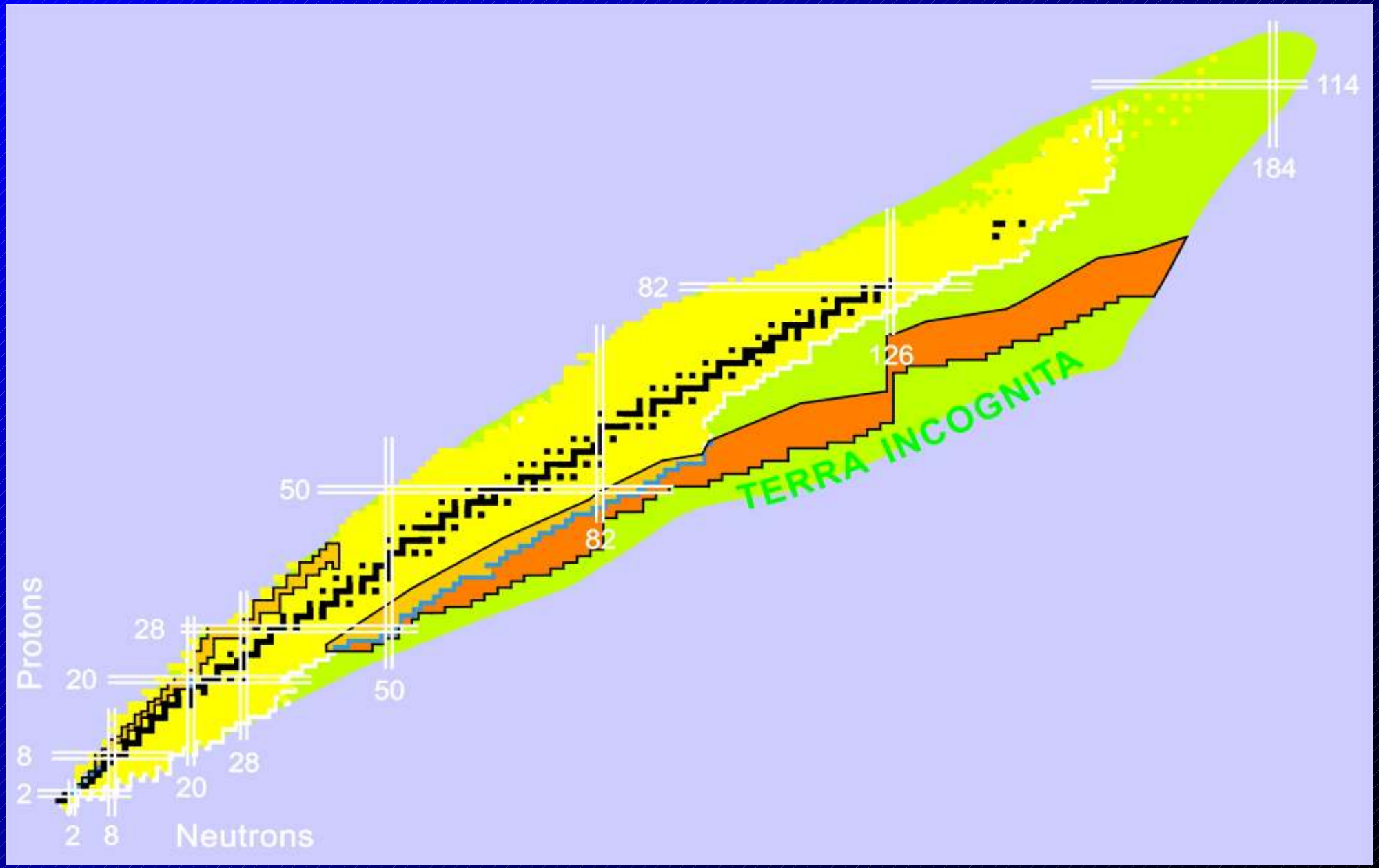
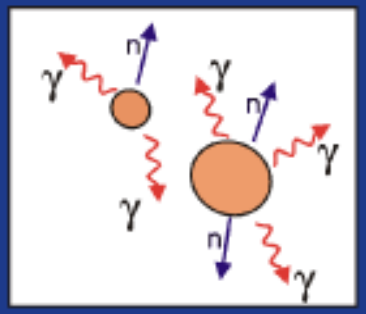
# Spektroskopia jądrowa w głęboko-nieelastycznych zderzeniach ciężkich jonów

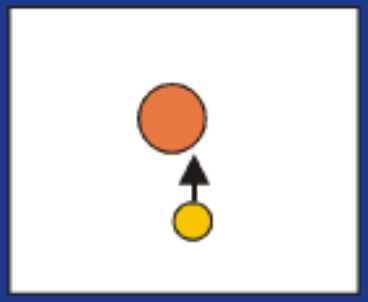
**Rafał Broda**

**Instytut Fizyki Jądrowej im. H.Niewodniczańskiego**
**Polska Akademia Nauk**
**Kraków**

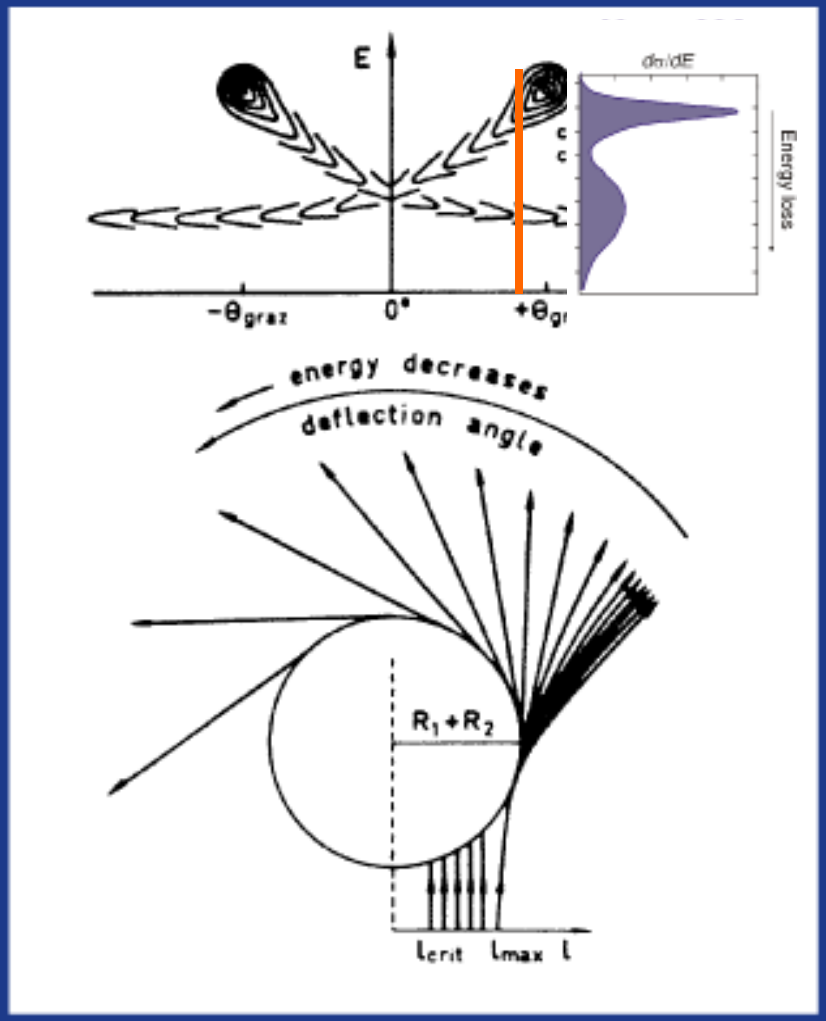

114
184
82
126
TERRA INCOGNITA
50
82
28
20
50
8
2
28
20
2
8
Protons
Neutrons

# Deep inelastic reactions

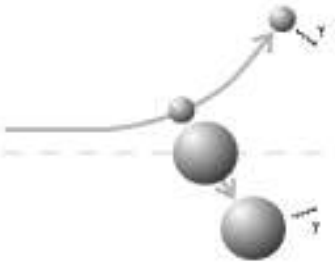


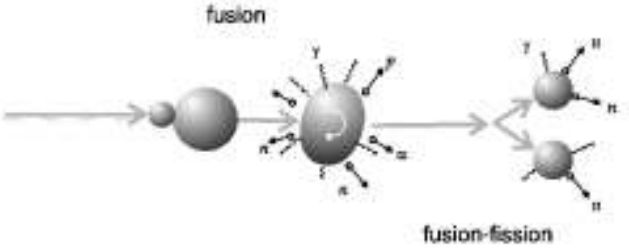



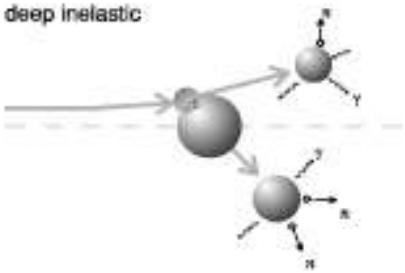
## Wilczynski plot



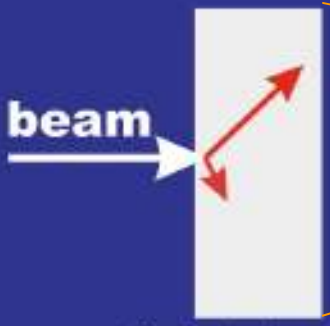

*J. Wilczynski, Phys. Lett. B 47, 484 (1973).*

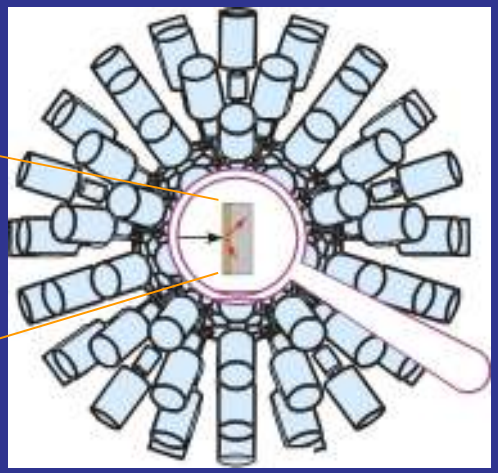

quasielastic


fusion
fusion-fission

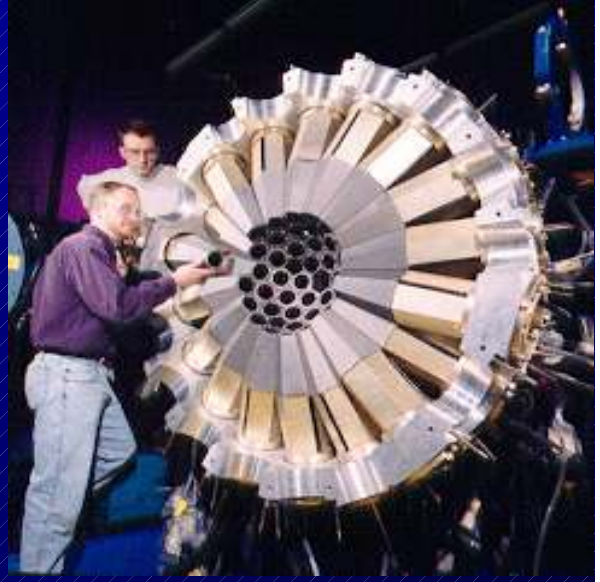

deep inelastic

# Deep inelastic reactions - a tool for nuclear spectroscopy

# Eksperymenty z grubą tarczą



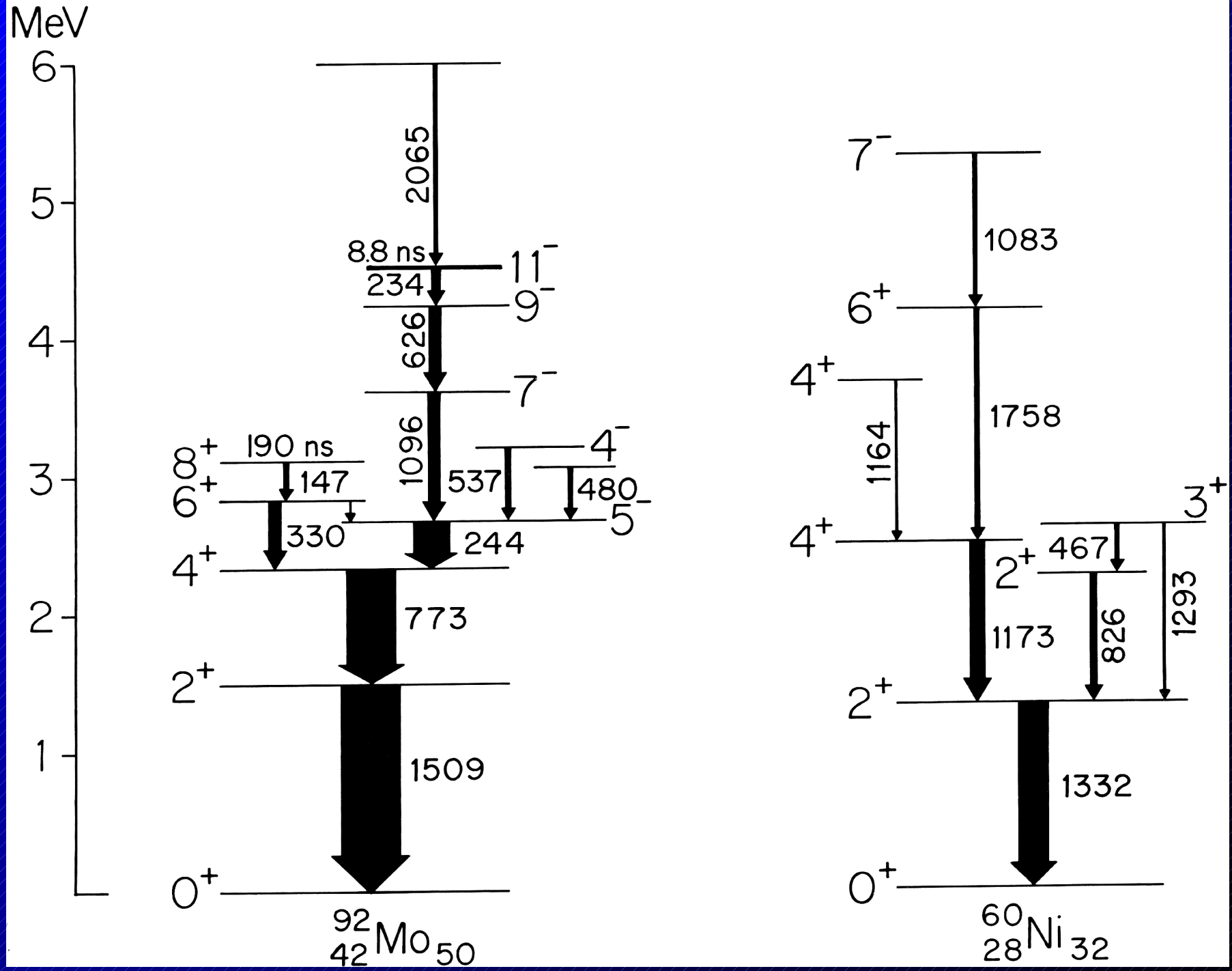
GAMMASPHERE

- Produkty zatrzymane w tarczy, dyskretne linie gamma, za wyjątkiem krótkożyciowych stanów wzbudzonych
- Koincydencje $\gamma$ -$\gamma$ zebrane z dużymi statystykami i krotnościami
- Selektywność oparta na wielostronnej analizie koincydencji gamma - w wyniku- struktury stanów jądrowych w nowych jądrach –
- Identyfikacja przez koincydencje krzyżowe

✔ R. Broda et al., JPG 32, 151 (2006)

**B.Fornal, W.Królas, T.Pawłat, J.Wrzesiński, R.B.**

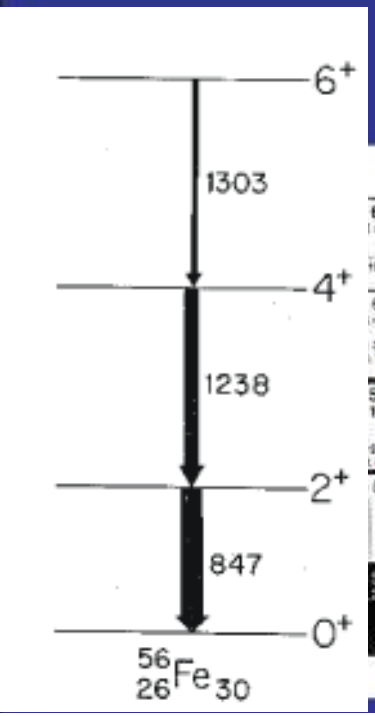
Purdue University, W.Lafayette, IN, USA
**Argonne National Laboratory, Argonne, Ill, USA**
Hahn-Meitner Institut, Berlin, Germany
**INFN LNL Legnaro/Padova University, Włochy**
Gesellschaft fuer Schwere Ionen, Darmstadt, Germany
JYFL-University of Jyvaskyla, Finland
LBL Berkeley, Cf, USA


MeV
6
5
4
3
2
1
2065
8.8 ns
11⁻
234
9⁻
626
7⁻
1096
8⁺
190 ns
147
6⁺
330
537
4⁻
480
5⁻
244
4⁺
773
2⁺
1509
0⁺
92 42 Mo 50
7⁻
1083
6⁺
4⁺
1164
1758
4⁺
3⁺
467
2⁺
1173
826
1293
2⁺
1332
0⁺
60 28 Ni 32

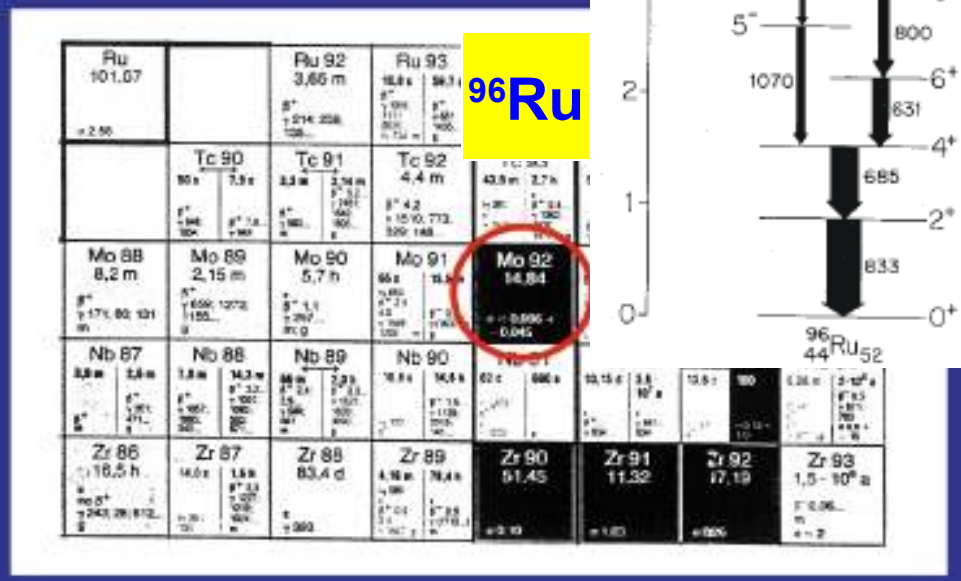
# Deep inelastic reactions

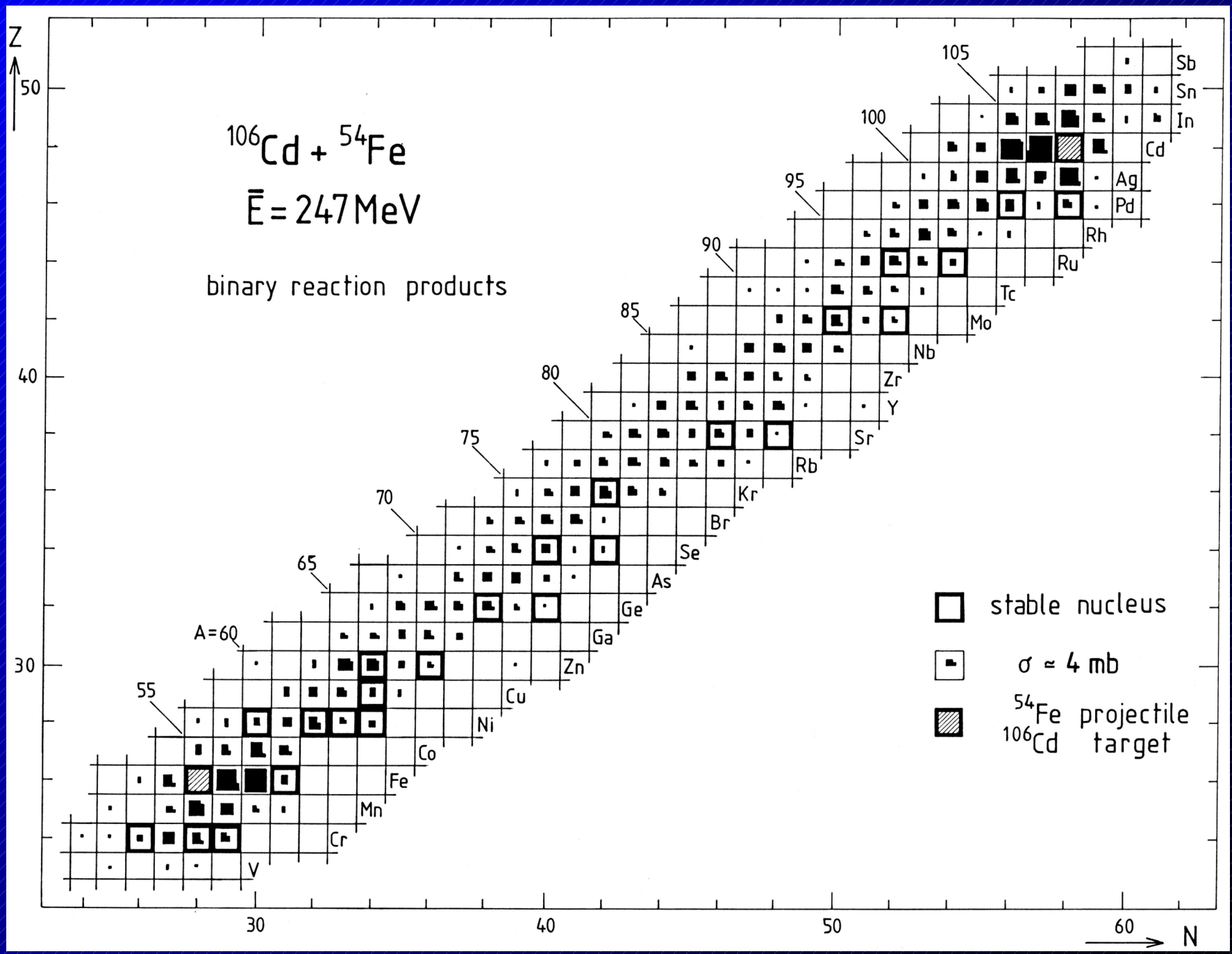
## $^{60}$Ni(255 MeV)+$^{92}$Mo

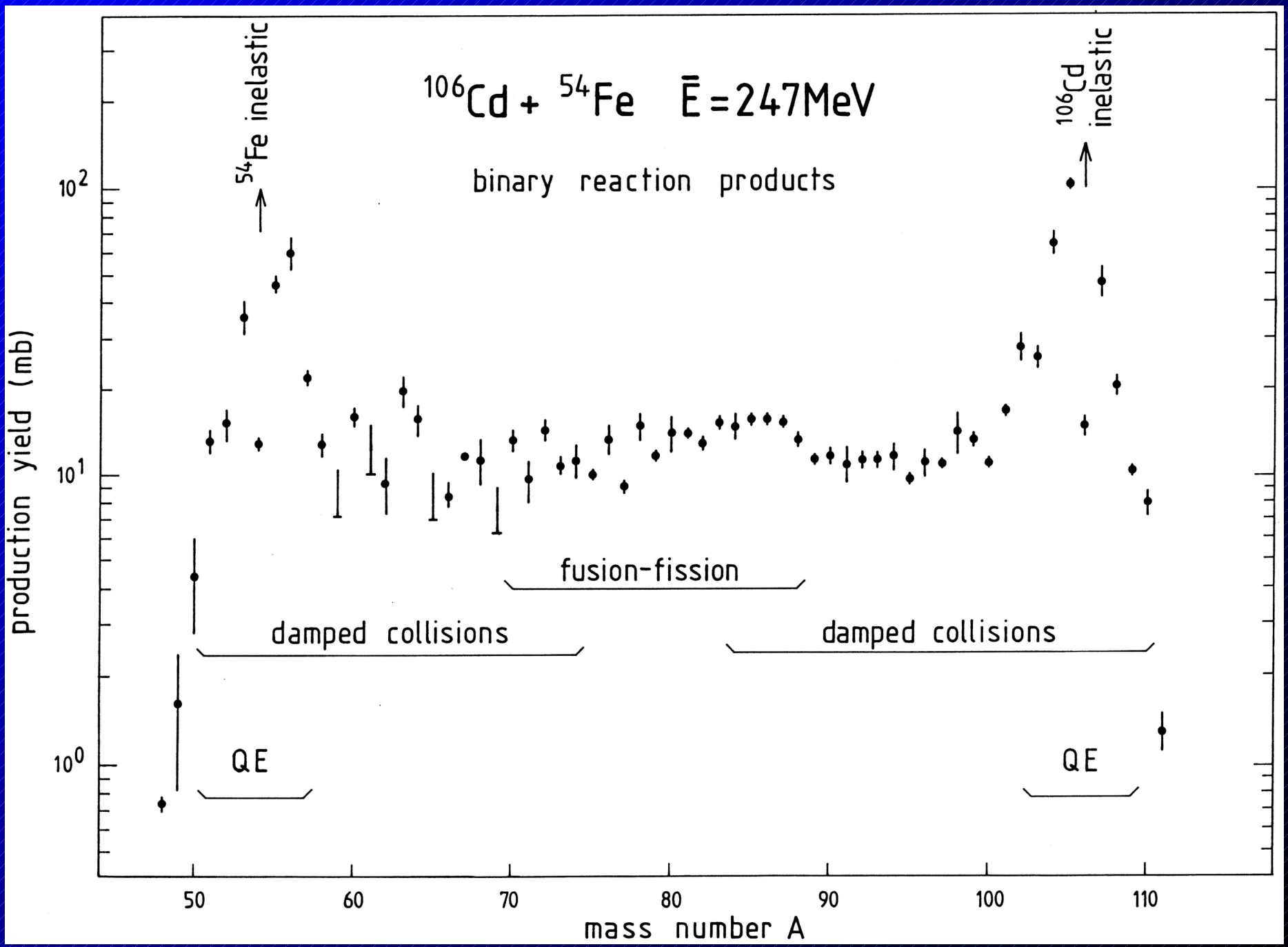
(Argonne-Notre Dame Array)

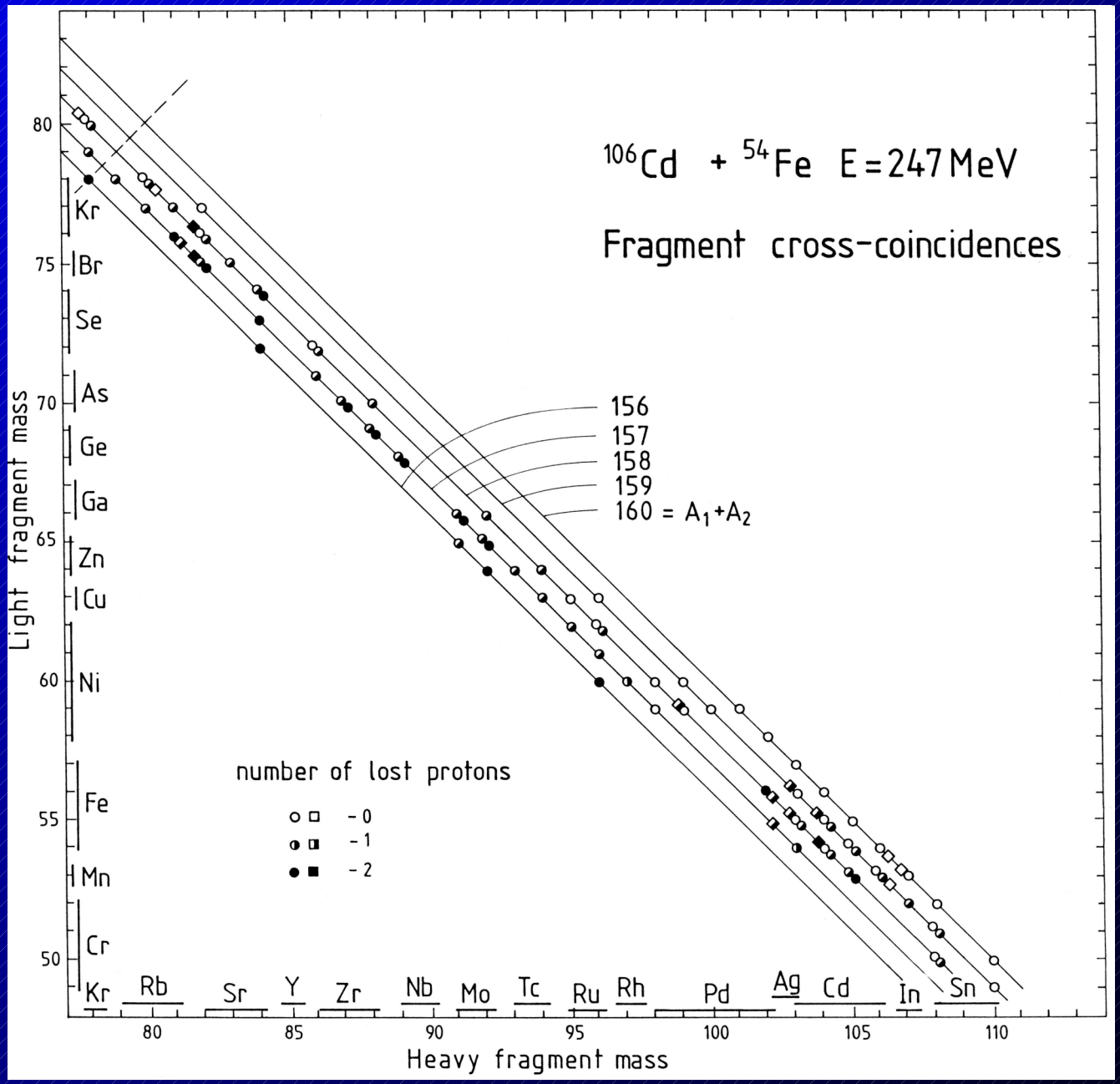


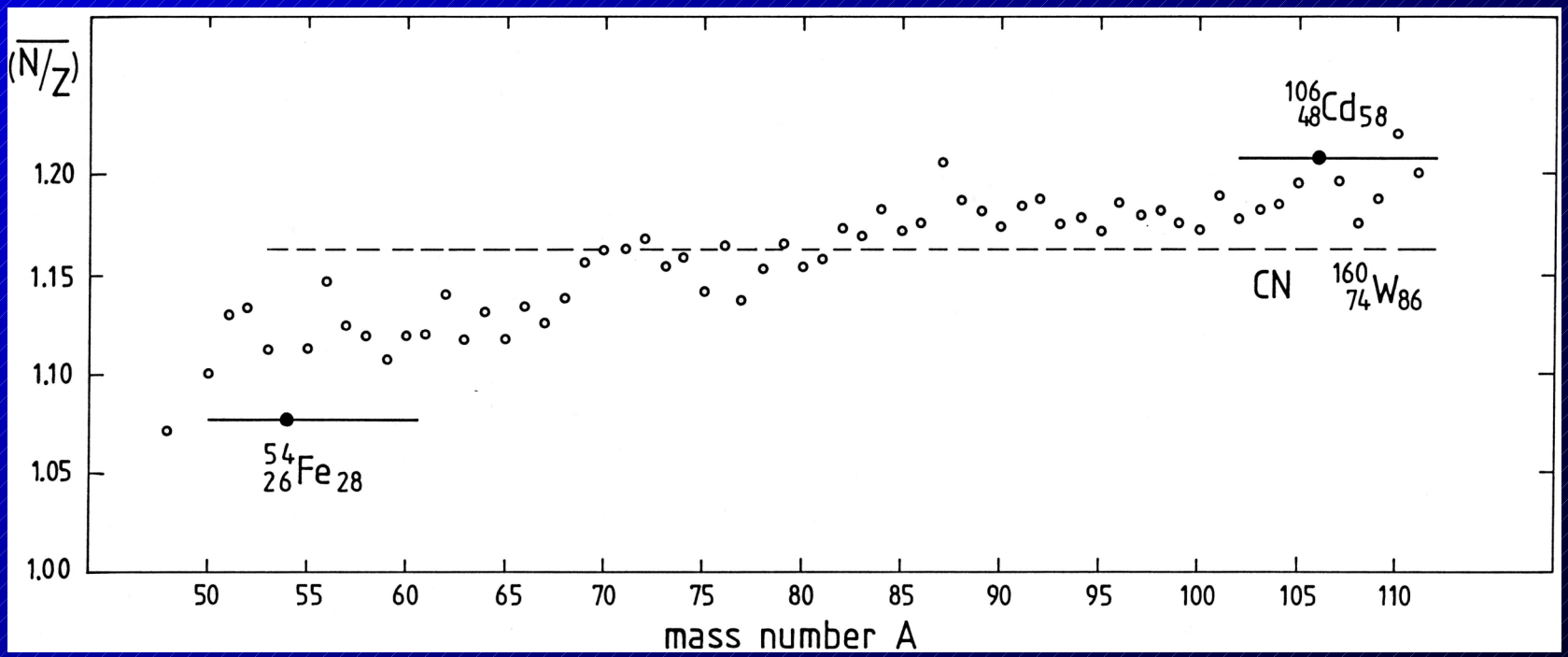





$^{106}Cd + ^{54}Fe$
$\bar{E} = 247\,MeV$
binary reaction products
stable nucleus
$\sigma \simeq 4$ mb
$^{54}Fe$ projectile
$^{106}Cd$ target
Z
N
A=60
55
65
70
75
80
85
90
95
100
105
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Tc
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
30
40
50
60

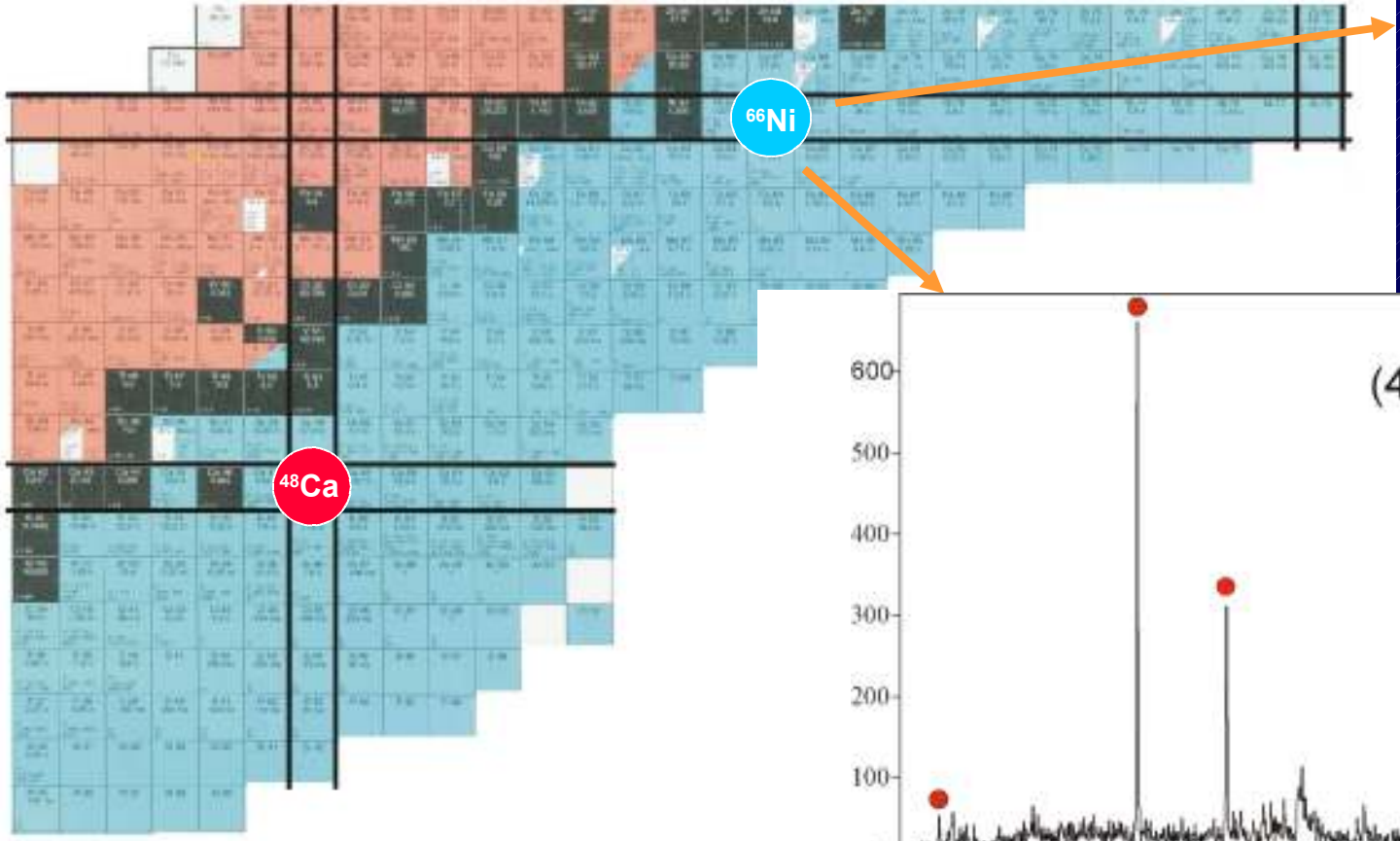

$^{106}Cd + {}^{54}Fe$ $\bar{E} = 247MeV$
binary reaction products
$^{54}Fe$ inelastic
$^{106}Cd$ inelastic
production yield (mb)
$10^2$
$10^1$
$10^0$
fusion-fission
damped collisions
damped collisions
QE
QE
50
60
70
80
90
100
110
mass number A

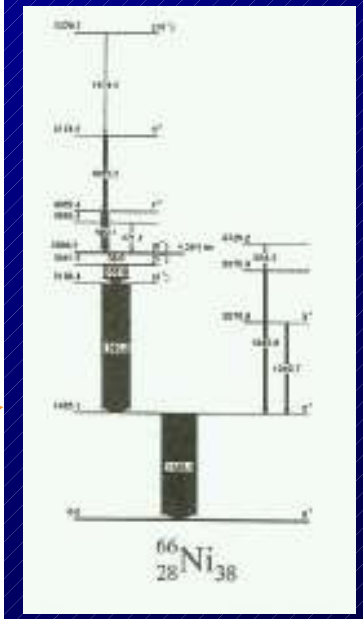

$^{106}Cd$ + $^{54}Fe$ E=247 MeV
Fragment cross-coincidences
156
157
158
159
160 = $A_1$+$A_2$
number of lost protons
- 0
- 1
- 2
Light fragment mass
Heavy fragment mass
Kr
Br
Se
As
Ge
Ga
Zn
Cu
Ni
Fe
Mn
Cr
Kr
Rb
Sr
Y
Zr
Nb
Mo
Tc
Ru
Rh
Pd
Ag
Cd
In
Sn
80
75
70
65
60
55
50
80
85
90
95
100
105
110

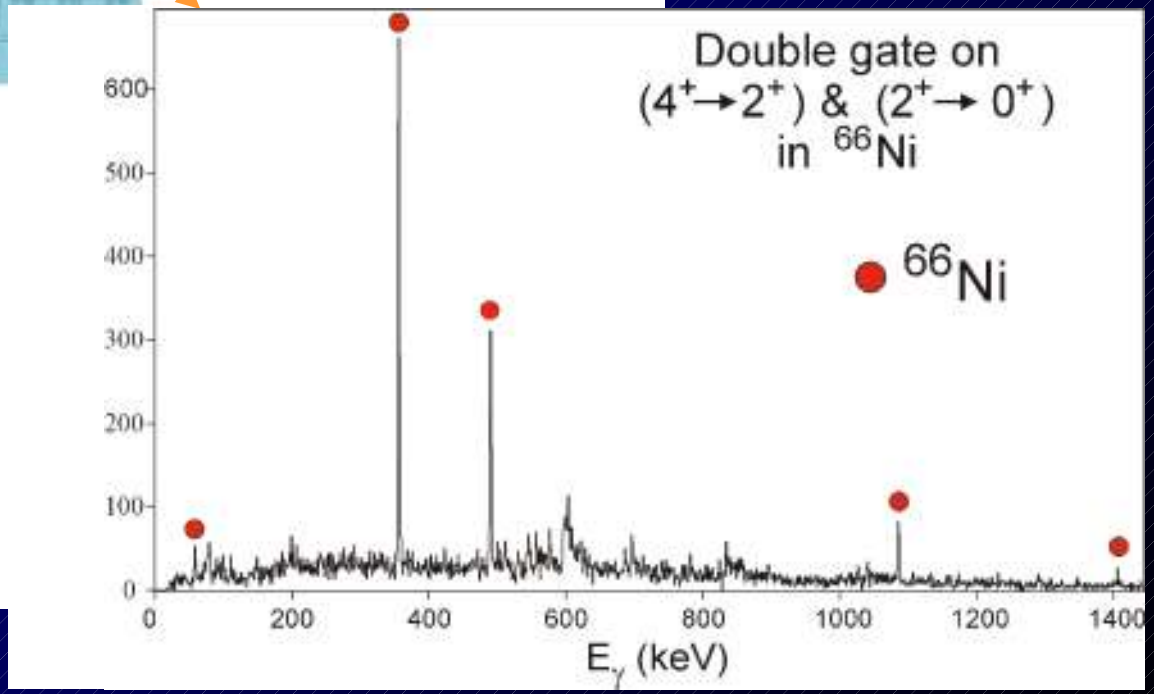

$(\overline{N/Z})$
1.20
1.15
1.10
1.05
1.00
50
55
60
65
70
75
80
85
90
95
100
105
110
mass number A
$^{106}_{48}Cd_{58}$
CN
$^{160}_{74}W_{86}$
$^{54}_{26}Fe_{28}$

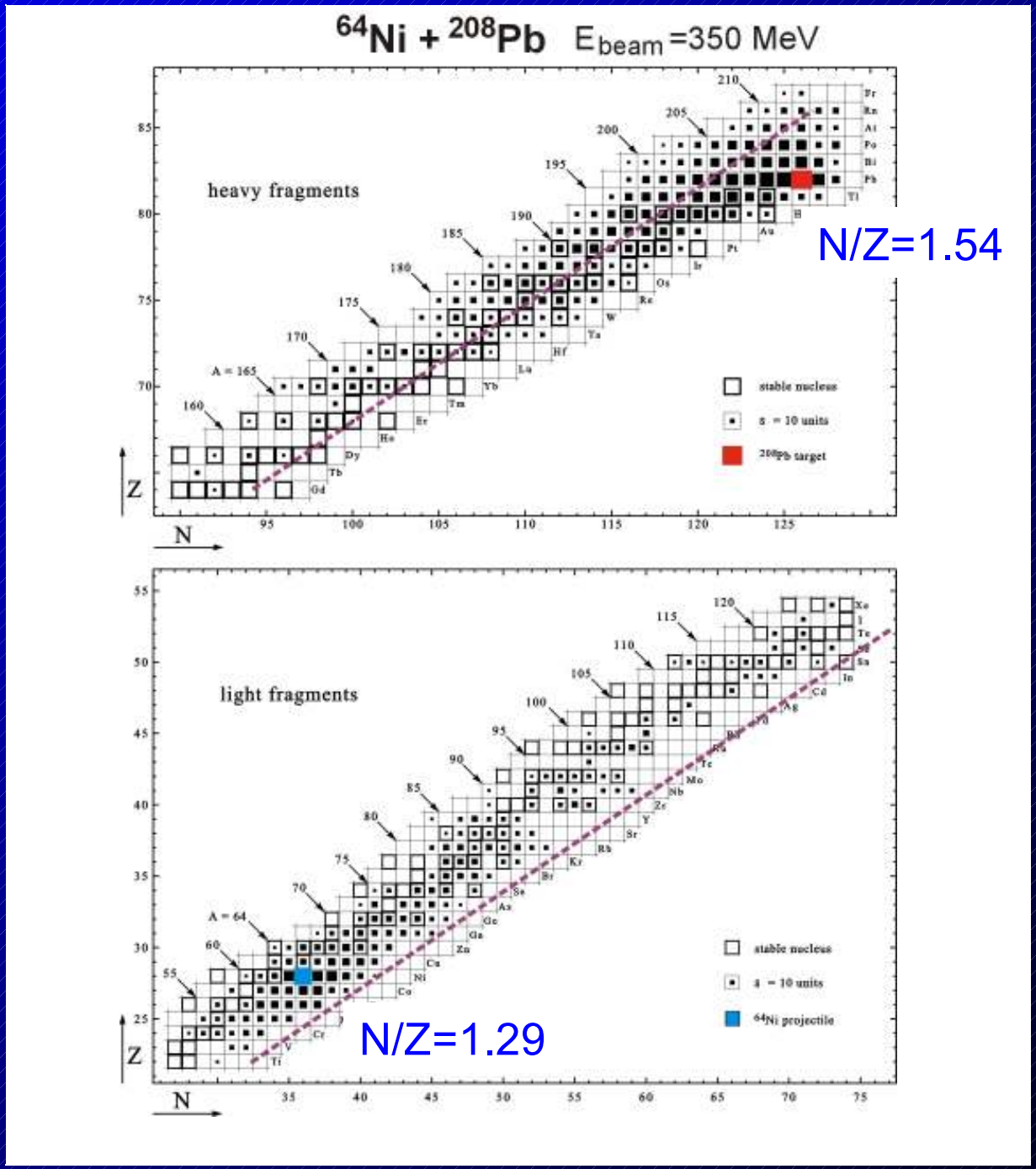
# $^{48}$Ca (330 MeV) + $^{238}$U (thick target)

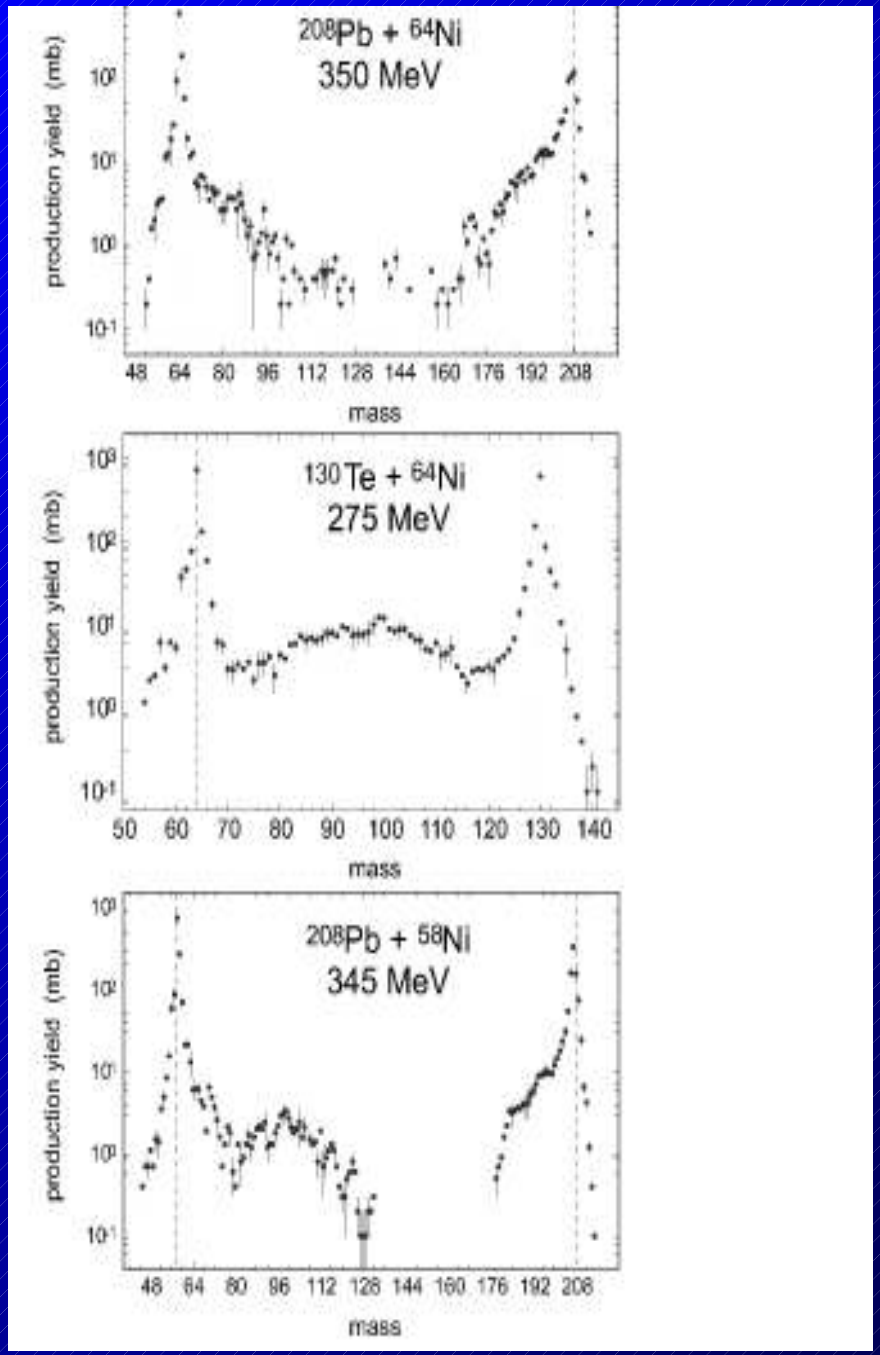
GAMMASPHERE at Argonne

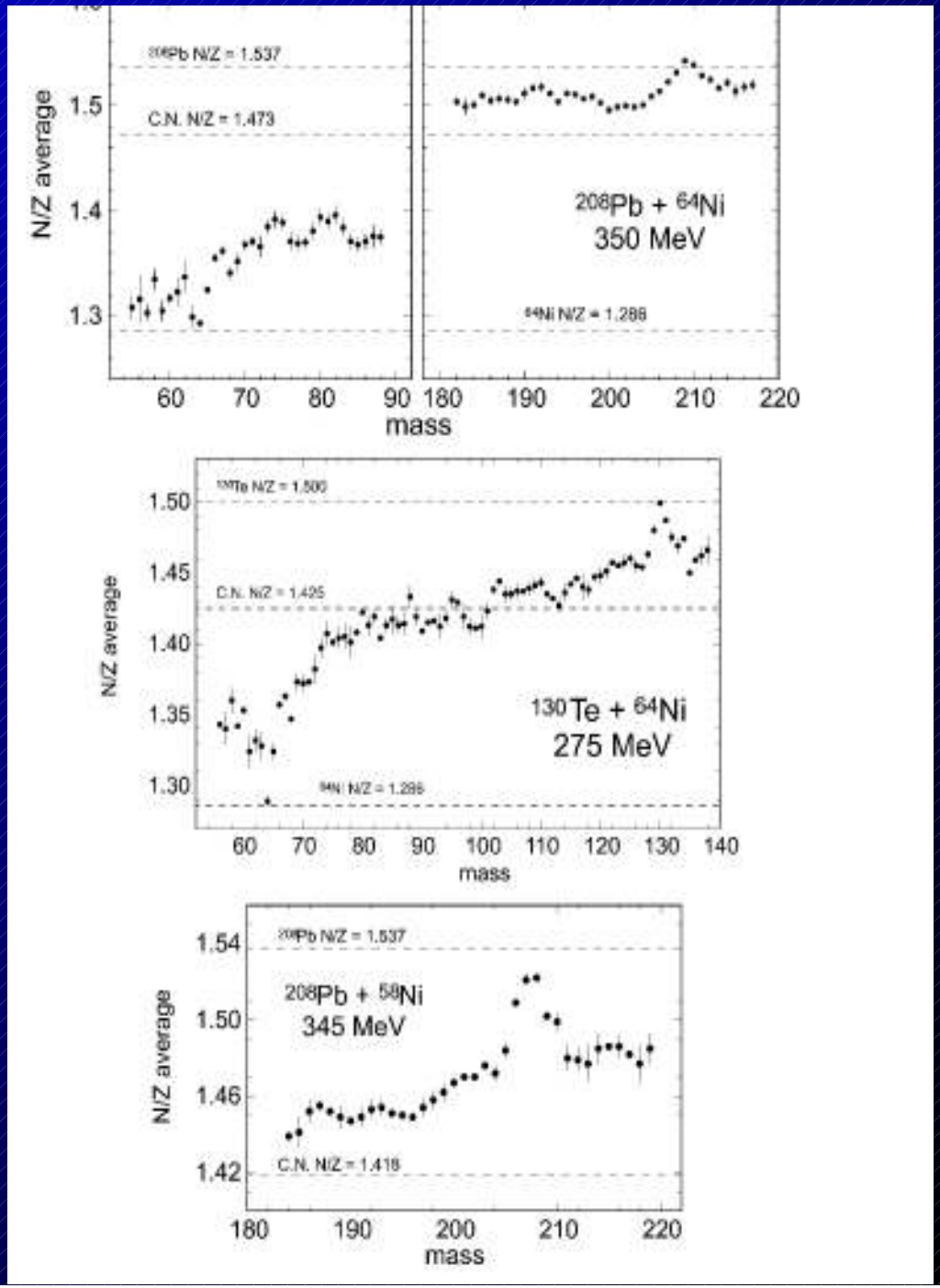


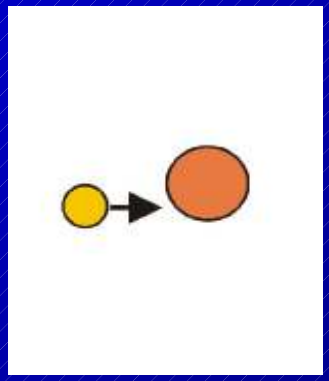



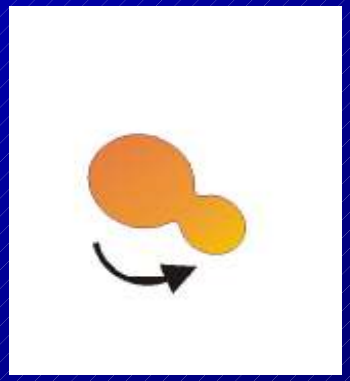

64Ni + 208Pb Ebeam =350 MeV
heavy fragments
N/Z=1.54
stable nucleus
s = 10 units
208Pb target
light fragments
N/Z=1.29
stable nucleus
s = 10 units
64Ni projectile
Z
N

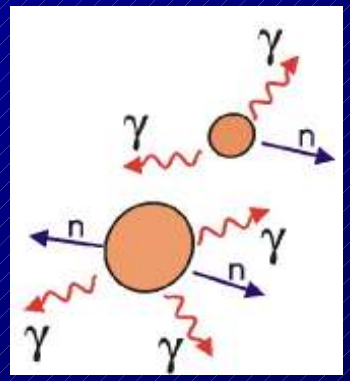

208Pb + 64Ni
350 MeV
production yield (mb)
mass
130Te + 64Ni
275 MeV
production yield (mb)
mass
208Pb + 58Ni
345 MeV
production yield (mb)
mass


208Pb N/Z = 1.537
C.N. N/Z = 1.473
N/Z average
208Pb + 64Ni
350 MeV
64Ni N/Z = 1.286
mass
130Te N/Z = 1.500
C.N. N/Z = 1.425
N/Z average
130Te + 64Ni
275 MeV
64Ni N/Z = 1.286
mass
208Pb N/Z = 1.537
208Pb + 58Ni
345 MeV
C.N. N/Z = 1.418
N/Z average
mass

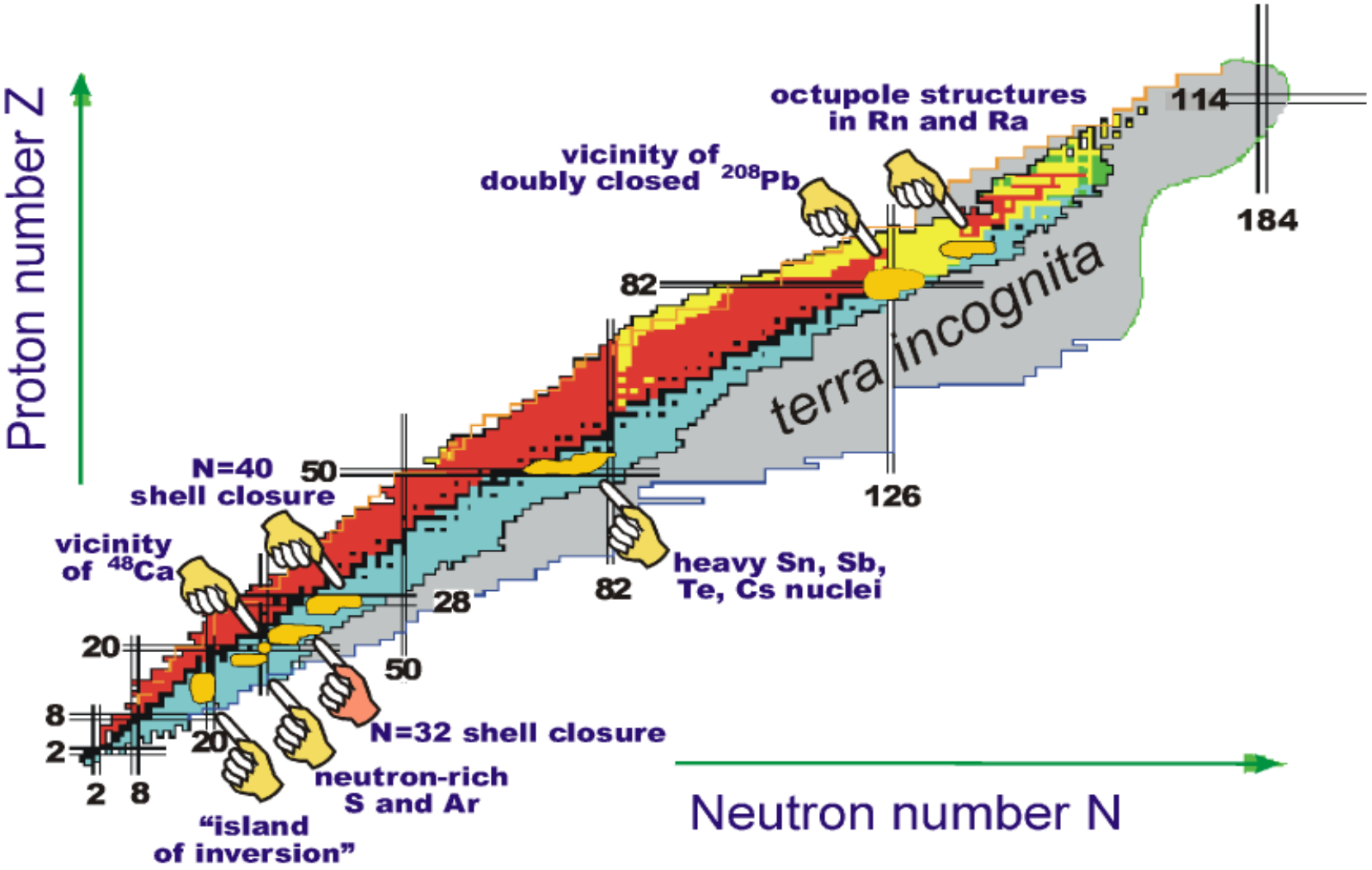
# Jądra z nadmiarem neutronów produkowane w głęboko-nieelastycznych procesach



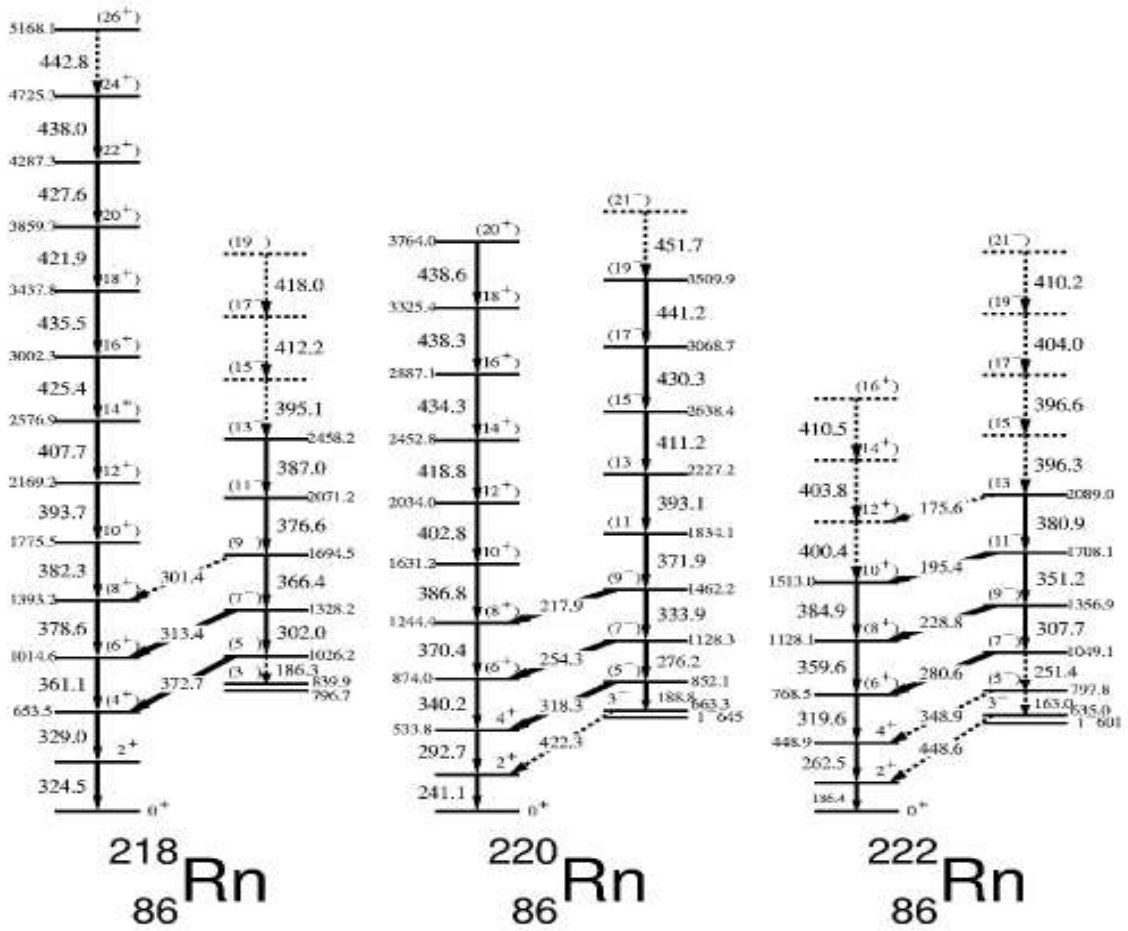





- Wiązki ciężkich jonów o energiach powyżej bariery kulombowskiej,
- Jądra stabilne z nadmiarem neutronów używane jako jądra wiązki i tarczy
- Transfer nukleonów – tendencja do równoważenia N/Z
- Populacja stanów o wysokich spinach -yrast


Proton number Z
Neutron number N
terra incognita
octupole structures
in Rn and Ra
vicinity of
doubly closed $^{208}$Pb
N=40
shell closure
vicinity
of $^{48}$Ca
heavy Sn, Sb,
Te, Cs nuclei
N=32 shell closure
neutron-rich
S and Ar
"island
of inversion"
114
184
126
82
50
28
20
8
2
2
8
20
82
50

232Th + 136Xe  Berkeley experiment
with ~ 80 Gammasphere detectors
J.F.C.Cocks et al. Phys.Rev.Lett.78,2920 (1997)
J.F.C.Cocks et al. Nucl.Phys.A645, 61 (1999)



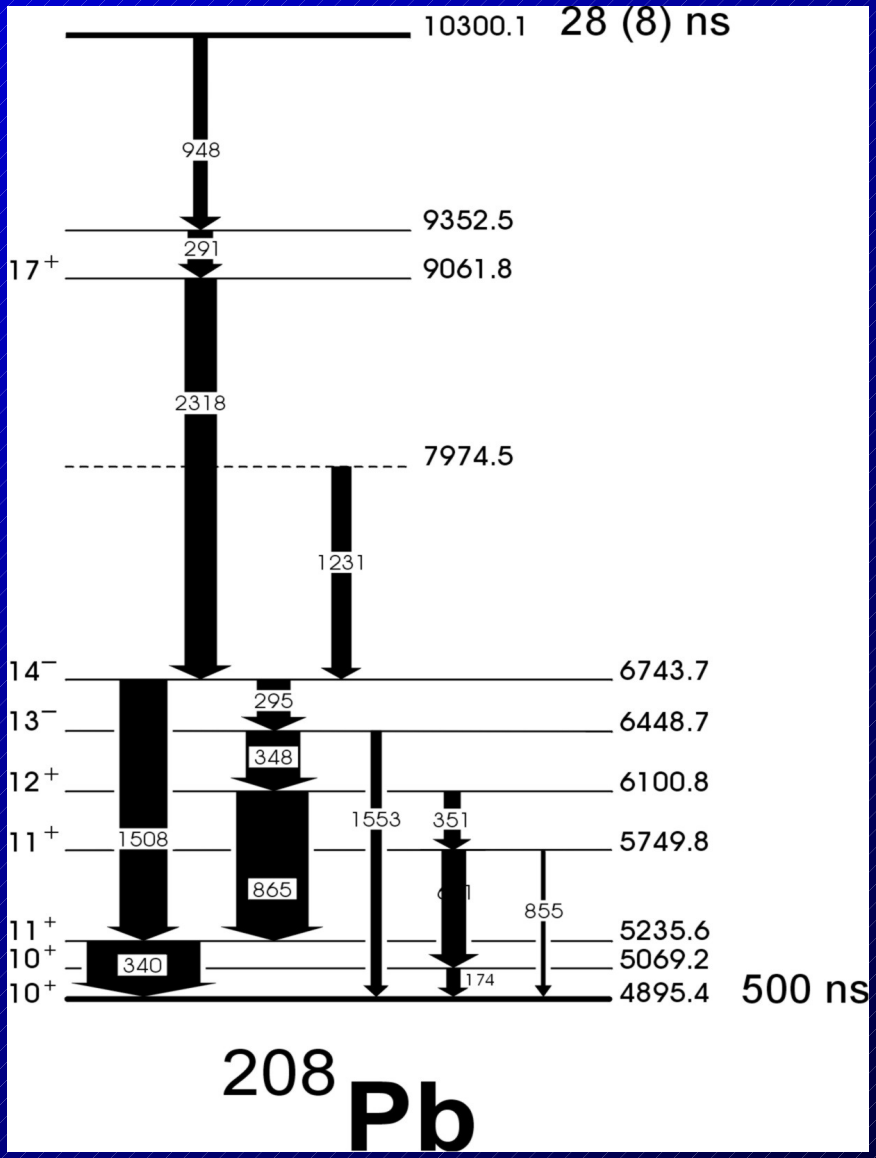
# $^{208}$Pb early high spin states study

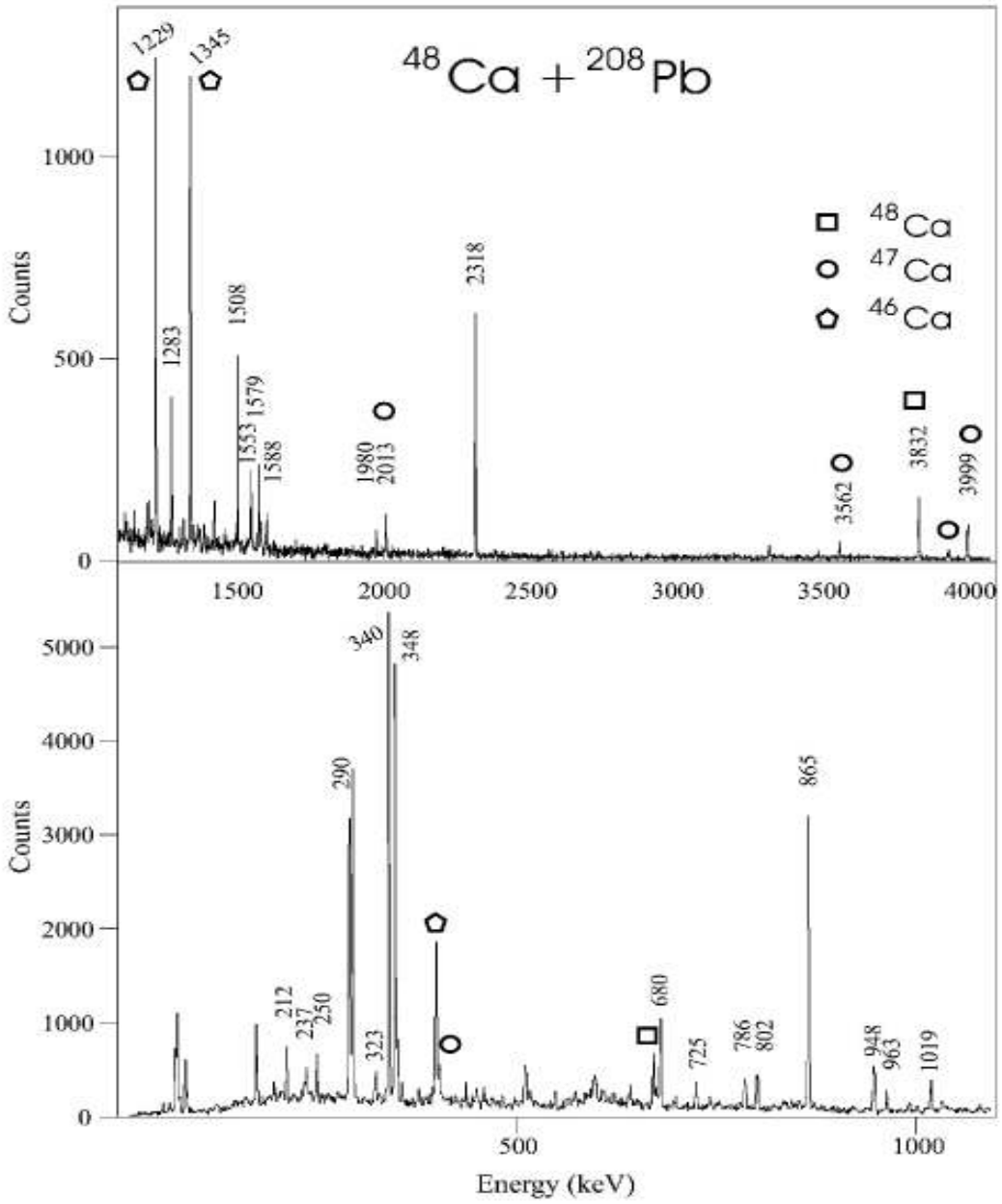
**(e,e')  - J.P. Connelly at al., Phys. Rev. C 45, 2711 (1992)**

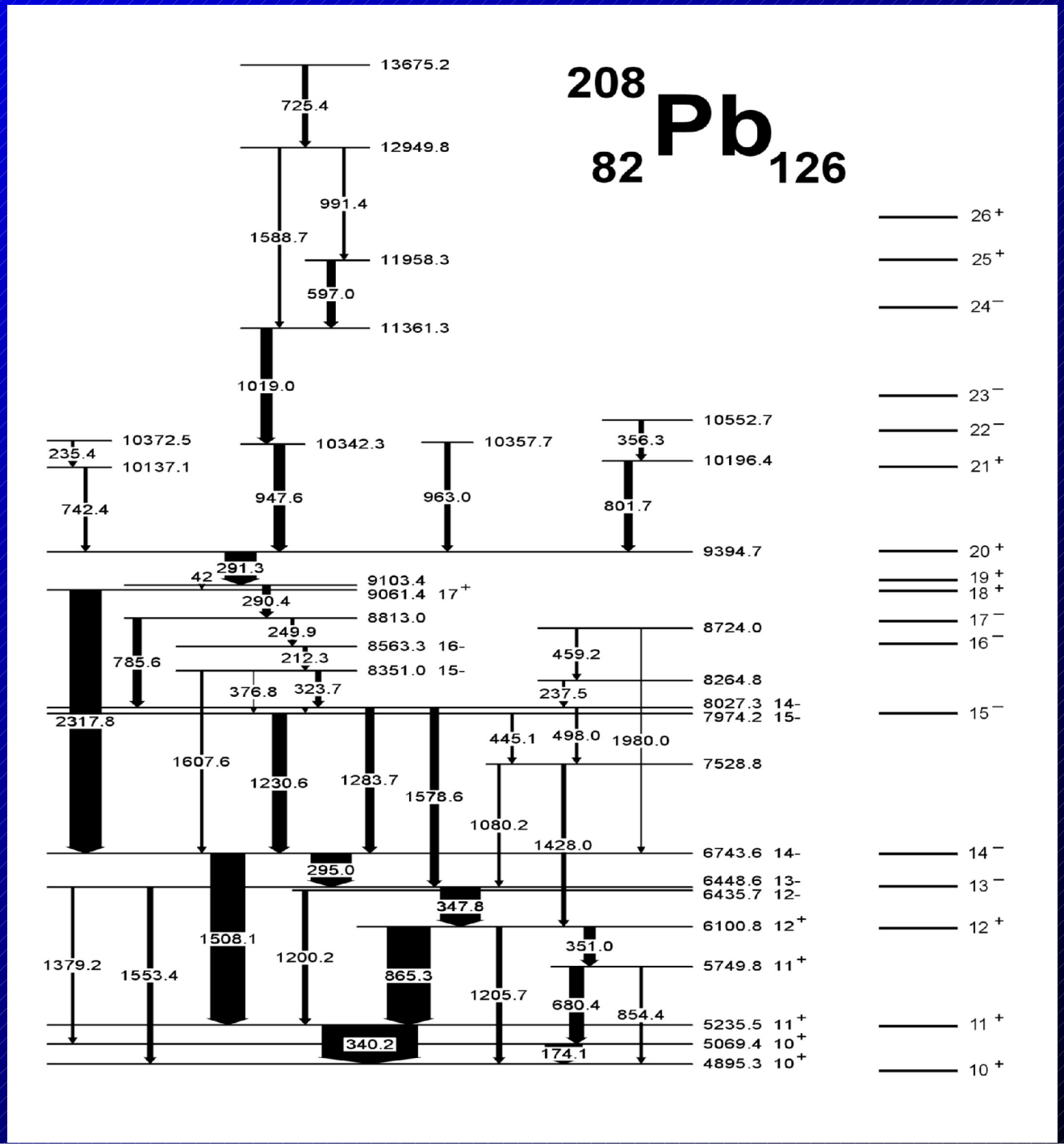
***Deep Inelastic Reactions***

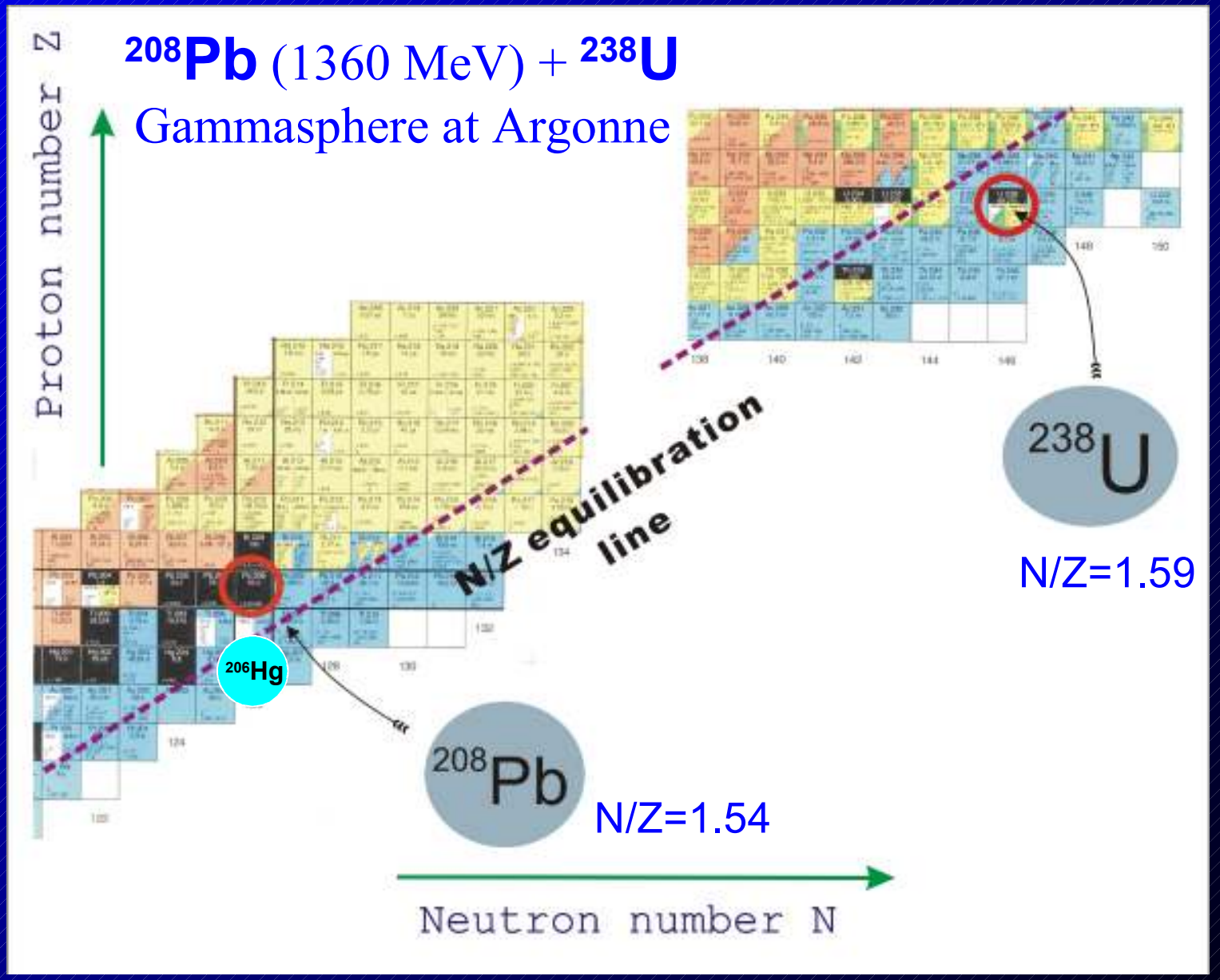
**$^{64}$Ni + $^{208}$Pb  -  M. Schramm at al.,  Z. Phys. A 344, 363, (1993)**


Gasp


10300.1
28 (8) ns
948
9352.5
291
17+
9061.8
2318
7974.5
1231
14−
6743.7
295
13−
6448.7
348
12+
6100.8
1553
351
11+
1508
5749.8
865
855
11+
5235.6
10+
340
5069.2
174
10+
4895.4
500 ns
208Pb


$^{48}Ca + ^{208}Pb$
$^{48}Ca$
$^{47}Ca$
$^{46}Ca$
Counts
Energy (keV)
1229
1345
1283
1508
1553
1579
1588
1980
2013
2318
3562
3832
3999
340
348
290
865
212
237
250
323
680
725
786
802
948
963
1019

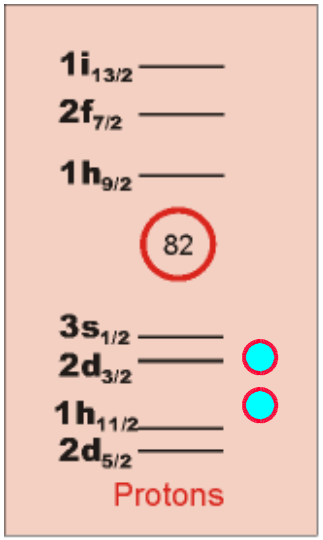

208 82 Pb 126
13675.2
725.4
12949.8
991.4
1588.7
11958.3
597.0
11361.3
1019.0
10372.5
235.4
10137.1
742.4
10342.3
947.6
10357.7
963.0
10552.7
356.3
10196.4
801.7
9394.7
291.3
42
9103.4
9061.4 17+
290.4
8813.0
249.9
8563.3 16-
212.3
8351.0 15-
785.6
376.8
323.7
2317.8
8724.0
459.2
8264.8
237.5
8027.3 14-
7974.2 15-
445.1
498.0
1980.0
7528.8
1607.6
1230.6
1283.7
1578.6
1080.2
1428.0
6743.6 14-
295.0
6448.6 13-
6435.7 12-
347.8
6100.8 12+
1508.1
1200.2
865.3
1205.7
351.0
5749.8 11+
1379.2
1553.4
680.4
854.4
5235.5 11+
340.2
5069.4 10+
174.1
4895.3 10+
26+
25+
24−
23−
22−
21+
20+
19+
18+
17−
16−
15−
14−
13−
12+
11+
10+

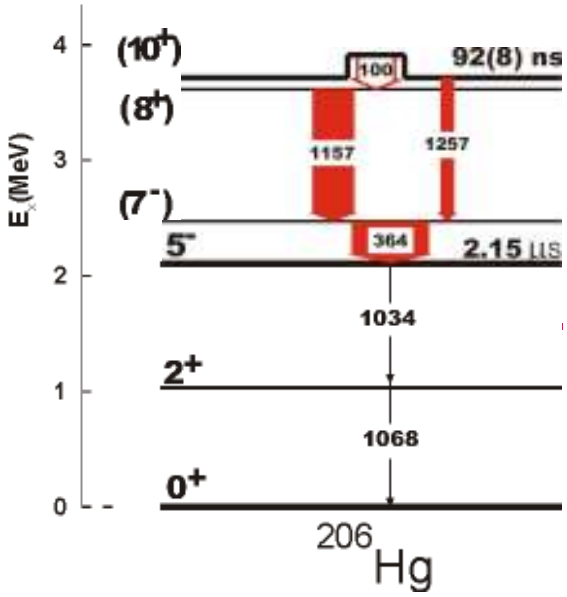

208Pb (1360 MeV) + 238U
Gammasphere at Argonne
Proton number Z
N/Z equilibration line
206Hg
208Pb
N/Z=1.54
238U
N/Z=1.59
Neutron number N

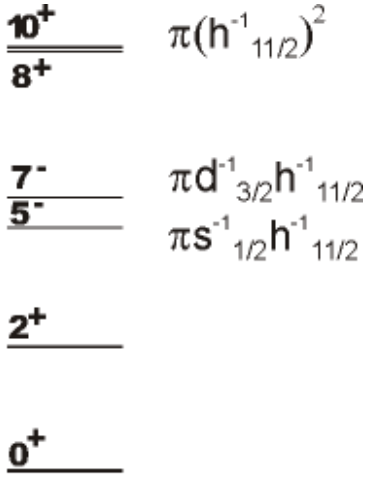
$$e_{pol}(\pi h_{11/2}^{-1}) = 0.60(7)\ e$$

$$Q_{exp}(\pi h_{11/2}^{-1}) = 48(2)\ fm^2 \qquad Q_{s.p.}(\pi h_{11/2}^{-1}) = 30\ fm^2$$

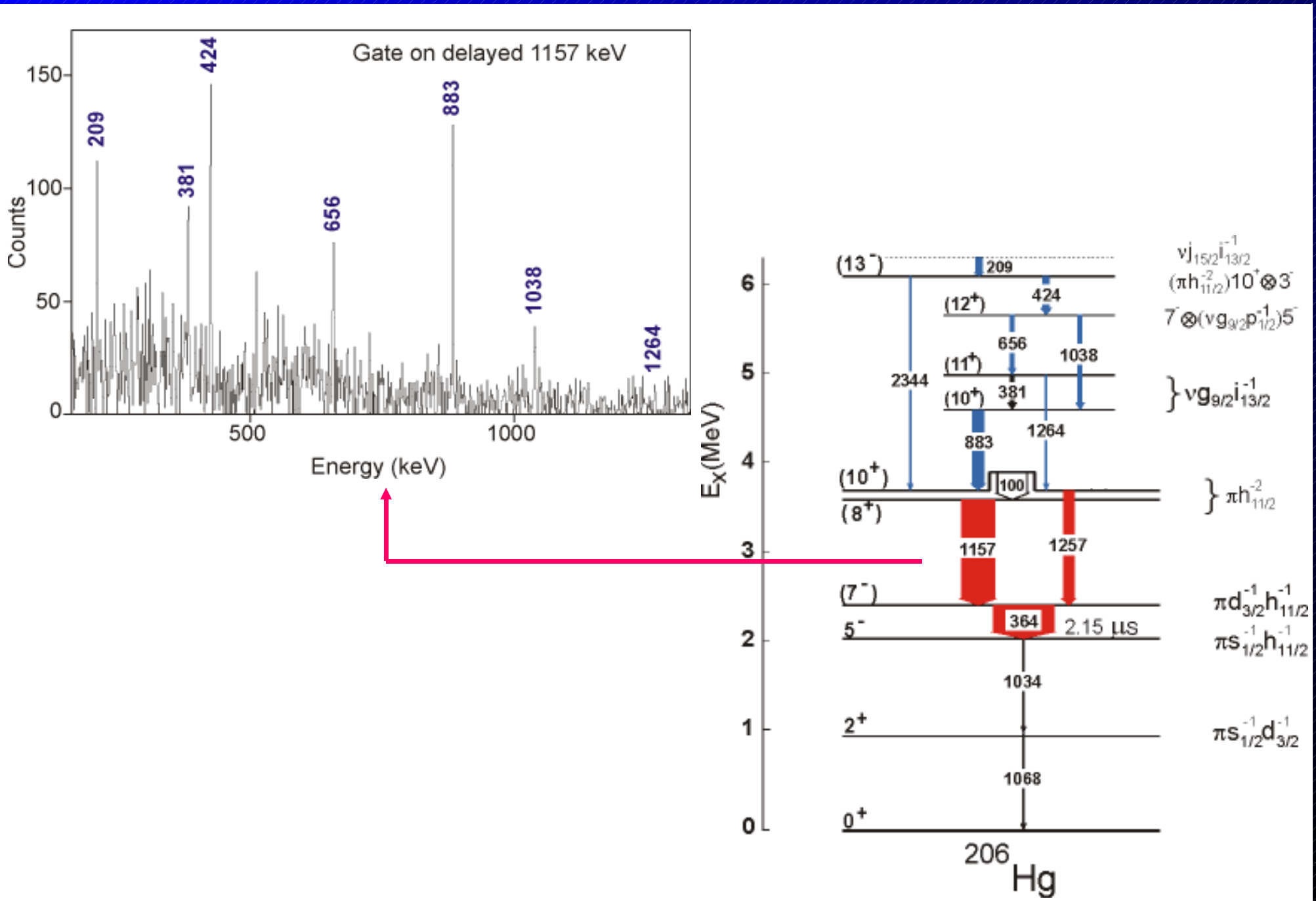
$$B(E2;10^+ \rightarrow 8^+) = 70(7)\ e^2fm^4$$

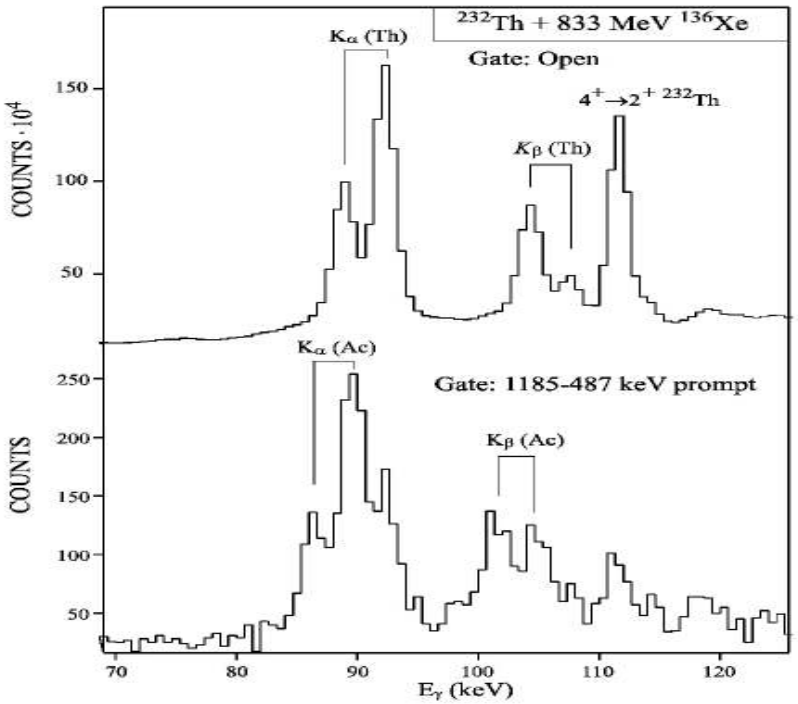


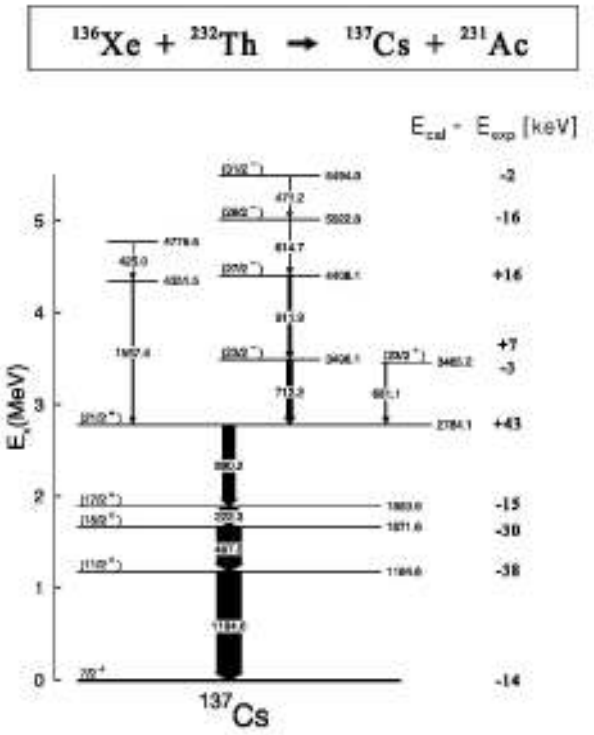



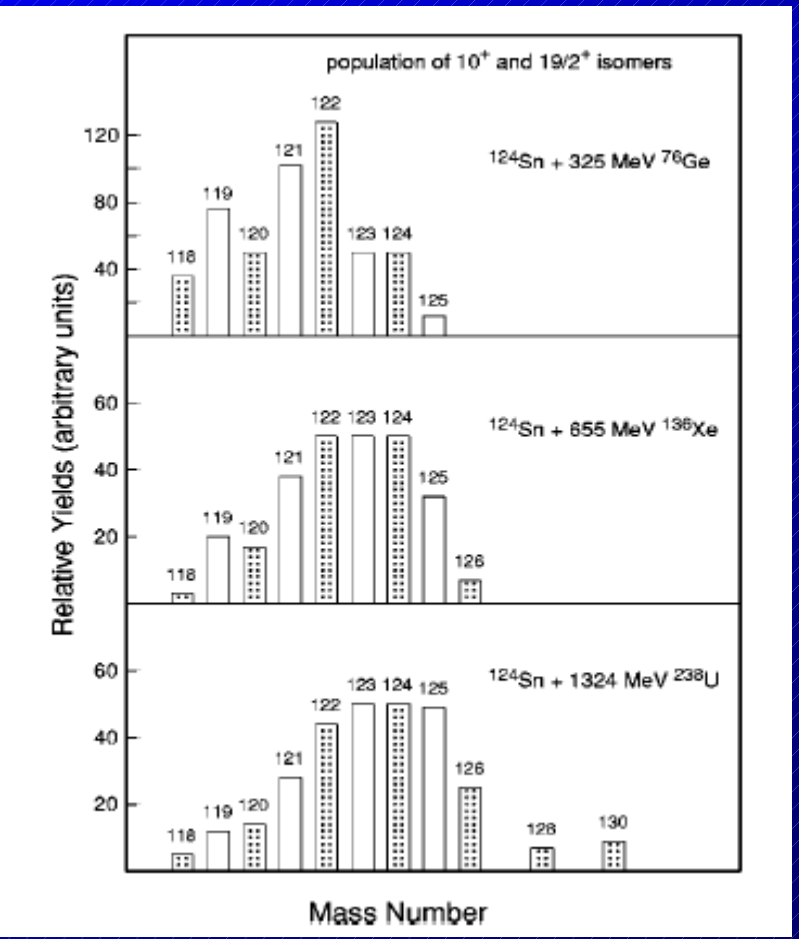

**shell model calc.**

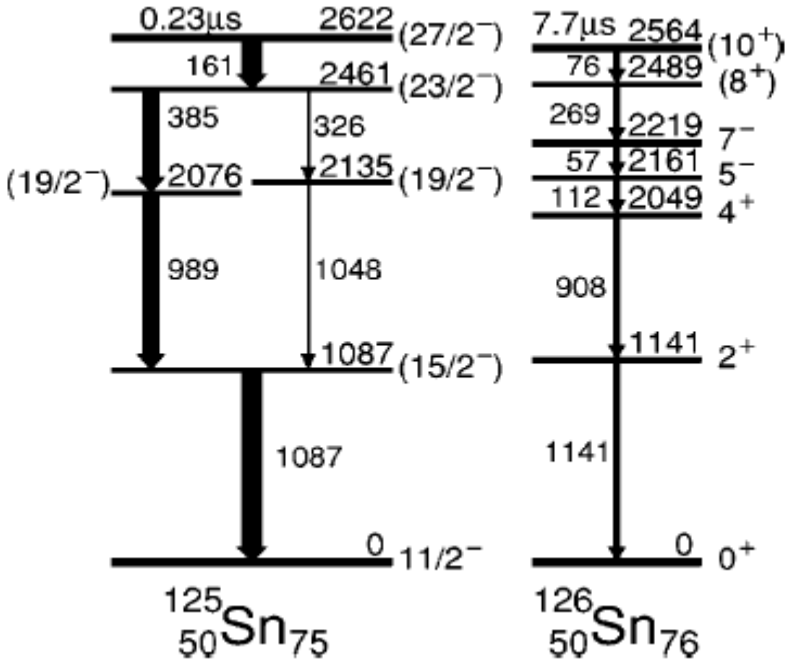

Gate on delayed 1157 keV
Counts
Energy (keV)
209
381
424
656
883
1038
1264
$E_X$(MeV)
(13⁻)
(12⁺)
(11⁺)
(10⁺)
(10⁺)
(8⁺)
(7⁻)
5⁻
2⁺
0⁺
2344
100
1157
1257
364
2.15 μs
1034
1068
$\nu j_{15/2} i_{13/2}^{-1}$
$(\pi h_{11/2}^{-2})10^+ \otimes 3^-$
$7^- \otimes (\nu g_{9/2} p_{1/2}^{-1})5^-$
$\nu g_{9/2} i_{13/2}^{-1}$
$\pi h_{11/2}^{-2}$
$\pi d_{3/2}^{-1} h_{11/2}^{-1}$
$\pi s_{1/2}^{-1} h_{11/2}^{-1}$
$\pi s_{1/2}^{-1} d_{3/2}^{-1}$
$^{206}$Hg

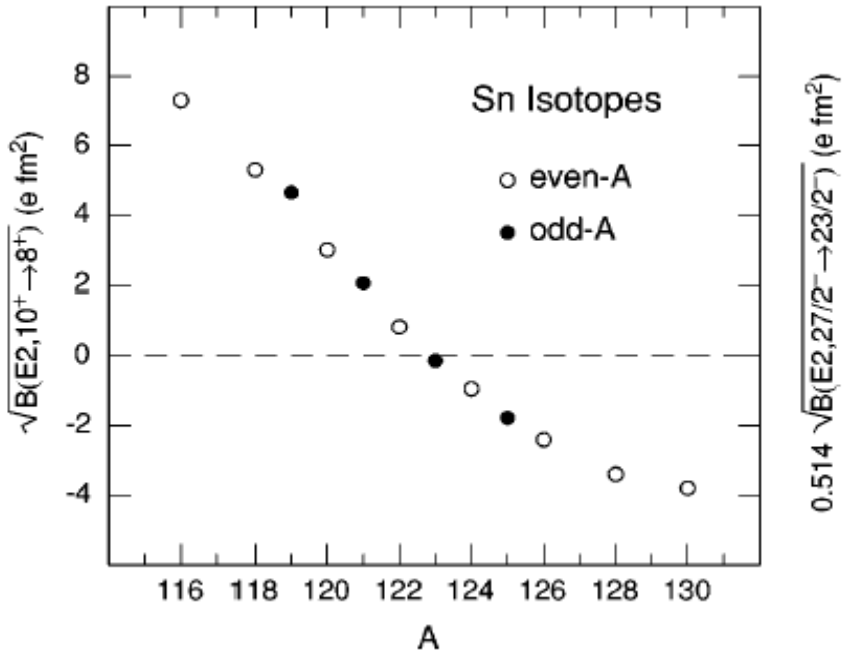


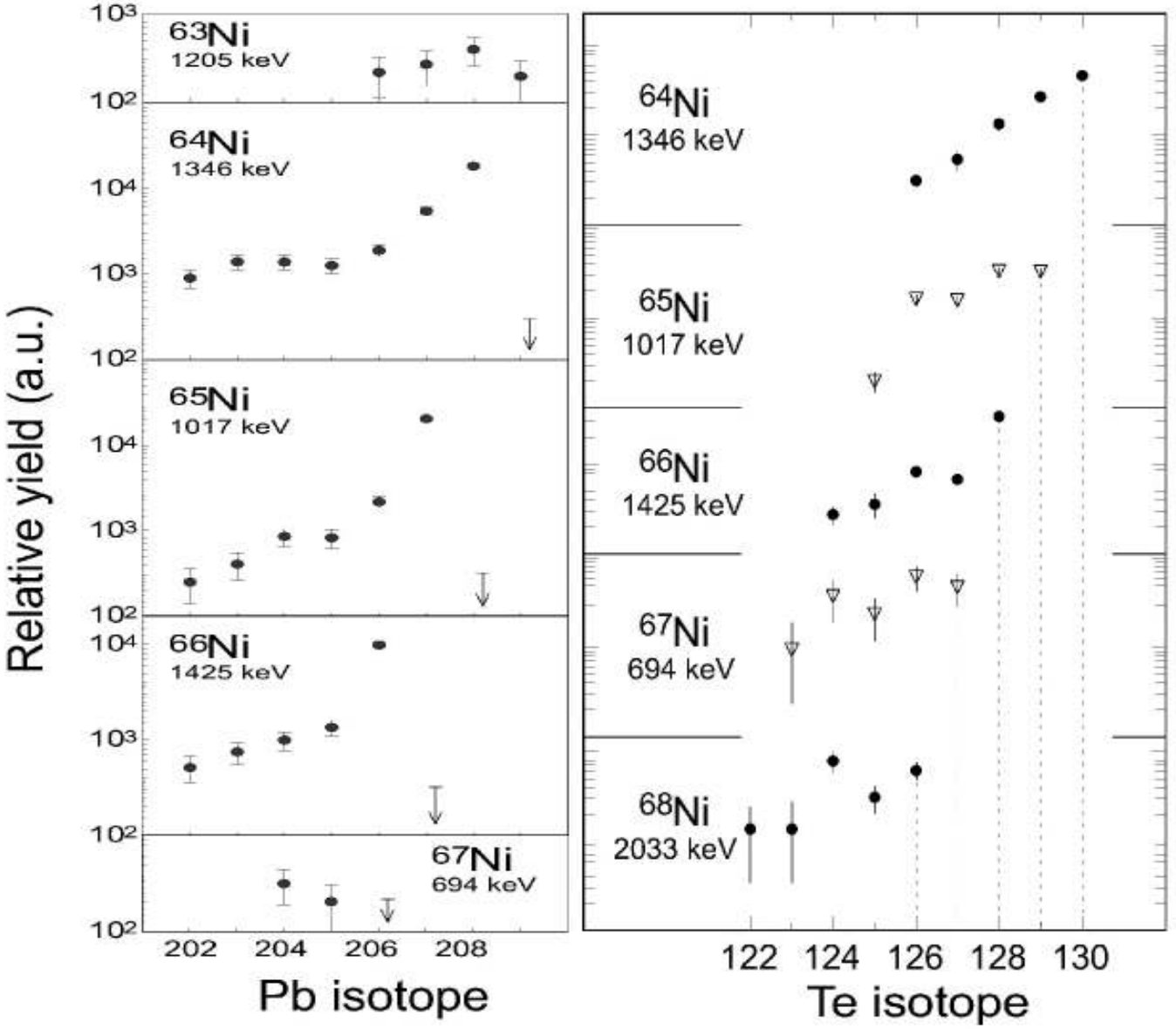

| | | | | | | |
|---|---|---|---|---|---|---|
| $^{132}$Sn | $^{133}$Sb | $^{134}$Te | $^{135}$I | $^{136}$Xe | $^{137}$Cs | $^{138}$Ba |


population of 10+ and 19/2+ isomers
124Sn + 325 MeV 76Ge
124Sn + 655 MeV 136Xe
124Sn + 1324 MeV 238U
Relative Yields (arbitrary units)
Mass Number

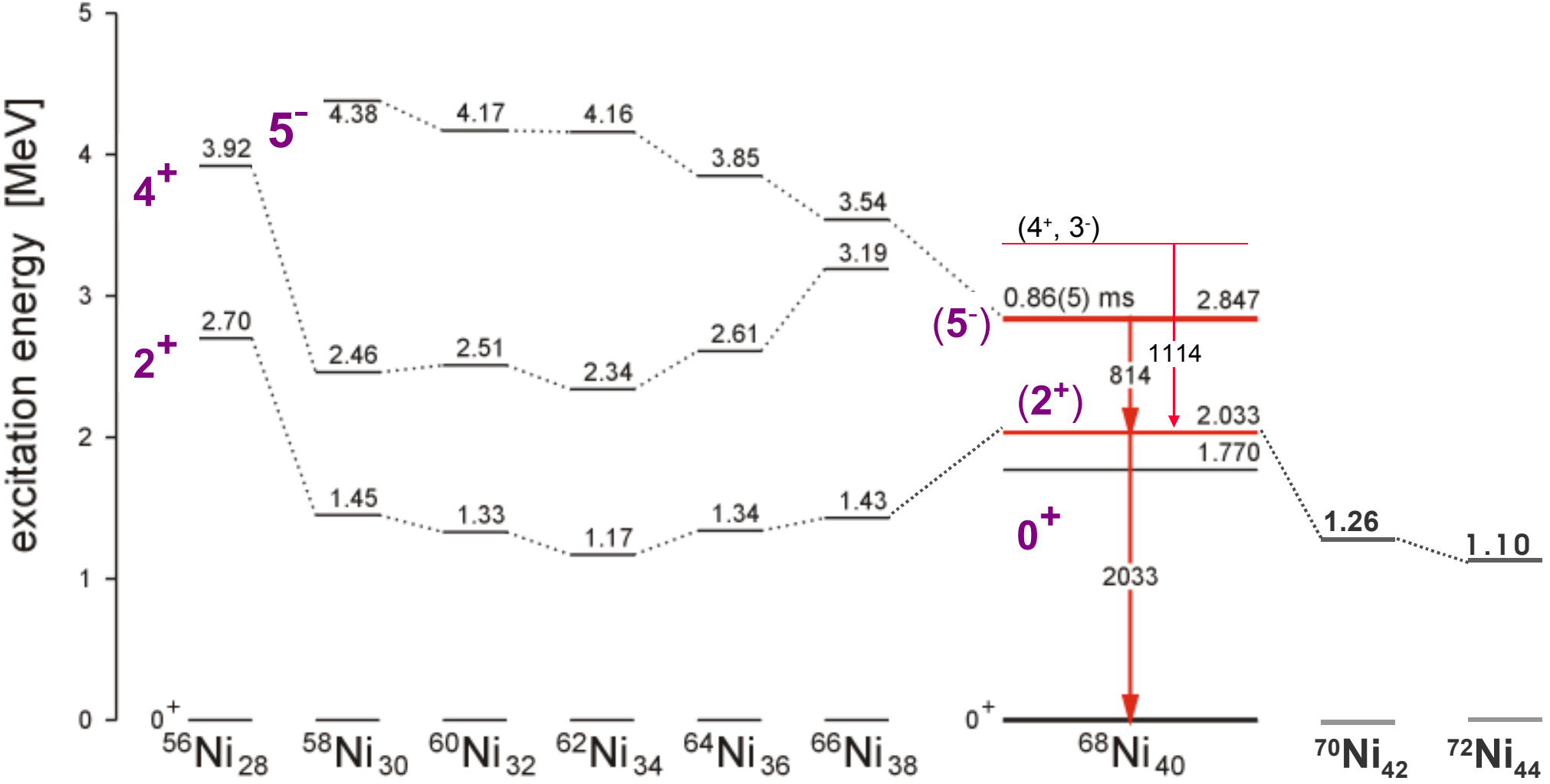

0.23μs
2622 (27/2−)
161
2461 (23/2−)
385
326
(19/2−) 2076
2135 (19/2−)
989
1048
1087 (15/2−)
1087
0 11/2−
125 50Sn75
7.7μs 2564 (10+)
76 2489 (8+)
269 2219 7−
57 2161 5−
112 2049 4+
908
1141 2+
1141
0 0+
126 50Sn76


Sn Isotopes
even-A
odd-A
√B(E2,10+→8+) (e fm2)
0.514 √B(E2,27/2−→23/2−) (e fm2)
A

$^{64}Ni + ^{208}Pb$ $^{64}Ni + ^{130}Te$



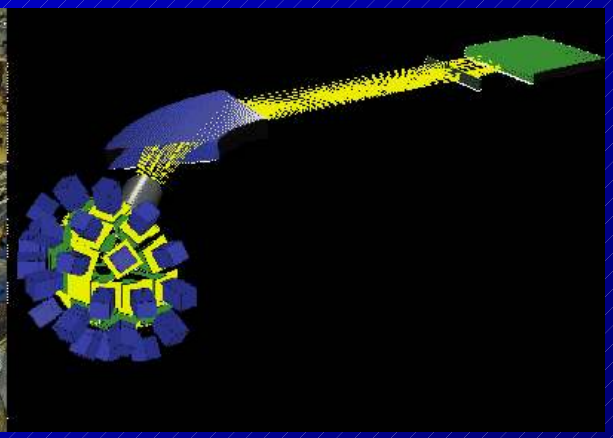
R.Broda et al., Phys.Rev. Lett. 74, 868 (95)



# Eksperymenty z grubą tarczą są źródłem większości informacji o strukturze nowych jąder, ale:

- Ograniczone możliwości identyfikacji nowych jąder, zwłaszcza tych, produkowanych z małymi przekrojami czynnymi
- Niemożność obserwacji stanów krótkożyciowych – rozmycie dopplerowskie

# PRISMA spectrometer

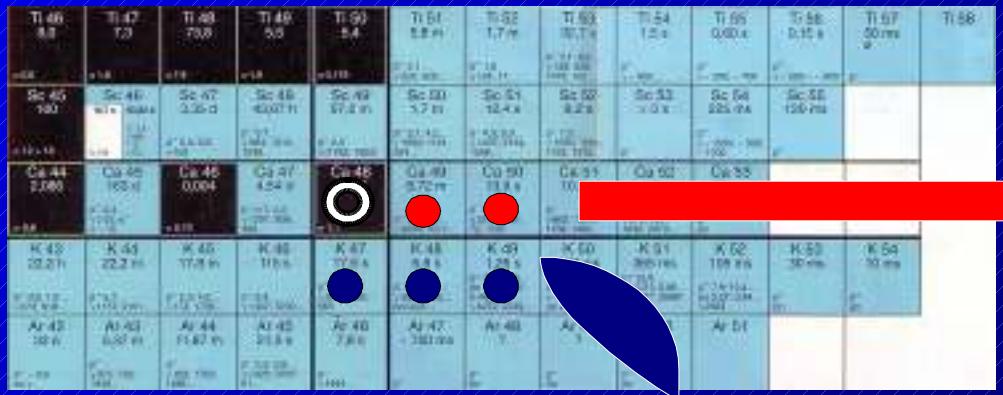


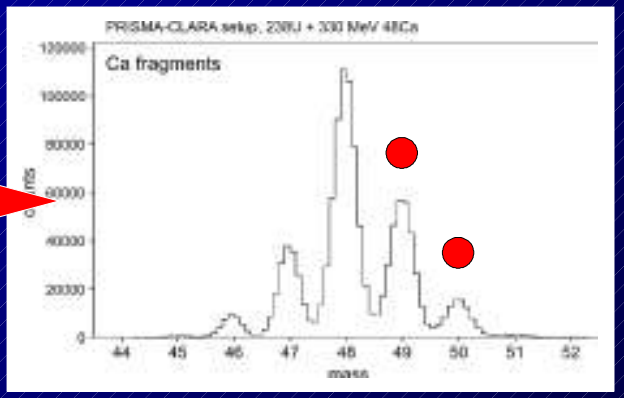
- A magnetic heavy ion spectrometer designed to fully identify *(A, Z)* fragments deflected at large angles
- CLARA: an array of 24 Clover detectors

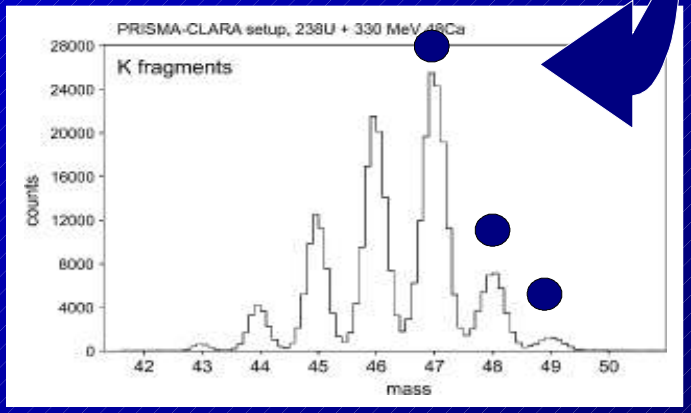
$^{238}$U + 330 MeV $^{48}$Ca

- Complementary sets of data:
  PRISMA – *(A,Z)* identification, fast γ transitions
  and GAMMASPHERE – γ -γ coincidence data

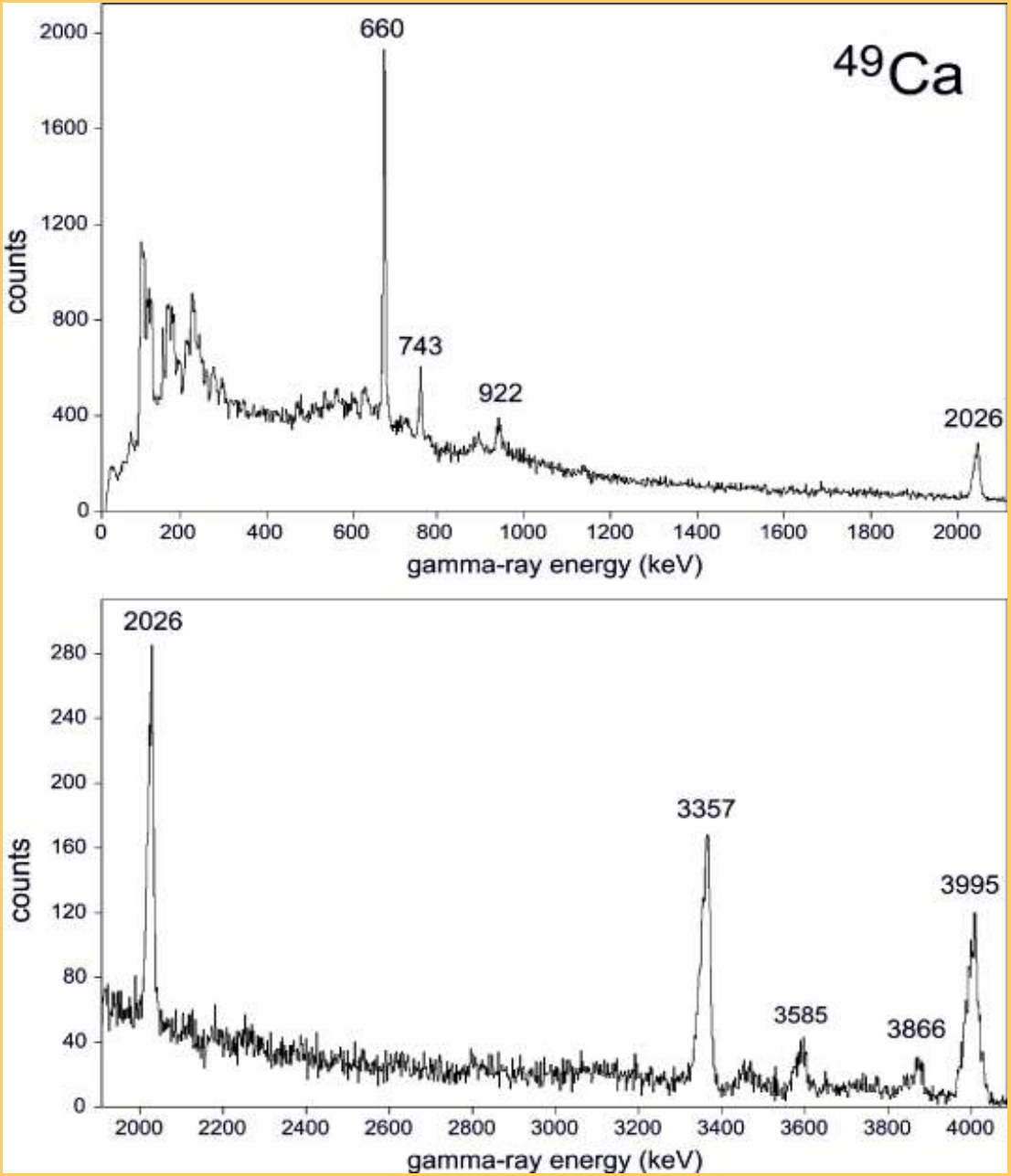
# New results for N ≥ 28 Ca and K isotopes

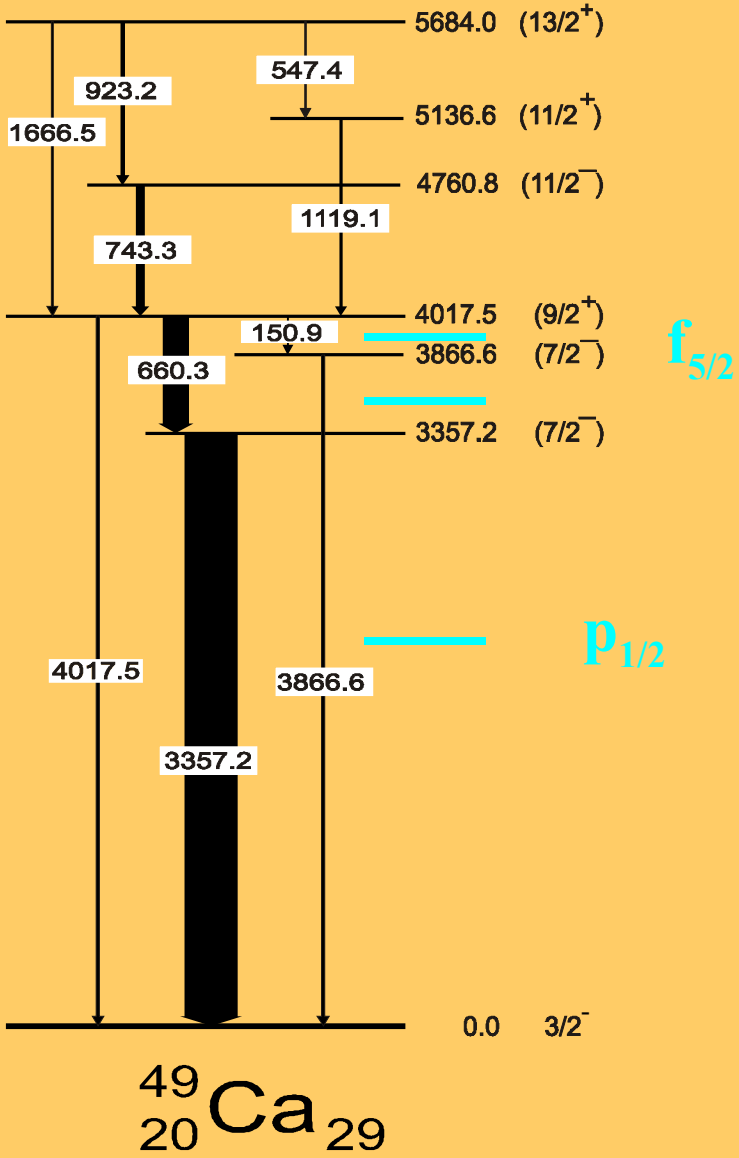


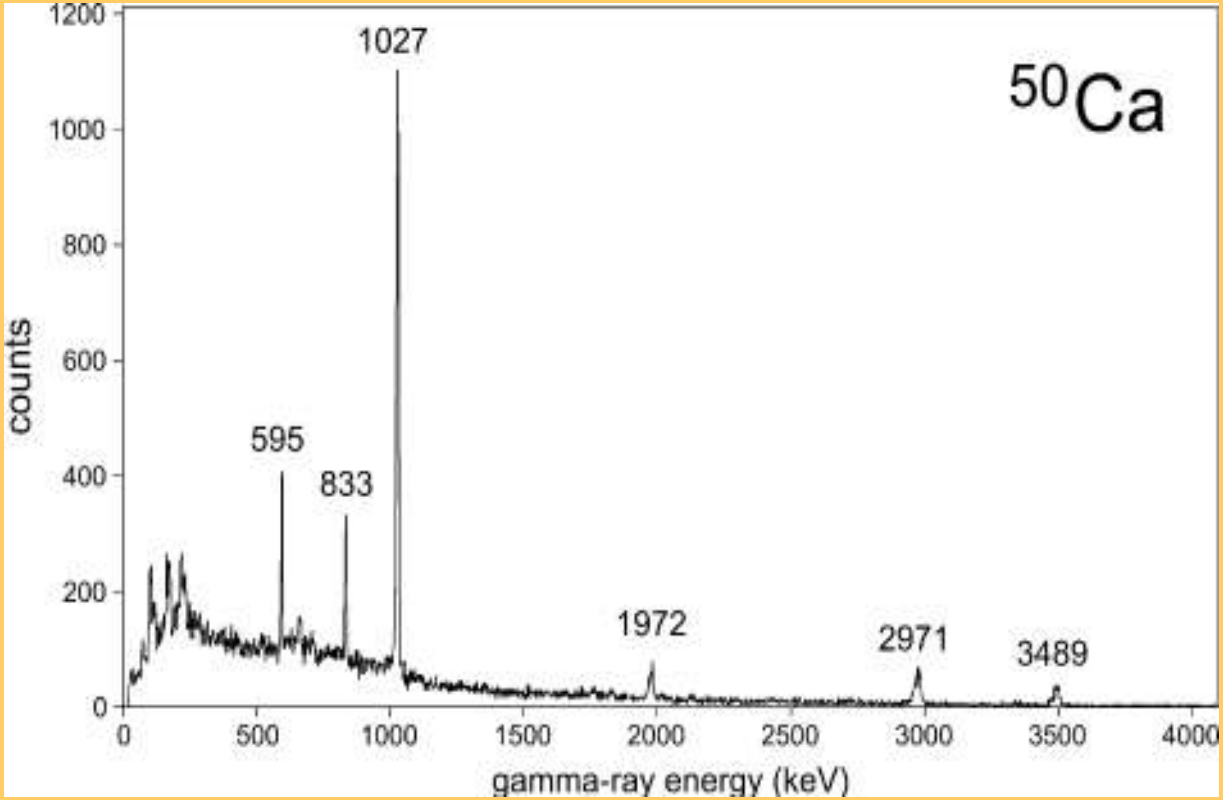


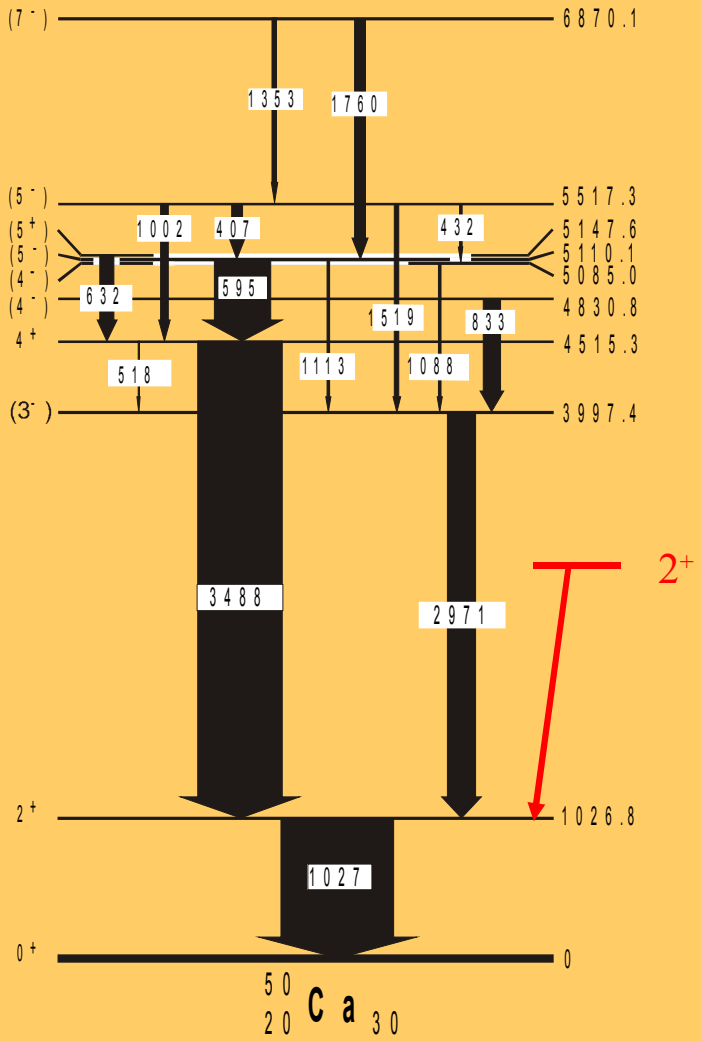




- Identification of new short-lived states in $^{49}$Ca ($\pi$ $p_{1/2}$, $\pi$ $f_{5/2}$ single particle energies) and $^{50}$Ca ( $2^+_2$ )
- A new $7/2^-$ isomer in $^{47}$K
- Observation of excited states in $^{48}$K and $^{49}$K

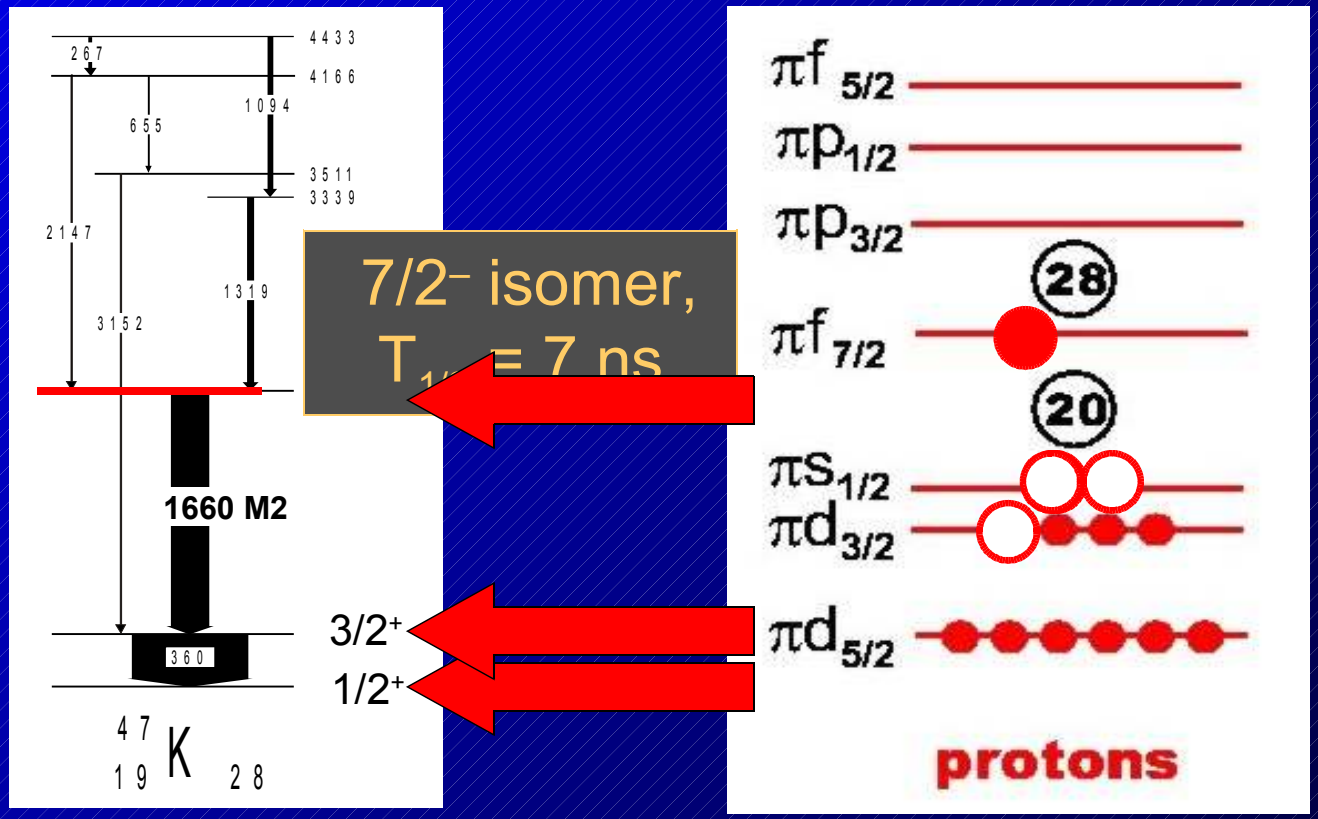

$^{49}$Ca
660
743
922
2026
counts
gamma-ray energy (keV)
2026
3357
3995
3585
3866
counts
gamma-ray energy (keV)


5684.0 (13/2$^+$)
547.4
923.2
1666.5
5136.6 (11/2$^+$)
4760.8 (11/2$^-$)
1119.1
743.3
4017.5 (9/2$^+$)
150.9
3866.6 (7/2$^-$)
660.3
3357.2 (7/2$^-$)
f$_{5/2}$
p$_{1/2}$
4017.5
3866.6
3357.2
0.0 3/2$^-$
$^{49}_{20}$Ca$_{29}$

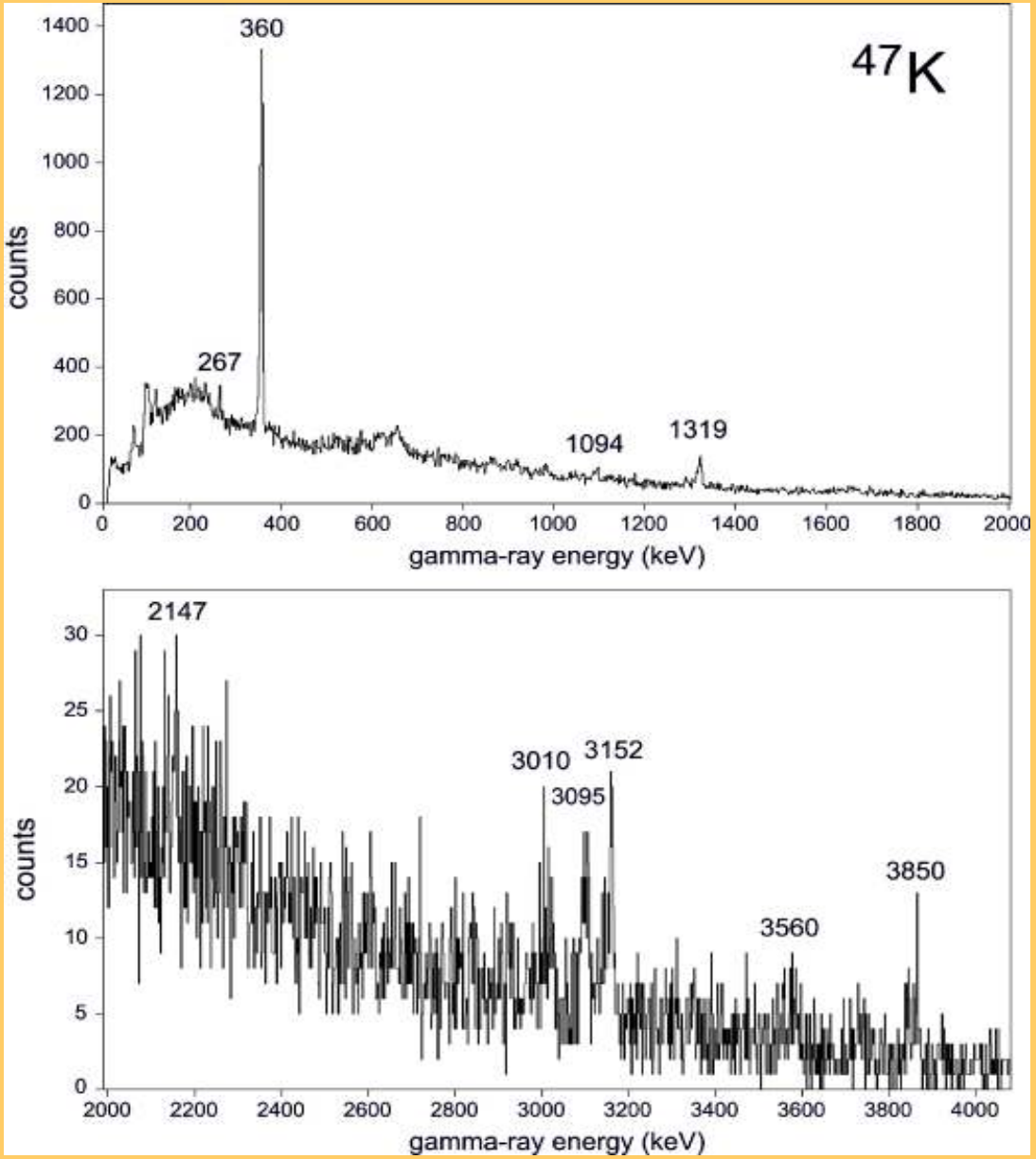

$^{50}$Ca
counts
gamma-ray energy (keV)
1027
595
833
1972
2971
3489
0
200
400
600
800
1000
1200
0
500
1000
1500
2000
2500
3000
3500
4000

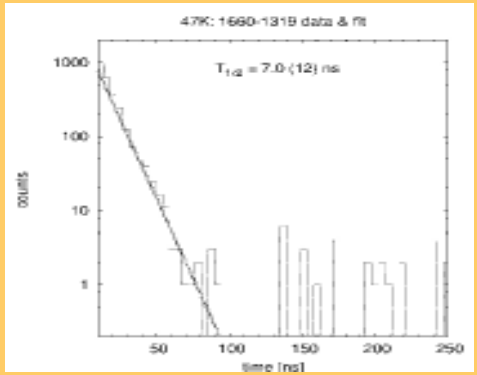

(7⁻)
6870.1
1353
1760
(5⁻)
5517.3
(5⁺)
1002
407
432
5147.6
(5⁻)
5110.1
(4⁻)
5085.0
(4⁻)
632
595
4830.8
1519
833
4⁺
4515.3
518
1113
1088
(3⁻)
3997.4
3488
2971
2⁺
1026.8
1027
0⁺
0
$^{50}_{20}$Ca$_{30}$
2⁺

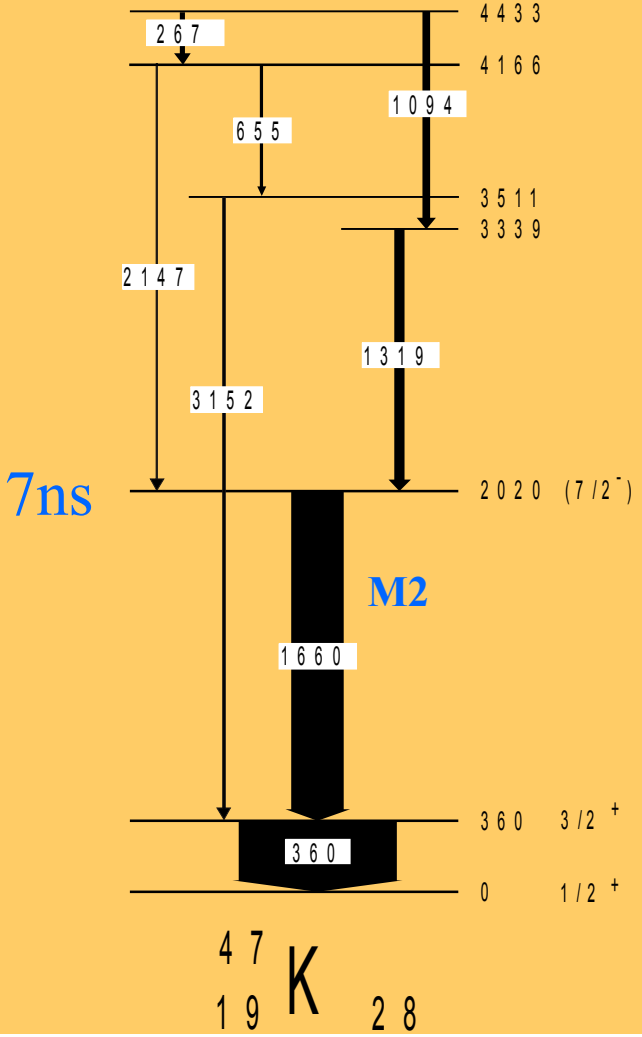
# Evidence of a $7/2^-$ isomer in $^{47}$K




1660 keV line not in prompt gamma spectrum, assigned as an M2 isomeric transition: $7/2^- \rightarrow 3/2^+$

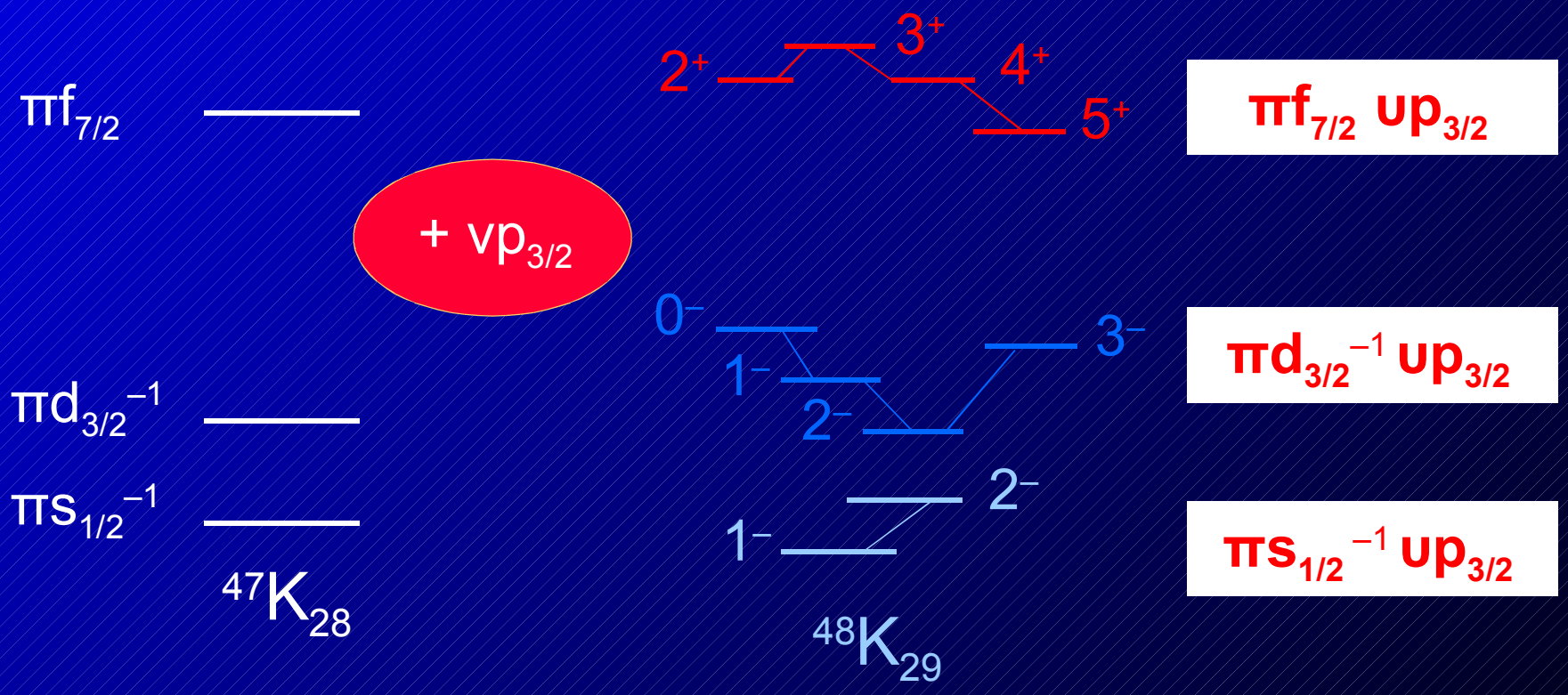

47K
360
267
1094
1319
counts
gamma-ray energy (keV)
2147
3010
3095
3152
3560
3850
counts
gamma-ray energy (keV)


47K: 1660-1319 data & fit
T1/2 = 7.0 (12) ns
counts
time [ns]

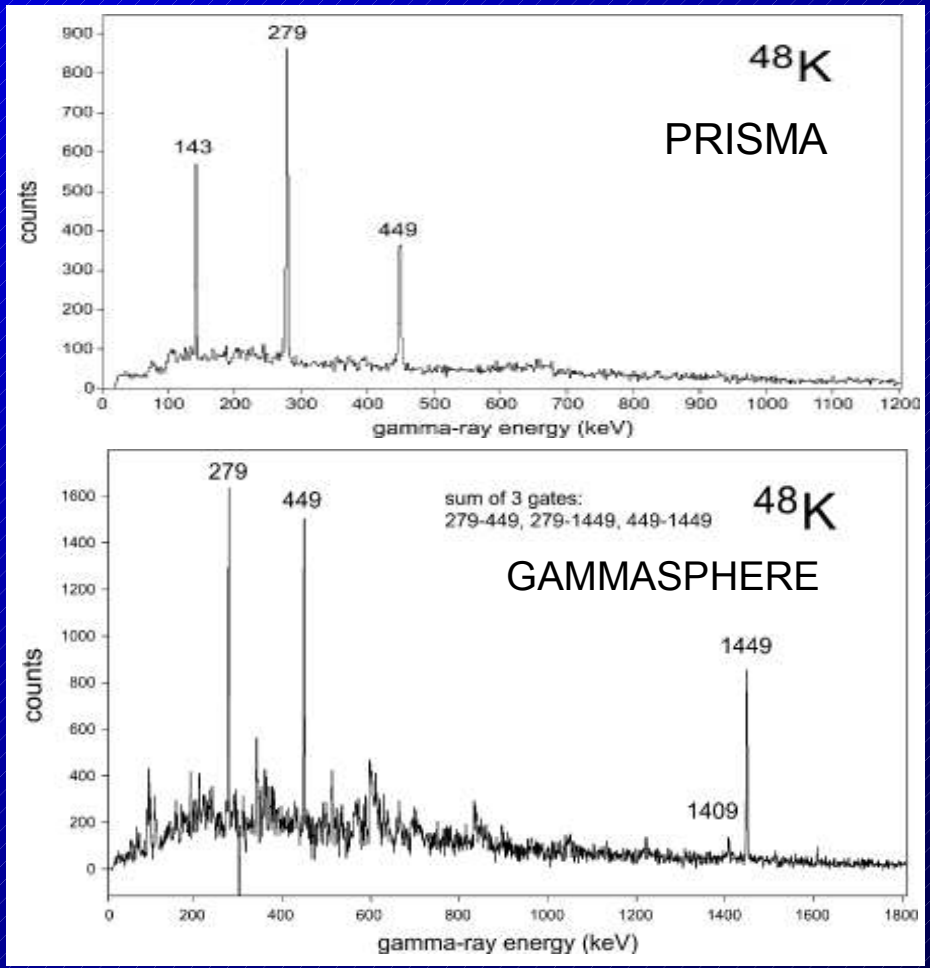

267
655
1094
2147
3152
1319
1660
360
4433
4166
3511
3339
2020 (7/2-)
360 3/2+
0 1/2+
7ns
M2

$^{47}_{19}K_{28}$

# Shell model configurations in $^{48}$K



# First experimental identification of excited states in $^{48}$K

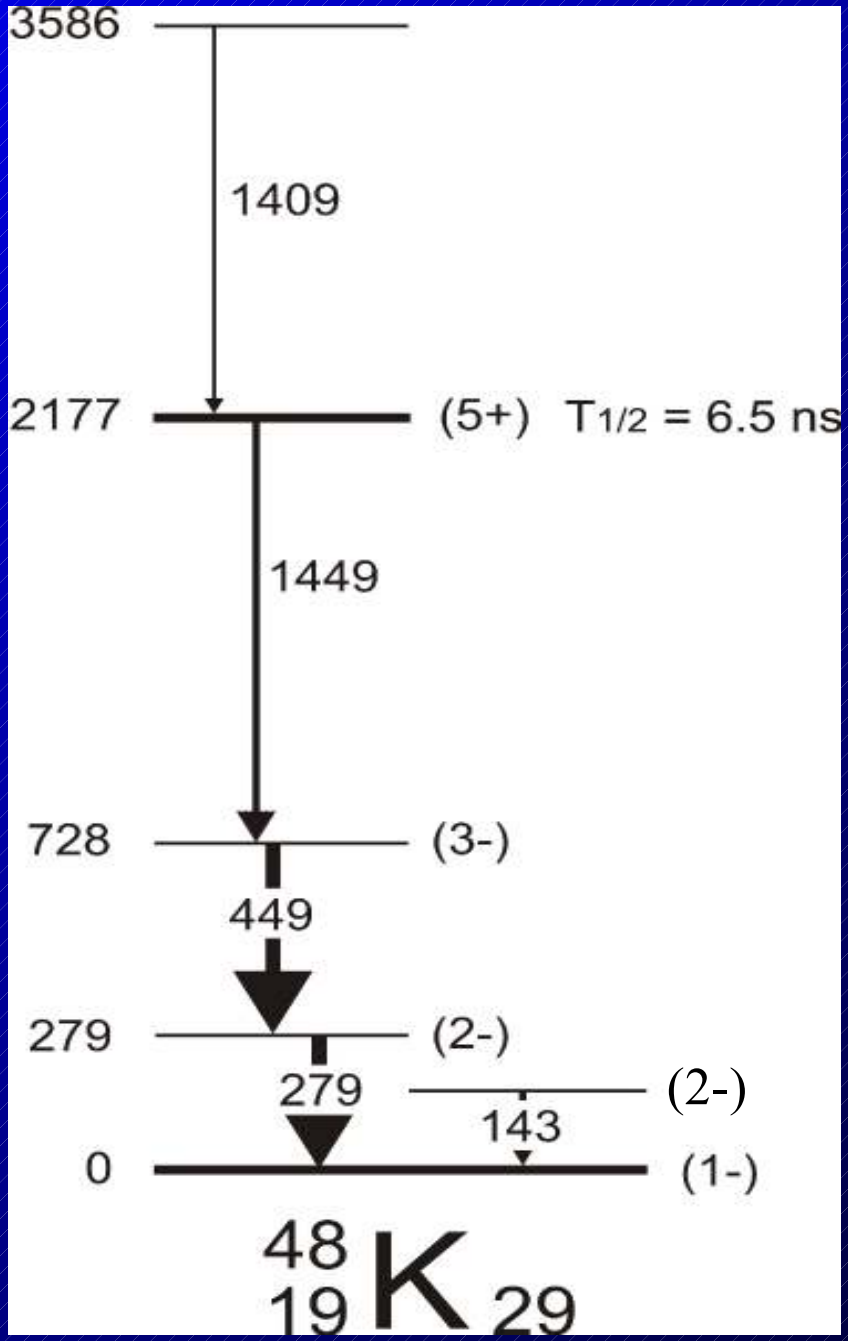


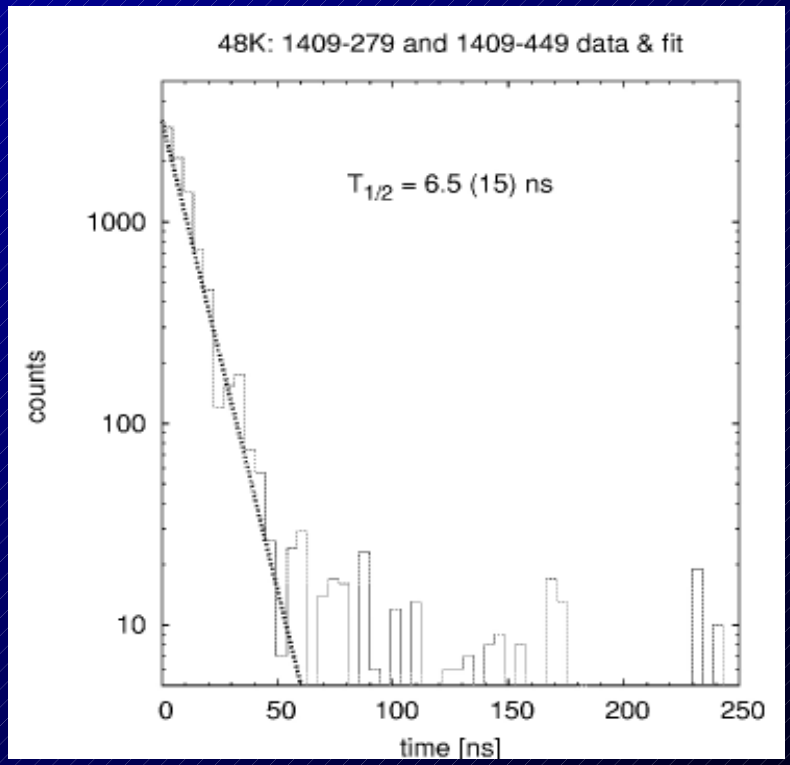

- Identification of $^{48}$K gamma lines from PRISMA
- Level scheme established from GAMMASPHERE coincidence data
- New 6.5 ns isomer placed in $^{48}$K

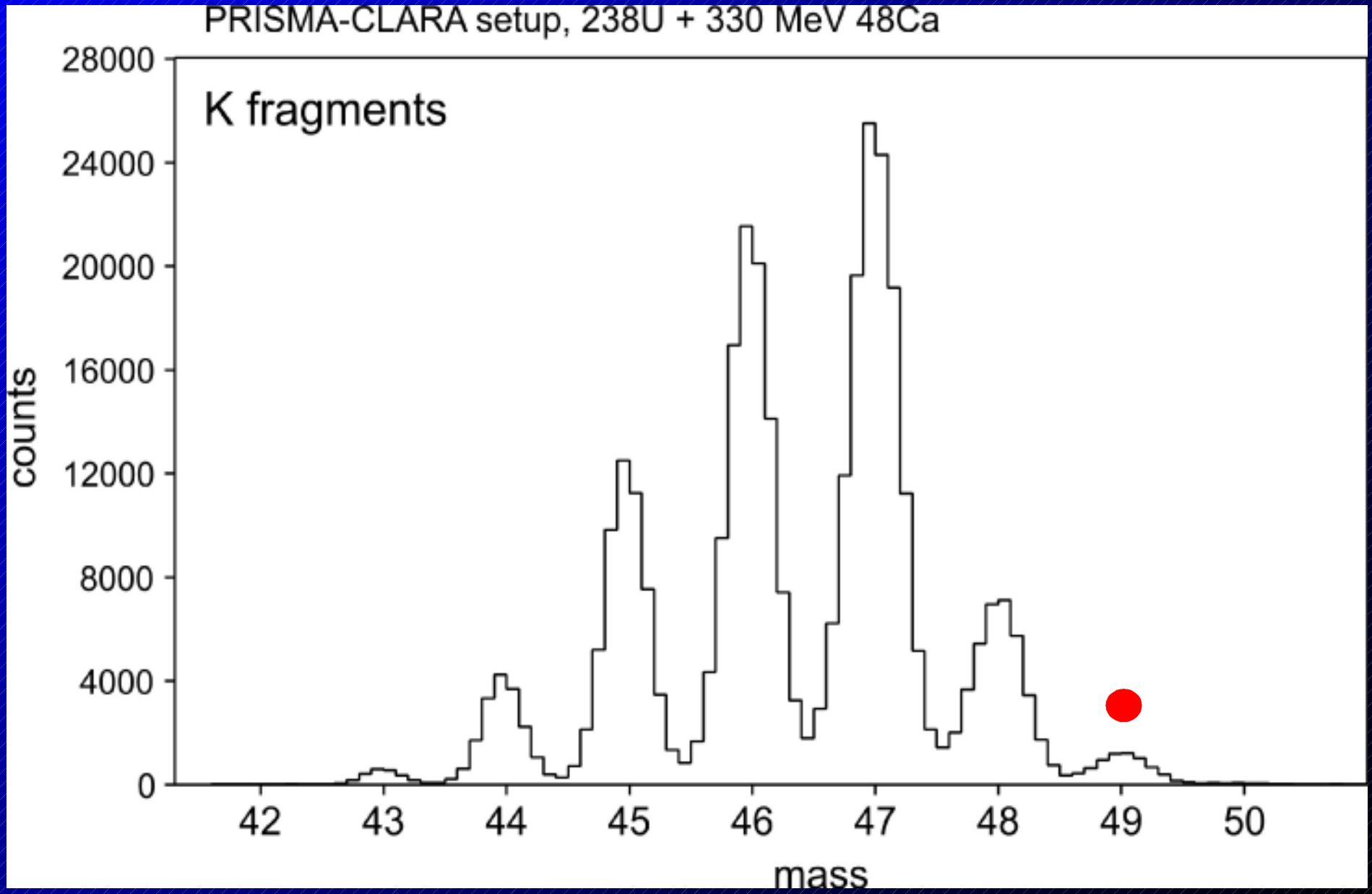
$\pi f_{7/2}\, \upsilon p_{3/2}\, \pi^{-2}$

$\pi d_{3/2}\, \upsilon p_{3/2}$

$\pi s_{1/2}\, \upsilon p_{3/2}$

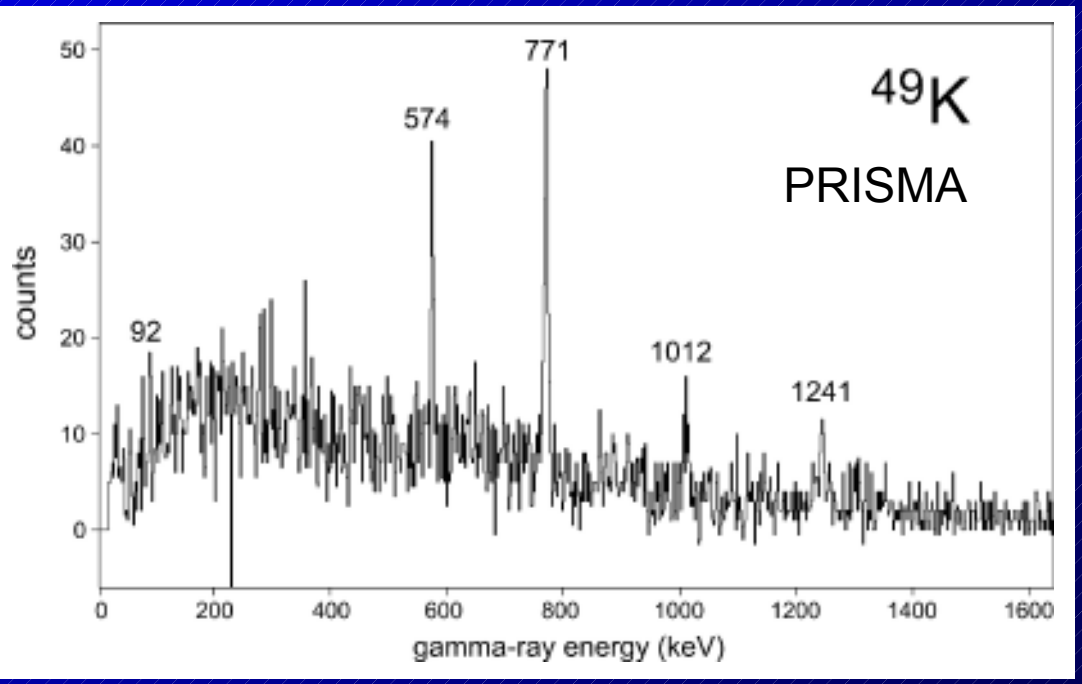


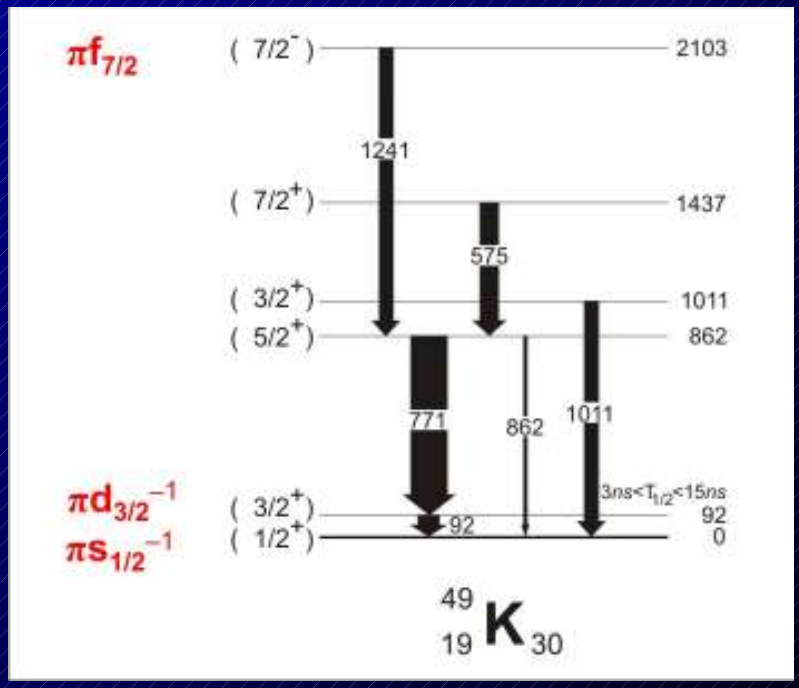




PRISMA-CLARA setup, 238U + 330 MeV 48Ca
K fragments
counts
mass
28000
24000
20000
16000
12000
8000
4000
0
42
43
44
45
46
47
48
49
50

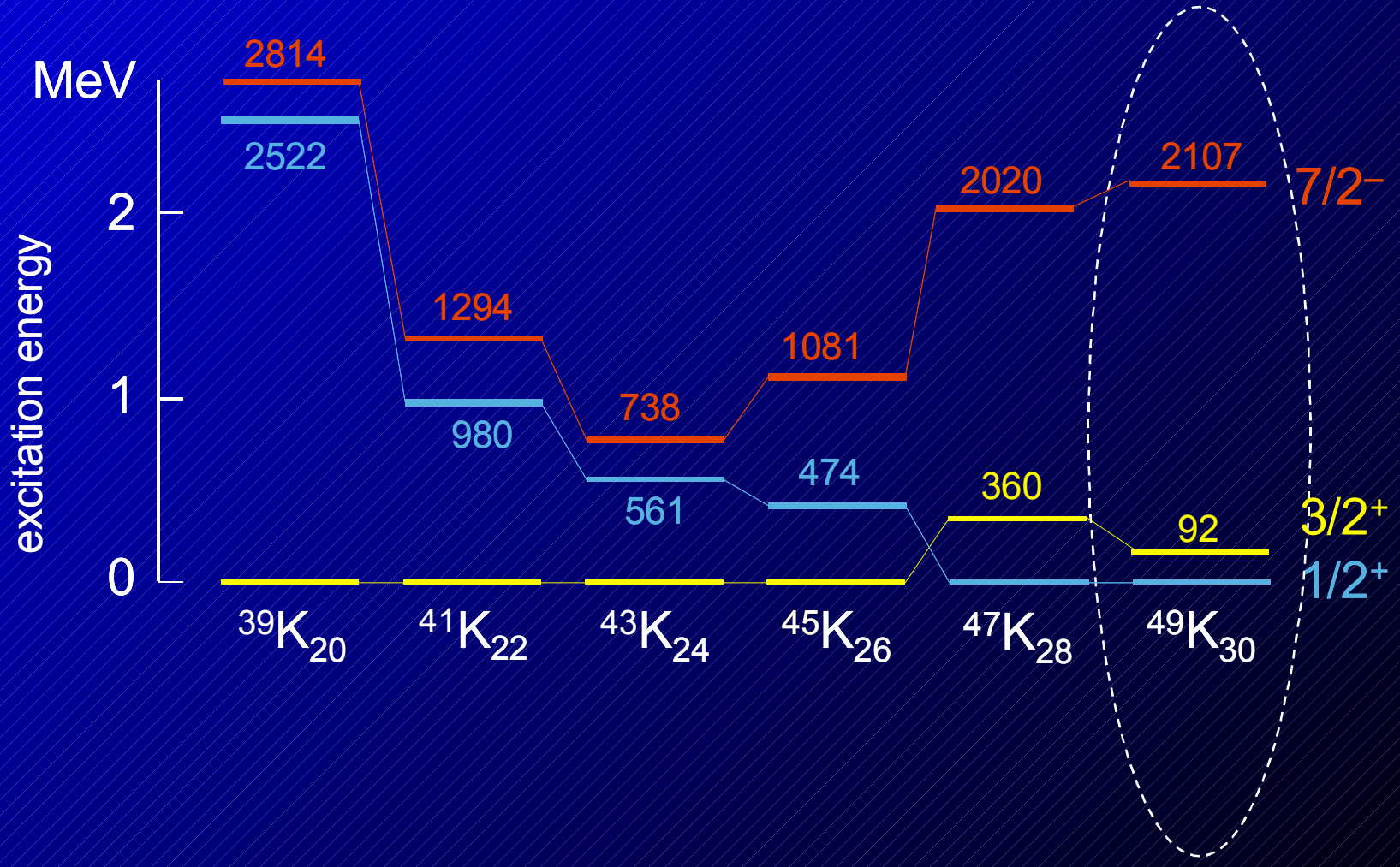
# First observation of excited states in $^{49}$K

- Gamma lines identified from PRISMA
- Level scheme from coincidence analysis



# Energies of lowest $1/2^+$, $3/2^+$ and $7/2^-$ states in odd K isotopes



# Kraków group and collaborators

R. Broda, B. Fornal, W. Królas, T. Pawłat, J. Wrzesiński
*IFJ PAN Kraków*

S. Lunardi, A. Gadea, N. Marginean, L. Corradi, A.M. Stefanini,
F. Scarlassara, G. Montagnoli, M. Trotta, D. Napoli, E. Farnea
*Laboratori Nazionali di Legnaro and INFN Padova*

R.V.F. Janssens, M.P. Carpenter, T. Lauritsen, D. Seweryniak, S. Zhu
*Argonne National Laboratory*

# Co dalej ?

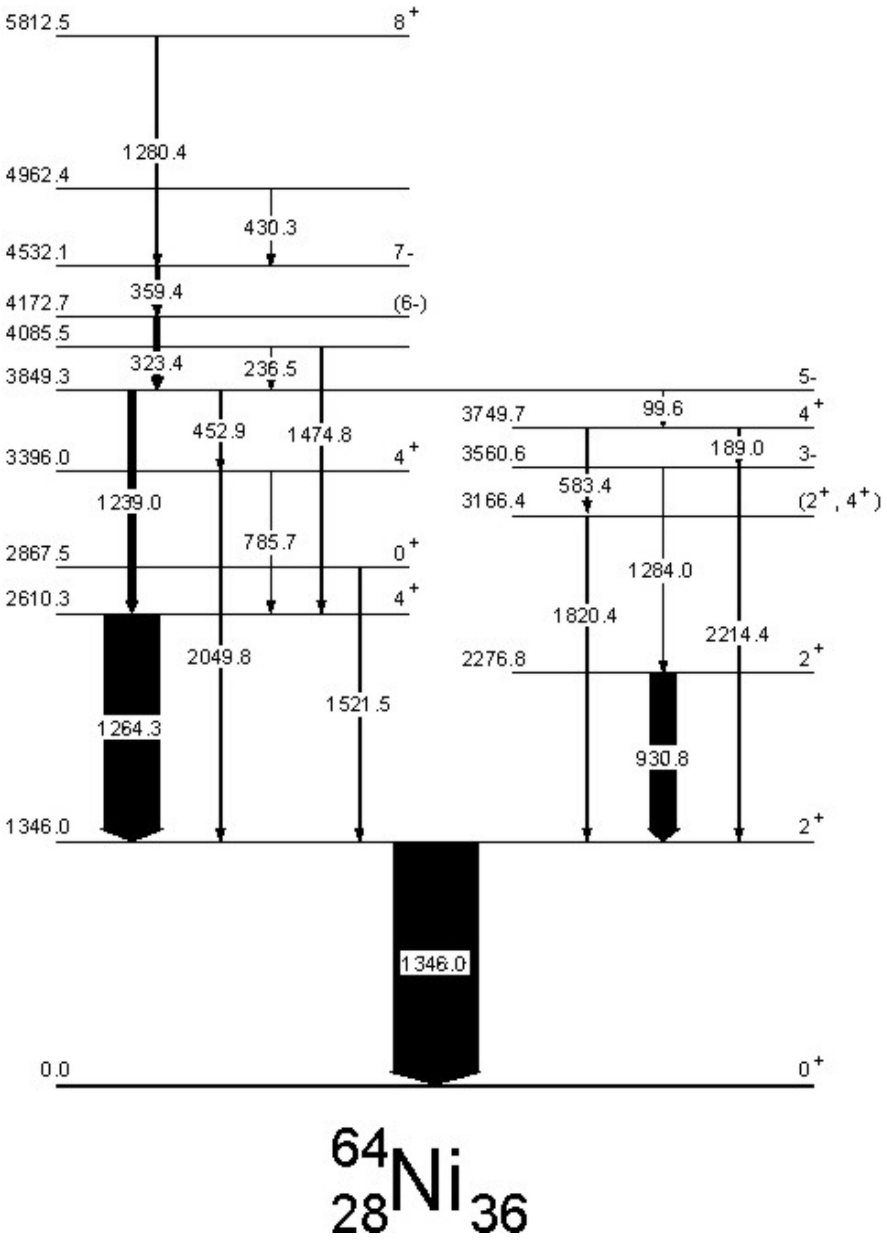
1. Ciągła analiza danych uzyskanych w eksperymentach

2. Analiza korelacji kątowych gamma-gamma - weryfikacja oznaczeń spinów i parzystości stanów jądrowych

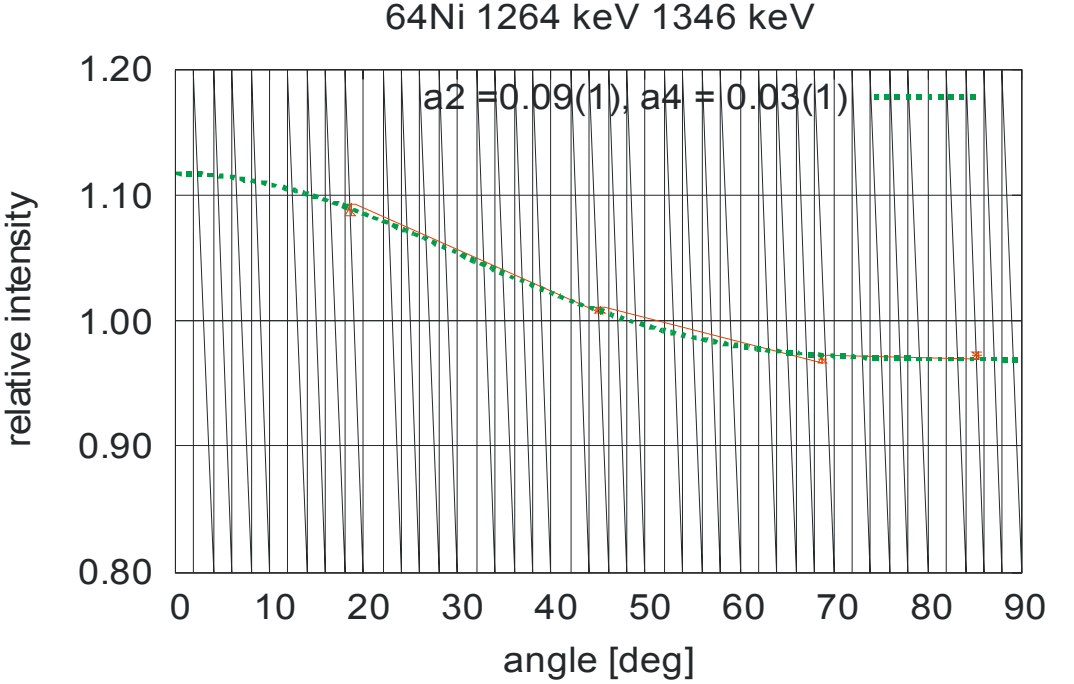
3. Planowane są dalsze eksperymenty z układem CLARA-PRISMA Pomiary czasów życia w obszarze pikosekund.

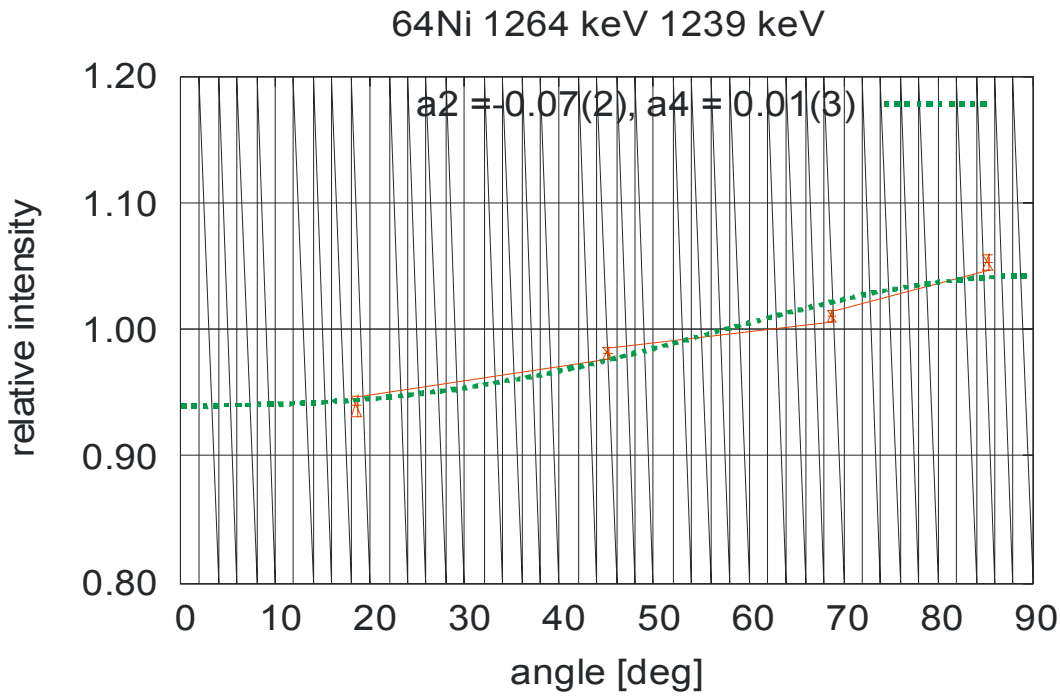
4. Jądra z egzotycznym nadmiarem neutronów produkowane w reakcjach fragmentacji – współpraca z NSCL Michigan State University i Argonne NL (rozpady beta i stany izomeryczne)

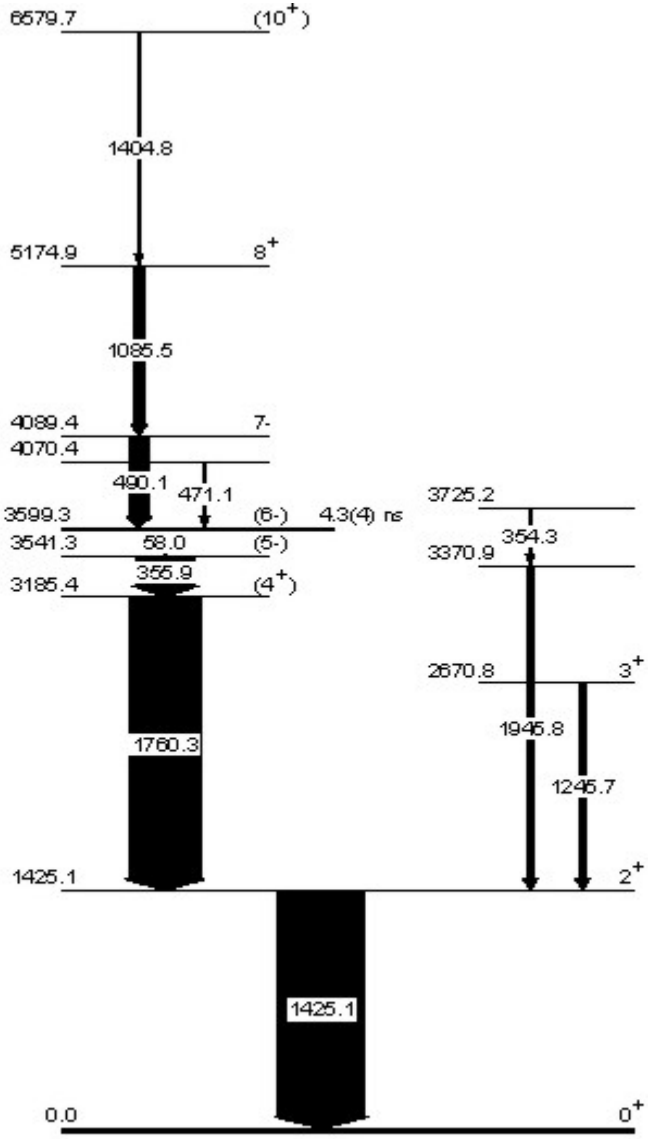
5. Współpraca z grupami teoretyków z MSU i z Japonii specjalizującymi się w obliczeniach modelu powłokowego

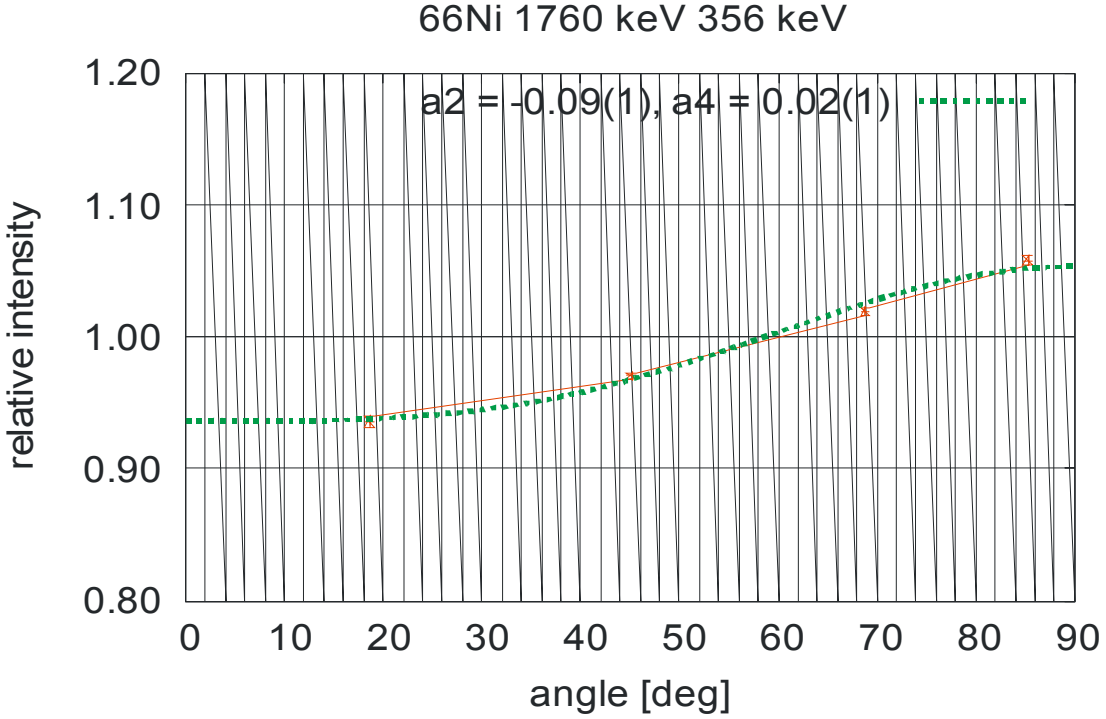


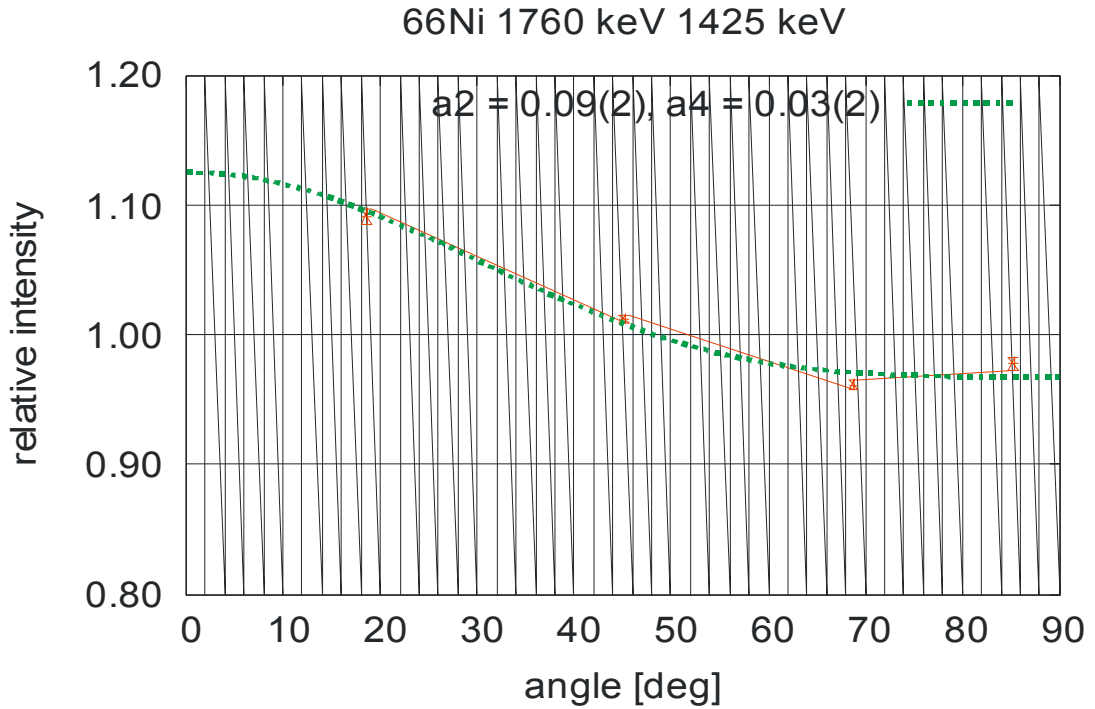

T.Pawlat et al. Nucl.Phys.A574(1994)

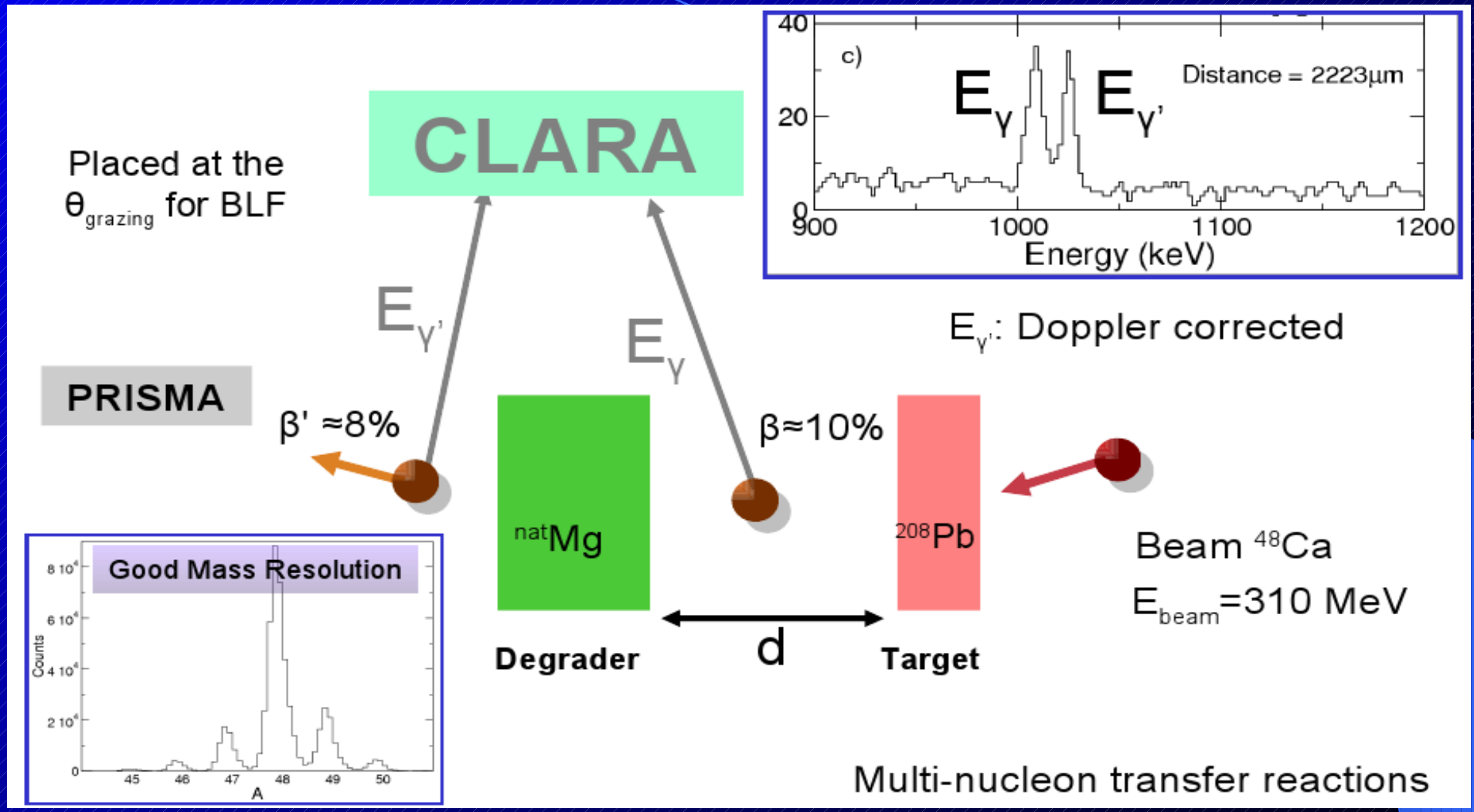


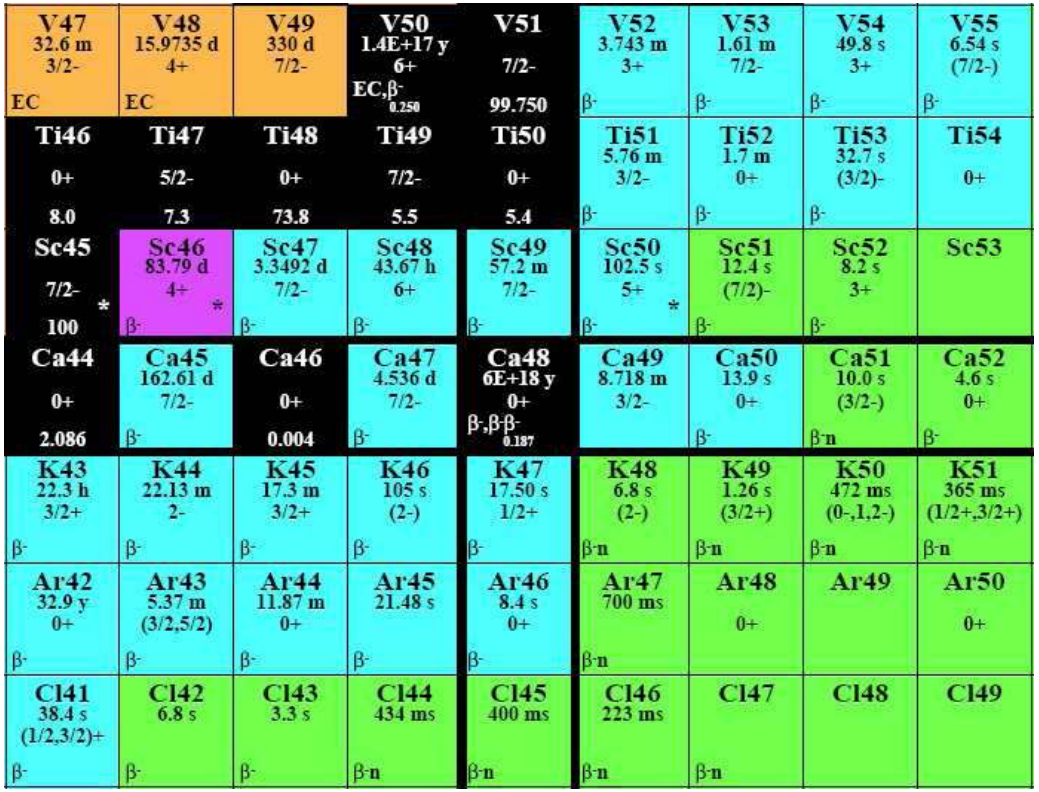




6579.7
(10+)
1404.8
5174.9
8+
1085.5
4089.4
7-
4070.4
490.1
471.1
3599.3
(6-)
4.3(4) ns
3541.3
58.0
(5-)
355.9
3185.4
(4+)
1760.3
1425.1
1425.1
0.0
0+
3725.2
354.3
3370.9
2670.8
3+
1945.8
1245.7
2+
66
28Ni38


66Ni 1760 keV 356 keV
a2 = -0.09(1), a4 = 0.02(1)
relative intensity
1.20
1.10
1.00
0.90
0.80
0
10
20
30
40
50
60
70
80
90
angle [deg]


66Ni 1760 keV 1425 keV
a2 = 0.09(2), a4 = 0.03(2)
relative intensity
1.20
1.10
1.00
0.90
0.80
0
10
20
30
40
50
60
70
80
90
angle [deg]


CLARA
Placed at the
θgrazing for BLF
Eγ'
Eγ
PRISMA
β' ≈8%
β≈10%
natMg
208Pb
Degrader
d
Target
Beam 48Ca
Ebeam=310 MeV
Eγ'
Eγ
Distance = 2223μm
c)
Energy (keV)
Eγ': Doppler corrected
Good Mass Resolution
Counts
A
Multi-nucleon transfer reactions




***beam*: 48Ca @ 310 MeV provided by TANDEM ALPI (1.5 pnA current) accelerator complex;**

***target* : 1 mg/cm2 stretched 208Pb (1 mg/cm2 Ta backing) ;**

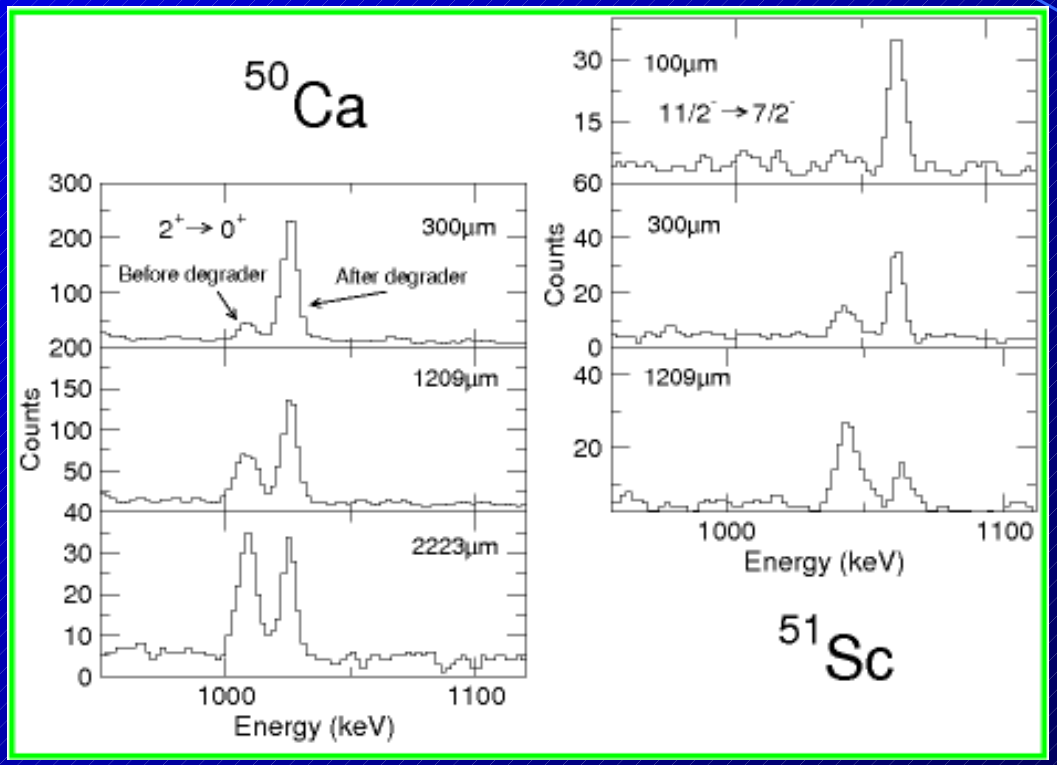
***degrader* : 4 mg/cm2 *nat*Mg;**

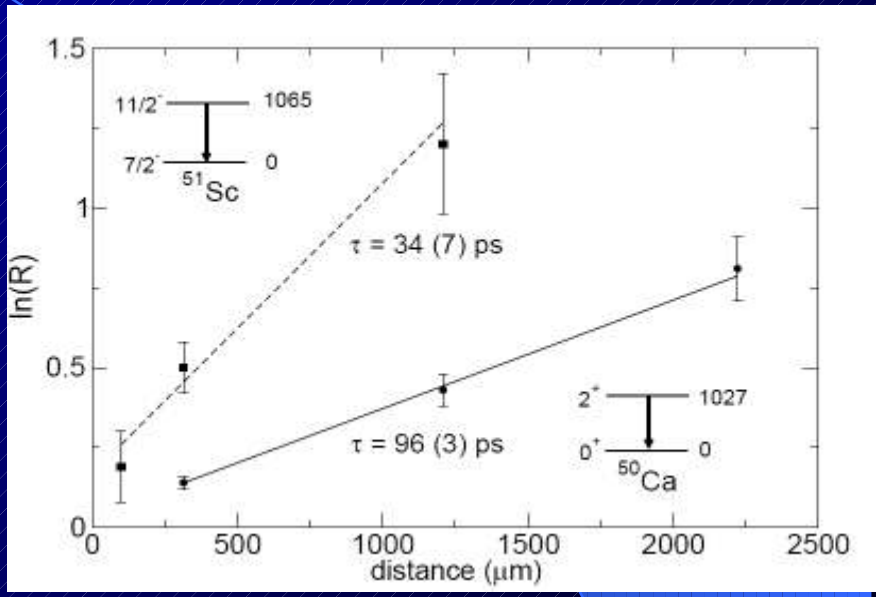
**PRISMA(49 grazing angle)+CLARA;**

**Distances: 30 μm, 100 μm, 300 μm, 1240 μm, 2200 μm;**

**8-days beam-time.**

J.J.Valiente-Dobon, D.Mengoni et al.


$^{50}$Ca
$2^+ \rightarrow 0^+$
300µm
Before degrader
After degrader
1209µm
2223µm
Counts
Energy (keV)
100µm
$11/2^- \rightarrow 7/2^-$
300µm
1209µm
$^{51}$Sc


$11/2^-$
1065
$7/2^-$
0
$^{51}$Sc
τ = 34 (7) ps
τ = 96 (3) ps
$2^+$
1027
$0^+$
0
$^{50}$Ca
ln(R)
distance (µm)

# Kraków group and collaborators

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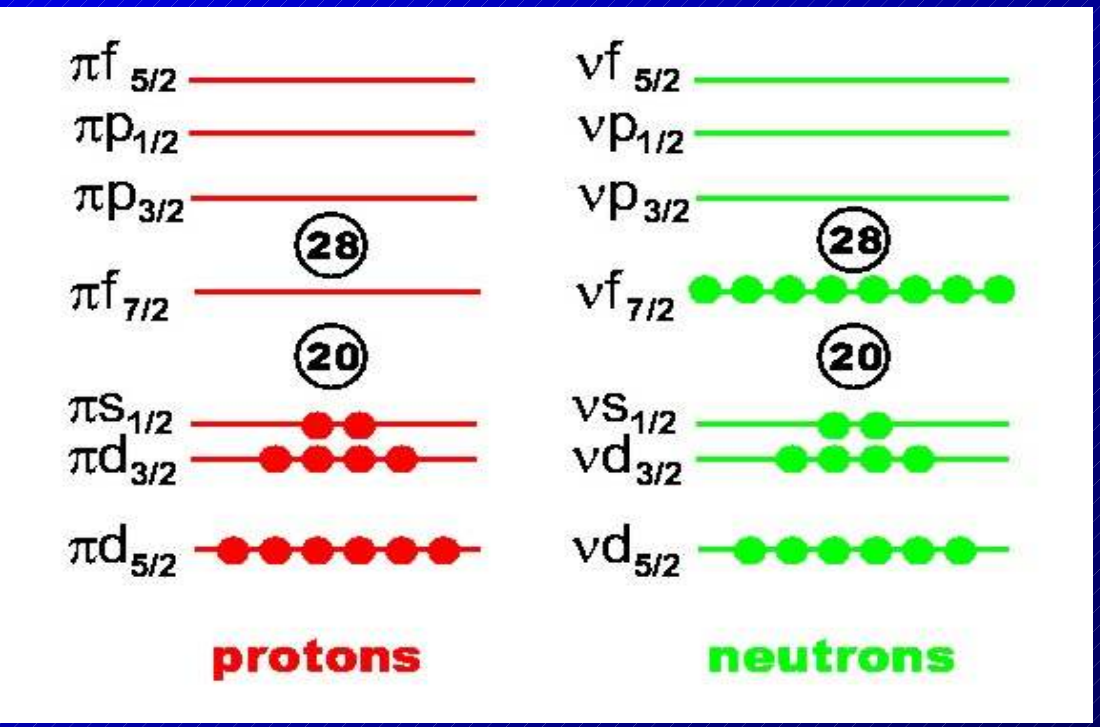
# Shell model




$^{48}$Ca doubly closed-shell configuration

- For Potassium (*Z=19*):
  a proton-hole, nearest shells are
  $\pi\ s_{1/2}$, $\pi\ d_{3/2}$
  and $\pi\ d_{5/2}$

- For neutron-rich (*N > 28*):
  neutrons in $\nu\ p_{3/2}$, $\nu\ p_{1/2}$ and/or
  $\nu\ f_{5/2}$ shells