov Lab in Dubna
    - Coincidences with neutrons (perpendicular to the fission axis) using 140 ^{3}He counters
  - 6 x Time + 2 x Energy using MCP spectrometer (4 MCP + 2 PIN) in Jyväskylä

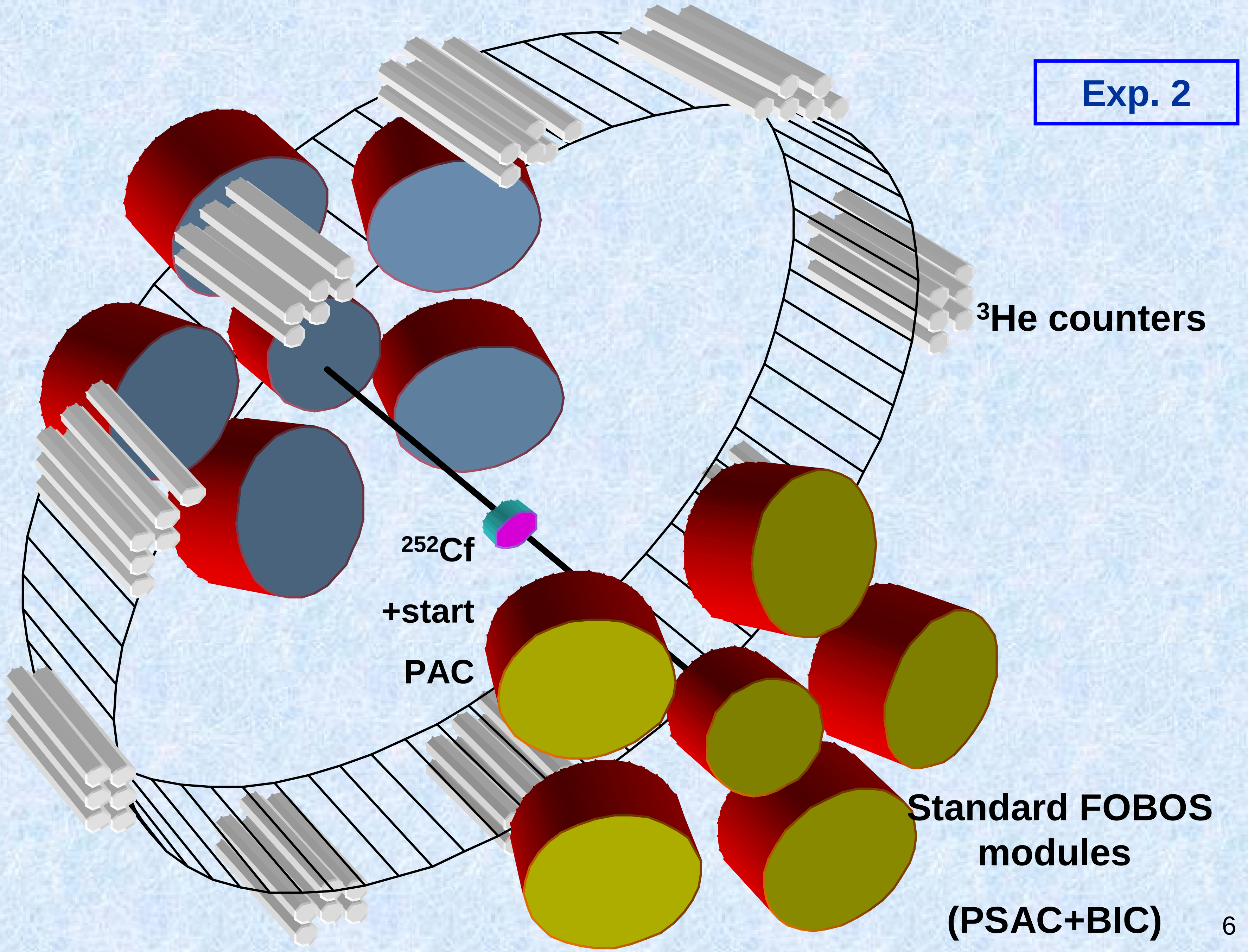
FOBOS spectrometer

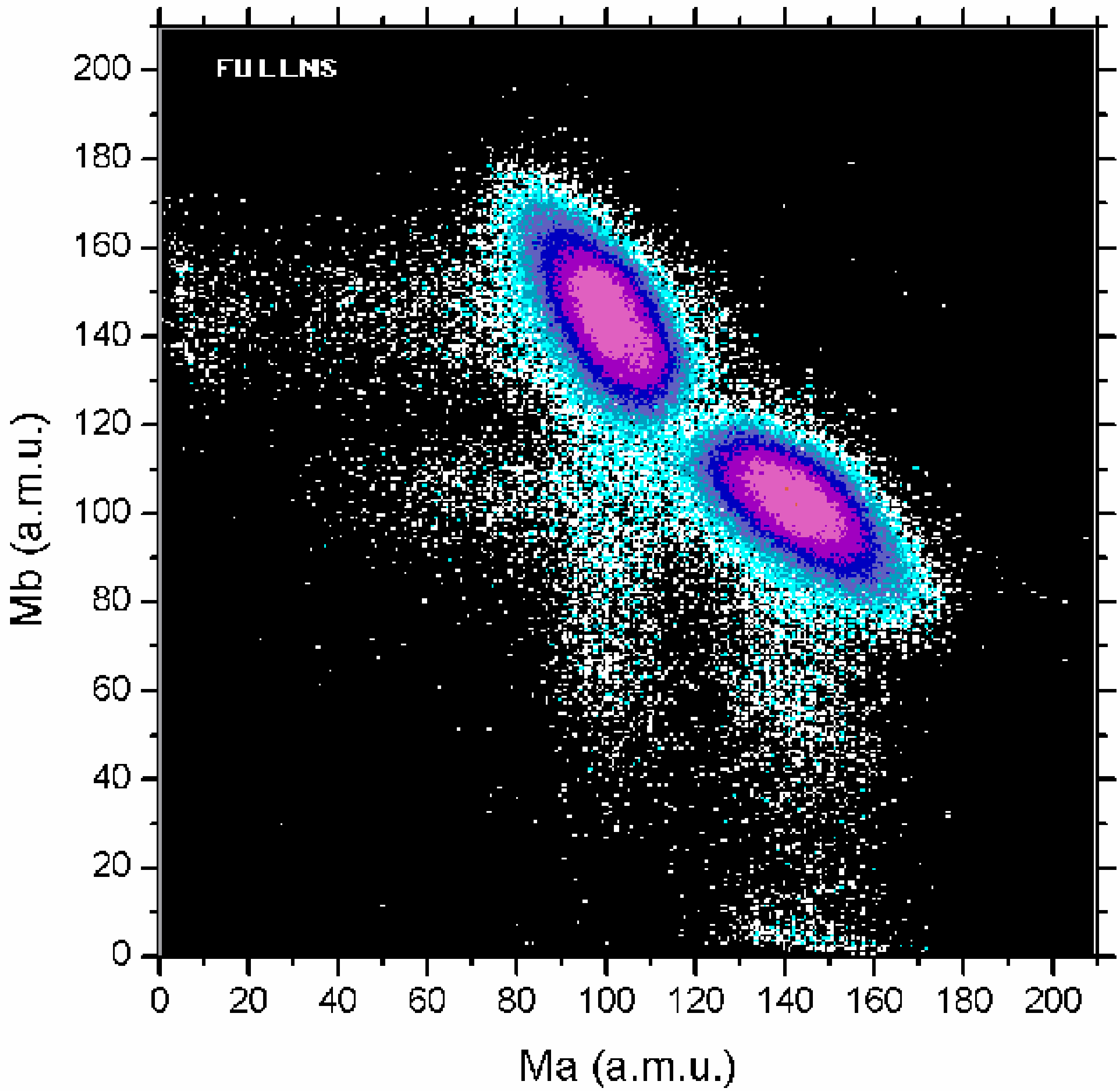


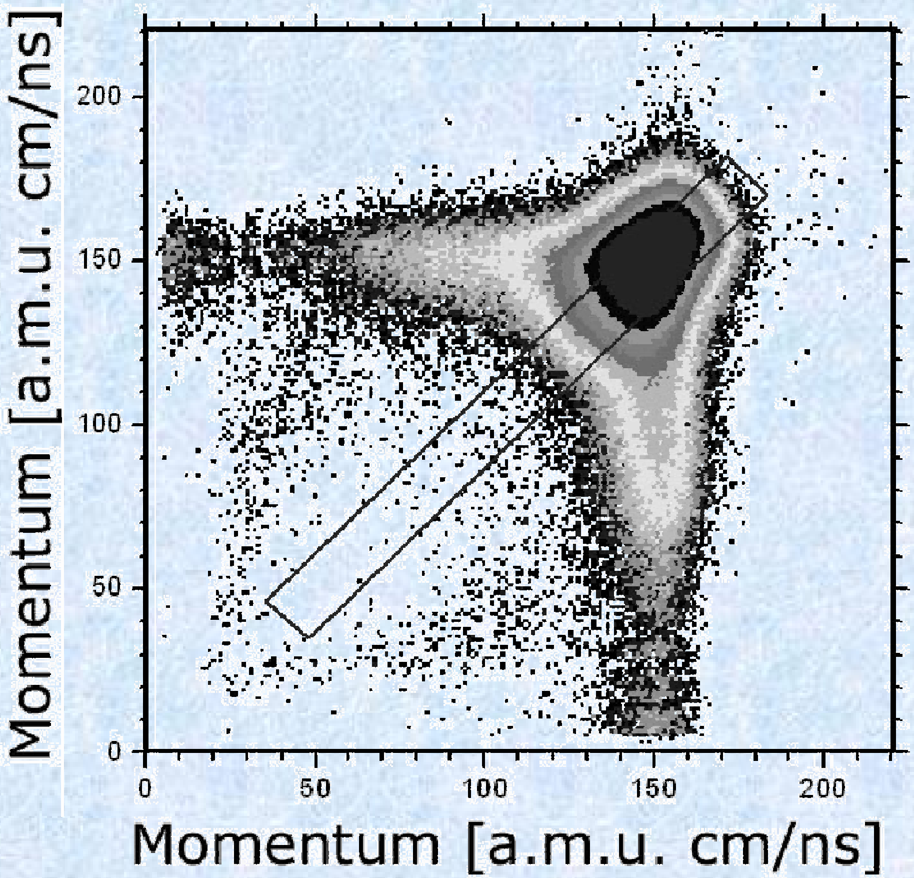


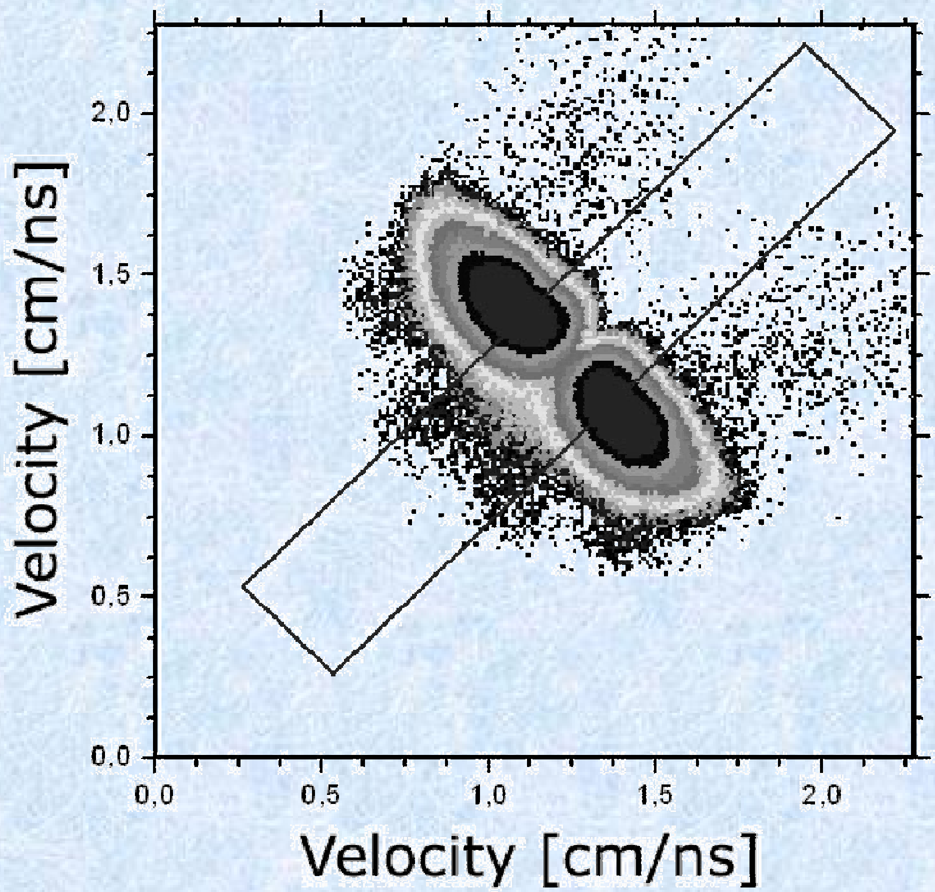


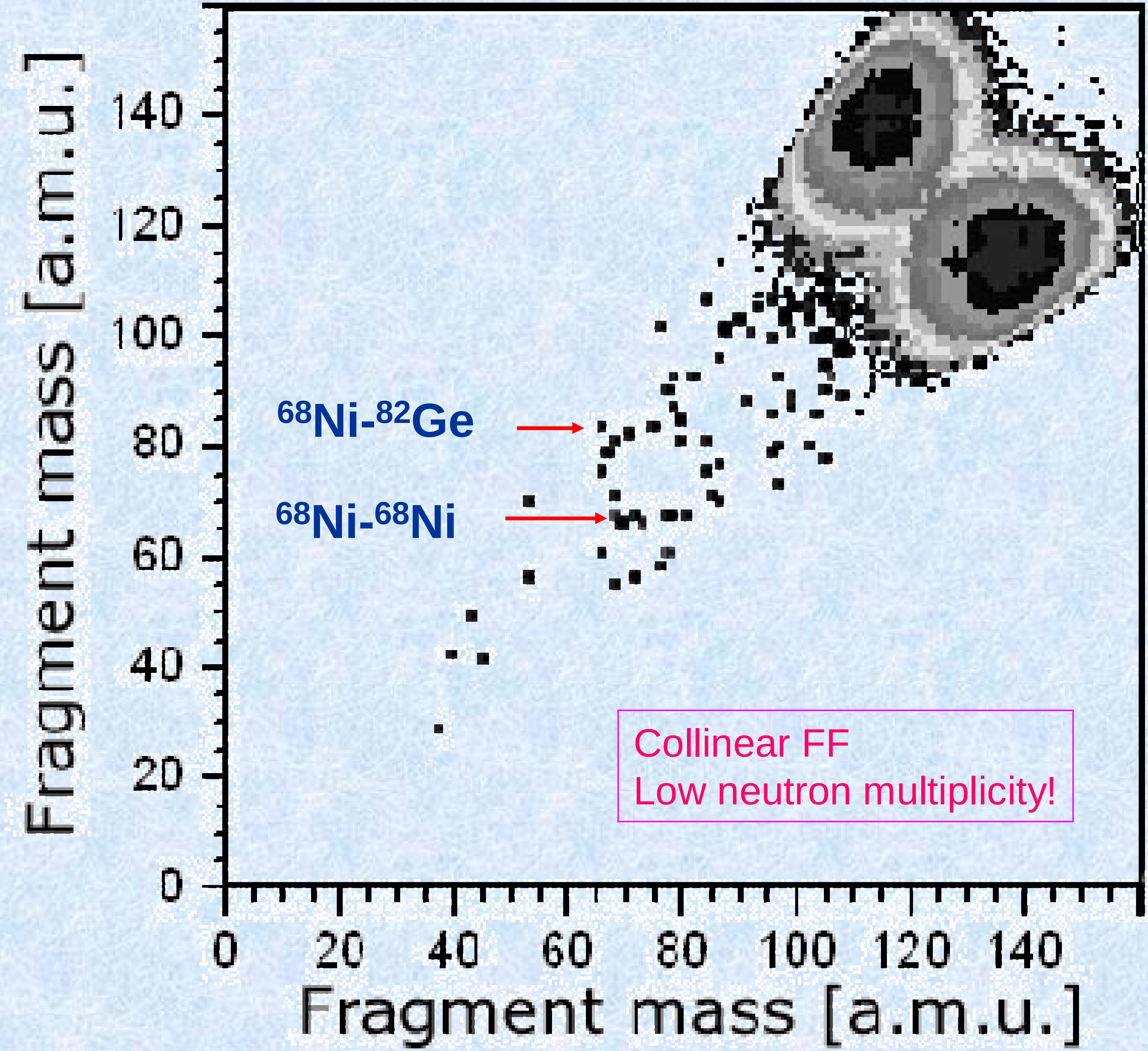



Exp. 2
^{3}He counters
^{252}Cf
+start
PAC
Standard FOBOS
modules
(PSAC+BIC)

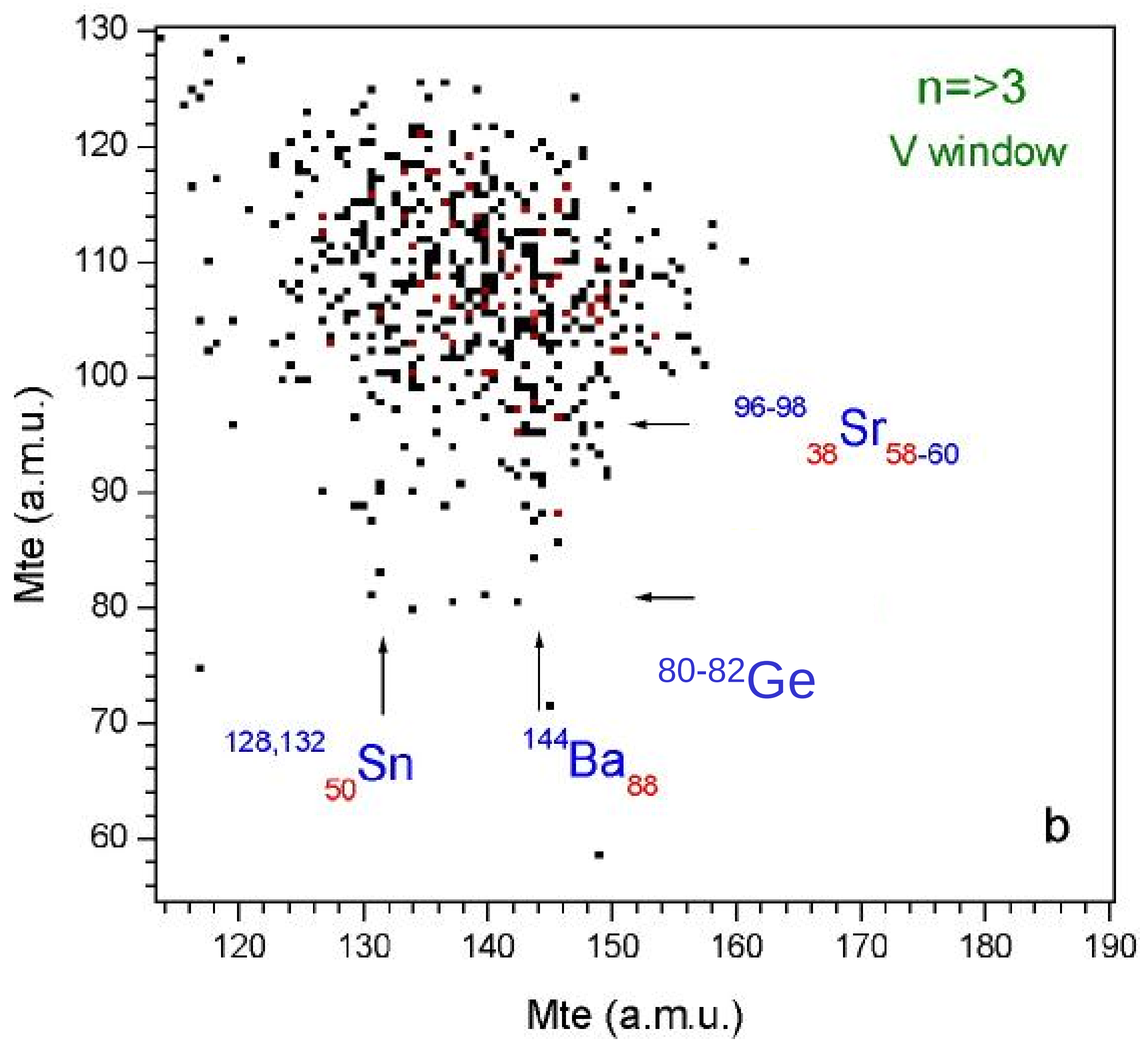

FULLNS
Mb (a.m.u.)
Ma (a.m.u.)
0
20
40
60
80
100
120
140
160
180
200


Momentum [a.m.u. cm/ns]
0
50
100
150
200
Momentum [a.m.u. cm/ns]


Velocity [cm/ns]
0,0
0,5
1,0
1,5
2,0
Velocity [cm/ns]

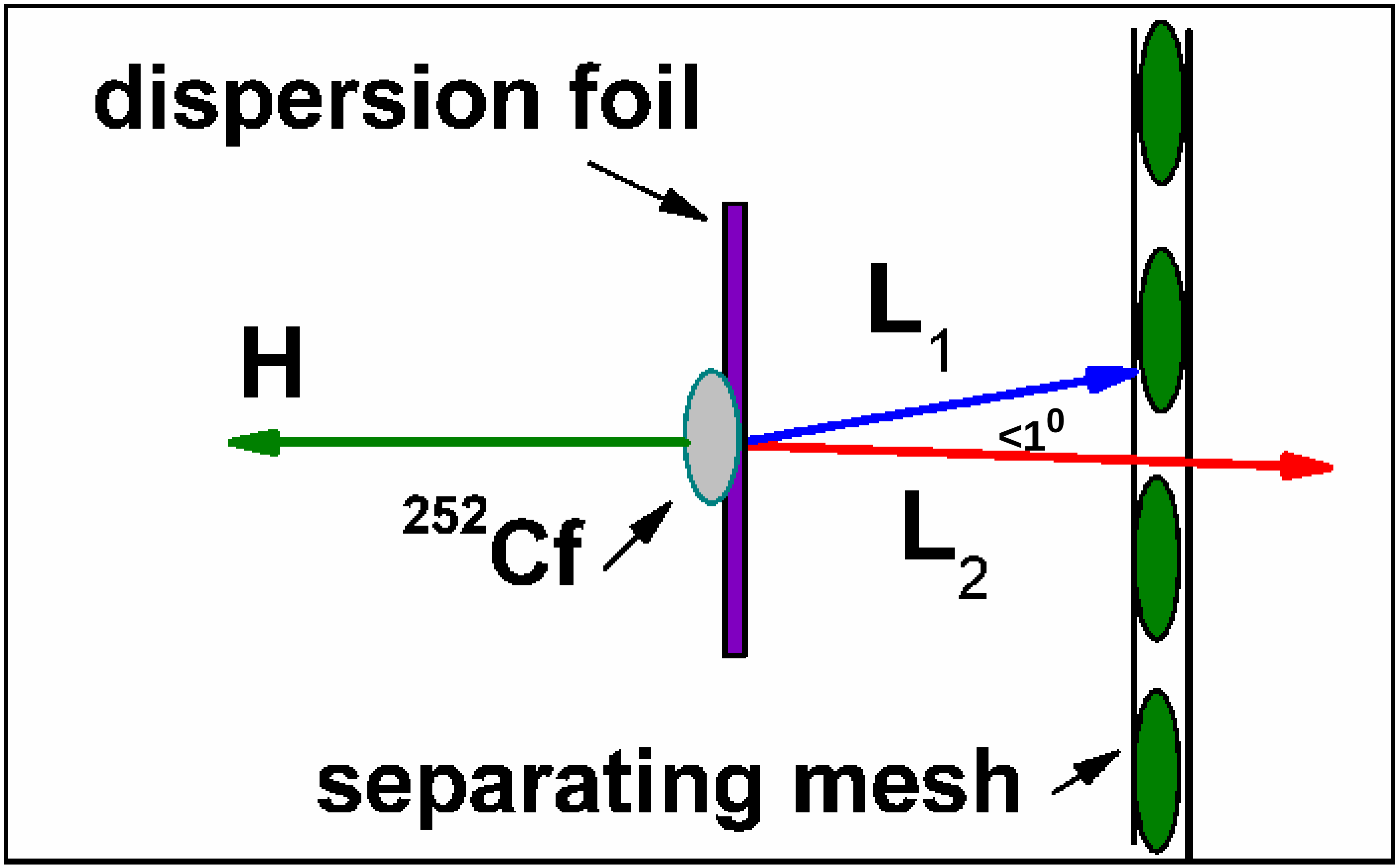


Fragment mass [a.m.u.]
140
120
100
80
60
40
20
0
0 20 40 60 80 100 120 140
Fragment mass [a.m.u.]
68Ni-82Ge
68Ni-68Ni
Collinear FF
Low neutron multiplicity!

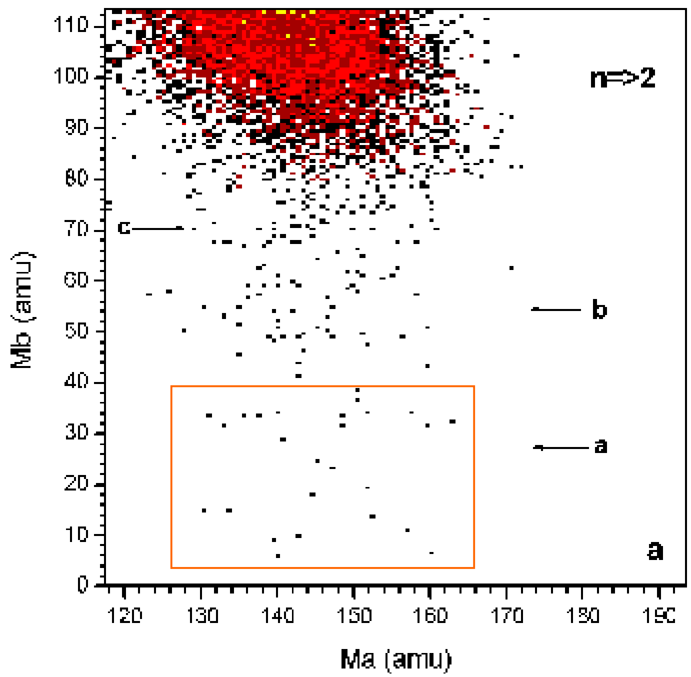


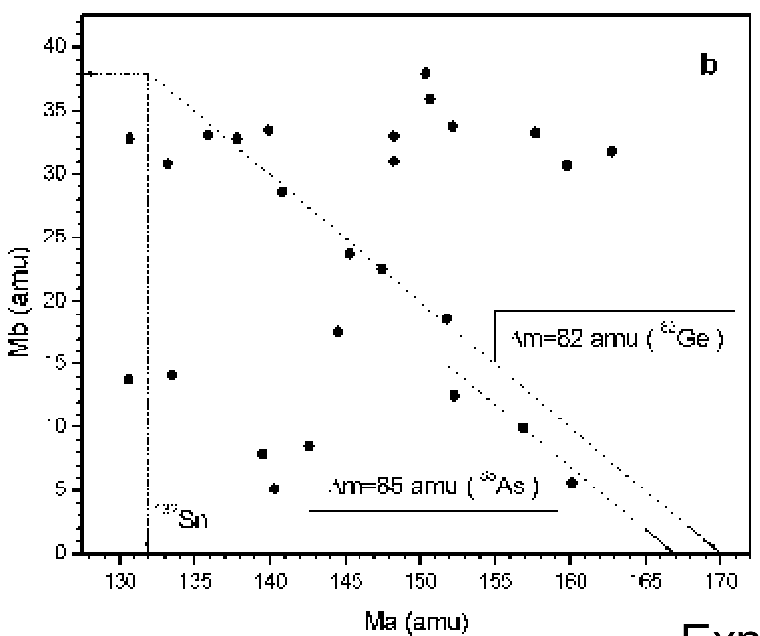
n=>3
V window
96-98
38Sr58-60
80-82Ge
128,132
50Sn
144Ba88
b
Mte (a.m.u.)
Mte (a.m.u.)
130
120
110
100
90
80
70
60
120
130
140
150
160
170
180
190

Scheme of detecting of the CCT partners



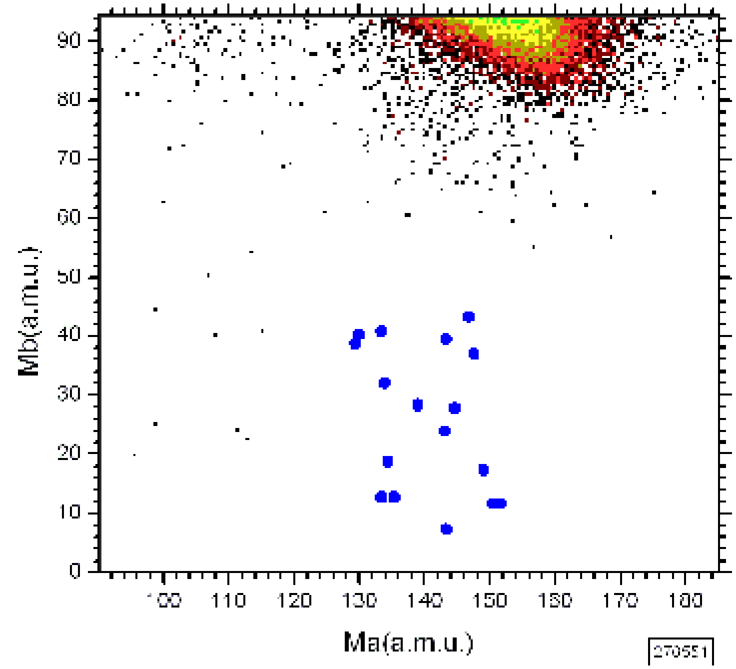
FLNR





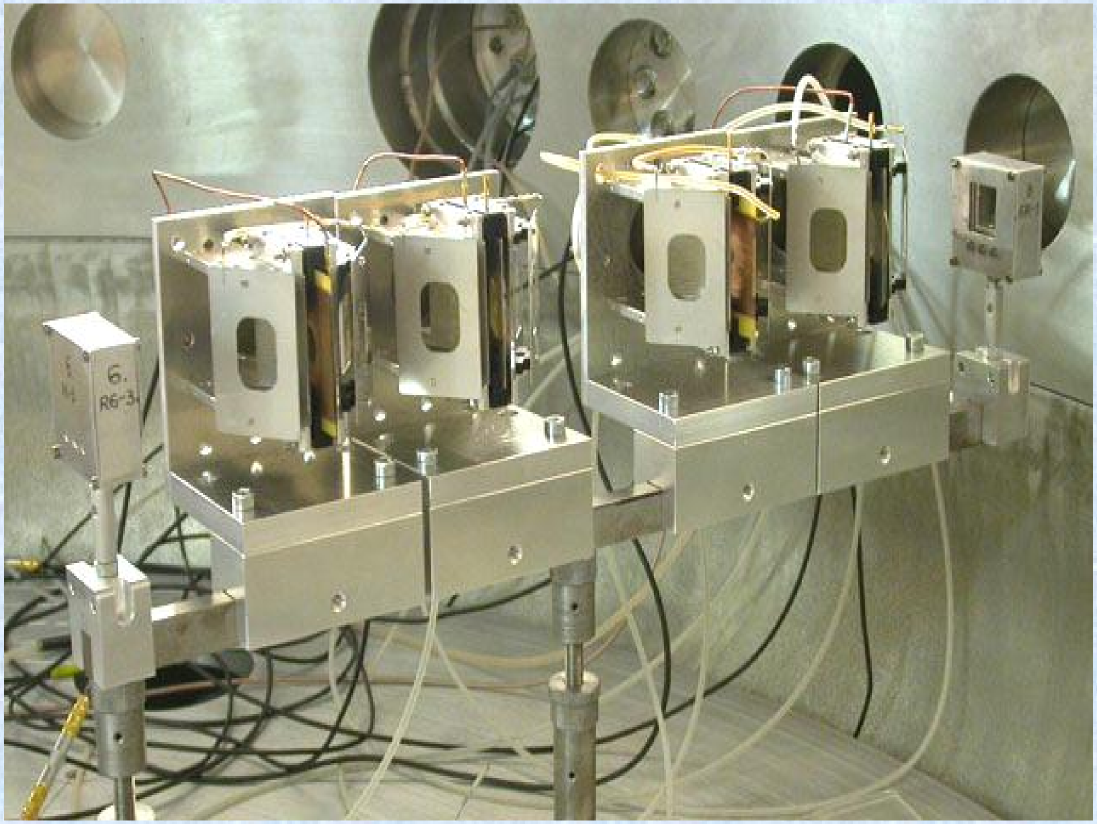
Exp. 2

JYFL

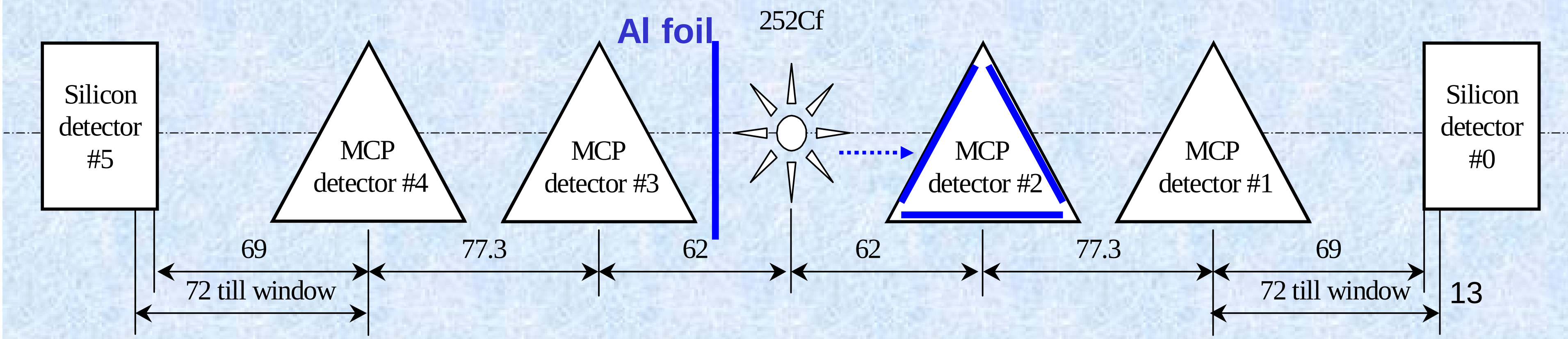


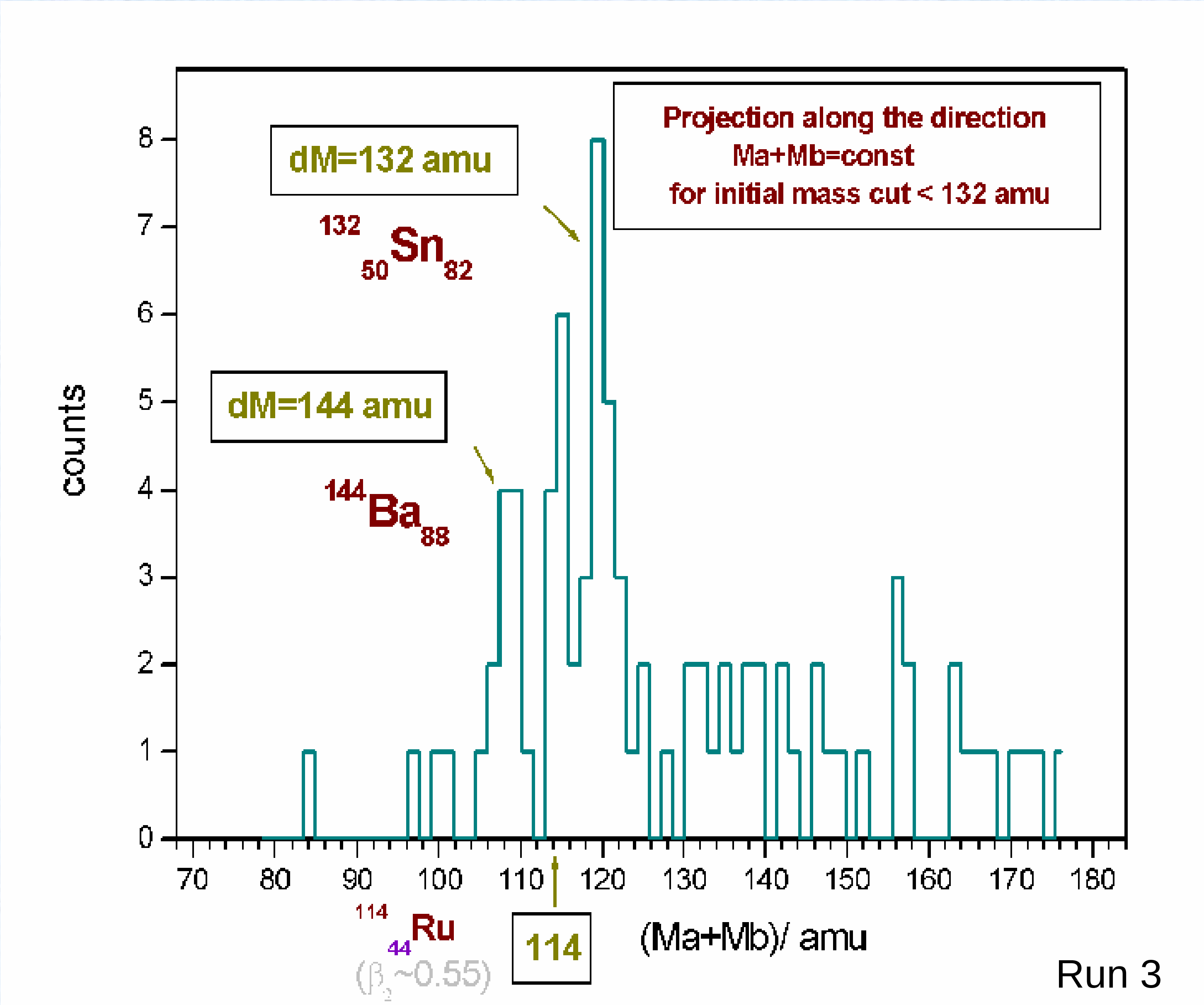
Exp. 3

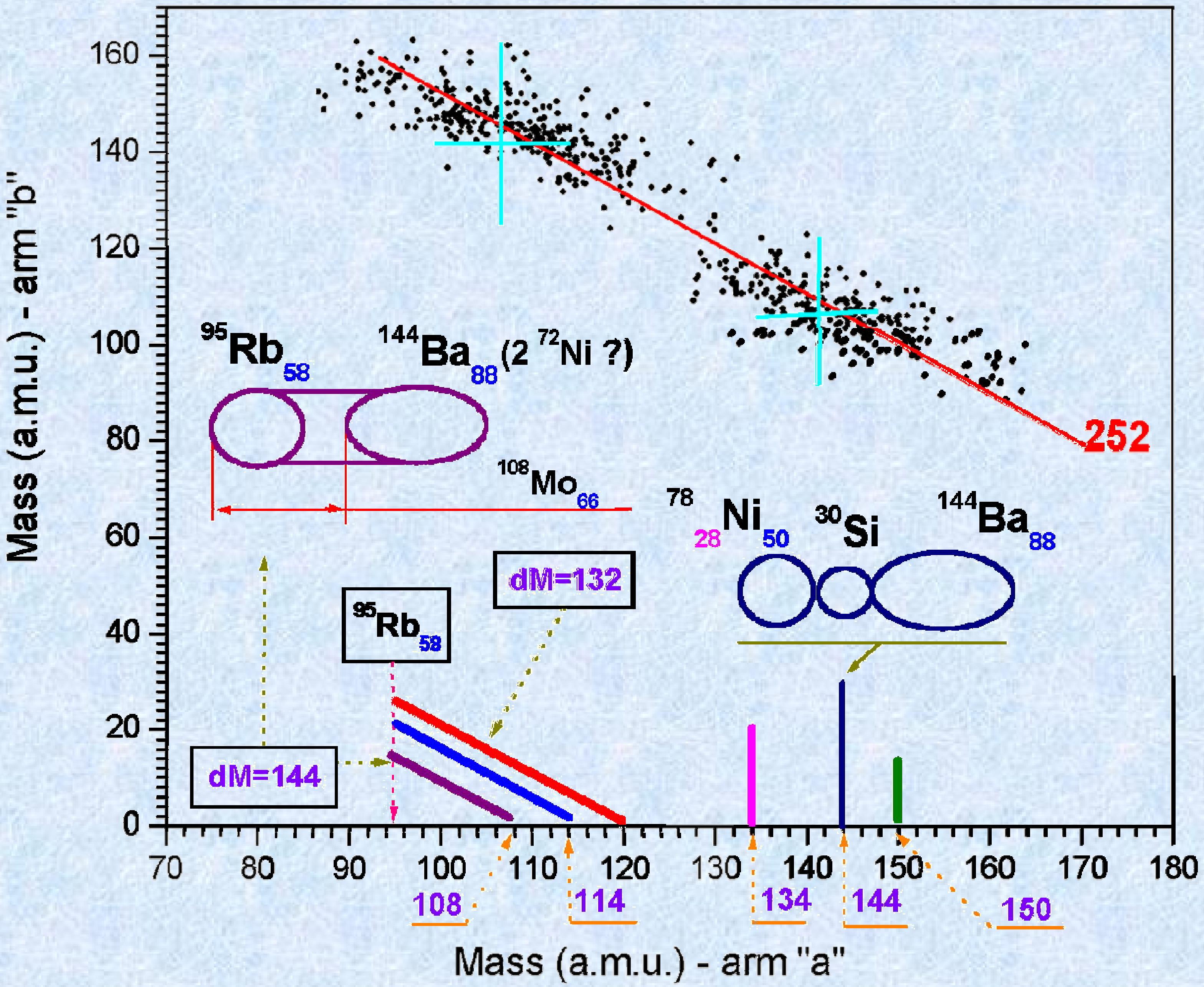
JYFL spectrometer



— Exp. 3




Projection along the direction
Ma+Mb=const
for initial mass cut < 132 amu
dM=132 amu
132 50 Sn 82
dM=144 amu
144 Ba 88
counts
(Ma+Mb)/ amu
114 44 Ru
(β2~0.55)
114
Run 3



Mass (a.m.u.) - arm "b"
Mass (a.m.u.) - arm "a"
95Rb58
144Ba88 (2 72Ni ?)
108Mo66
78 28Ni50
30Si
144Ba88
252
dM=132
dM=144
95Rb58
108
114
134
144
150

Experimental evidence of the collinear tripartiiton of the 252Cf nucleus obtained at the FOBOS setup (Exp. 1)

1

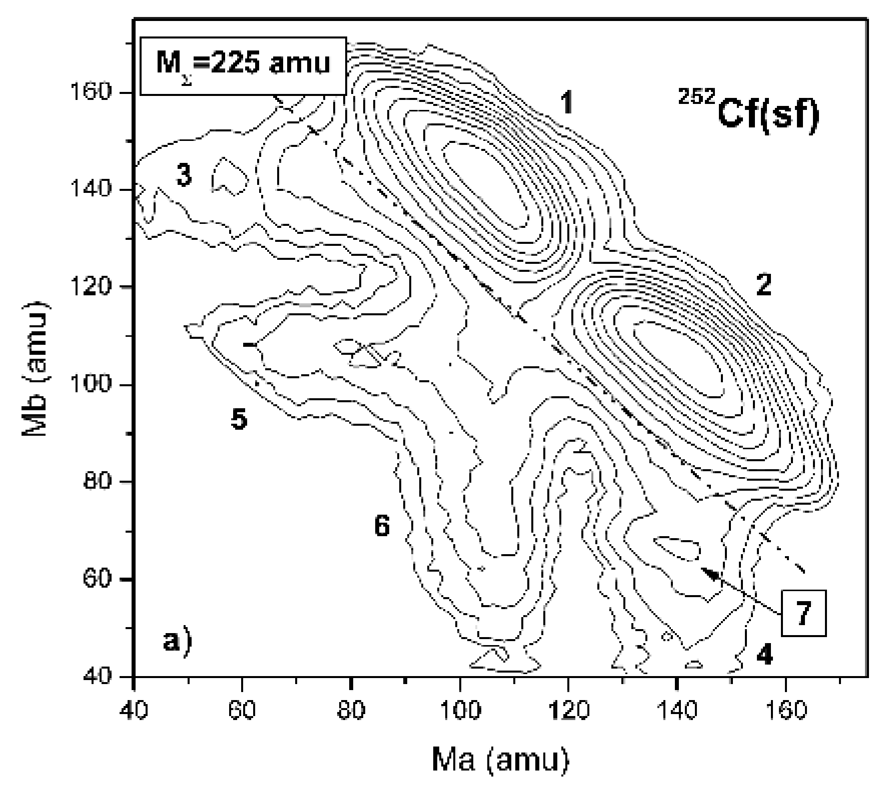
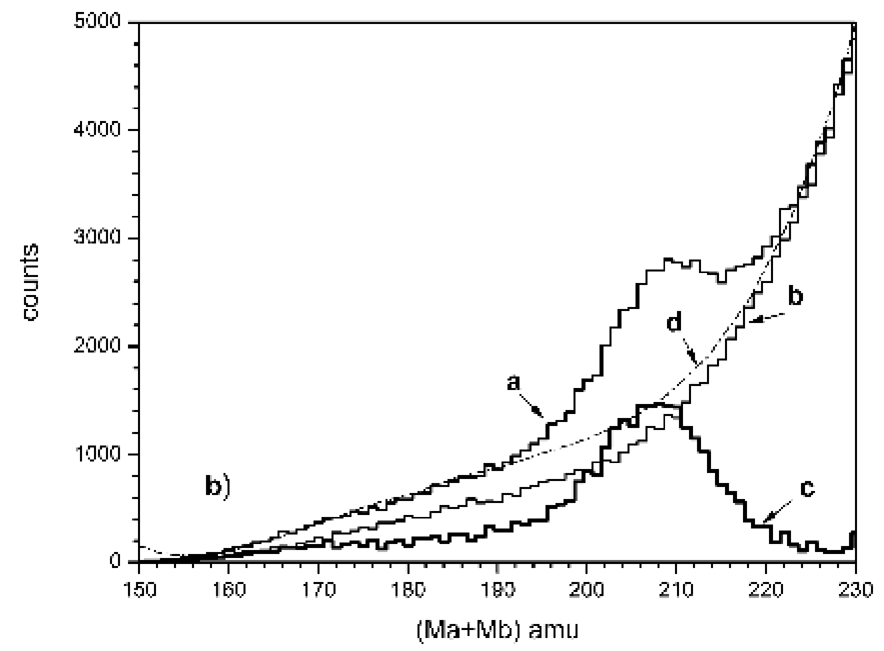


Fig.1 Contour map (in logarithmic scale) of the mass-mass distribution of the complimentary collinear fragments detected in the opposite arms of the spectrometer

Fig.2 The spectrum of total masse of two registered fragments for the "taile" 4 is marked as "a", the same for the "taile" 3 is marked by "b", their difference is marked by "c". Curve "d" is a polynomial fit via the points outside of the gross peak on curve "a". The area of spectrum "c" is $4.7*10^{-3}$ with respect to the conventional fission events contained in the locus 2 (fig.1).



Experimental evidence of the collinear tripartiiton of the 252Cf nucleus obtained at the FOBOS setup

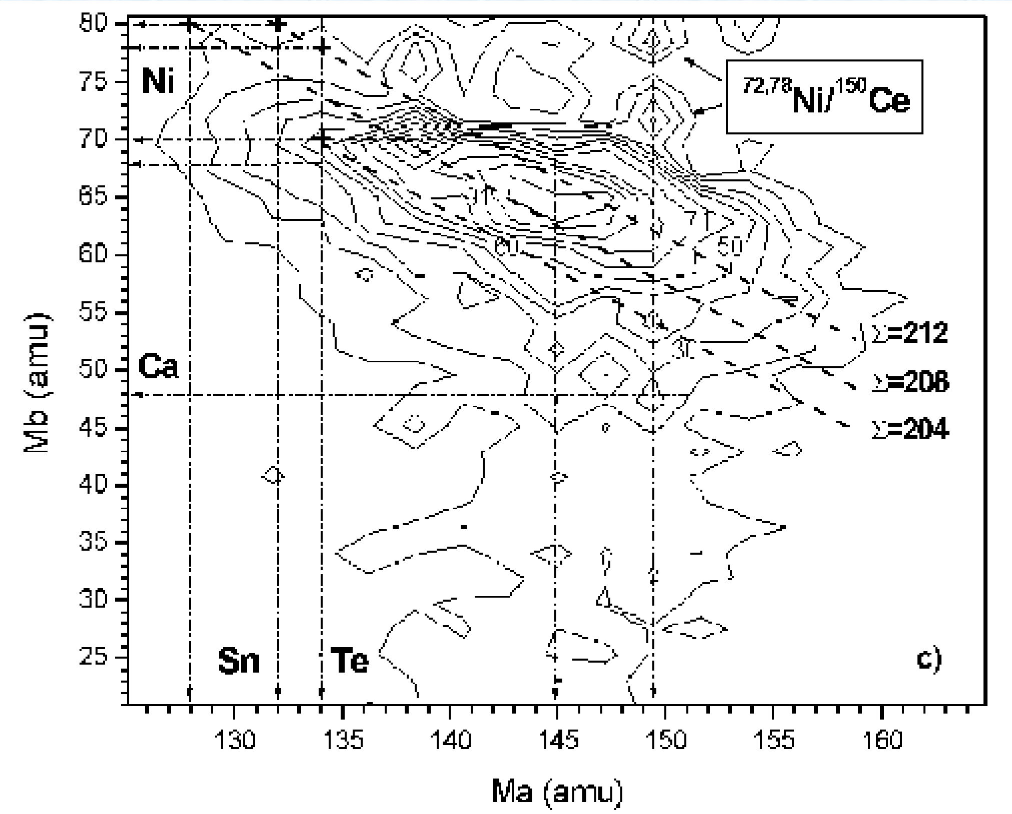


Fig. 4 presents a result of processing of the distribution from fig 3 with a second derivative filter.

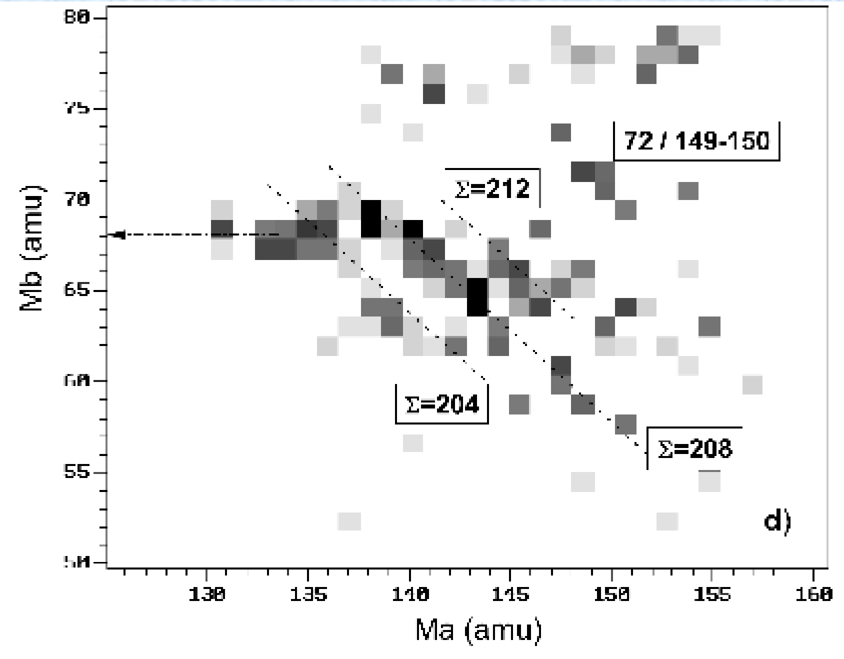
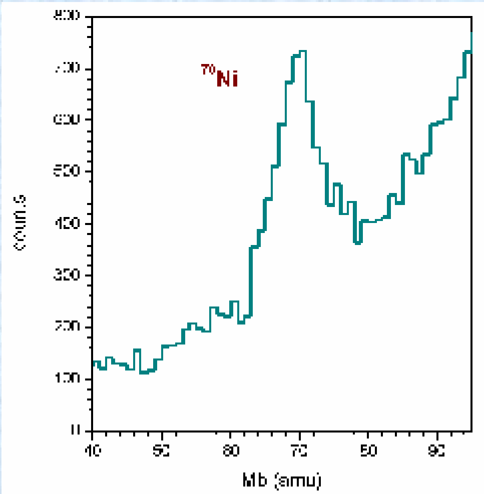
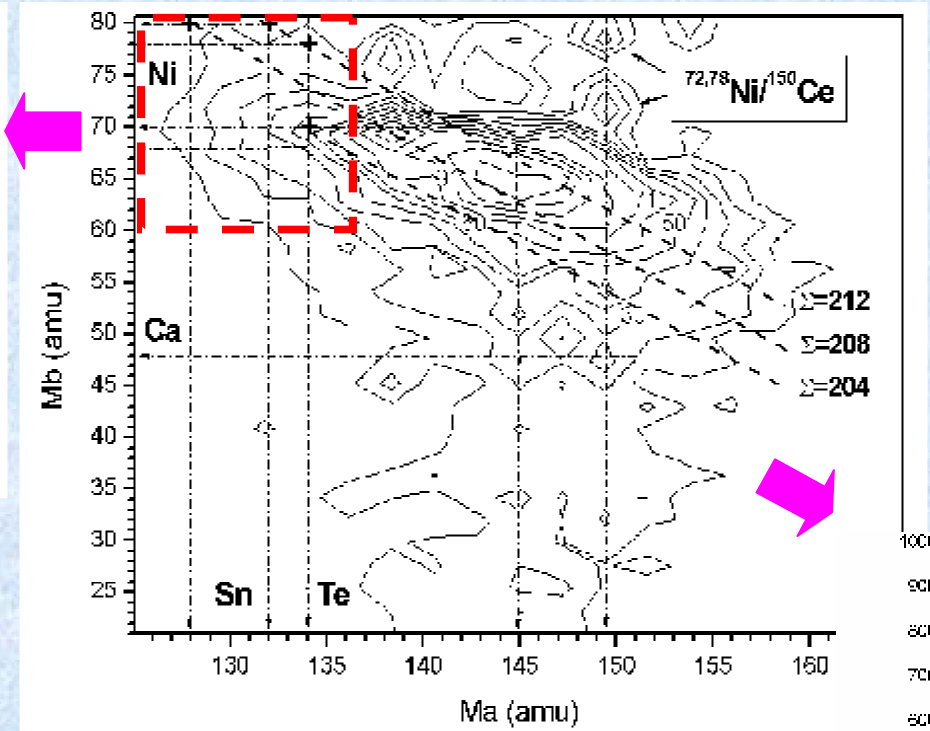
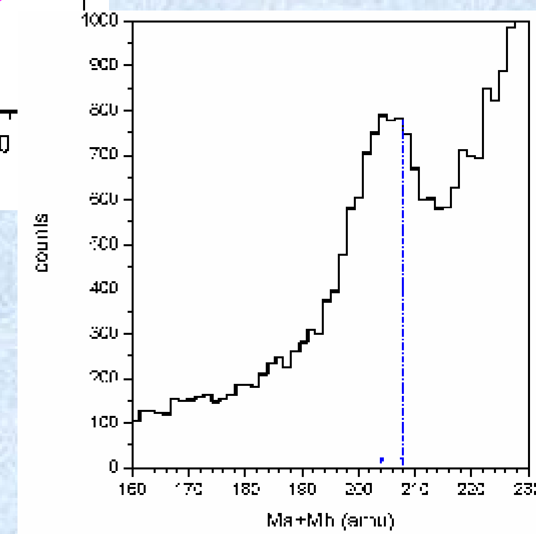


Fig.3 depicts as a contour map the difference between the "tailes" 4 and 3, i.d. shows bump 7 with out the background.

Experimental evidence of the collinear tripartition of the 252Cf nucleus obtained at the FOBOS setup.

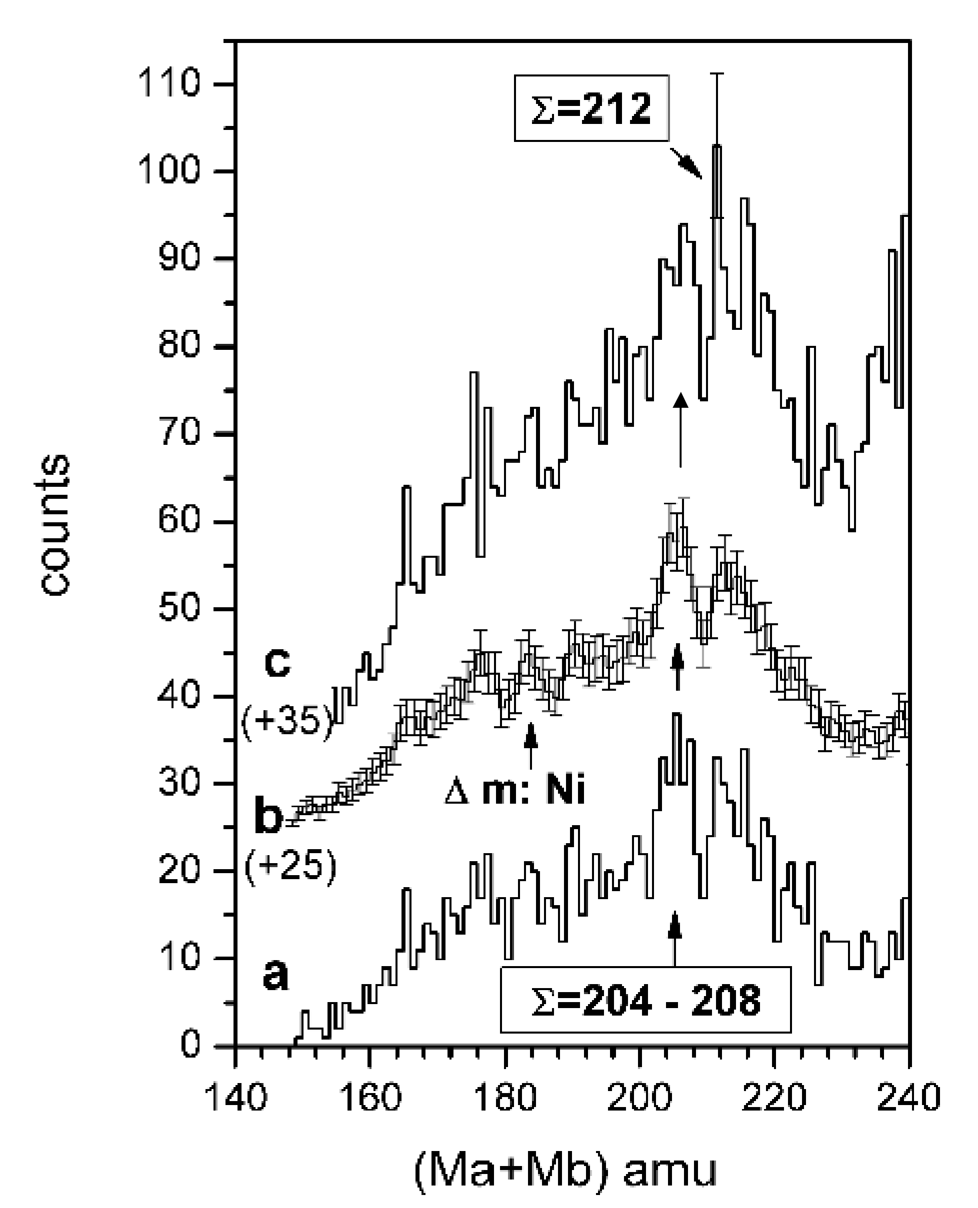






204 -> ^{70}Ni+^{134}Te;	Δm= 48 amu
208 -> ^{80}Ge + ^{128}Sn	Δm= 44 amu
212-> ^{80}Ge + ^{132}Sn or/and ^{78}Ni+^{134}Te or/and ^{68}Ni+^{144}Ba	Δm= 40 amu

JIFL- spectrometer (Exp. 3: 4 MCP- detectors, 72% transparency)

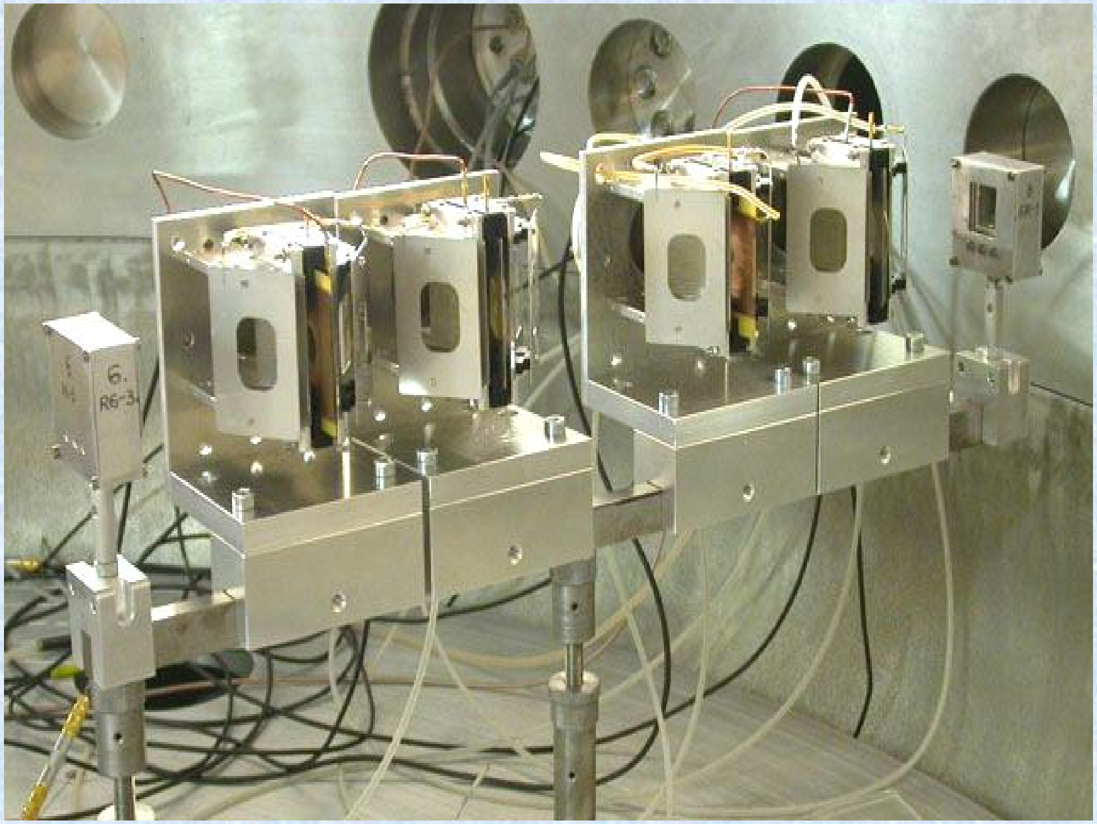


The sum of spectrum "a" and the complementary one obtained in the second arm of the spectrometer.

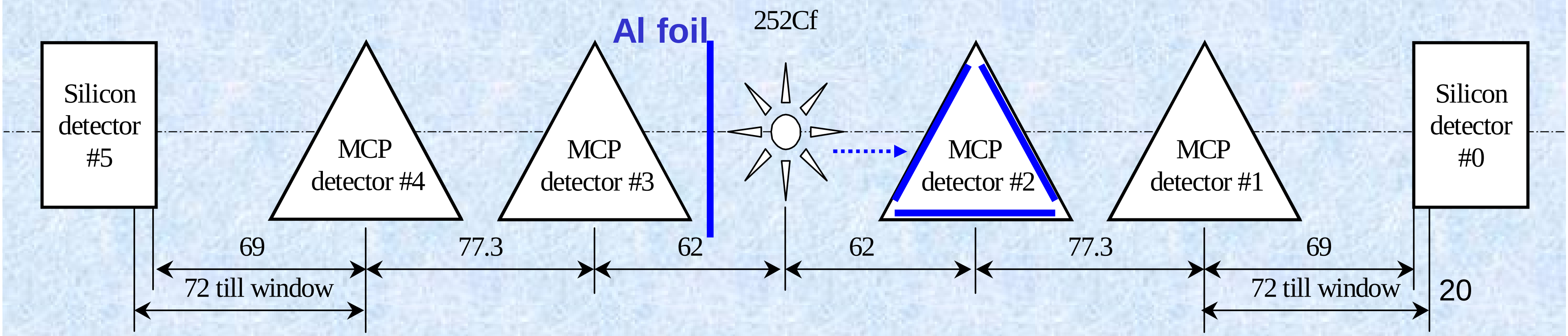
Averaging of counts in three adjacent channels of spectrum "a"

Spectrum "a" corresponds to the arm facing the source backing. Its relative yield amounts to $2.7 \cdot 10^{-3}$.

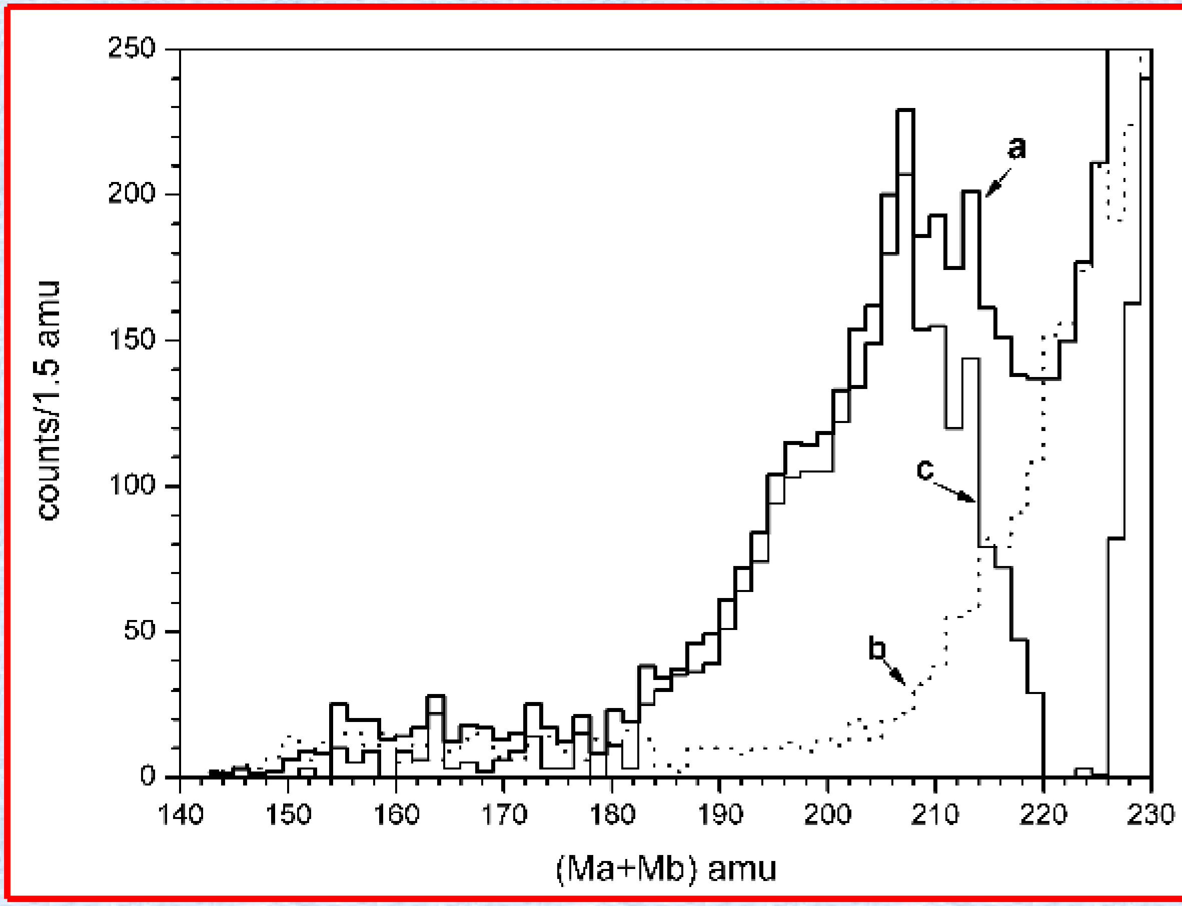
JYFL spectrometer



Exp. 4

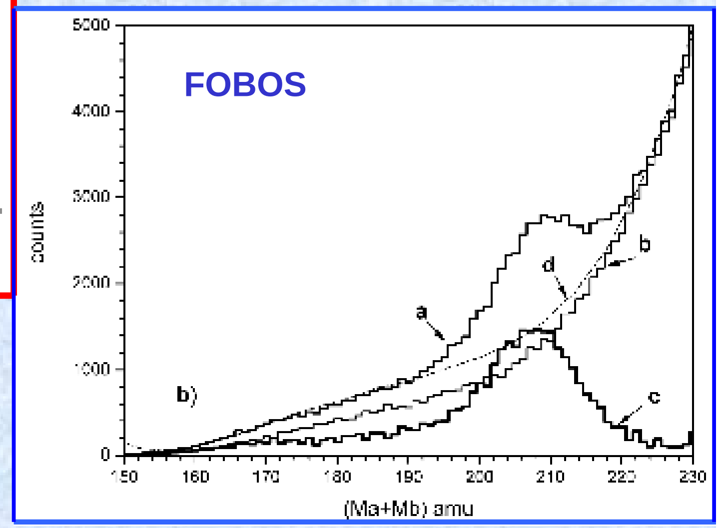


JIFL- spectrometer (Exp. 4, Al foil)



Al foil ~ 0.5 of full heavy fragment range

Thin source backing



Exp. 5: $^{238}U + ^{4}He$(40 MeV) reaction, JYFL, summer 2005

W. H. Trzaska, S. Yamaletdinov, V. Lyapin, M. Sillanpää

JYFL, Jyväskylä, Finland

M. Mutterer

Technical University, Darmstadt, Germany

Yu. V. Pyatkov

MEPhI, Moscow, Russia

V.G. Tishchenko, Yu. N. Kopach

JINR, Dubna, Russia

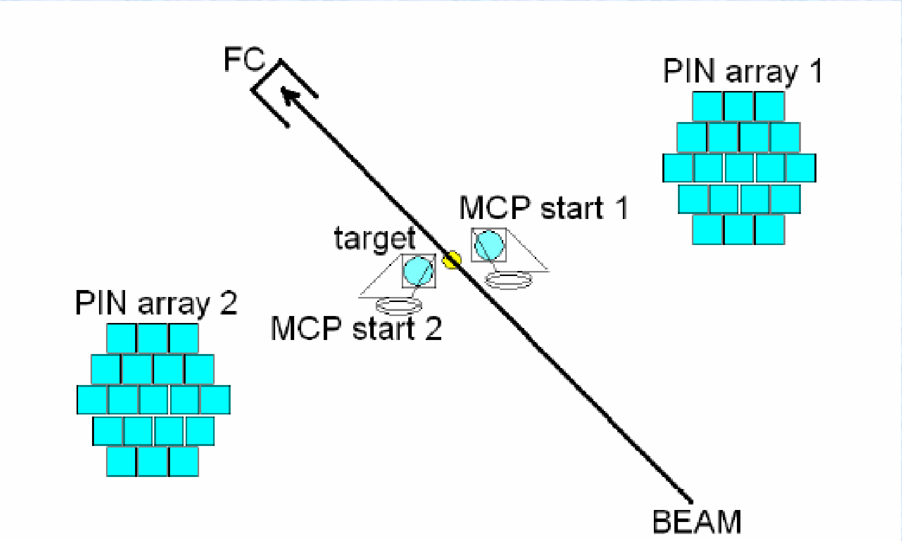
S. V. Khlebnikov, G. P. Tyurin

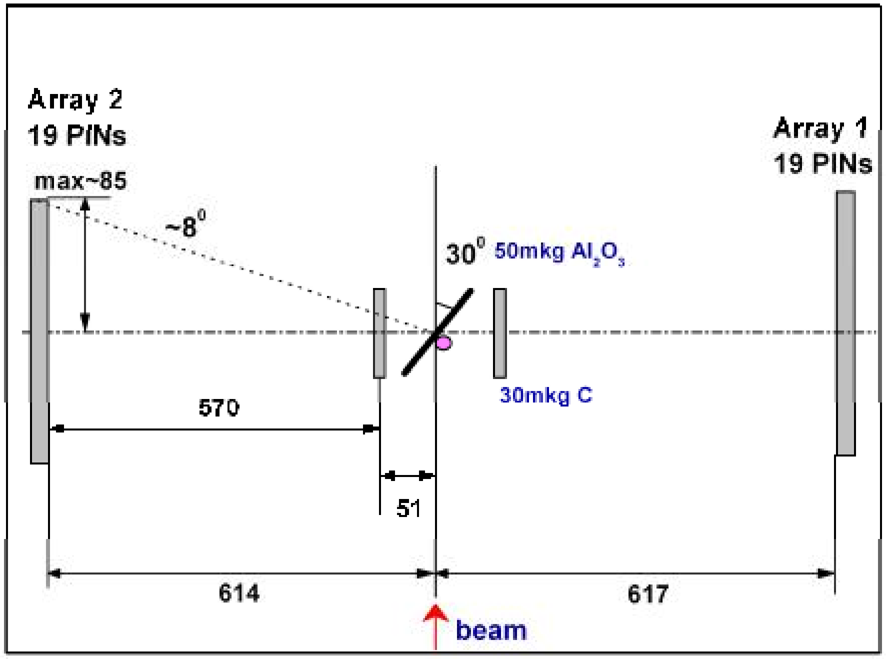
KRI, Sankt-Peterburg, Russia

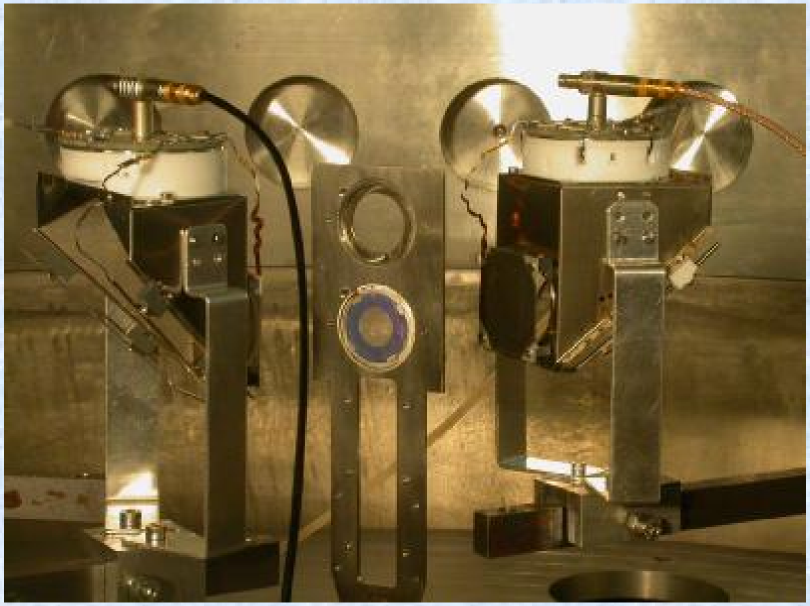
+ involved in data processing : A. Tyukavkin, D. Kamanin, E. Kuznetsova, D. Bolgov

FLNR, JINR

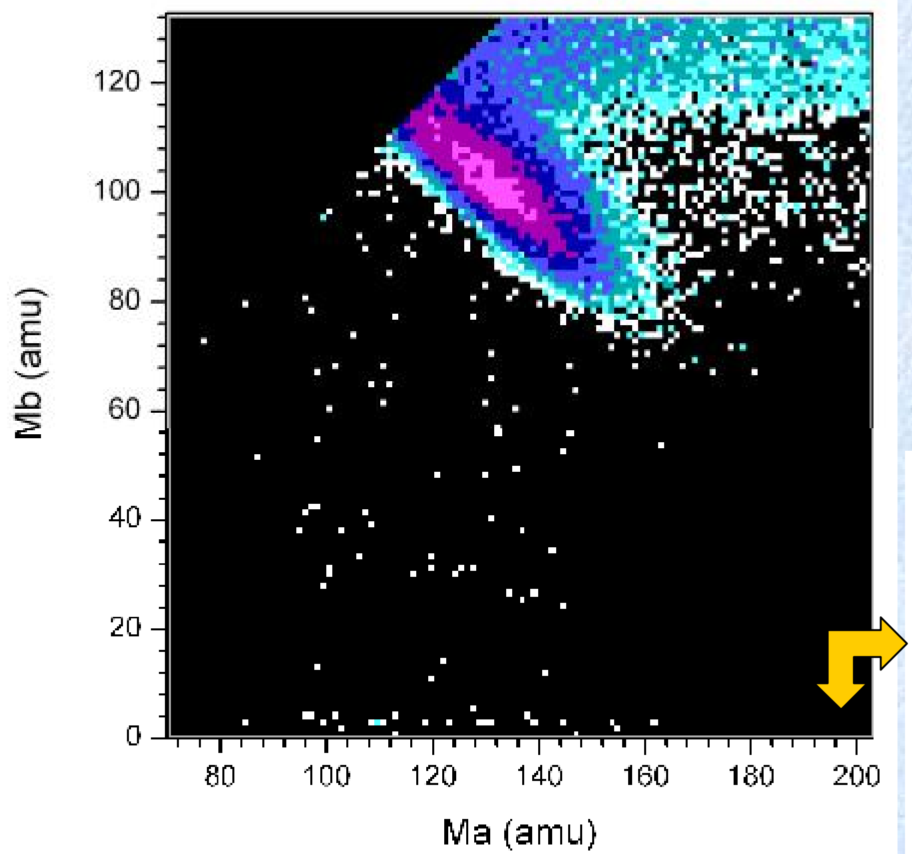
Experimental setup



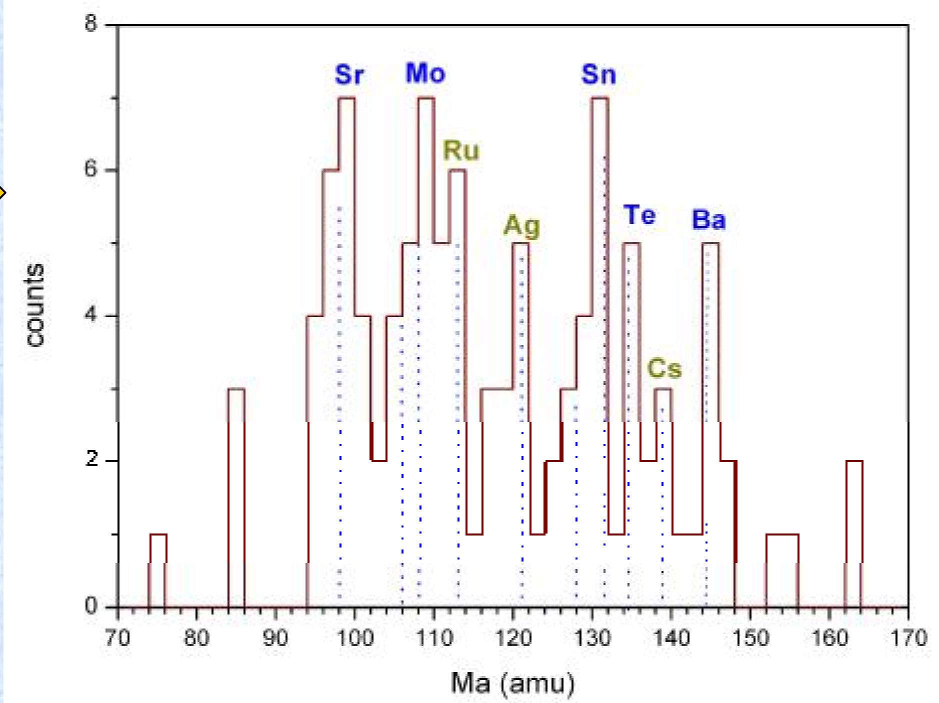




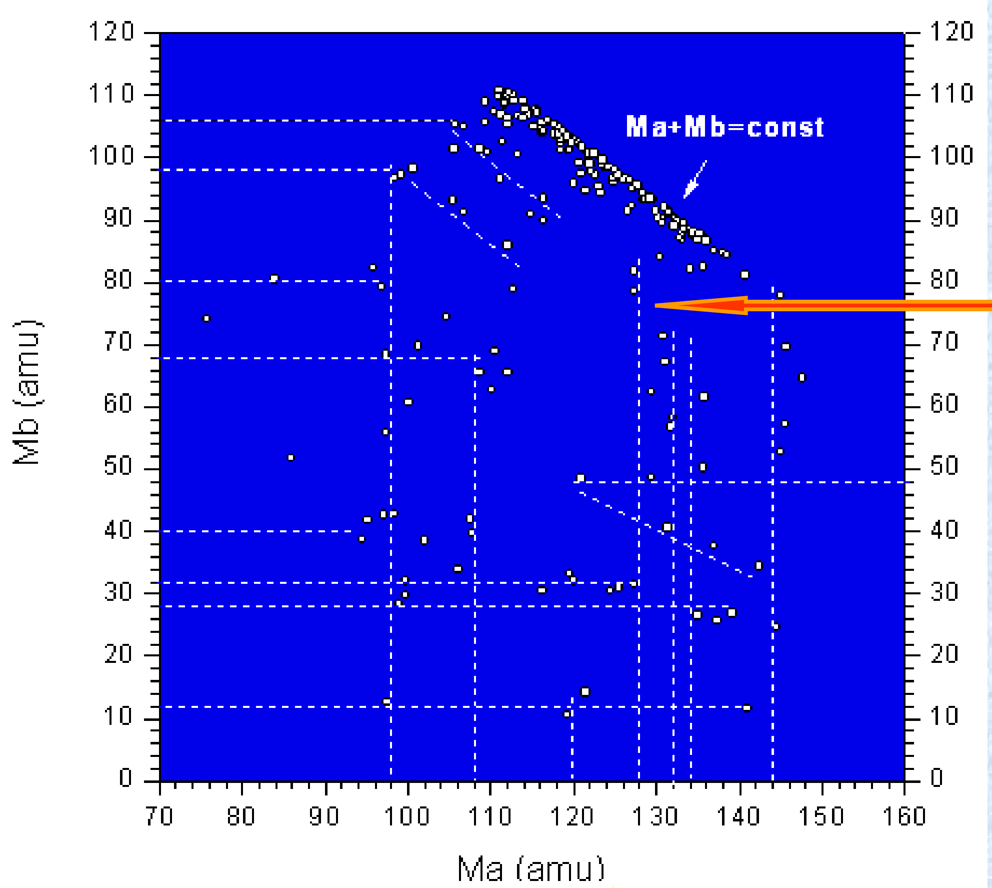
Preliminary results, fragment multiplicity 3.

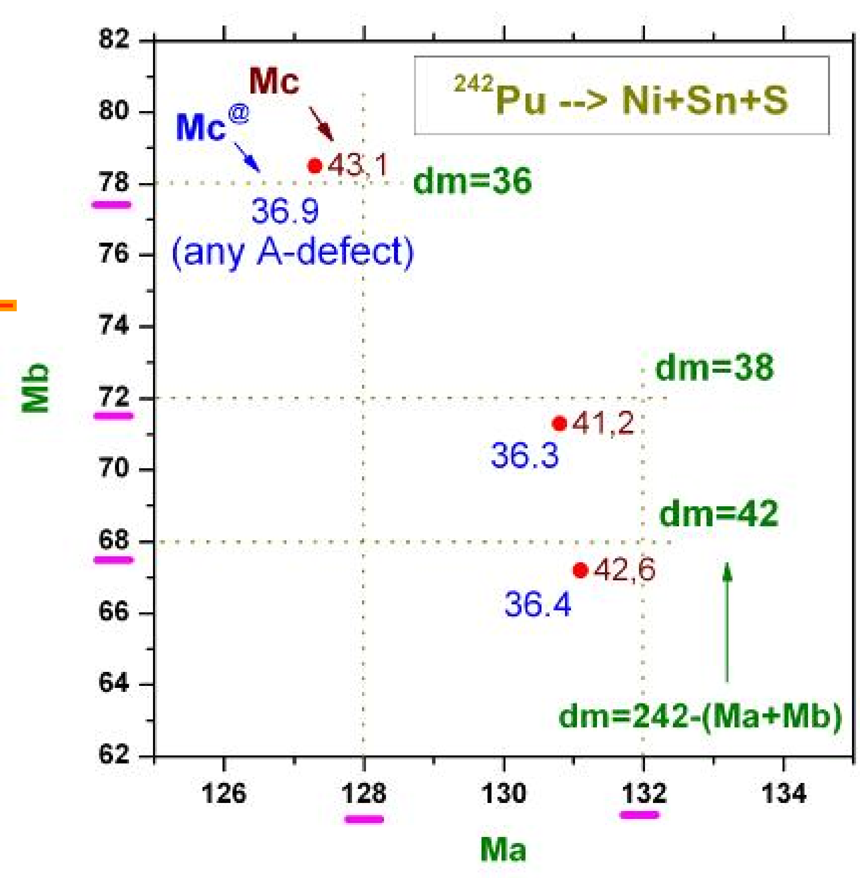


Projection onto Ma-axis



Clustering in ternary collinear fragmentation of $^{242}Pu^*$

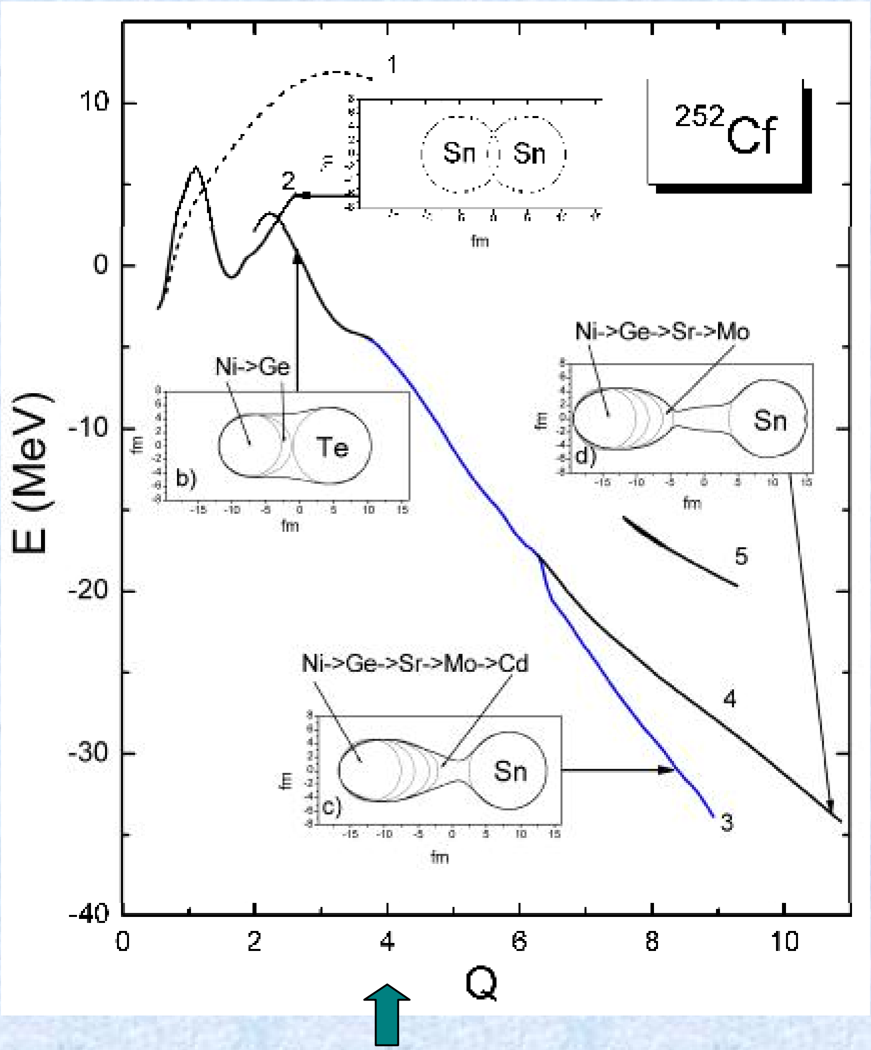




Position of magic fragments are marked by the dot lines.

Tilted lines correspond to Ma+Mb=const

Physics : what is already seen?



Yu.V. Pyatkov, V.V. Pashkevich,
Yu.E. Penionzhkevich et al.,
Nucl. Phys. A 624 (1997) 140

Double-cluster structure of the fissioning system

V.V. Vladimirski, JETP (USSR) 5 (1957) 673

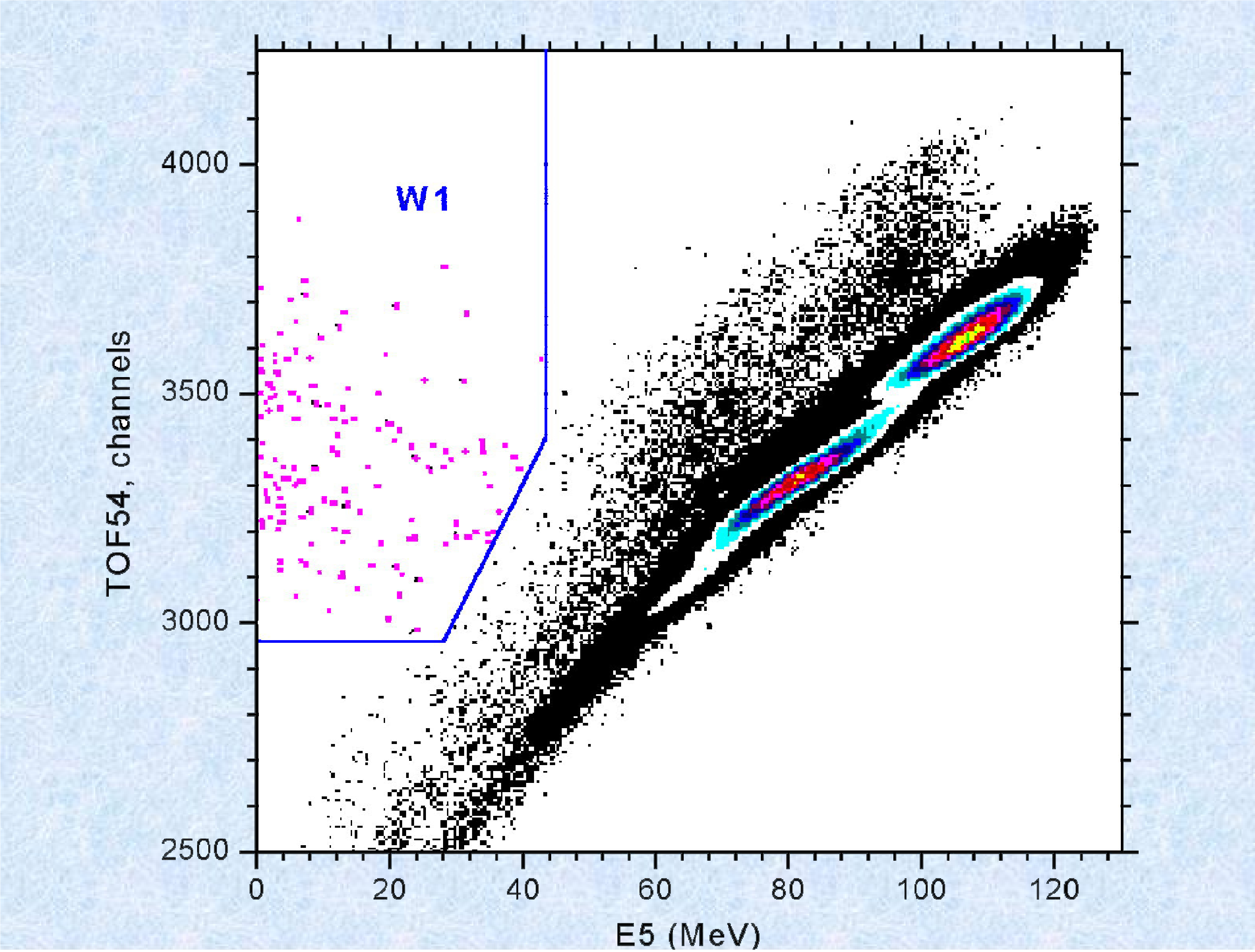
S.L. Whetstone, Phys. Rev. 114 (1959) 581

. . .

I.Tsekanovich,
H.-O.Denschlag, M.Davi,
Z. Büyükmumcu,
F. Gönnenwein, S Oberstedt,
H.R. Faust
Nucl. Phys. A 688 (2001) 633

Conclusions

- In the independent experiments we observe new at least ternary, almost collinear decay, named by us “collinear cluster tripartition” (CCT).
- Collected data let us to suppose a preformation of two magic constituents in the body of the fissioning system before scission.
- A scattering medium in the vicinity of the decay point enhances visible effect presumably due to multiple scattering of the CCT partners flying apart in the same direction.
- Maximum observed yield of the effect is about 10^{-3} per binary fission.

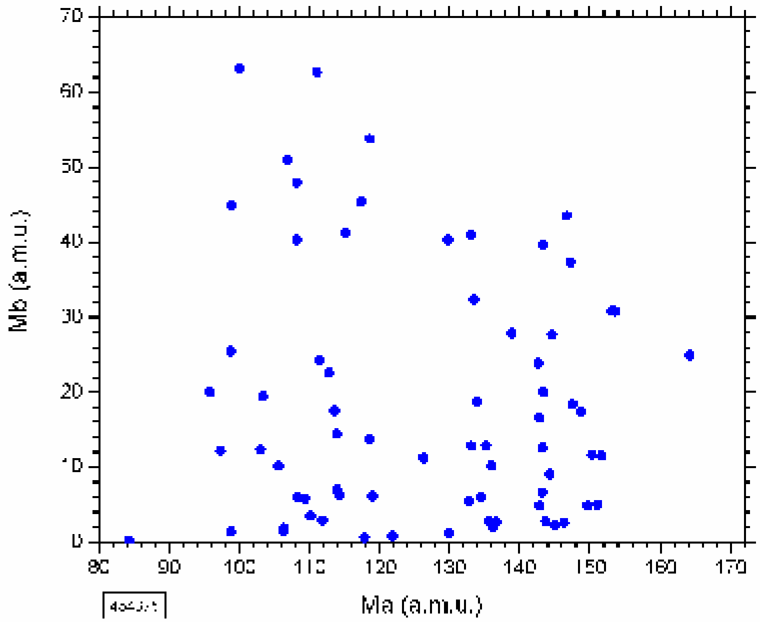

W1
TOF54, channels
2500
3000
3500
4000
0
20
40
60
80
100
120
E5 (MeV)

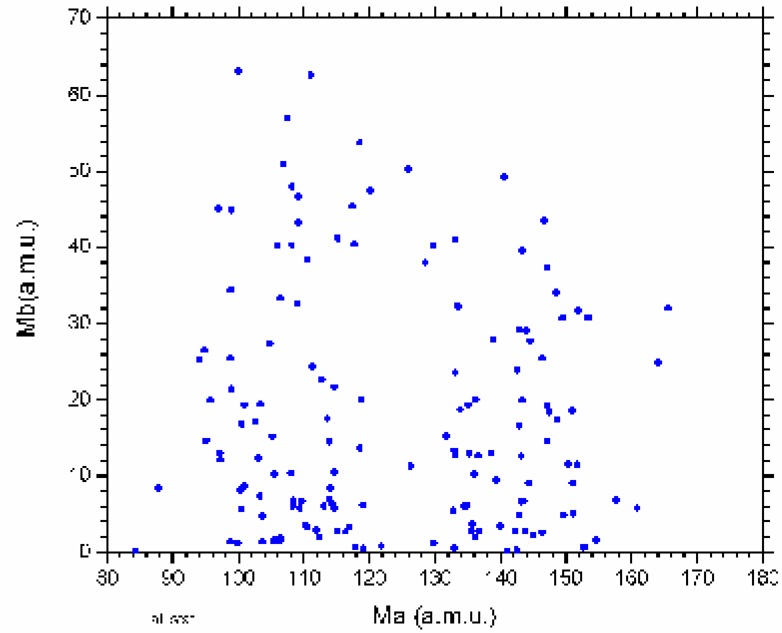
Conclusions

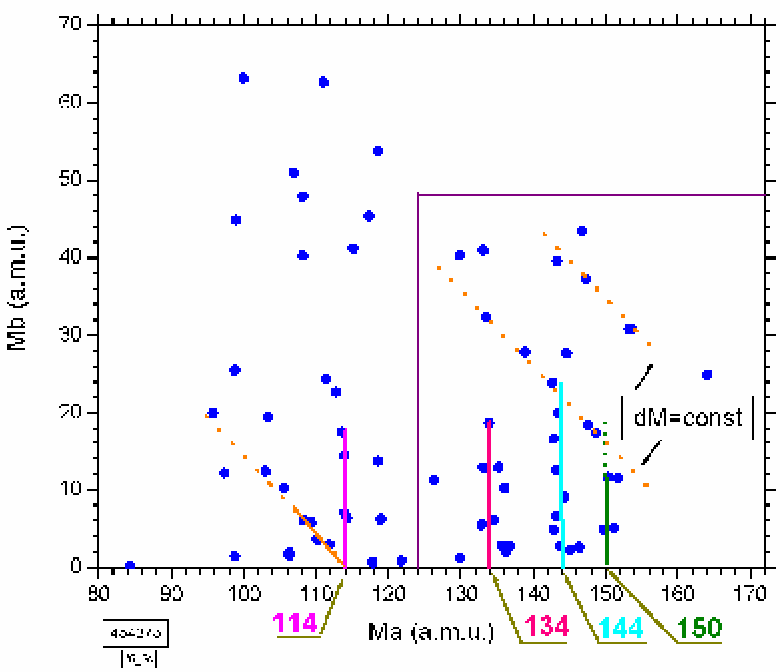
1. Experimental confirmation of a new type of spontaneous decay, namely, collinear cluster tripartition (CCT) is obtained at the total yield level of ~10-4 with respect to conventional binary fission.

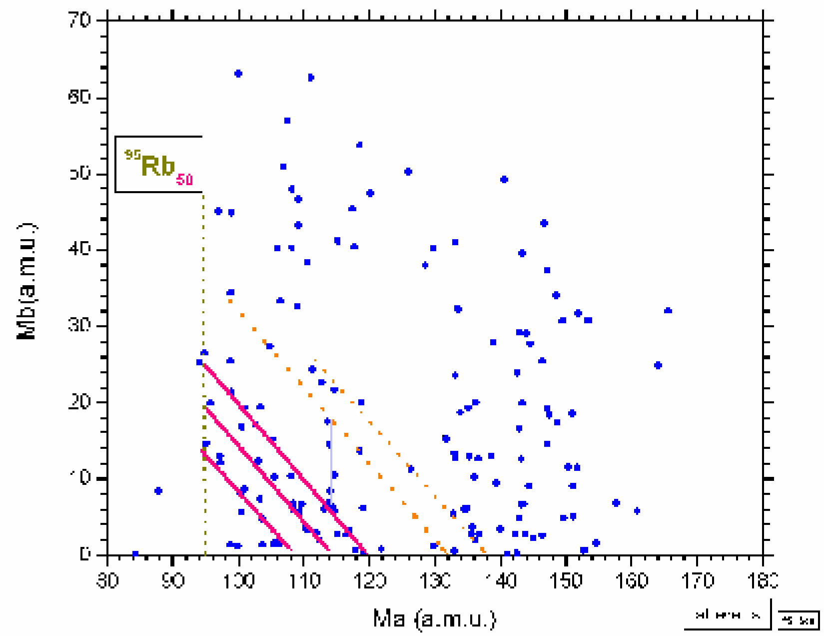
2. Clustering of the decaying system (preformation of at least two magic constituents in its body) gives rise to the effect observed.

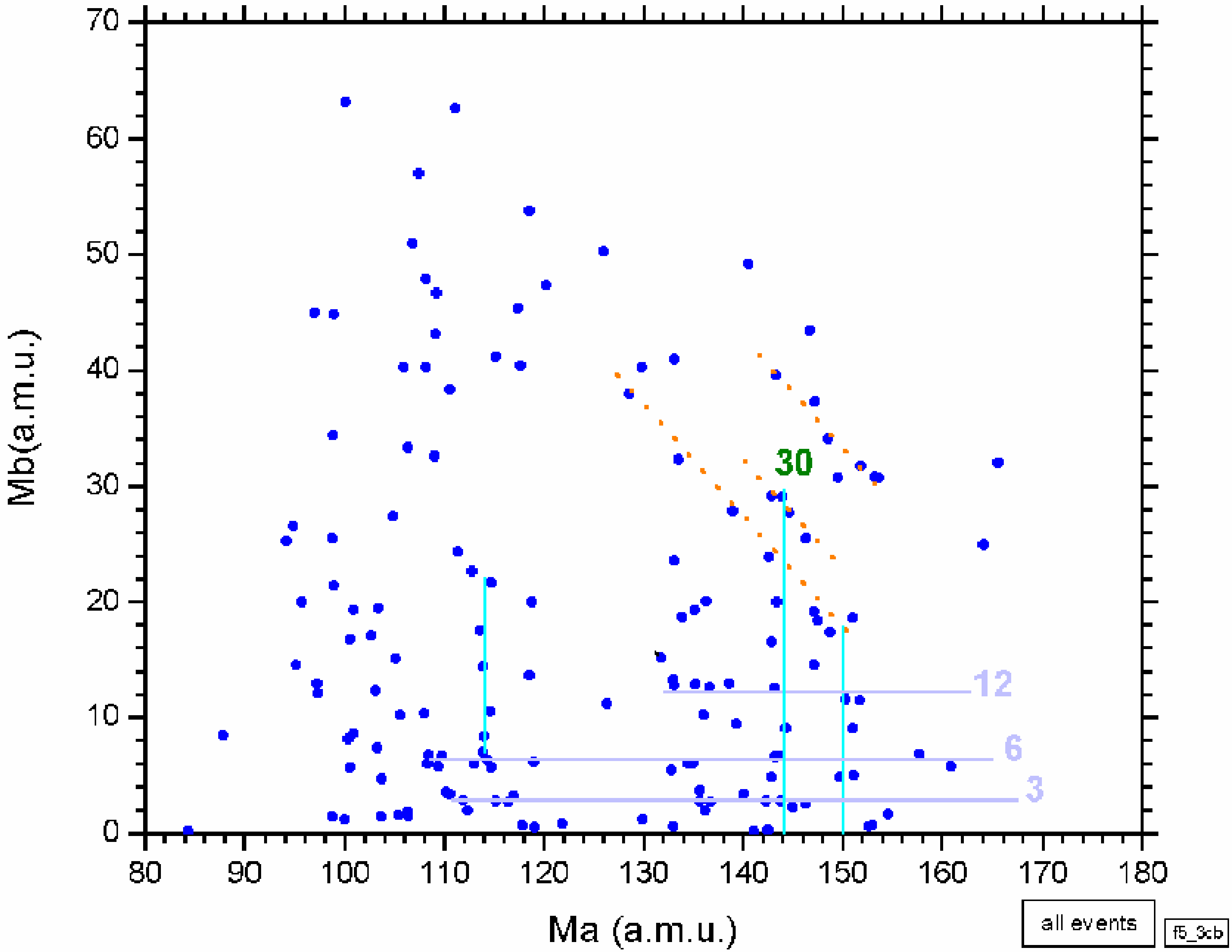
3. Studying of the CCT of low and middle excited nuclei seems to be very actual task, among other things as a possible source of exotic ions for RIB facilities.


Mb (a.m.u.)
Ma (a.m.u.)

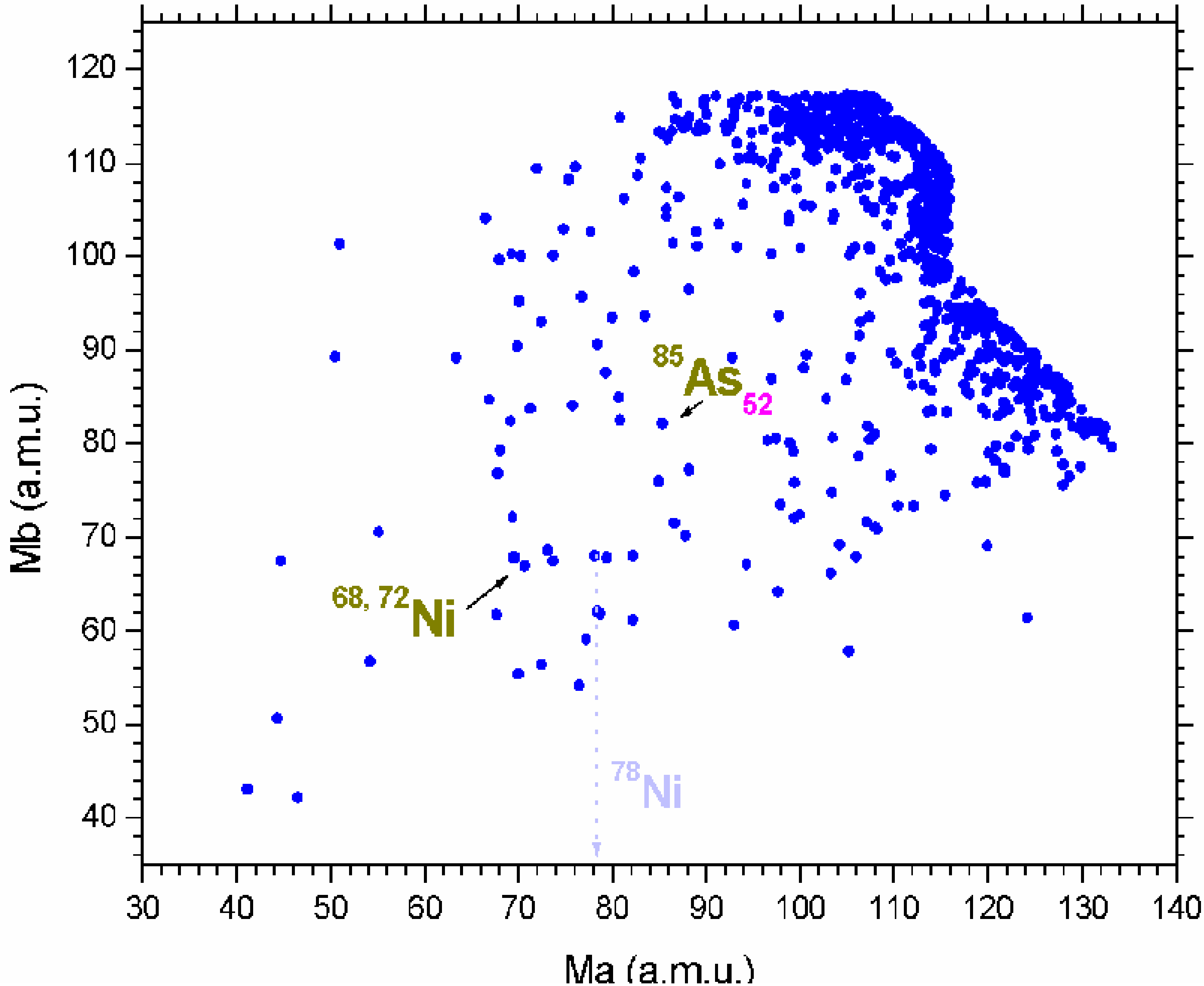

Mb(a.m.u.)
Ma (a.m.u.)


Mb (a.m.u.)
Ma (a.m.u.)
dM=const
114
134
144
150


$^{95}Rb_{50}$
Mb(a.m.u.)
Ma (a.m.u.)



Mb(a.m.u.)
Ma (a.m.u.)
30
12
6
3
all events
f5_3cb

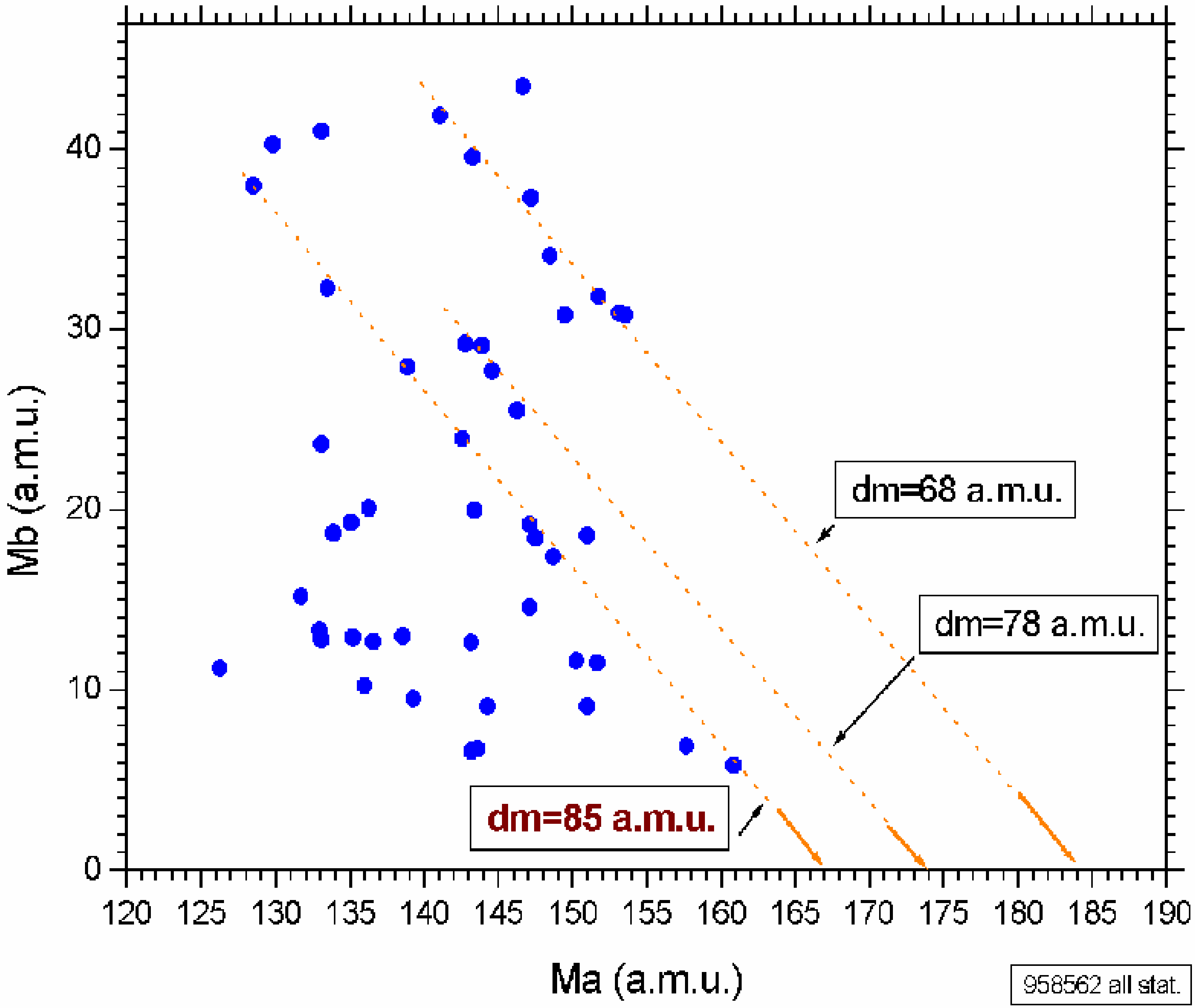


120
110
100
90
80
70
60
50
40
30
40
50
60
70
80
90
100
110
120
130
140
Mb (a.m.u.)
Ma (a.m.u.)
85As52
68, 72Ni
78Ni

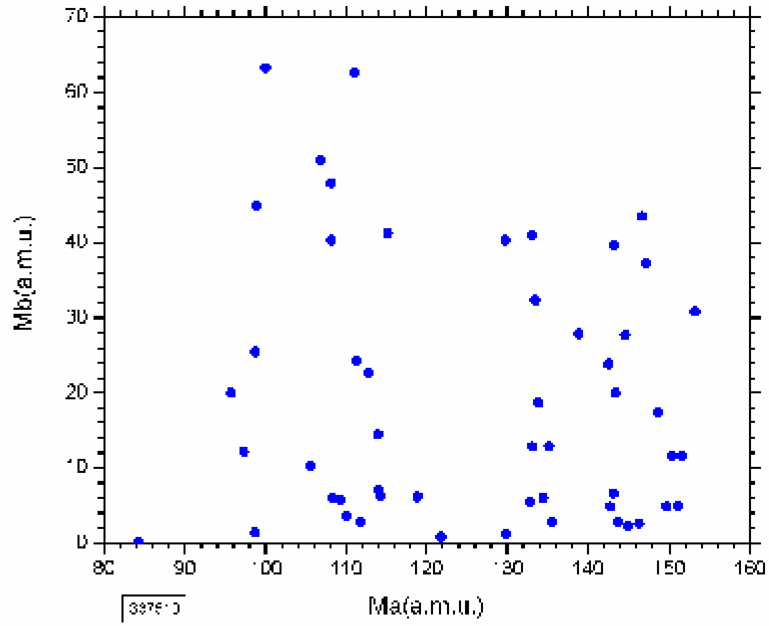
Background

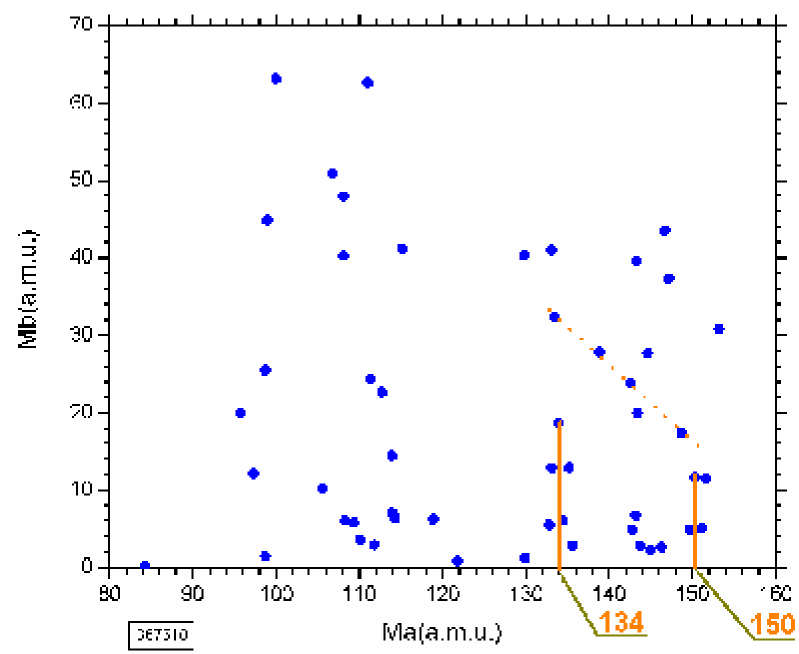
Cluster radioactivity		
$^{222-226}$Ra à ^{14}C **H.J. Rose and G.A. Jones, Nature 307 (1984) 245**	^{221}Fr ÷ ^{242}Cm à ^{14}C ÷ ^{34}Si (10^{-10}÷ 10^{-17}) P_{α} **"Lead radioactivity"**	**Binary decays**
Cold fission		
	"Tin radioactivity" ...	

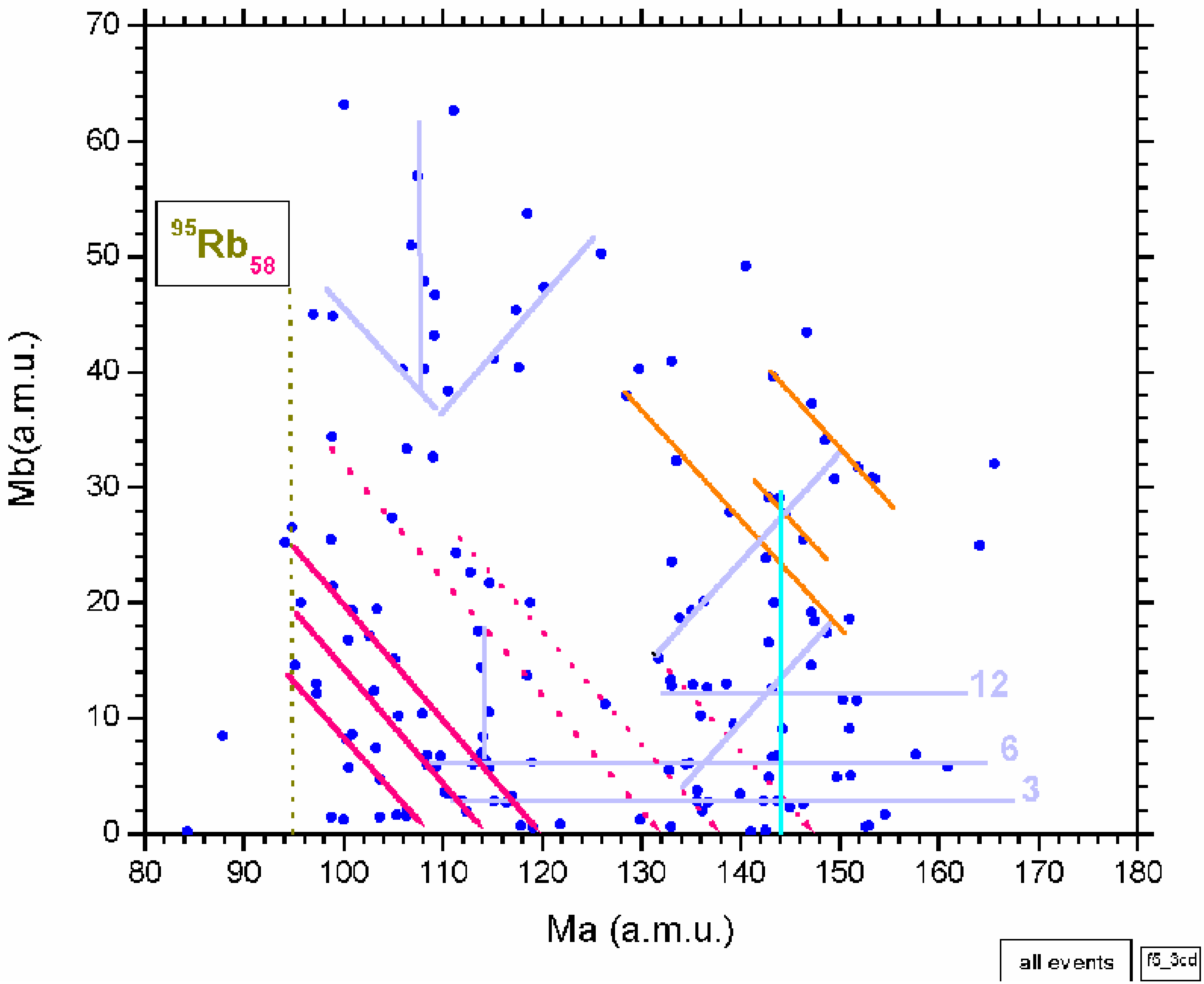
Light α – cluster nuclei	
"Ikeda et al. [Suppl. Prog. Phys. (Japan) Extra (1969) 464] speculated a rang of different cluster structures might occur in **^{24}Mg** nucleus: **α + ^{20}Ne, ^{8}Be + ^{16}O, ^{12}C + ^{12}C, ^{12}C + $^{12}C_{chain}$** and a **6α chain state**. There is now evidence for all these different structures [B.R. Fulton, Z. Phys A349 (1994) 227]"	**Multicomponent nuclear molecules**



Mb (a.m.u.)
Ma (a.m.u.)
0
10
20
30
40
120
125
130
135
140
145
150
155
160
165
170
175
180
185
190
dm=68 a.m.u.
dm=78 a.m.u.
dm=85 a.m.u.
958562 all stat.


Mb(a.m.u.)
Ma(a.m.u.)


Mb(a.m.u.)
Ma(a.m.u.)
134
150



95Rb58
12
6
3
Mb(a.m.u.)
Ma (a.m.u.)
all events
f5_3cd

Table 2. Experimental parameters of three a most symmetrical events.

Parameter	Event №1	№2	№3
Number of tripped neutron counters	0	0	1
Velocity in the arm ”a” (Va) cm/ns	1,147	1,102	1,135
Velocity in the arm ”b” (Vb) cm/ns	1,173	1,141	1,23
TOF-TOF mass (Mtta) a.m.u.	127,4	128,2	131,1
TOF-TOF mass (Mttb) a.m.u.	124,6	123,8	120,9
Momentum (Pa) (cm/ns)* (a.m.u.)	79,6	80,7	7,8
Momentum (Pb) (cm/ns)* (a.m.u.)	84,7	78,3	83,4
TOF-E mass (Mtea) a.m.u.	69,4	73,2	69,4
TOF-E mass (Mteb) a.m.u.	72,2	68,6	67,8
Etea (emission energy) MeV	47.5	46.3	46.5
Eteb MeV	51.7	46.5	53.4
TKEte (total kinetic energy) MeV	99,1	92,7	99,9

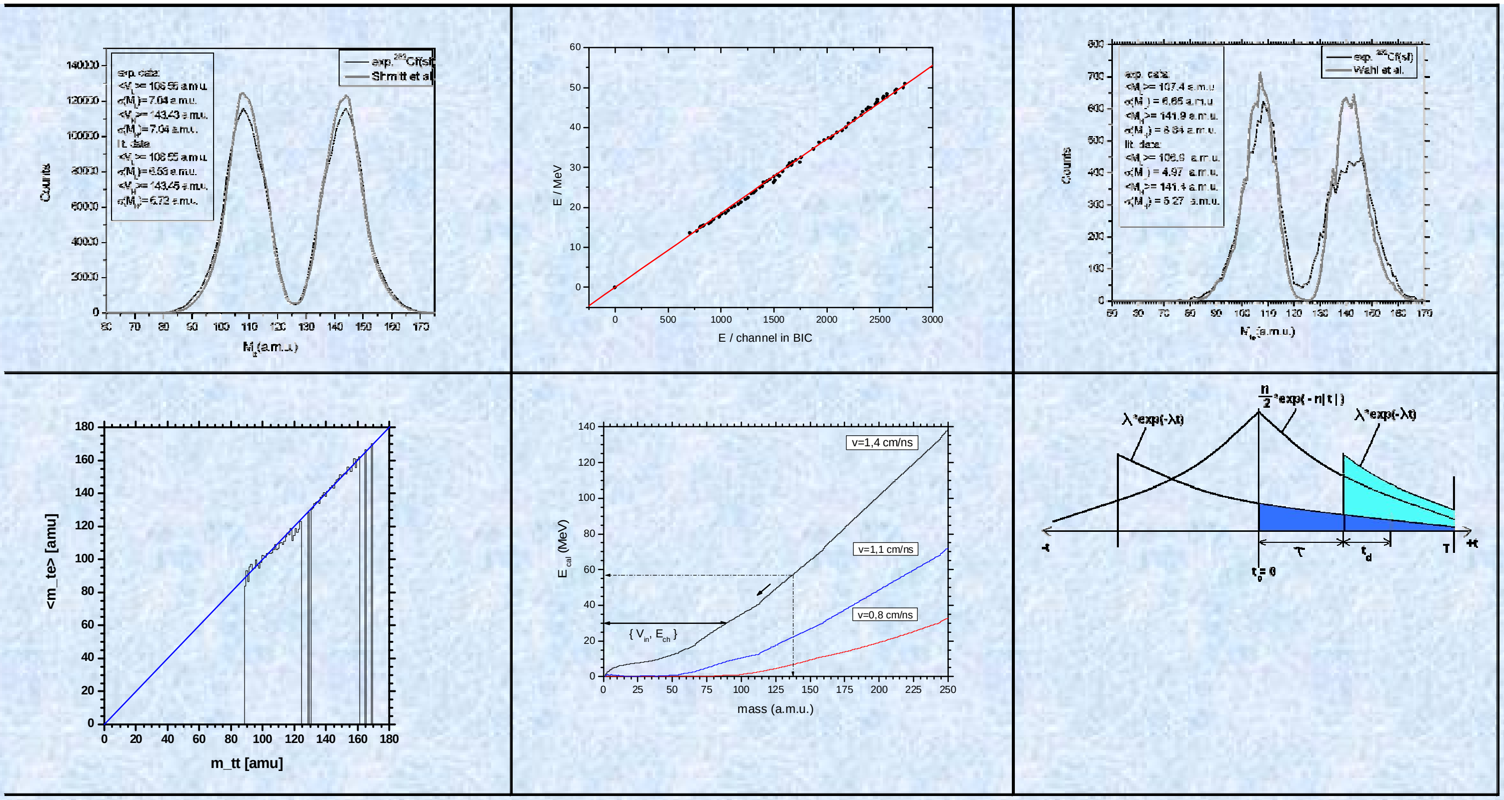
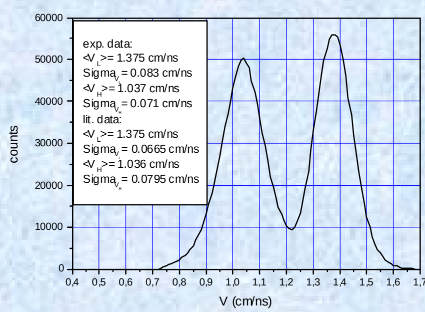


Table 1. Probability of emission of **k** neutrons from ^{252}Cf (sf) [16]

K	0	1	2	3	4	5	6	7
j_k	0.002	0.024	0.123	0.271	0.306	0.188	0.066	0.0163



Sequential (cascade) ternary fission

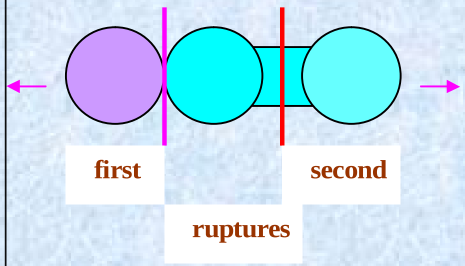
(excitation energy of a heavy fragment is enough for the second scission appears to occur).
^{238}U, ^{197}Au + ^{22}Ne (185 MeV)
^{209}Bi, ^{238}U + ^{40}Ar (310 MeV)

Karamian S.A., Kuznetsov I.V., Oganessian Yu.Ts. and Penionzkevich Yu.E.,

Jadernaja Fizika 5 (1963) 959

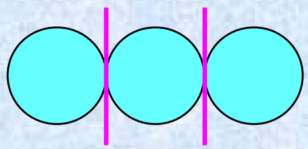
Two and three-body exit channels in the reactions
^{84}Kr + ^{166}Er → ^{252}100
^{129}Xe + ^{122}Sn → ^{251}104 at 12.5 MeV/u
"A fast two-step mechanism where a sequential fission-like process follows a deep inelastic collision with very large energy losses. **An orientation of the fission axis is approximately collinear with the axis of the first fission.** All the properties observed present consistent evidence for a new phenomenon of non-equilibrium fission"

P.Glässel et al., Z. Phys. A310 (1983) 189



"Besides the already observed sequential binary process, **the presence of prompt ternary break-up of the composite system is revealed** in
^{32}S + ^{59}Co → ^{91}Tc
^{32}S + ^{63}Cu → ^{95}Rh
reactions at 5.6 MeV/u. **The decay appears to occur in a collinear configuration.** In spite of the large energy dissipation some events shows structure effects, i.e. the possible **presence of slustering phenomena** in the reaction (at least one fragment is an **α-like nucleus**) "

L.Vannuci et al., Eur.Phys. J. A 7 (2000) 65



prompt ternary break-up of a collinear configuration

Background

<table>
<tr><th colspan="2">Cluster radioactivity</th><td rowspan="4">Binary decays</td></tr>
<tr><td>$^{222-226}$Ra à ^{14}C
H.J. Rose and G.A. Jones, Nature 307 (1984) 245</td><td>^{221}Fr ÷ ^{242}Cm à ^{14}C ÷ ^{34}Si
(10^{-10}÷ 10^{-17}) P_{α}
“Lead radioactivity”</td></tr>
<tr><th colspan="2">Cold fission</th></tr>
<tr><td colspan="2">“Tin radioactivity” ...</td></tr>
</table>

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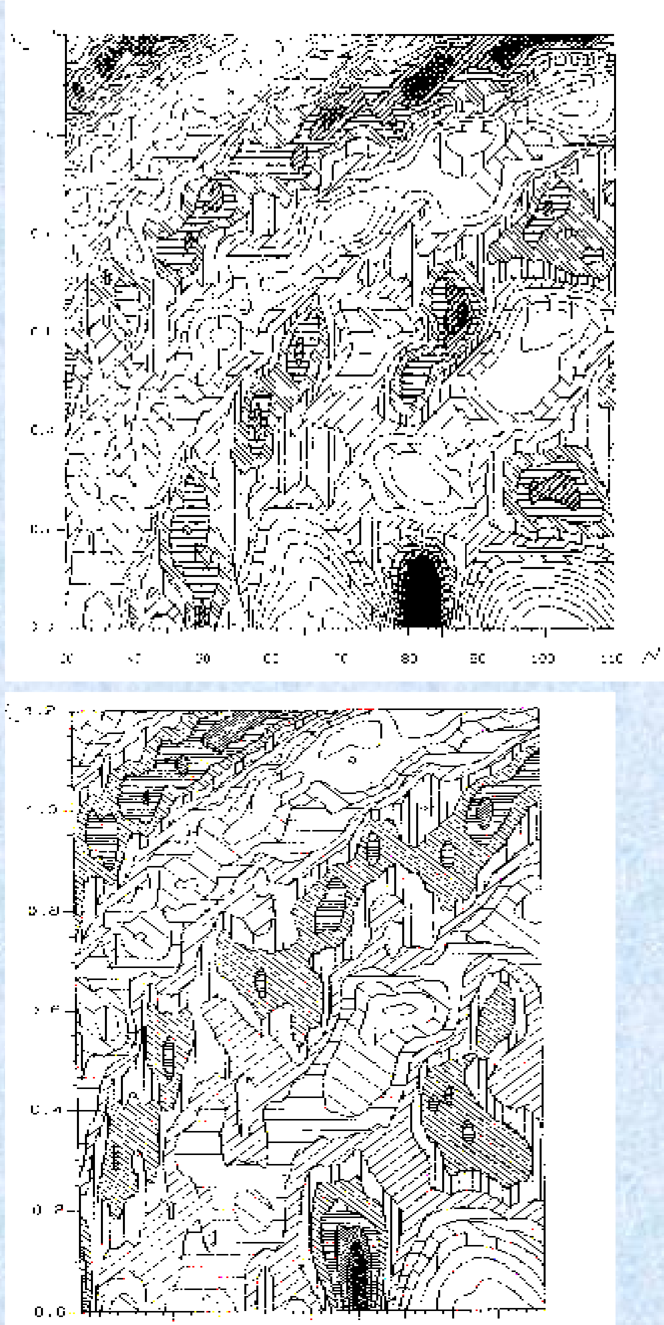
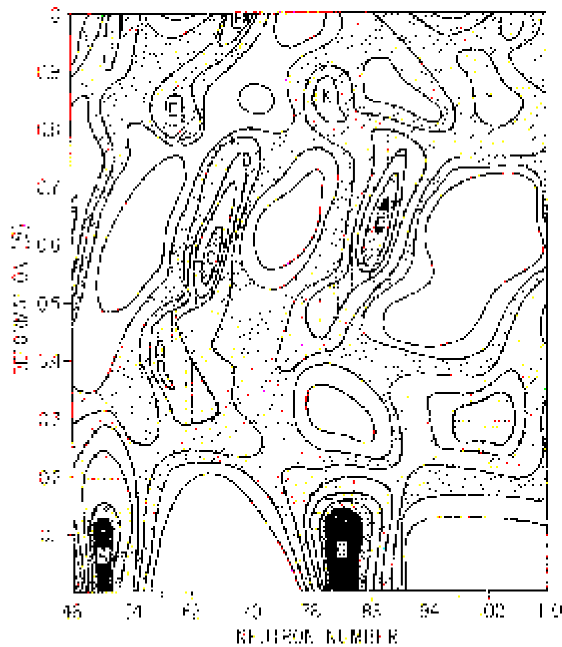


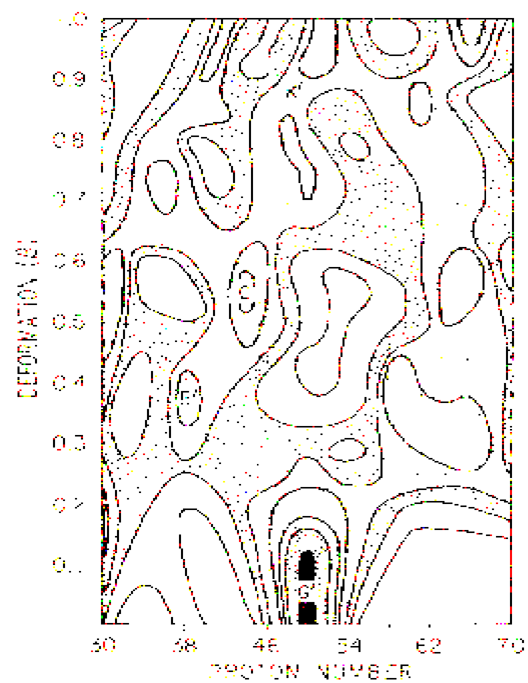
20 30 40 50 60 70

proton number

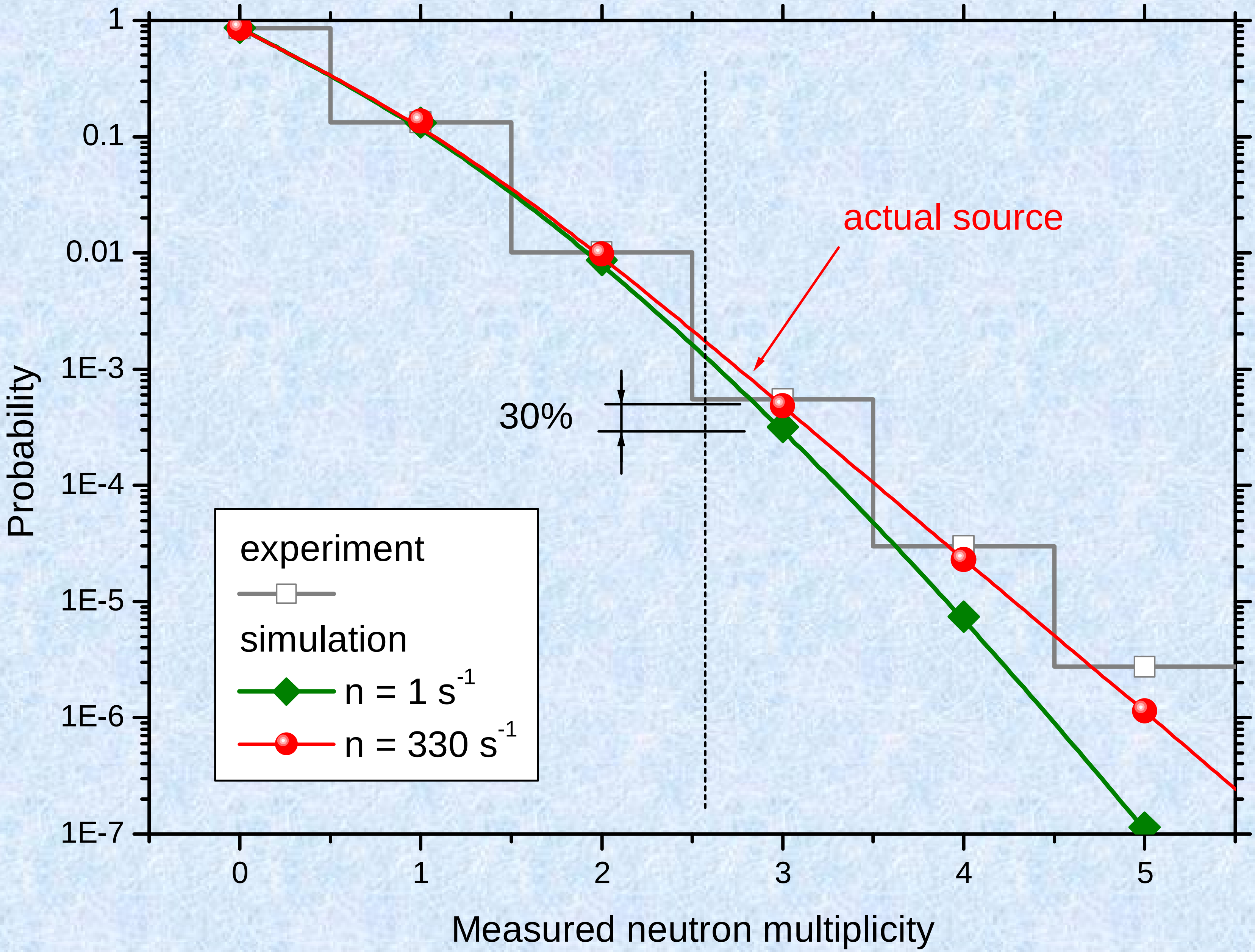
(H.Märton, private communication)

$\varepsilon_2=0.95\beta_2$





B.D. Wilkins et al., Phys Rev. C 14 (1976) 1832



actual source
30%
experiment
simulation
n = 1 s-1
n = 330 s-1
Probability
1
0.1
0.01
1E-3
1E-4
1E-5
1E-6
1E-7
0
1
2
3
4
5
Measured neutron multiplicity