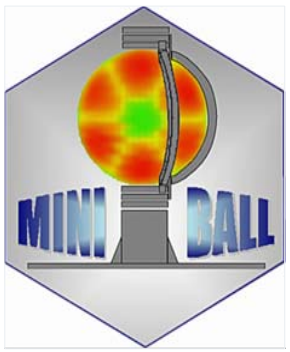
Coulomb excitation of ^{31}Mg - at the shore of the island of inversion

- Motivation
- New results from the island of inversion
- Coulomb excitation of ^{31}Mg
- Preliminary conclusions
- Outlook

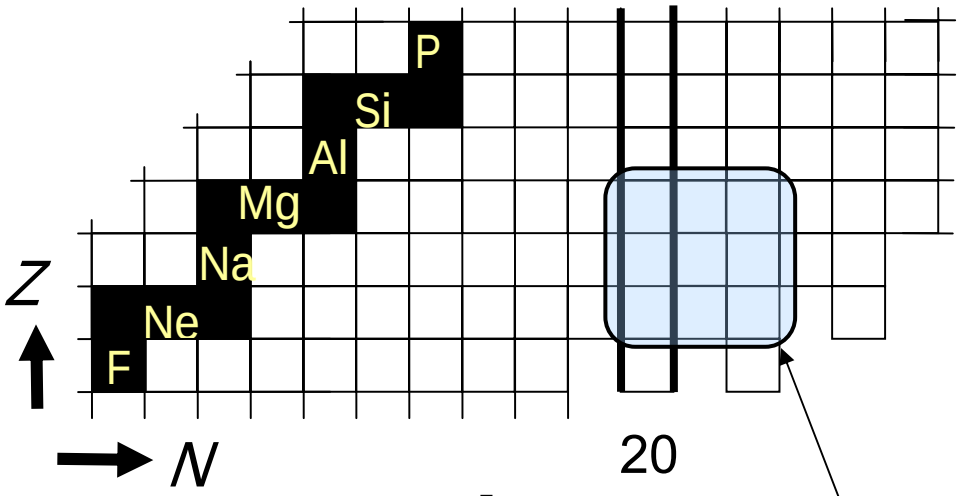


P. Reiter
Universität zu Köln

ISOLDE workshop

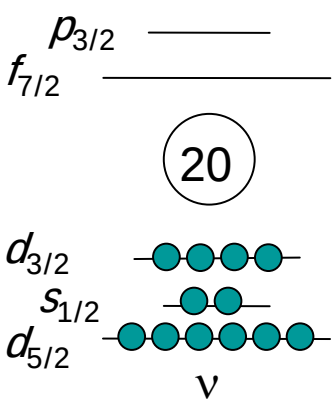
December 17-19, 2007

The island of inversion



Normal *sd*-shell configuration

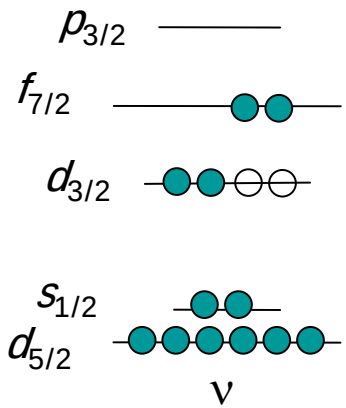
0p0h, spherical



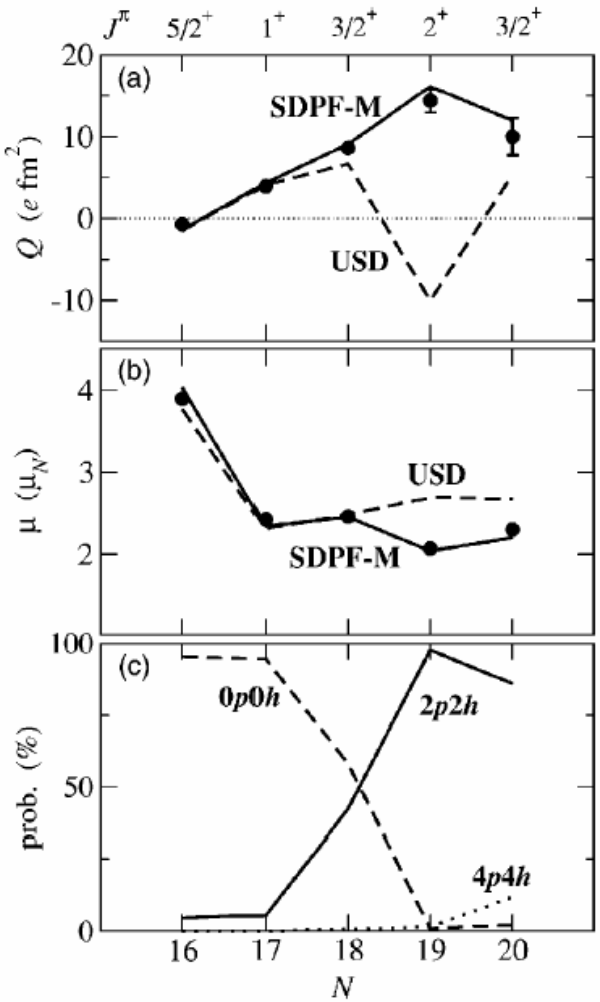
Island of Inversion

E.K. Warburton, J. A. Becker and B. A. Brown, PRC**41**(1990)1147.

2p2h (intruder), deformed

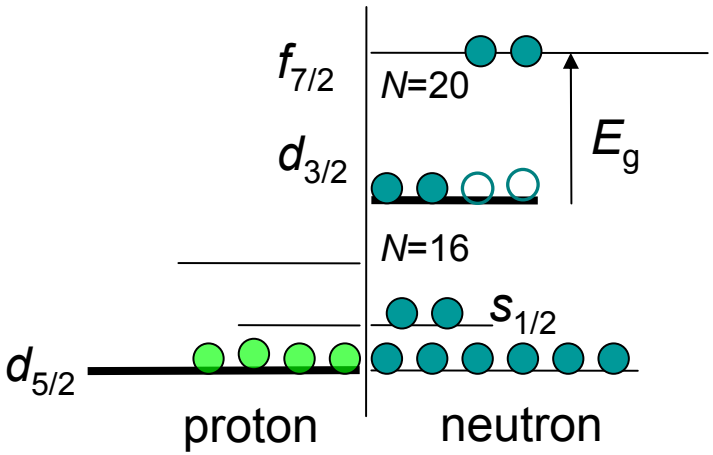


Monte Carlo shell model
sdpf model space: Na isotopes



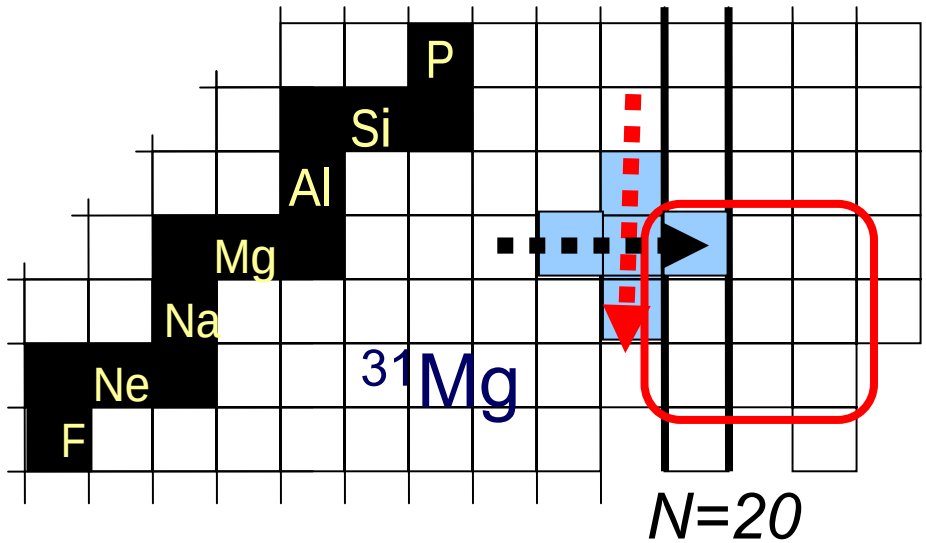
Y. Utsuno, *et al.*, Phys. Rev. C**70**(2004) 044307.

Where is the border of the “island of inversion” ?



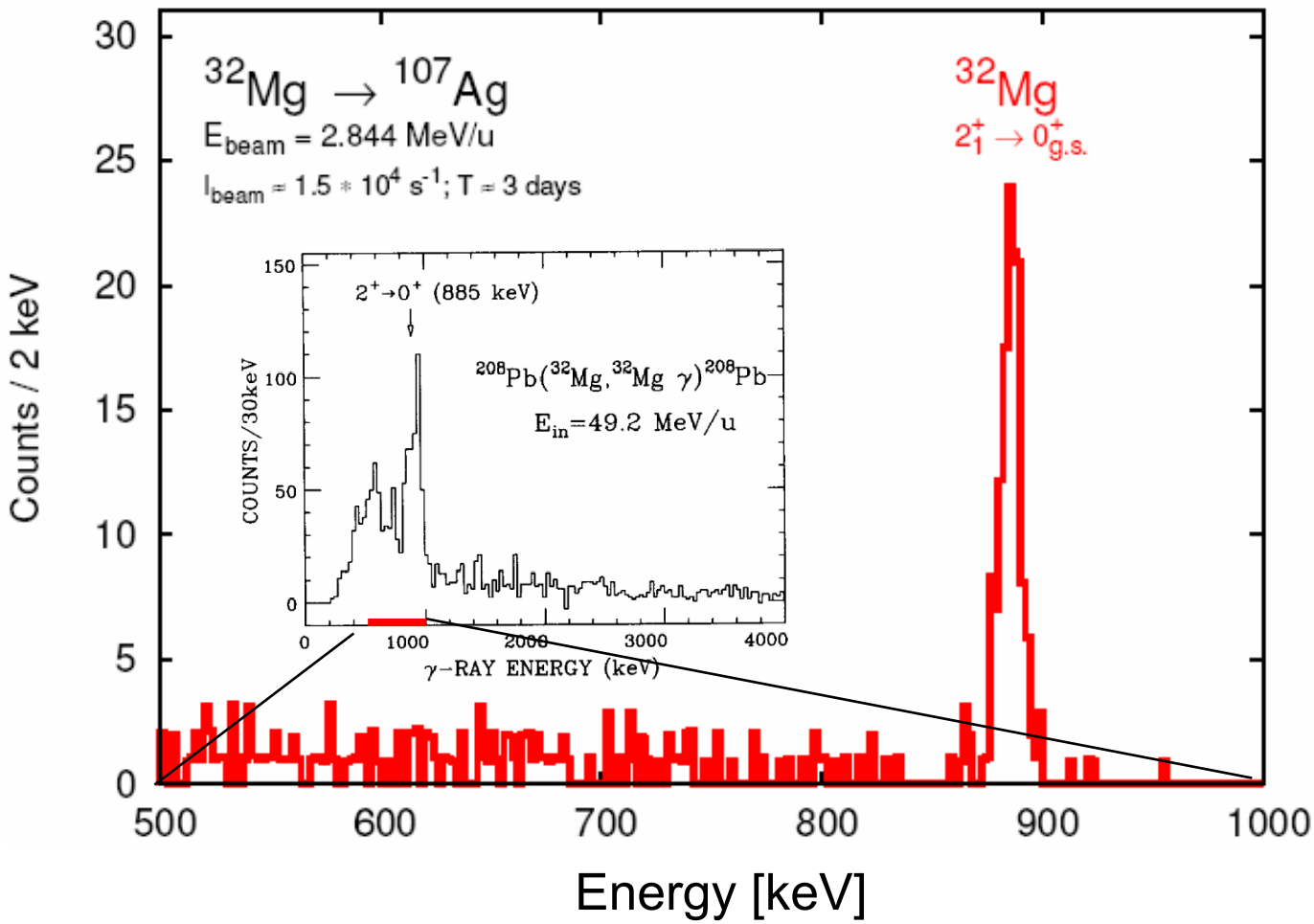
- small effective gap between $0d_{3/2}$ and *pf* shell for neutrons
- small gap is caused by strongly attractive interaction between protons in $0d_{5/2}$ and neutrons in $0d_{3/2}$
- disappearance of the N=20 semi-magic structure Z = 9 - 14 exotic nuclei and appearance of new magic structure in ^{24}O

1. Monopole term
   → Effective shell gap (E_g)
2. Multipole term
   → Correlation energy (E_c)



Y. Utsuno, *et al.*, Phys. Rev. C **60** (1999) 054315

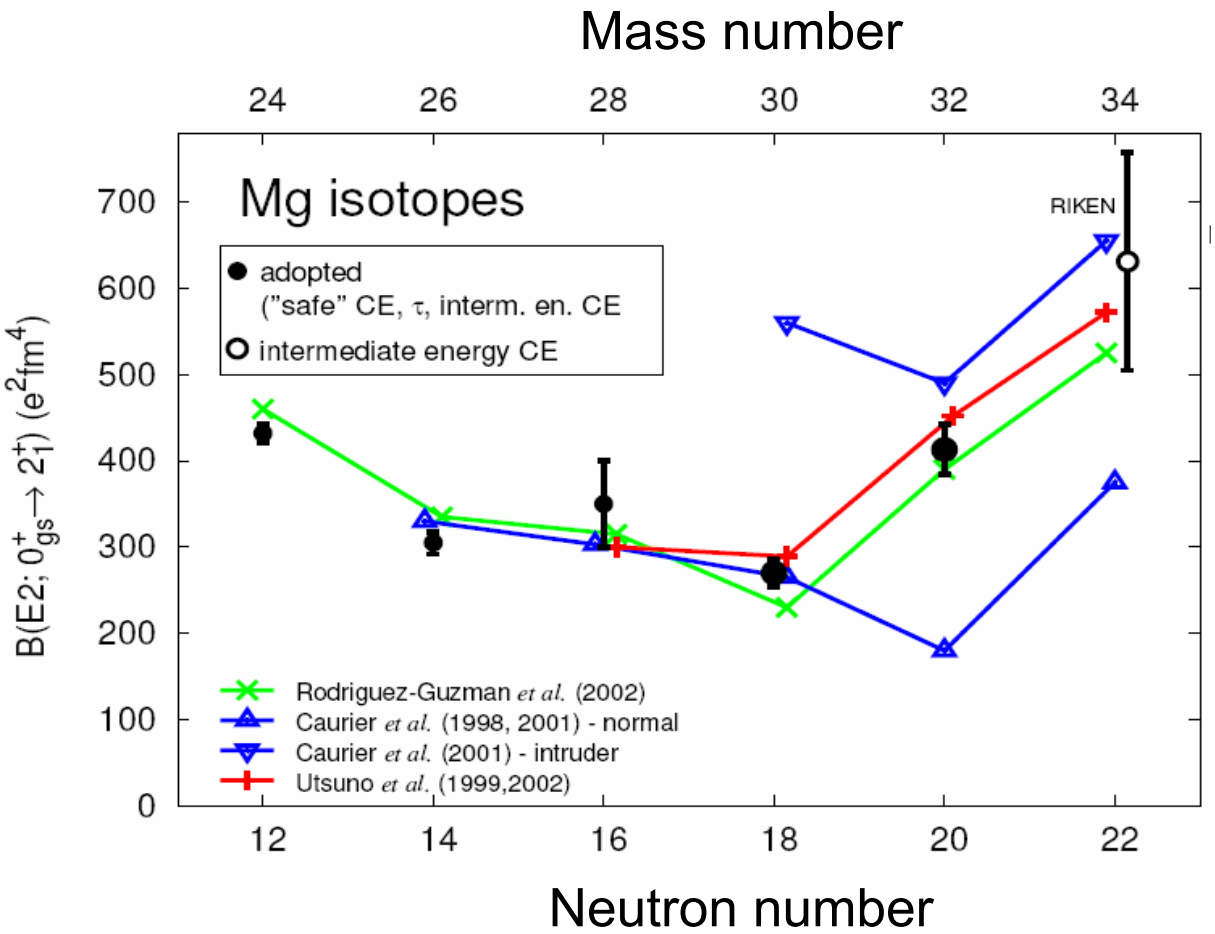
Coulomb excitation of ^{32}Mg at REX-ISOLDE



"safe" Coulomb excitation in reversed kinematics

H. Scheit et al.

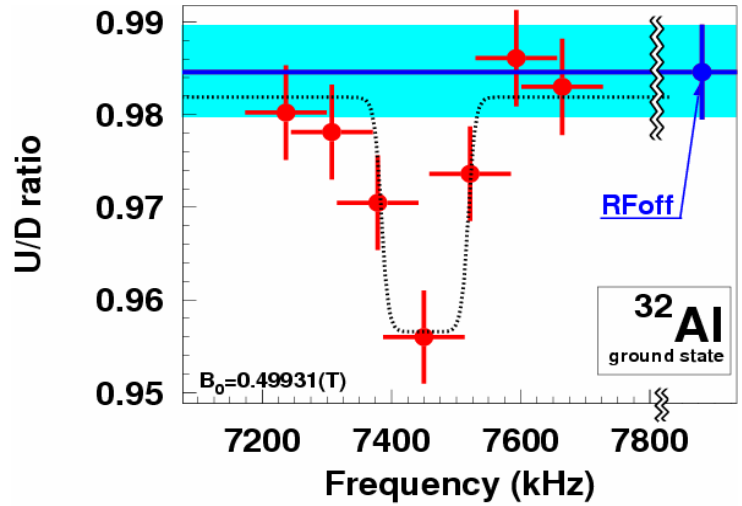
Comparison with theoretical predictions



O. Niedermeier et al. Phys. Rev. Lett. **94**, 172501 (2005)
H. Scheit et al.

N=19 Isotones: ^{30}Na, ^{31}Mg, ^{32}Al
^{32}Al Nuclear Moments

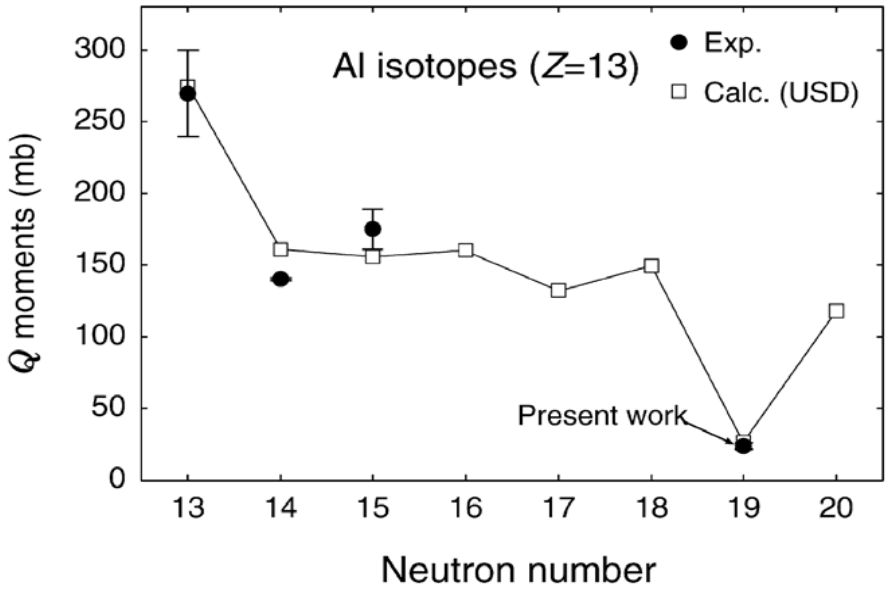
magnetic moment



$|\mu(^{32}\mathrm{Al};1^{+})| = 1.959(9)\mu_n$

H. Ueno *et al.*, Phys. Lett. B **615** (2005) 186

electric quadrupole moment



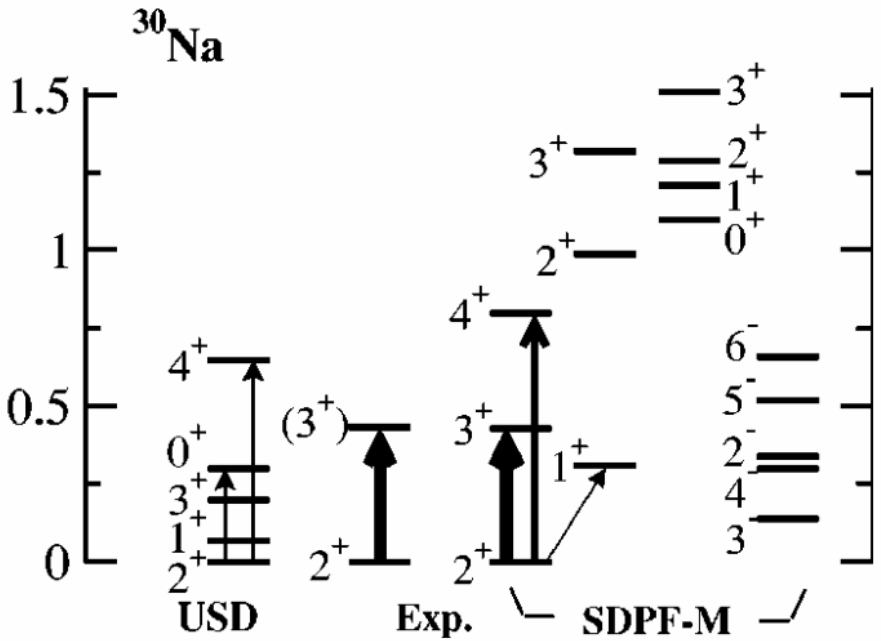
D. Kameda et al. / Phys. Lett. B 647 (2007) 93

- recent results from RIKEN: magnetic moment and electric quadrupole moment

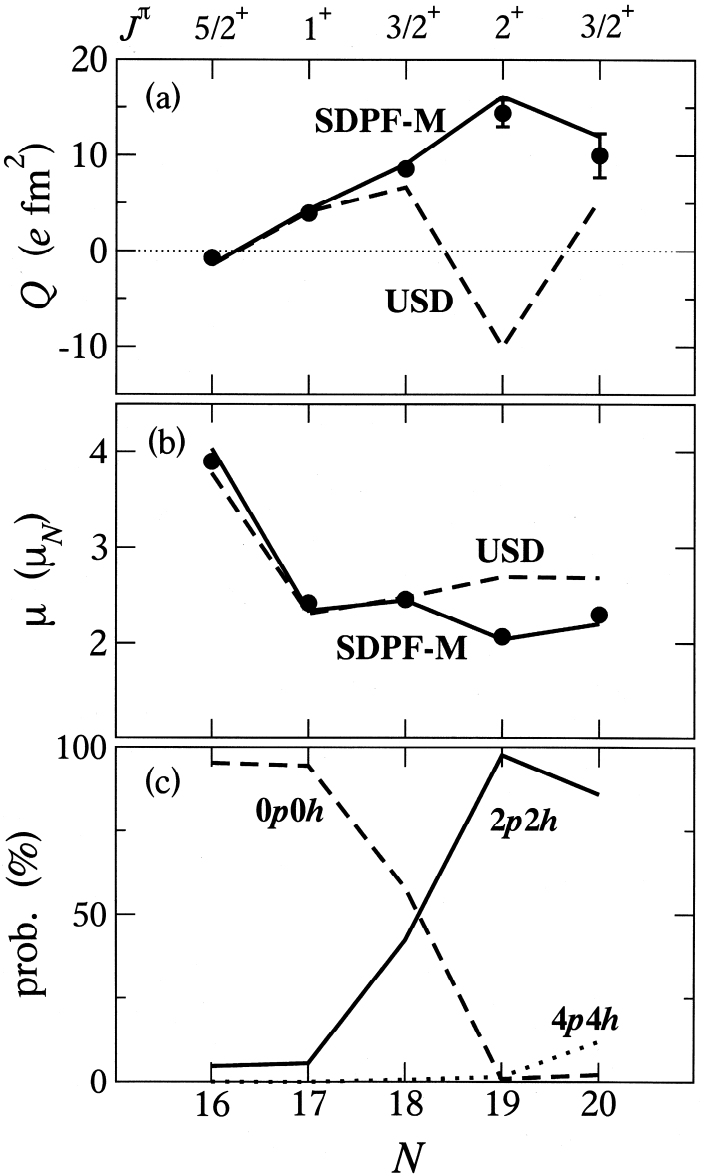
- compatible with conventional shell model calculations within the *sd*-model space clear evidence that the ground state of ^{32}Al is a normal *sd* shell state.

N=19 Isotones: ^{30}Na, ^{31}Mg, ^{32}Al

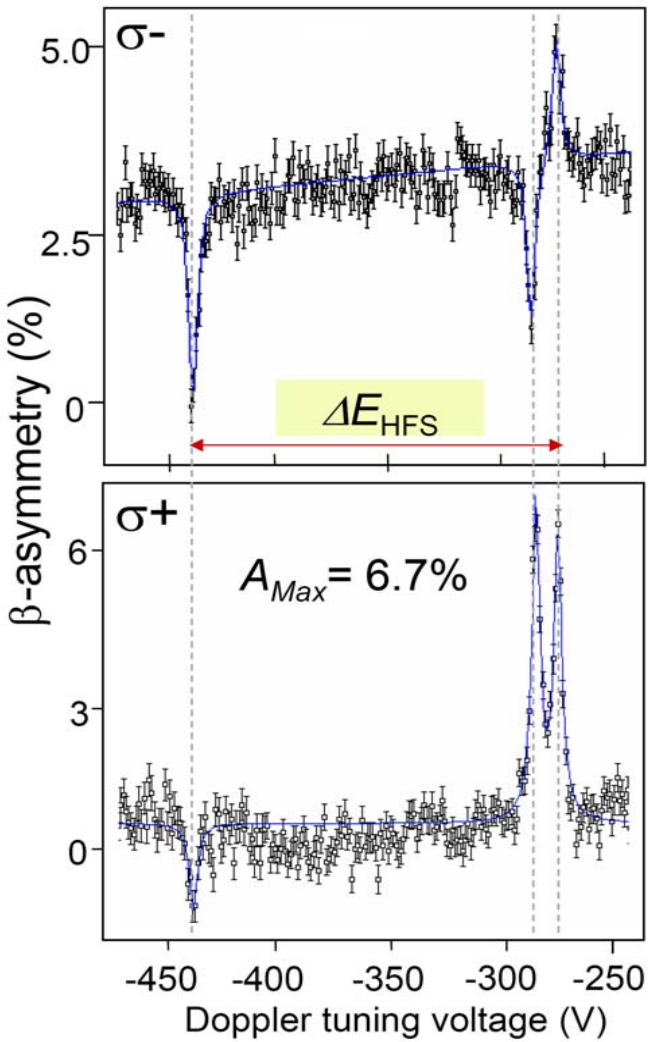
- ^{30}Na, nuclear moments:
  M. Keim *et al.,* Eur. Phys. J. A**8** (2000) 31
- Monte Carlo shell model (MCSM)
- onset of the intruder dominance occurs at **N=19**

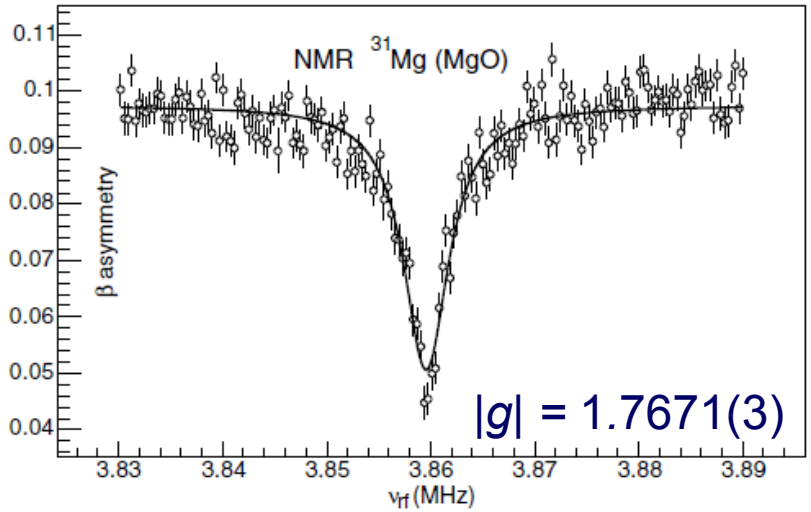


Y. Utsuno et al., Phys. Rev. C 70, 044315 (2004).



Nuclear moment studies at ISOLDE: ^{31}Mg





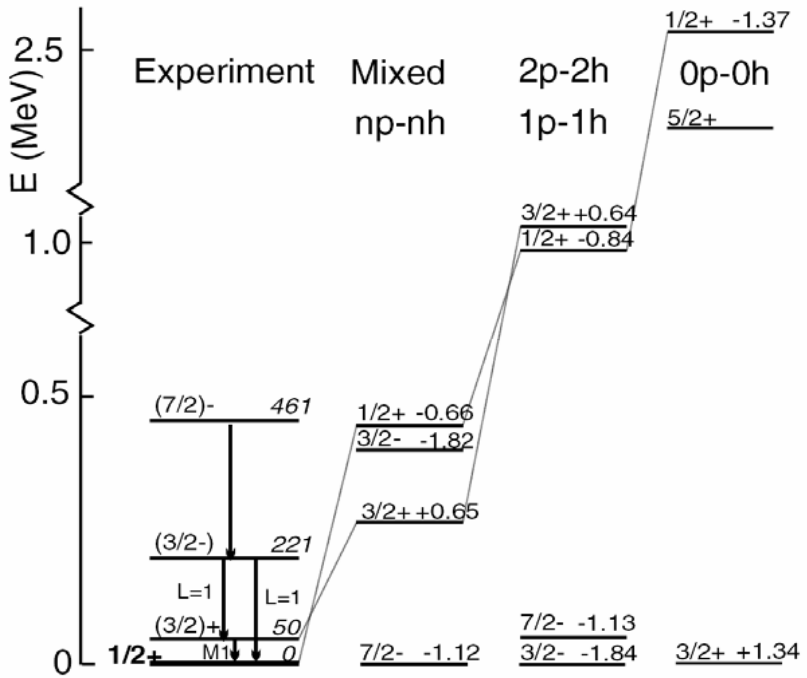
- Ground state spin of ^{31}Mg:
  $I^{\pi} = 1/2^{+}$

- Magnetic moment:
  $\mu = -0.88355(15)\ \mu N$

- sudden inversion between *sd* and *pf* configurations between ^{32}Al and ^{31}Mg
- drastic change of nuclear shapes?

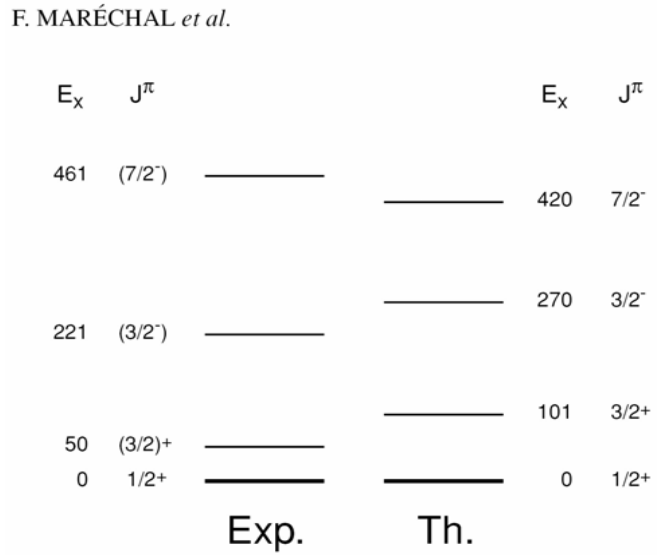
G. Neyens, M. Kowalska, D. Yordanov, et al., PRL 94, 022501 (2005),
33Mg: D. Yordanov, M. Kowalska, et al., PRL **99,** 212501 (2007)

^{31}Mg MCSM calculations and β-decay study



Problem: ^{31}Mg (1/2+)→ ^{31}Al (5/2+)

- *β* decay study of ^{31}Mg at GANIL
- very weak feeding to the ^{31}Al ground state
- new shell-model calculations in *sd-fp* valence space
- interaction was modified in order to reproduce low-energy level scheme of 31Mg.



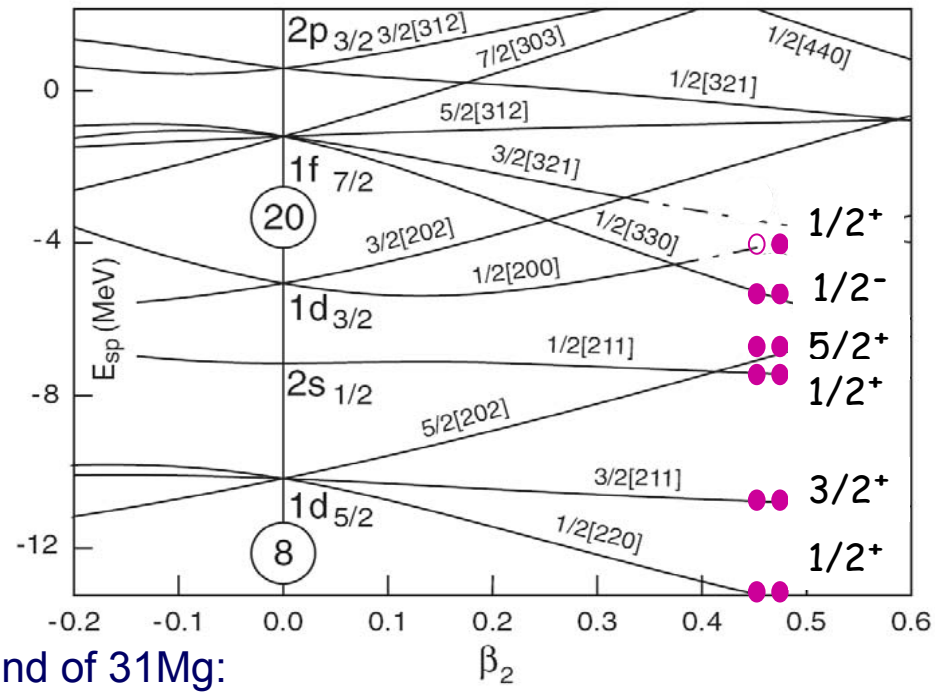
G. Neyens et al., PRL 94, 022501 (2005)

F. Maréchal et al., PRC 72, 044314 (2005)

positive yrast band of 31Mg

Deformed positive parity yrast band in 31Mg

- K =1/2 band, neutron hole in [200]1/2+
- crossing of lowest K =1/2− neutron orbit from *fp* shell
- K =3/2+ and K =1/2+ components from *d*3/2 spherical orbit.
- Deformation: β =0.48



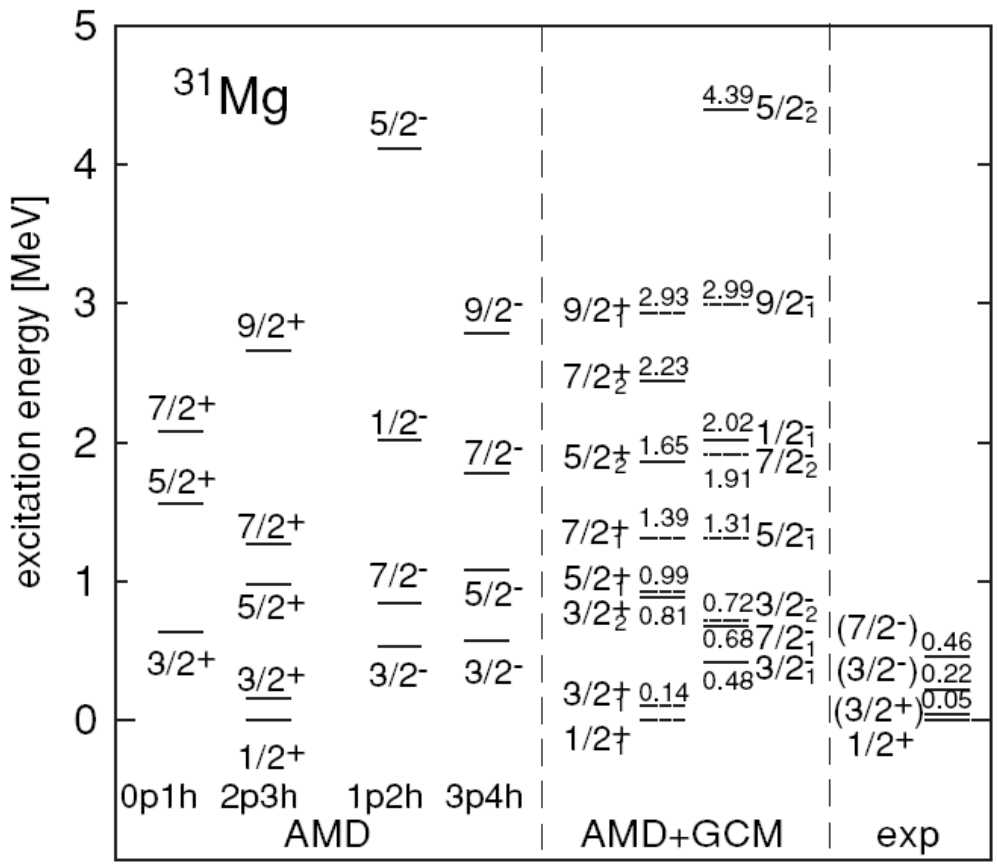
Calculated properties of the positive yrast band of 31Mg: *Q* values, *B*(*E*2), magnetic moments μ, *B*(*M*1)

J	E_x	$n^{\nu}_{d_{5/2}}$	$n^{\nu}_{d_{3/2}}$	$n^{\nu}_{s_{1/2}}$	Q_s/Q_0	$B(E2)$	μ	$B(M1)$
1/2	0	5.62	1.99	1.33			−0.98	
3/2	101	5.63	1.77	1.56	−17/84	106	+0.56	0.06
5/2	988	5.60	2.02	1.31	−17/59	127	−0.30	0.38
7/2	1236	5.63	1.68	1.64	−25/75	151	+0.94	0.04
$K = 1/2^+$		5.75	1.52	1.73				

F. Maréchal et al., PRC 72, 044314 (2005)

^{31}Mg AMD + GCM calculation

antisymmetrized molecular dynamics (AMD) plus generator coordinate method (GCM) with the Gogny D1S force



electric quadrupole moment of positive-parity states

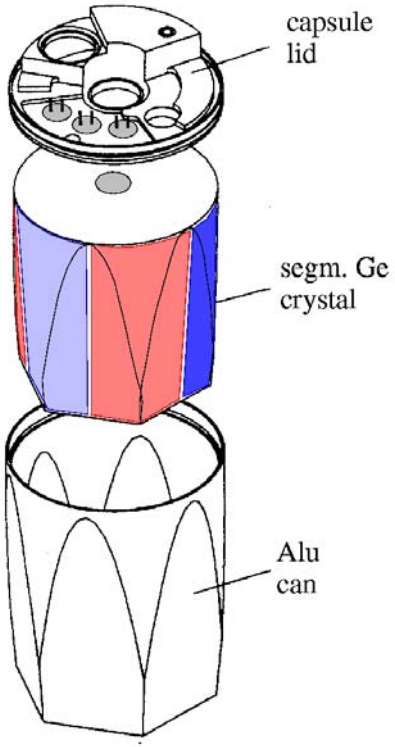
J^π	Q 1	Q_s 2
$3/2^+$	−18.9	−17.1
$5/2^+$	−19.1	−21.6
$7/2^+$	−23.2	−22.5
$9/2^+$	−17.2	−19.5
$3/2^+_2$	8.2	7.4
$5/2^+_2$	4.8	−2.7
$7/2^+_2$	−2.4	−5.3

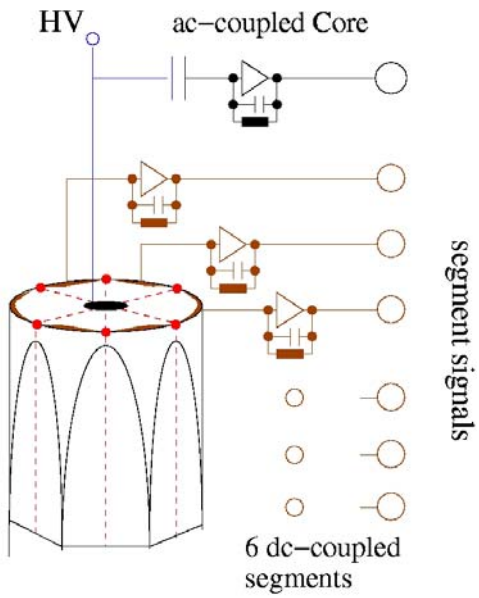
1 AMD + GCM

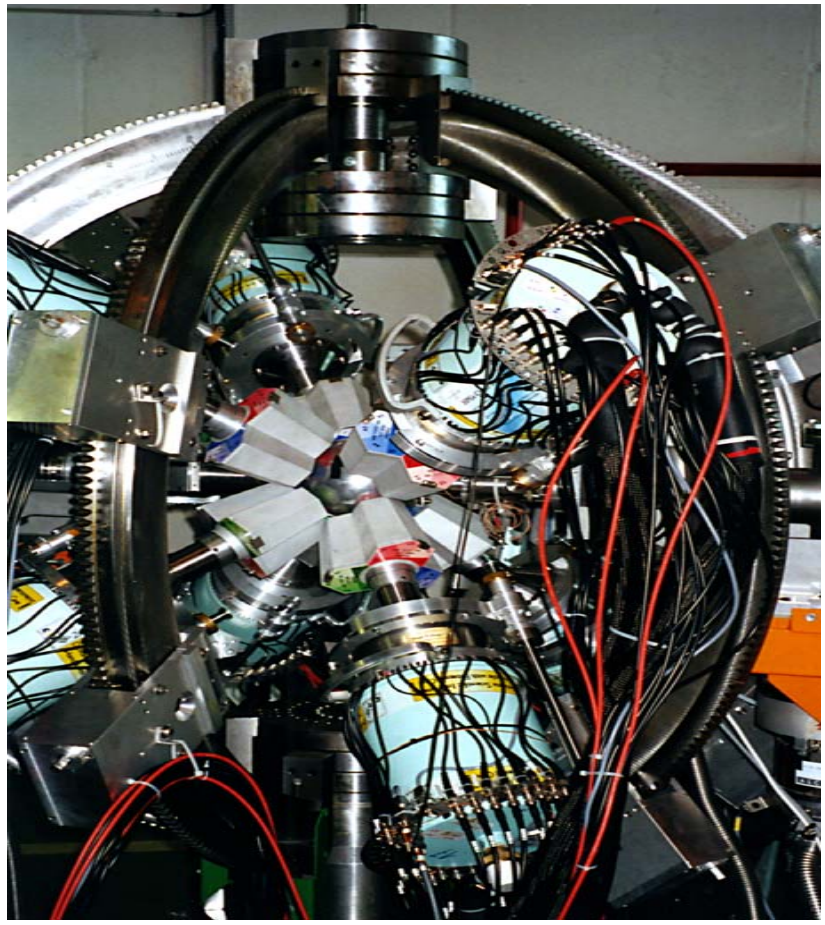
2 Rigid rotor

M. Kimura, Phys. Rev C **75**, 041302(R) (2007)

MINIBALL







- 8 clusters, 24 Ge-detectors, 6-fold segmented crystals
- MINIBALL efficiency ~8% at 1.3 MeV
- digital electronics, on-board online pulse shape analysis (PSA) for better position resolution

Set-up for safe Coulomb-excitation

Gamma-spectroscopy

MINIBALL

Particles
- angle
- energies

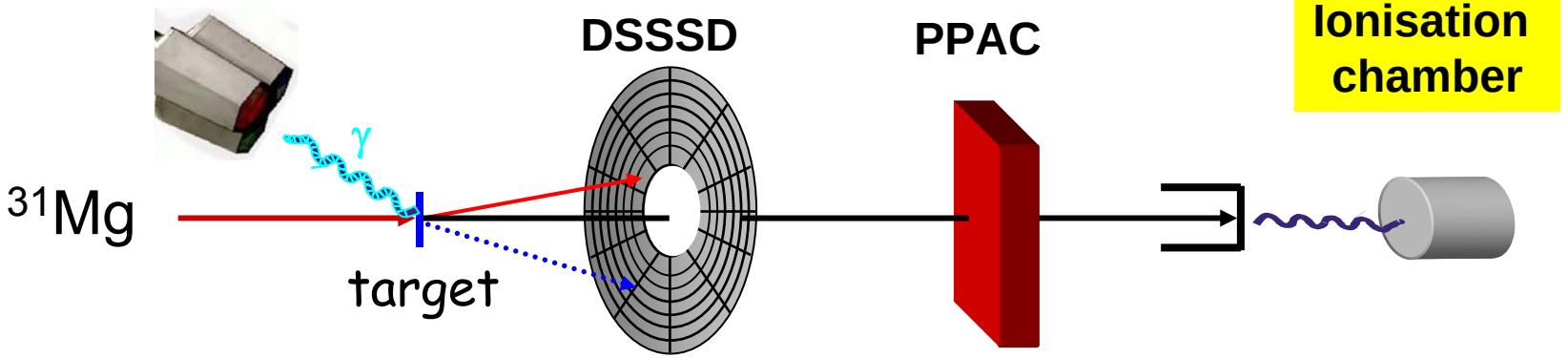
DSSSD

Beam-monitor

PPAC

Beam-purity

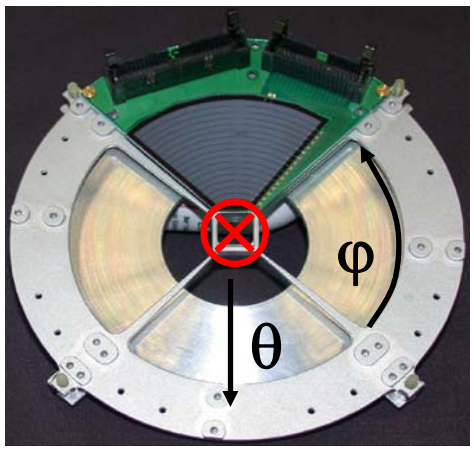
Ionisation chamber



Univ. of Edinburgh

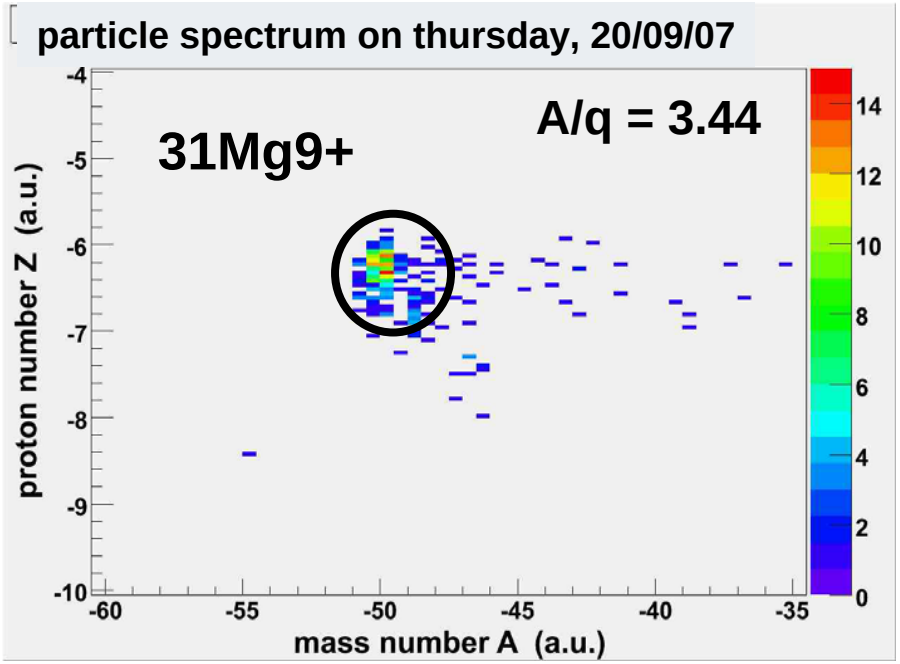
TU Darmstadt

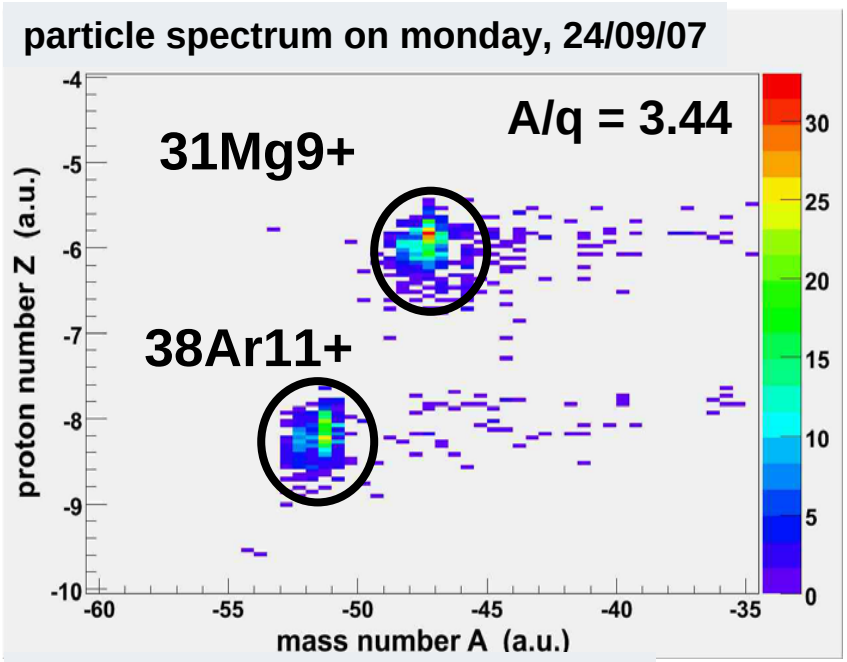
TU Munich

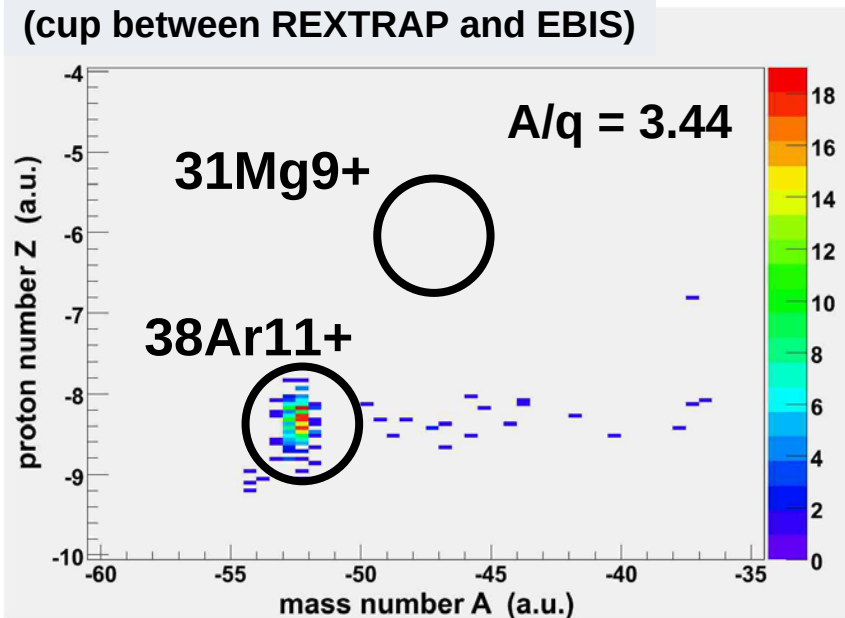


beam energy: 3.0 MeV/u
beam intensity: ~ 10^4 part/s
beam time: 90 hours
target: ^{109}Ag 1.9 mg/cm^2 4.0 mg/cm^2

Data analysis: beam composition



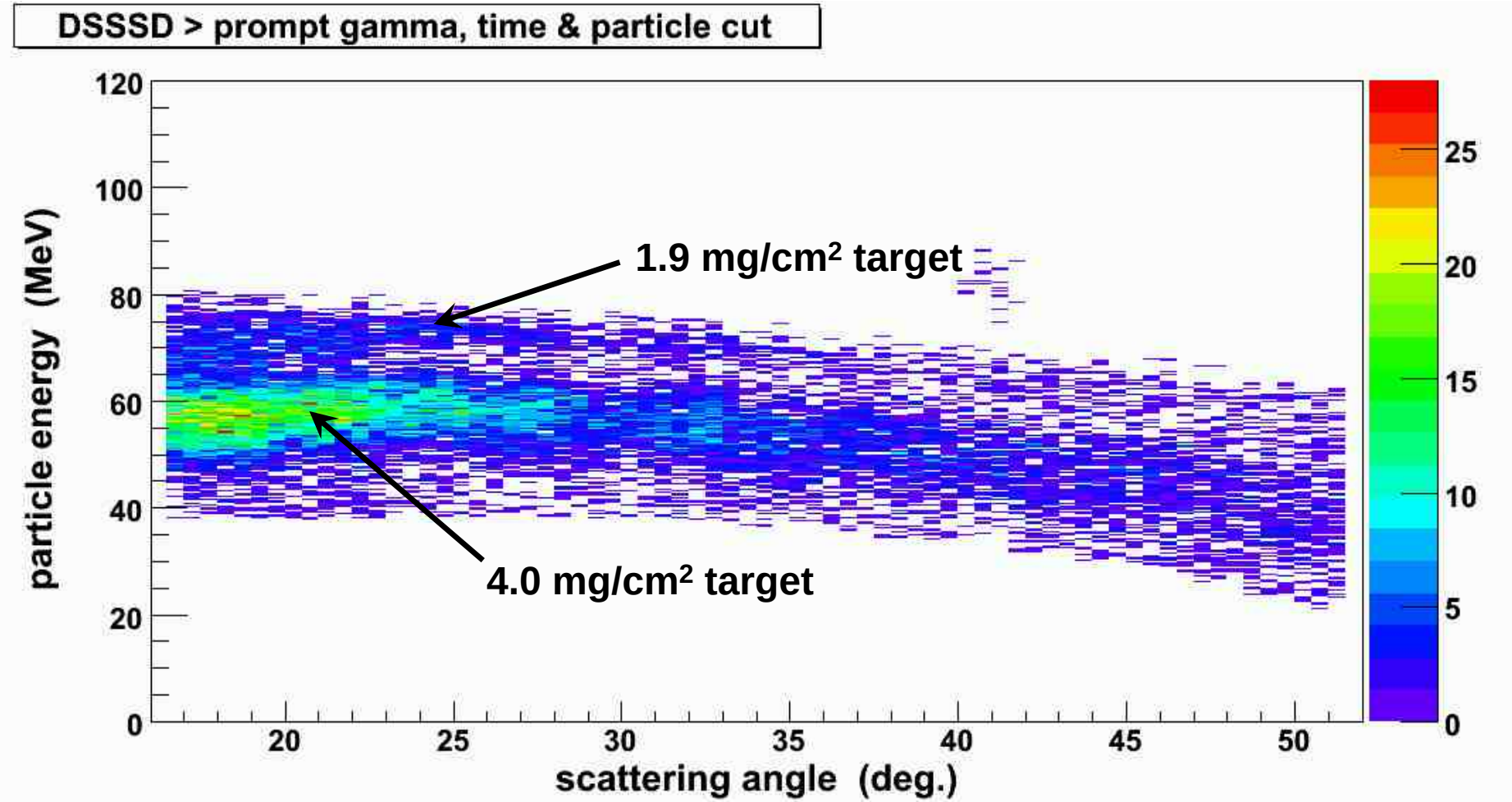




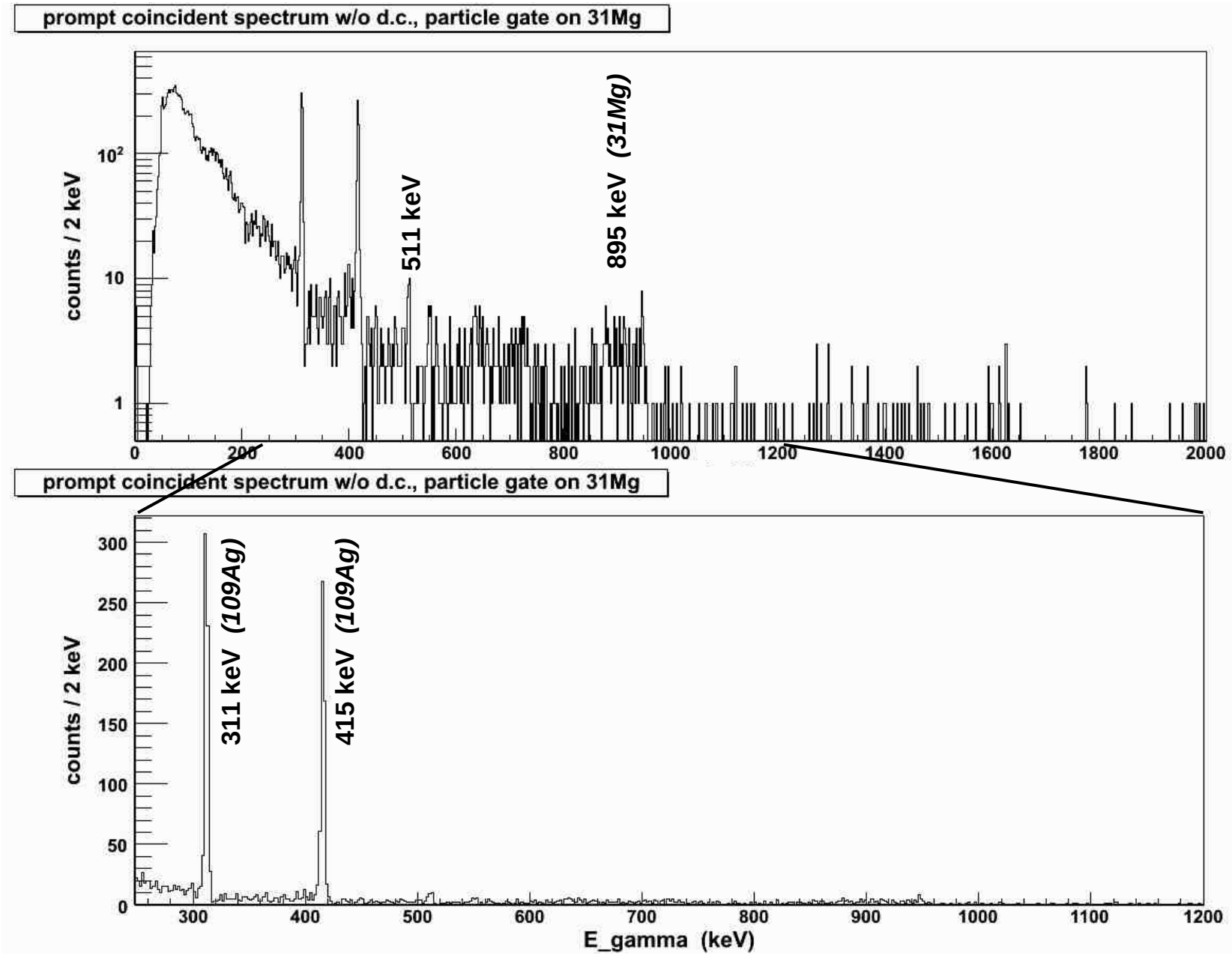
Beam composition is monitored continuously with ionisation chamber

particle spectrum of DSSSD

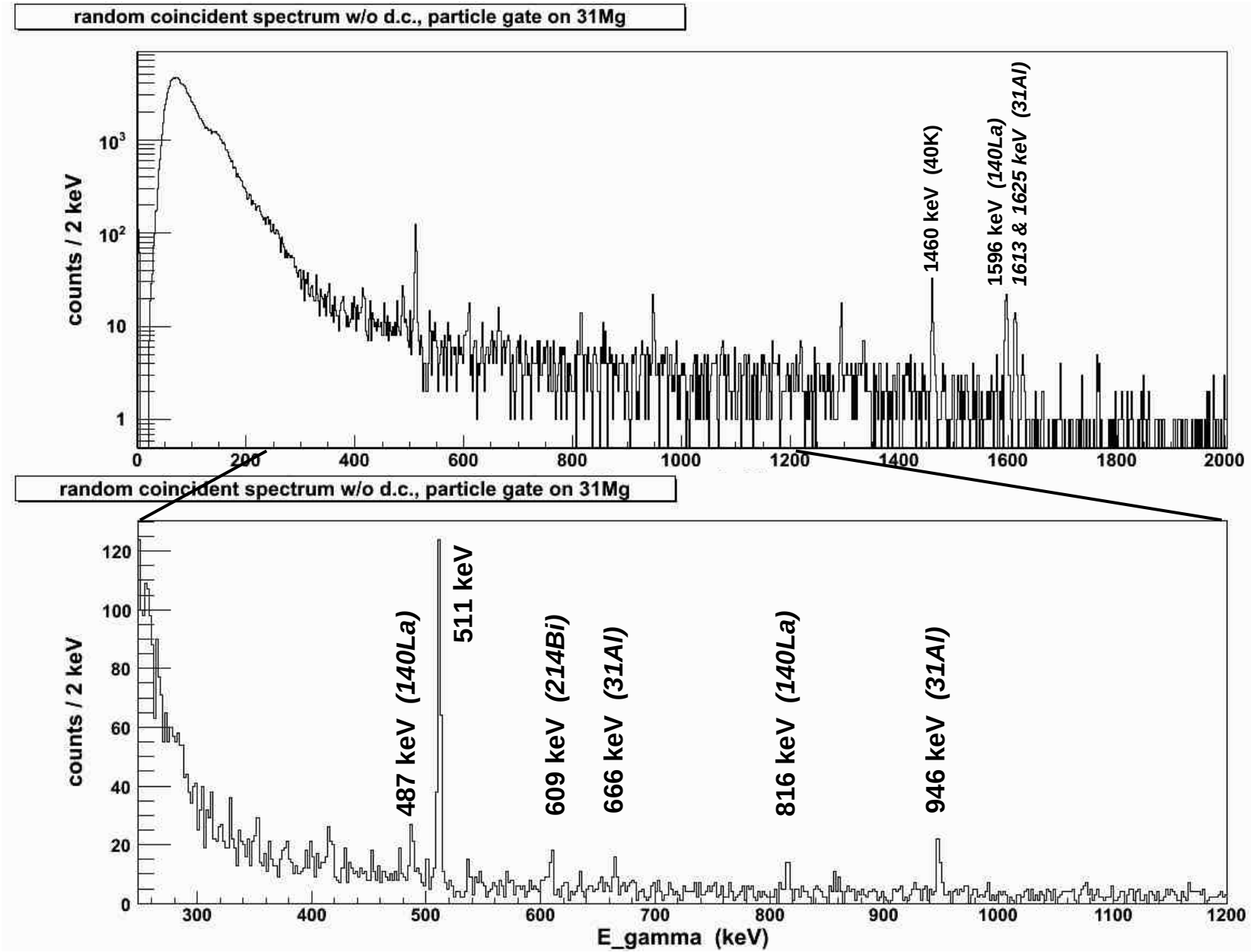
conditions: **particle within first 500 ms after proton pulse**
particle with prompt gamma ray
particle cut on 31Mg



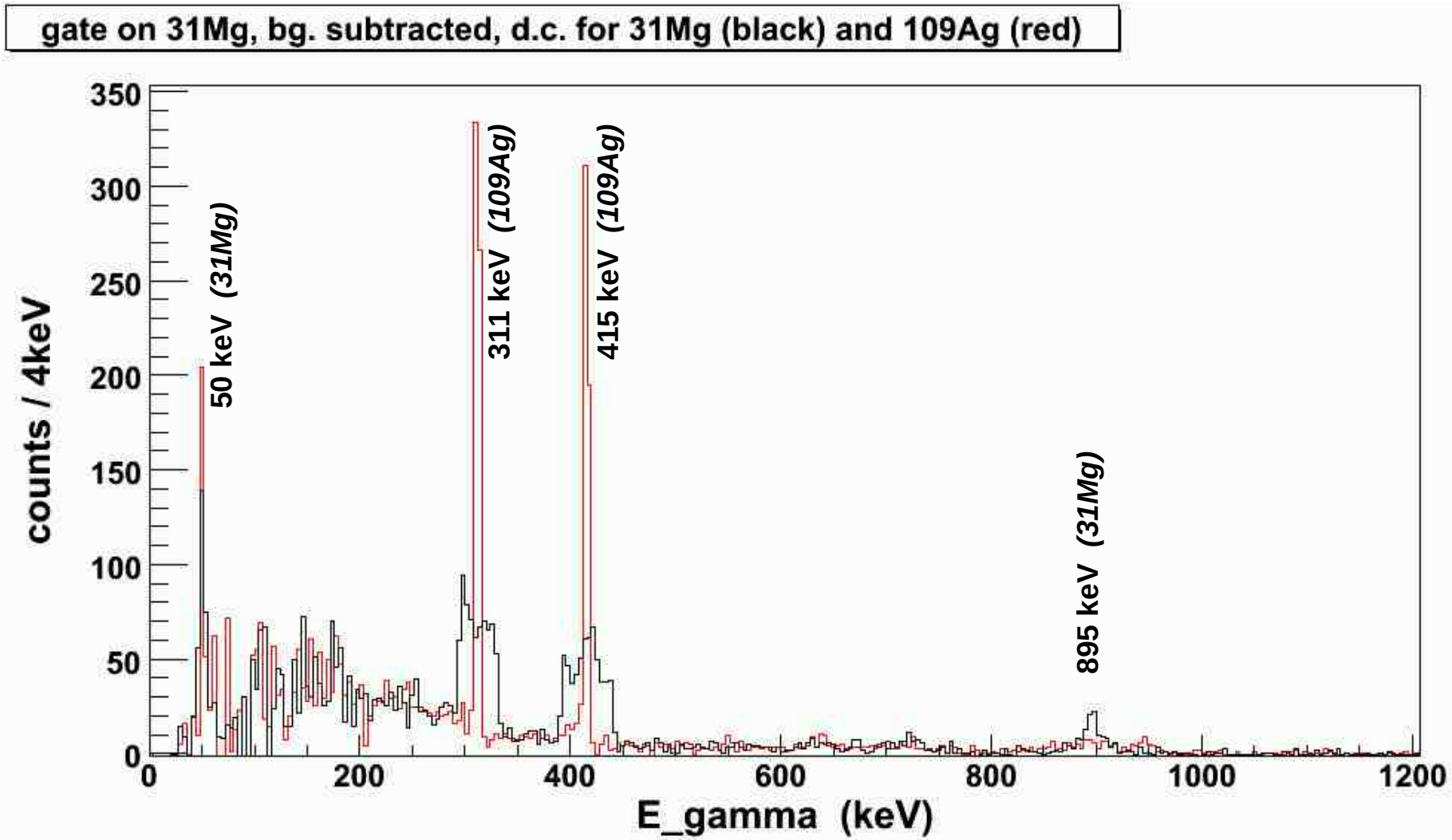
prompt coincident gamma spectrum (w/o d.c.)



random coincident gamma spectrum (w/o d.c.)



gamma spectrum
(Coulomb excitation of 31Mg and 109Ag)



gamma spectrum
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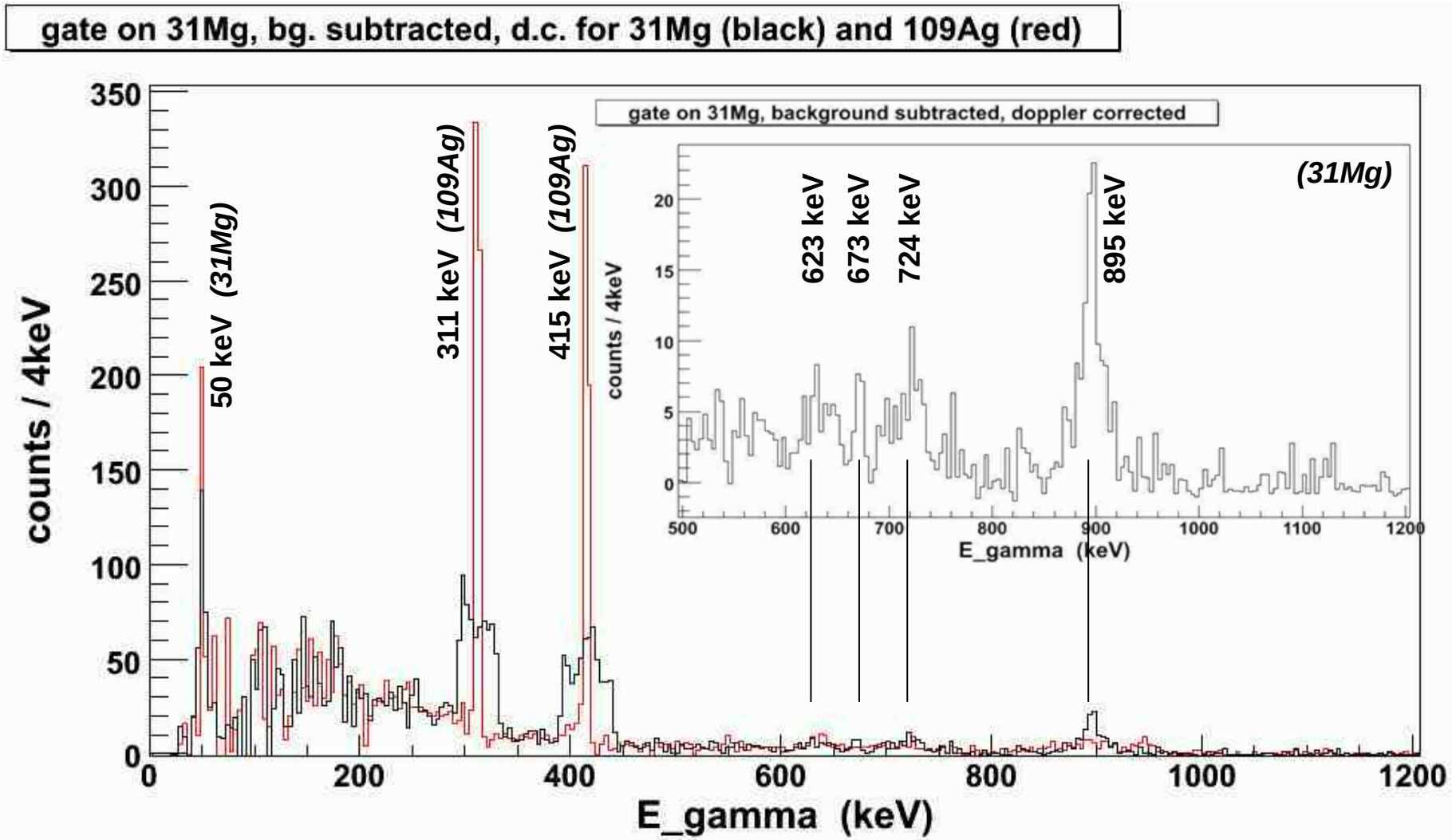
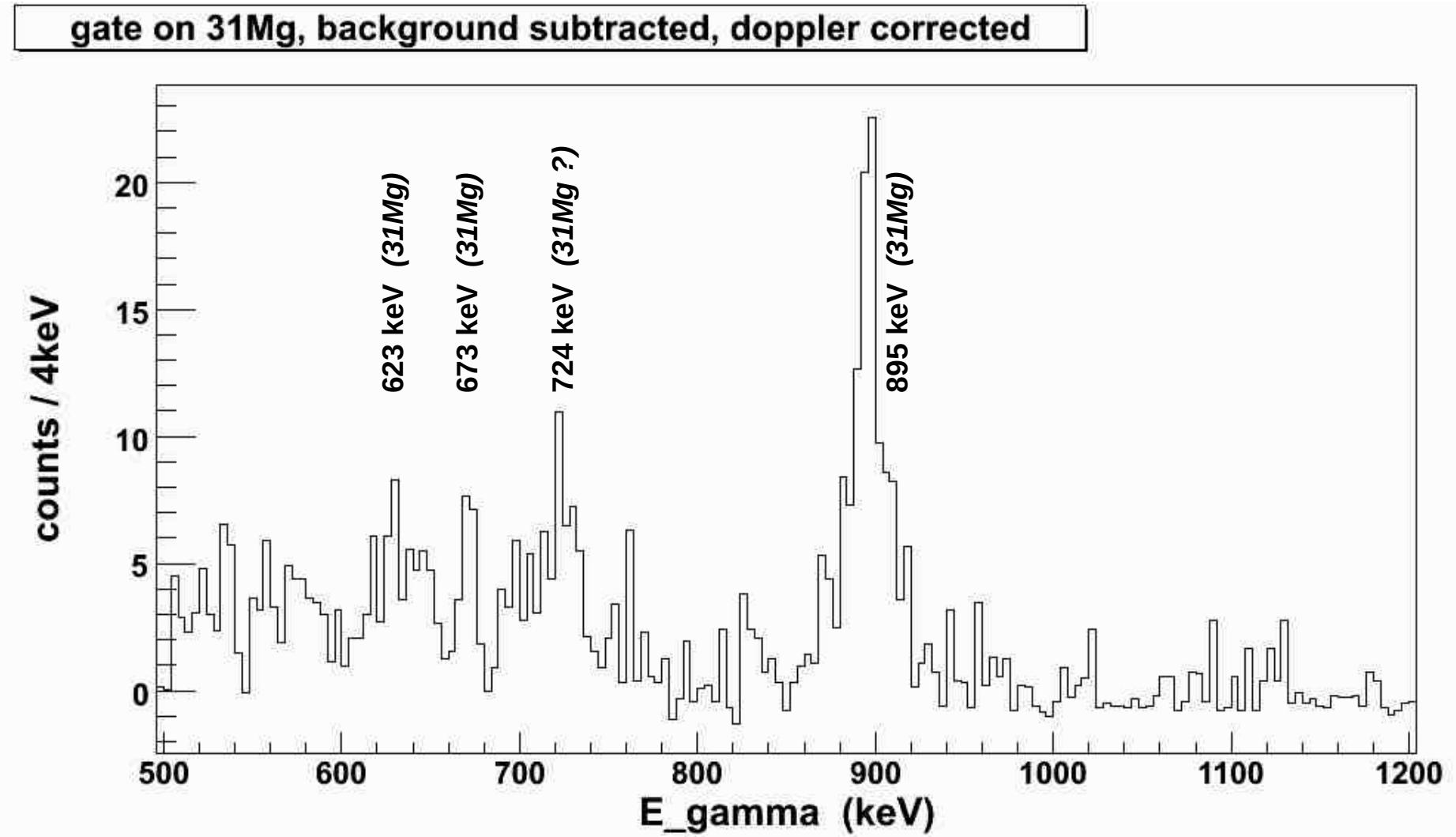
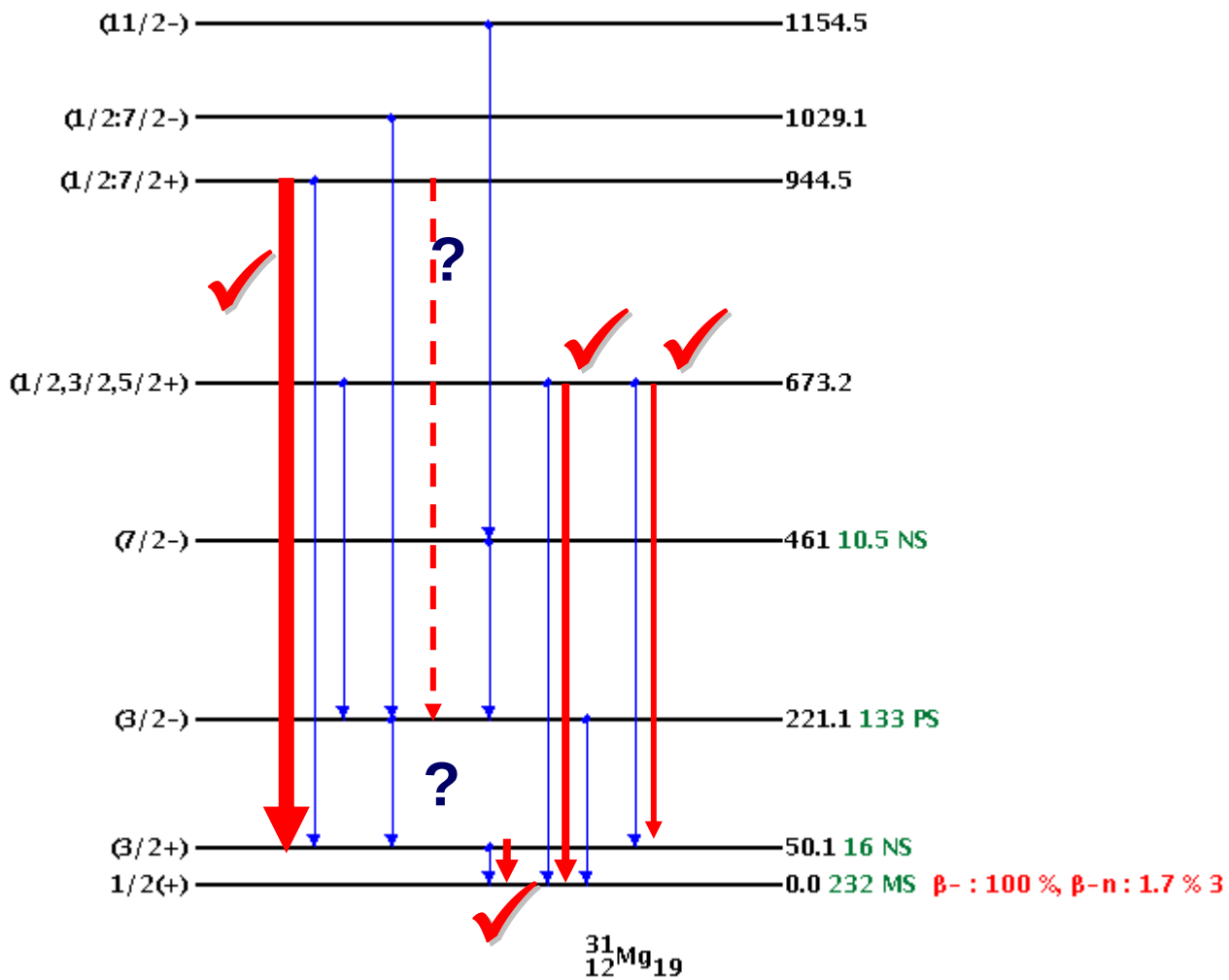


gamma spectrum
(doppler correction for 31Mg)



Observed γ-decays

Low lying ^{31}Mg levels from β-decay studies



Very preliminary B(E2) estimate

Transition moment B(E2,$5/2^+ \rightarrow 3/2^+$)

Events in coincidence with forward scattered ^{31}Mg,
γ-decay of potential $5/2^+$ state relative to Coulomb excitation cross section of ^{109}Ag from measured γ-ray yields

assumptions:
- no angular correlation factors
- no E2/M1 mixing
- no branching of γ-decay
- prolate deformation

preliminary value is in good agreement with theoretical prediction by Marechal et al., PRC 72, 044314 (2005)

Summary of Results and Outlook

Coulomb excitation of odd ^{31}Mg

Deexcitation of state at 945 keV

- Properties of 945 keV state
- Branching?
- Angular distribution?
- Coincidences?

Consistent with 5/2$^+$ state of positive yrast band of ^{31}Mg

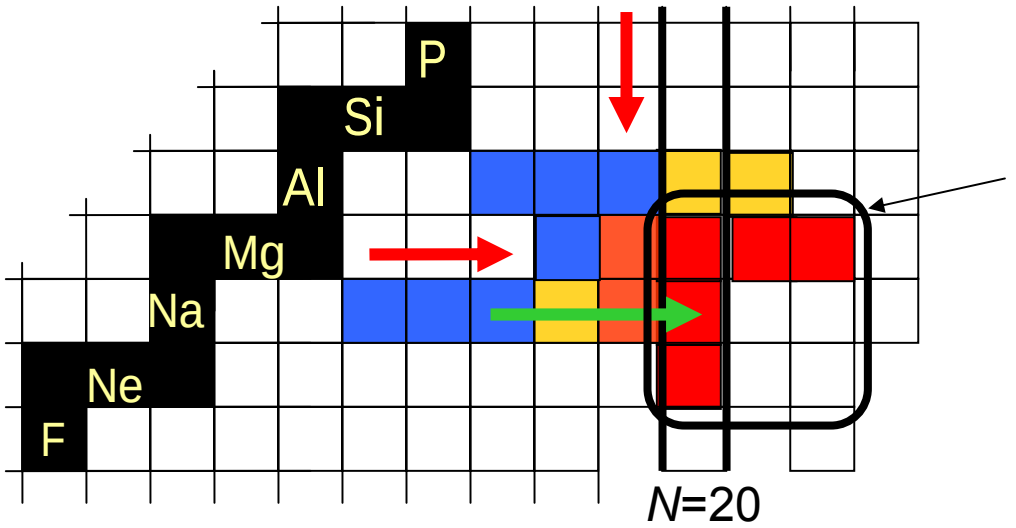
Deexcitation of state at 673 keV

Location and variation of the island of inversion

sd-normal shell structure

Transitional structure: mixing between *sd*-normal and *pf*-intruder configurations

pf-Intruder structure



Inversion process along the Z=11 line

inversion occurs *gradually* via transitional nucleus ^{29}Na

Inversion process along the Z=12 line and N=19 line

inversion occurs *suddenly* between ^{30}Mg and ^{31}Mg,

^{32}Al and ^{31}Mg with drastic shape change

Collaboration

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MLL Munich

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MPI Heidelberg, RIKEN

31Mg List of Levels

E_{level} (keV)	XREF	Jπ	$T_{1/2}$	E_γ (keV)	I_γ	γ mult.	Final level	
0.0	ABCDE	1/2(+)	232 ms *15* % β^- = 100 % β^-n = 1.7 *3*					
50.1 *2*	ABCD	(3/2+)	16 ns *3*	50.3 *3*	100	[M1]	0.0	1/2(+)
221.1 *2*	ABCD	(3/2-)	133 ps *8*	171.1 *2* 221.0 *2*	100 *6* 41 *4*	[E1] [E1]	50.1 0.0	(3/2+) 1/2(+)
461.0 *6*	B	(7/2-)	10.5 ns *8*	239.9 *5*	100	[E2]	221.1	(3/2-)
673.2 *6*	A	(1/2,3/2,5/2+)		451.1 *11* 623.4 *8* 673.5 *12*	11 *2* 100 *17* 46 *9*		221.1 50.1 0.0	(3/2-) (3/2+) 1/2(+)
944.5 *5*	AB	(1/2:7/2+)		894.4 *4*	100		50.1	(3/2+)
1029.1 *6*	A	(1/2:7/2-)		808.0 *6*	100		221.1	(3/2-)
1154.5 *8*	B	(11/2-)		693.5 *5*	100		461.0	(7/2-)
1390.1 *12*	B			929 *1*	100		461.0	(7/2-)
2243.4 *4*	A	(1/2,3/2,5/2+)		1214.5 *9* 2022.1 *7* 2192.9 *6* 2243.6 *6*	11 *2* 35 *7* 29 *6* 100 *18*		1029.1 221.1 50.1 0.0	(1/2:7/2-) (3/2-) (3/2+) 1/2(+)
3759.7 *10*	A	(1/2,3/2,5/2+)		3537.6 *12* 3710.0 *20* 3761.1 *20*	100 *30* 60 *40* 90 *40*		221.1 50.1 0.0	(3/2-) (3/2+) 1/2(+)
3814.5 *13*	A	(1/2,3/2,5/2) (+)		1571.1 *12*	100		2243.4	(1/2,3/2,5/2+)

31Mg List of Levels

ADOPTED LEVELS, GAMMAS for ^{31}Mg

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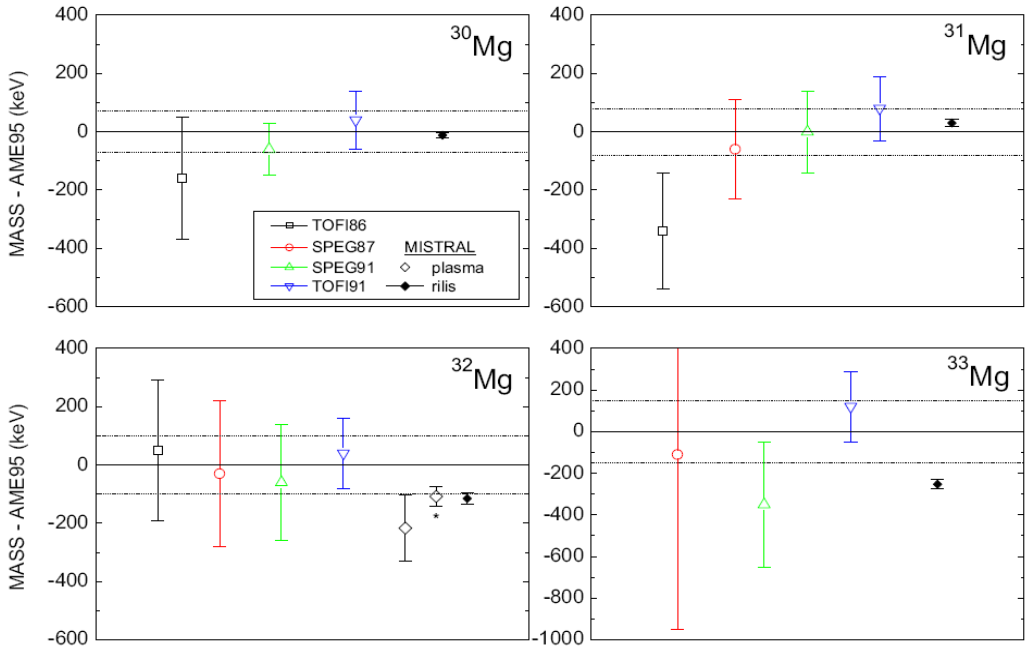
Full ENSDF file

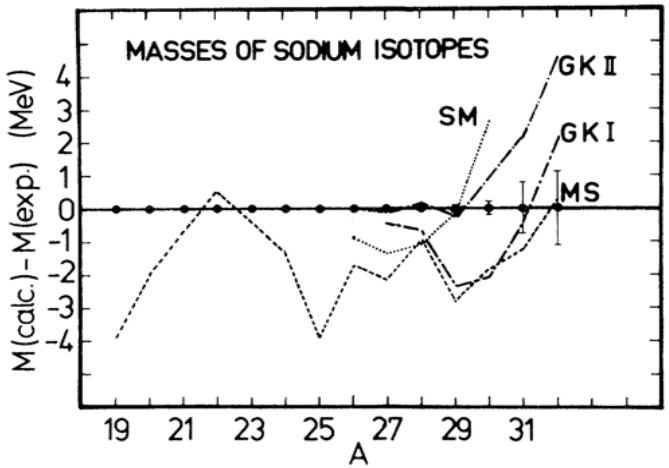
Q(β-)=11764 keV *26* S_n= 2378 keV *15* S_p= 18867 keV *28* Q_α= -12.71E3 keV *11*

References:
A: 31NA β- DECAY (17.0 MS)
B: 32NA β-N DECAY (13.2 MS)
C: 33NA B-2N DECAY (8.0 MS)
D: 2H(30MG,31MGG)
E: 9BE(HI,XG)

E_{level} (keV)	XREF	Jπ	$T_{1/2}$	E_γ (keV)	I_γ	γ mult.	Final level	
0.0	ABCDE	1/2(+)	232 ms *15* % β⁻ = 100 % β⁻n = 1.7 *3*					
50.1 *2*	ABCD	(3/2+)	16 ns *3*	50.3 *3*	100	[M1]	0.0	1/2(+)
221.1 *2*	ABCD	(3/2-)	133 ps *8*	171.1 *2* 221.0 *2*	100 *6* 41 *4*	[E1] [E1]	50.1 0.0	(3/2+) 1/2(+)
461.0 *6*	B	(7/2-)	10.5 ns *8*	239.9 *5*	100	[E2]	221.1	(3/2-)
673.2 *6*	A	(1/2,3/2,5/2+)		451.1 *11* 623.4 *8* 673.5 *12*	11 *2* 100 *17* 46 *9*		221.1 50.1 0.0	(3/2-) (3/2+) 1/2(+)
944.5 *5*	AB	(1/2:7/2+)		894.4 *4*	100		50.1	(3/2+)
1029.1 *6*	A	(1/2:7/2-)		808.0 *6*	100		221.1	(3/2-)
1154.5 *8*	B	(11/2-)		693.5 *5*	100		461.0	(7/2-)
1390.1 *12*	B			929 *1*	100		461.0	(7/2-)
2243.4 *4*	A	(1/2,3/2,5/2+)		1214.5 *9* 2022.1 *7* 2192.9 *6* 2243.6 *6*	11 *2* 35 *7* 29 *6* 100 *18*		1029.1 221.1 50.1 0.0	(1/2:7/2-) (3/2-) (3/2+) 1/2(+)
3759.7 *10*	A	(1/2,3/2,5/2+)		3537.6 *12* 3710.0 *20* 3761.1 *20*	100 *30* 60 *40* 90 *40*		221.1 50.1 0.0	(3/2-) (3/2+) 1/2(+)
3814.5 *13*	A	(1/2,3/2,5/2)(+)		1571.1 *12*	100		2243.4	(1/2,3/2,5/2+)

New experiments: Mass measurements

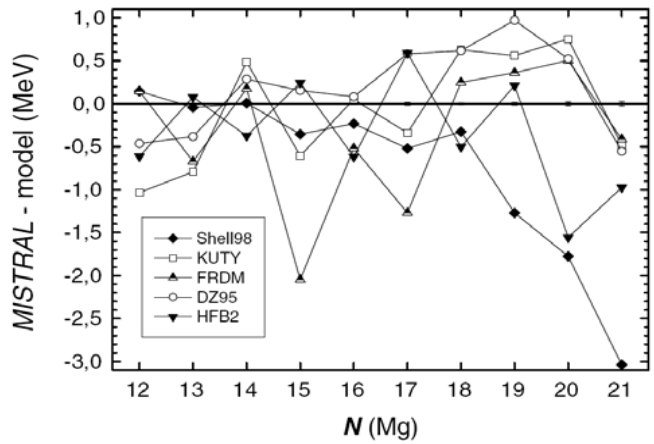




C. Thibault et al, Phys. Rev. C 12, 644 (1975)

The criterion for deciding whether a given nuclide is part of the island of inversion or not, is somewhat subjective.

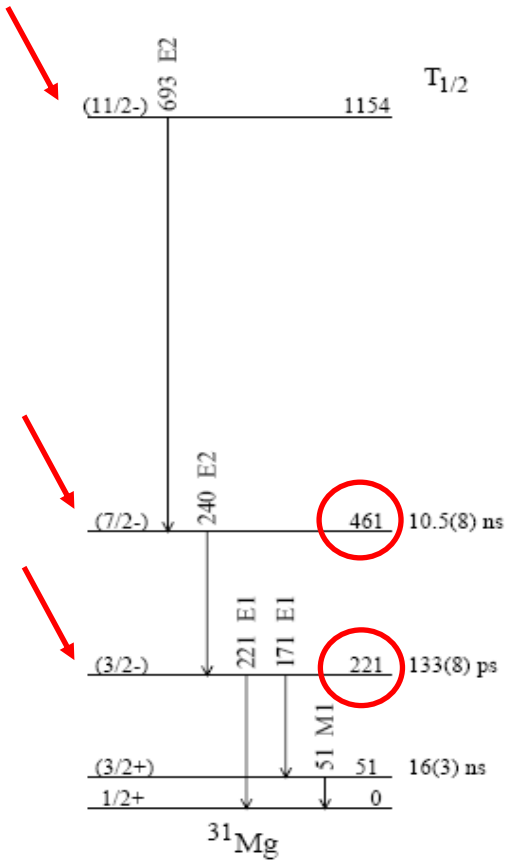
The older arguments derived from binding energies could be questioned on one hand, by more precise mass data that has since become available, and on the other hand by more recent shell model calculations that indicate a departure from the universal sd shell" already at N = 19 for Na.

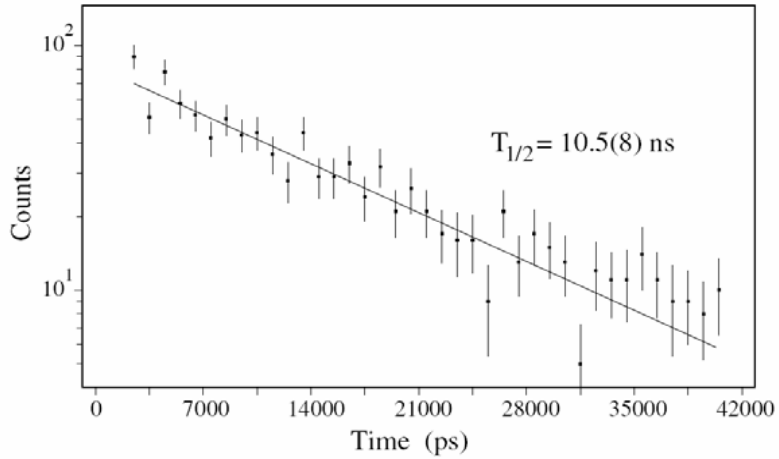


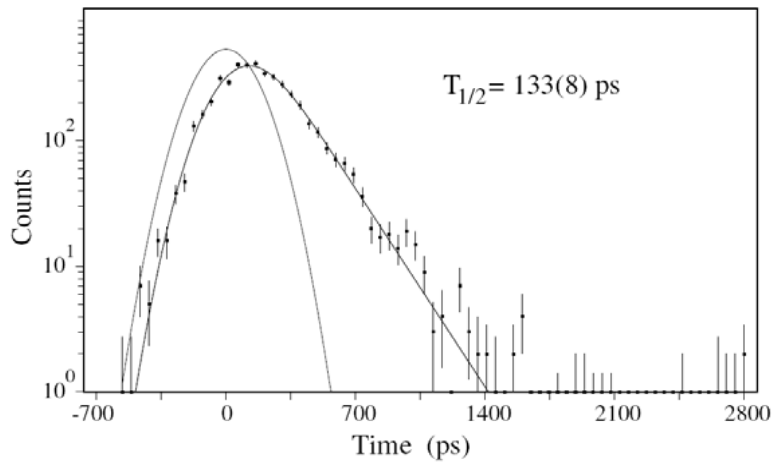
Precision MISTRAL mass measurements

D. Lunney et al, Eur. Phys. J. A 28, 129 (2006)

Lifetime studies: ^{31}Mg



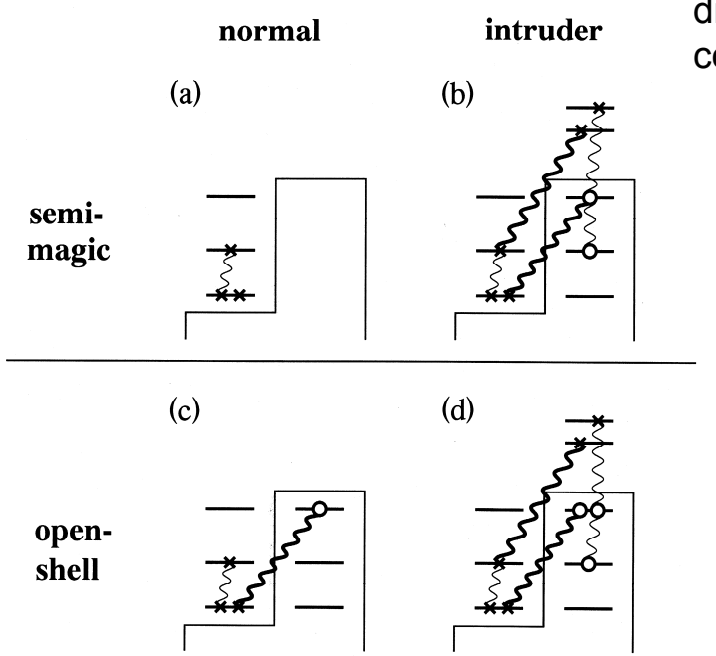




fast timing measurements
Advanced Time Delayed βγγ(t) Method

H.Mach et al, Eur. Phys. J. A 25, 105 (2005)

^{31}Mg MCSM calculations

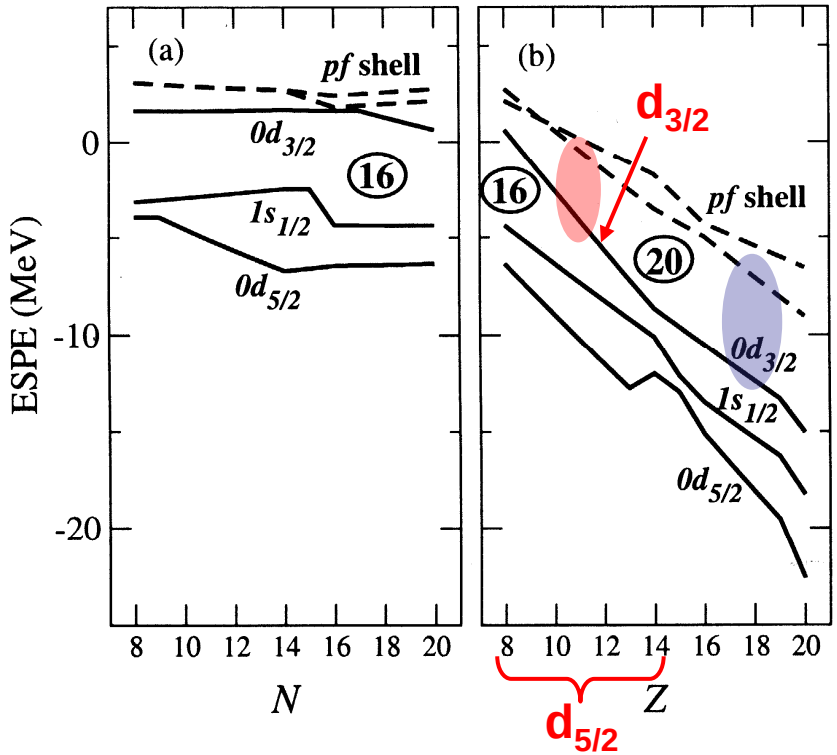


difference in correlation energy

largest

smaller

"SDPF-M" interaction

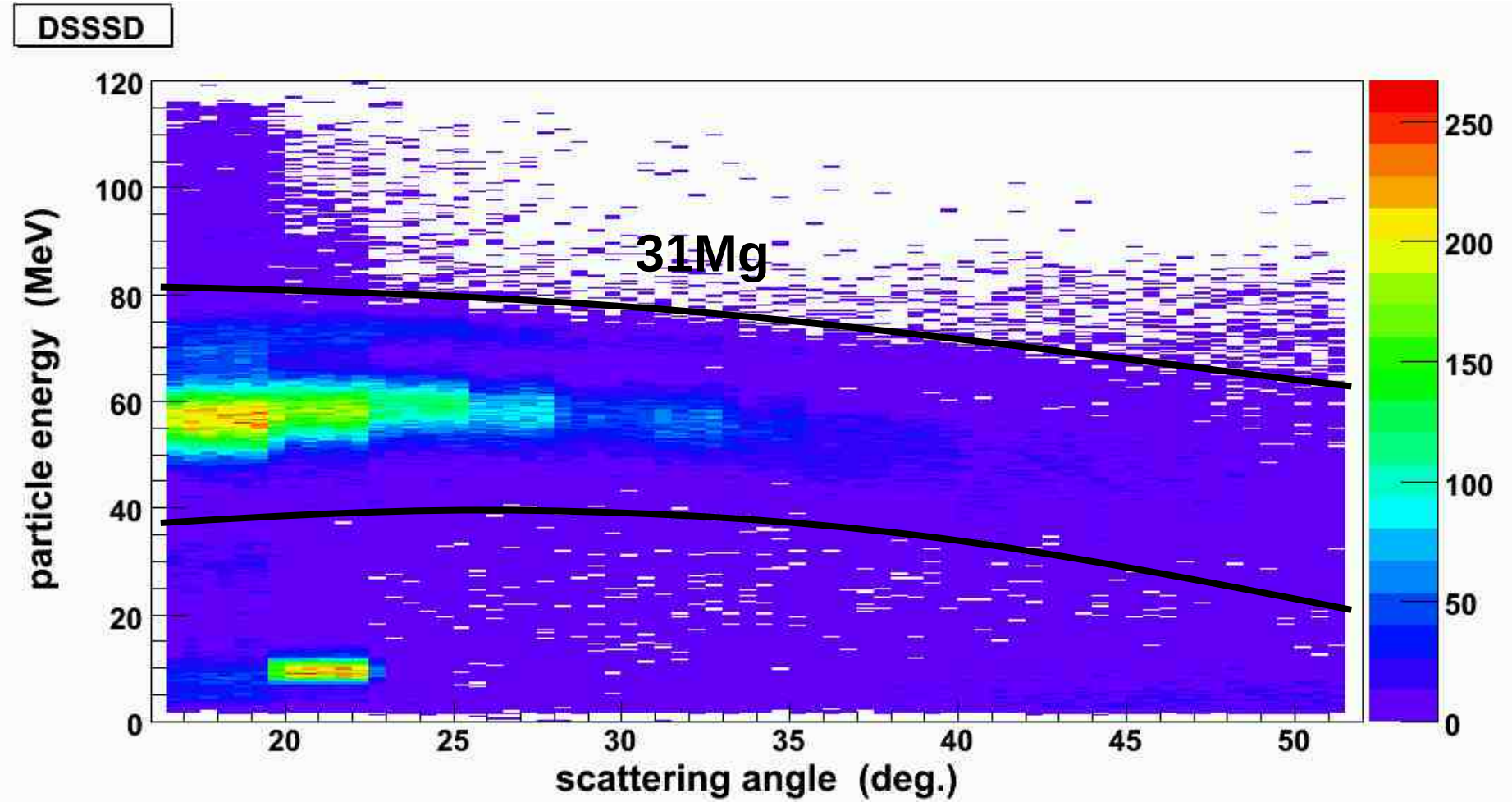
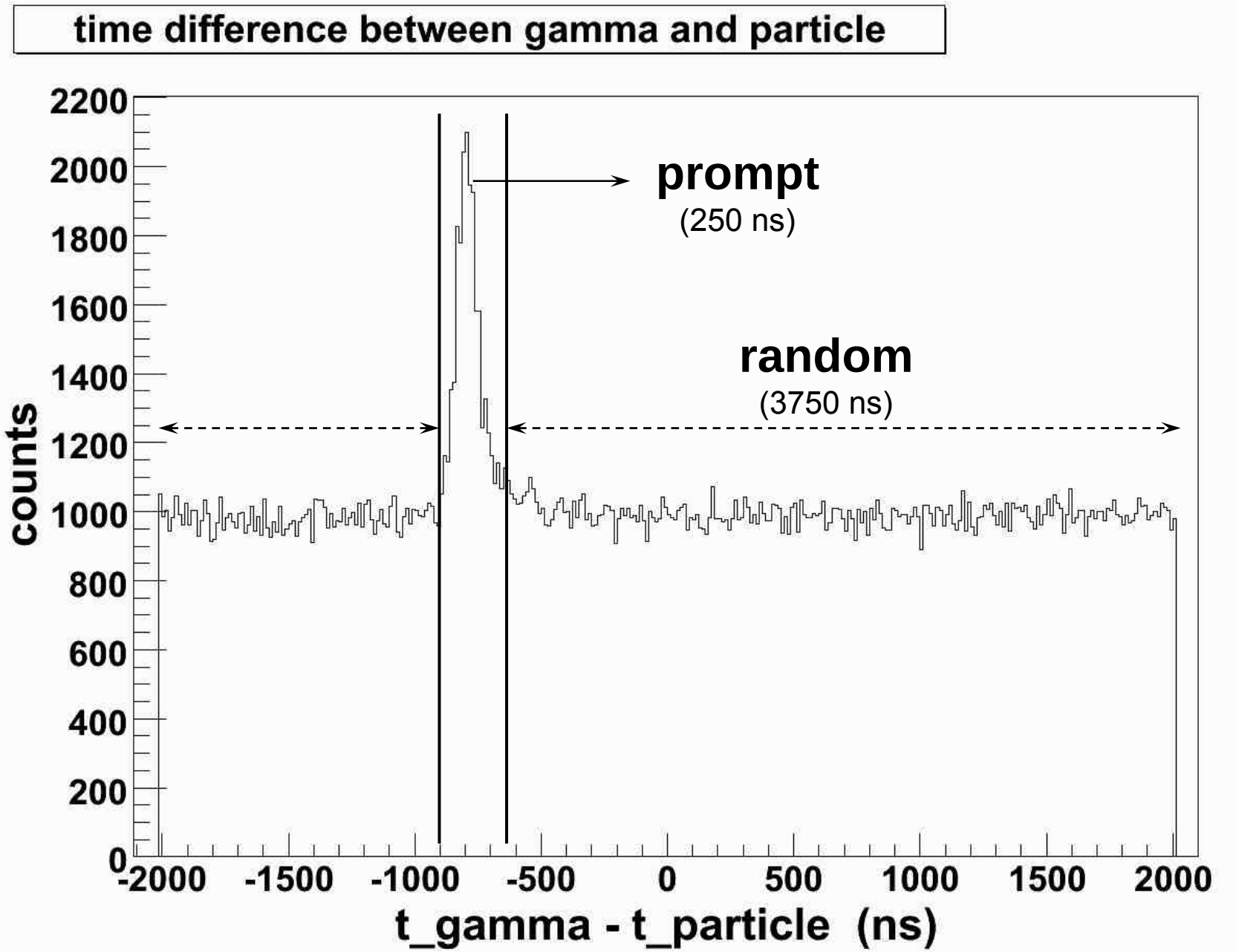


Strongly attractive T=0 $d_{3/2}$-$d_{5/2}$ monopole interaction
N=16 magic number

Y. Utsuno, *et al.*, Phys. Rev. C**70**(2004) 044307.
Y. Utsuno, *et al.*, Phys. Rev. C **60** (1999) 054315

particle spectrum of DSSSD

coincidence between particle and a gamma ray



definition of prompt and random coincidence