RIKEN
NiSHiNA
CENTER

Level, $E(2_1^+)$, $E(4_1^+)$, and $B(E2)\!\uparrow$ Systematics around the "Island of Inversion"

Pieter Doornenbal
ピーター　ドルネンバル

RIKEN
NiSHiNA
CENTER

Outline

- Experimental status of:
  - $E(2^+_1)$ and $E(4^+_1)$ systematics of Ne and Mg isotopes
  - $B(E2)\uparrow$ and δ systematics of Ne and Mg isotopes
  - Level systematics of odd-even Na isotopes

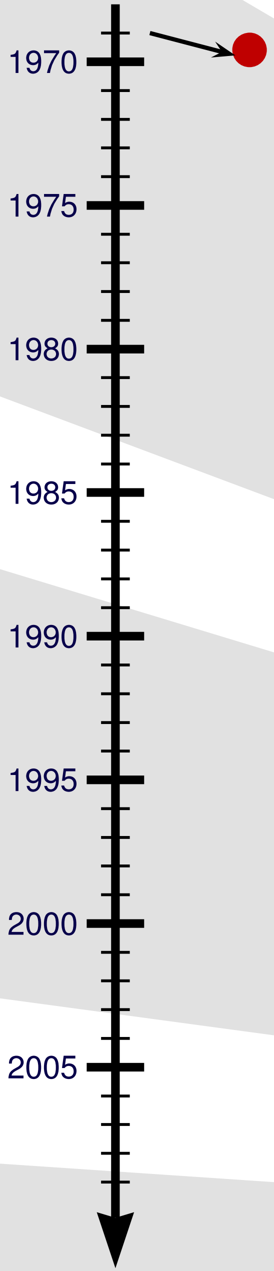
Outline

- Experimental status of:
  - $E(2_1^+)$ and $E(4_1^+)$ systematics of Ne and Mg isotopes
  - $B(E2)\uparrow$ and δ systematics of Ne and Mg isotopes
  - Level systematics of odd-even Na isotopes

- Completing the systematics:
  - The $E(2_1^+)$ of ^{40}Mg
  - $B(E2)\uparrow$ of ^{32}Ne and ^{38}Mg

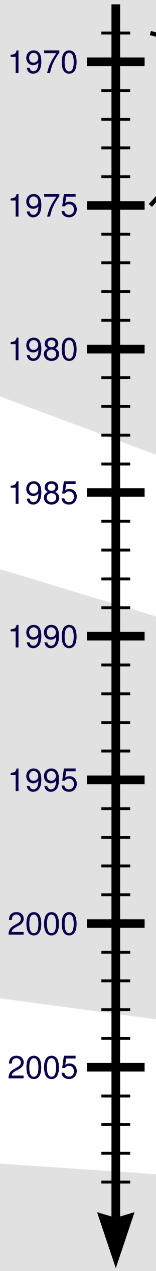
Introduction

Time Line (1969-2000)

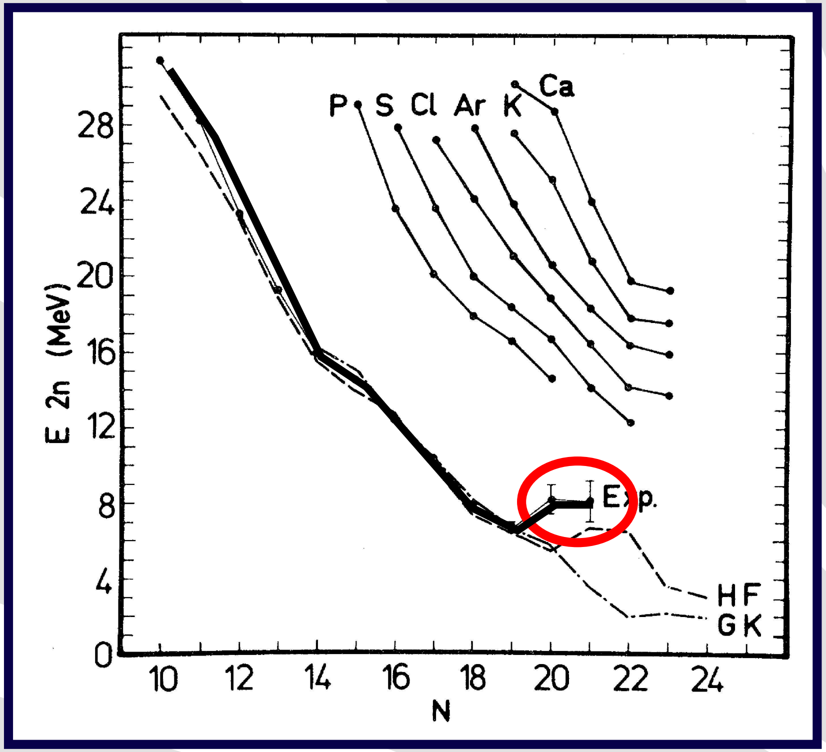


First observation of $^{27\text{-}32}$Na isotopes R. Klapisch *et al.*, PRL 23, 652 (1969)

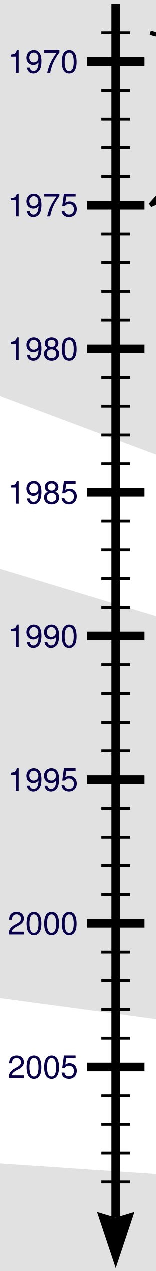
Time Line (1969-2000)



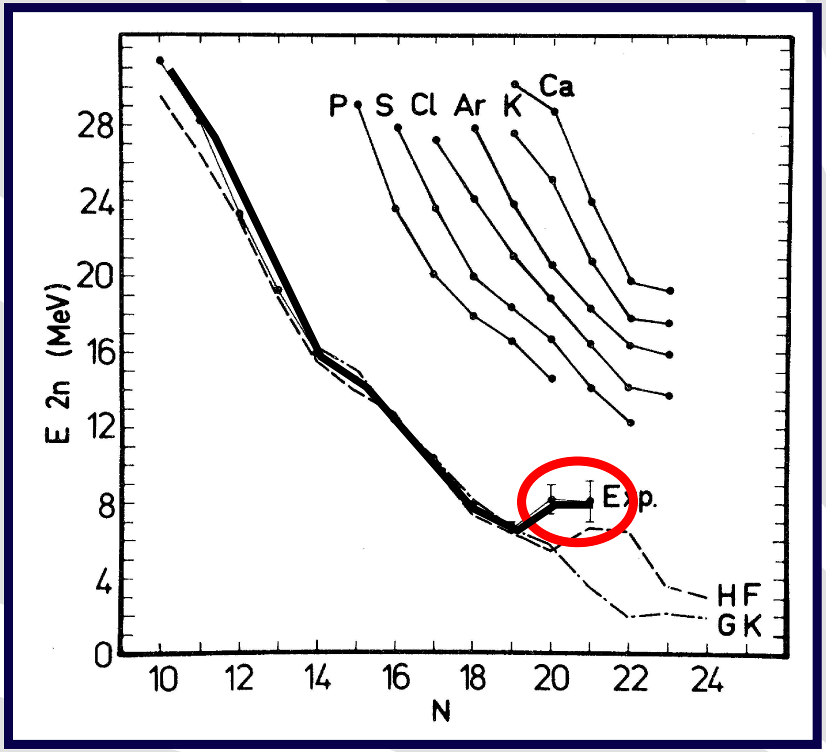
- First observation of $^{27\text{-}32}$Na isotopes R. Klapisch *et al.*, PRL 23, 652 (1969)
- Mass measurement C. Thibault *et al.*, PRC 12, 644 (1975)



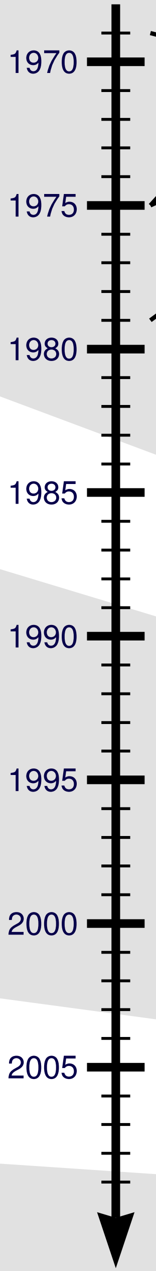
Time Line (1969-2000)



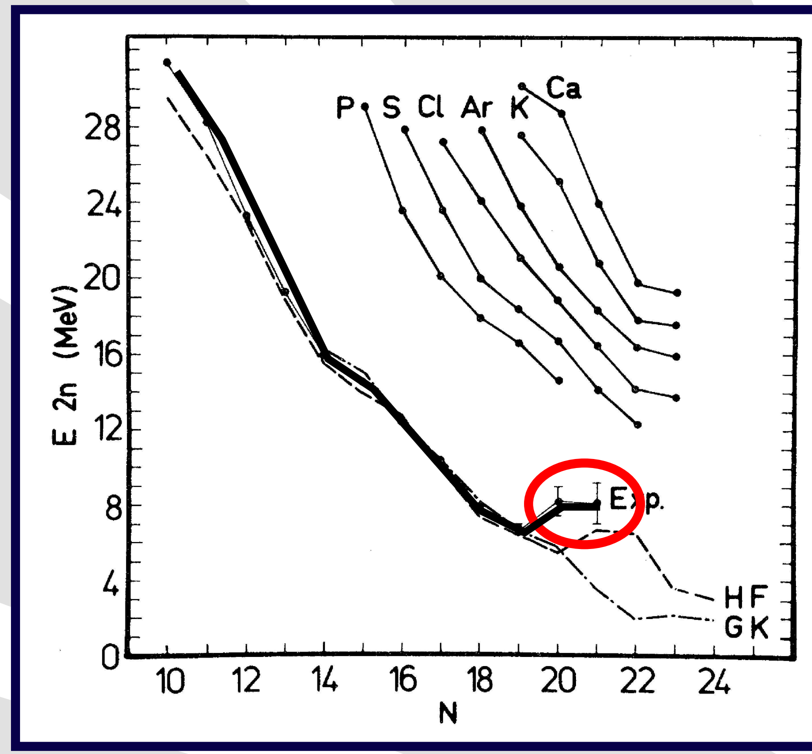
- First observation of $^{27\text{-}32}$Na isotopes R. Klapisch *et al.*, PRL 23, 652 (1969)
- Mass measurement C. Thibault *et al.*, PRC 12, 644 (1975)
- Explanation of “unusual” masses
  X. Campi *et al.*, NPA 251, 193 (1975)

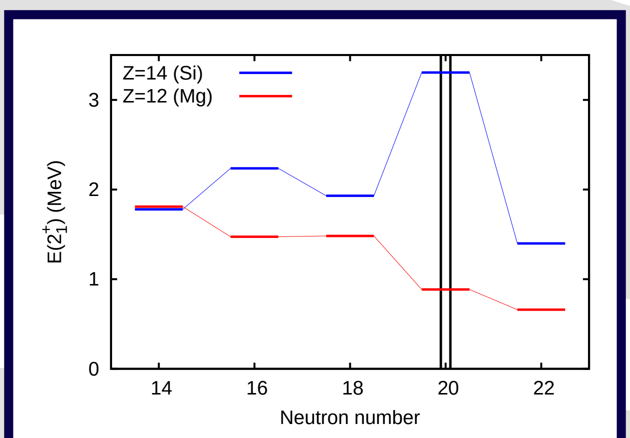


Time Line (1969-2000)

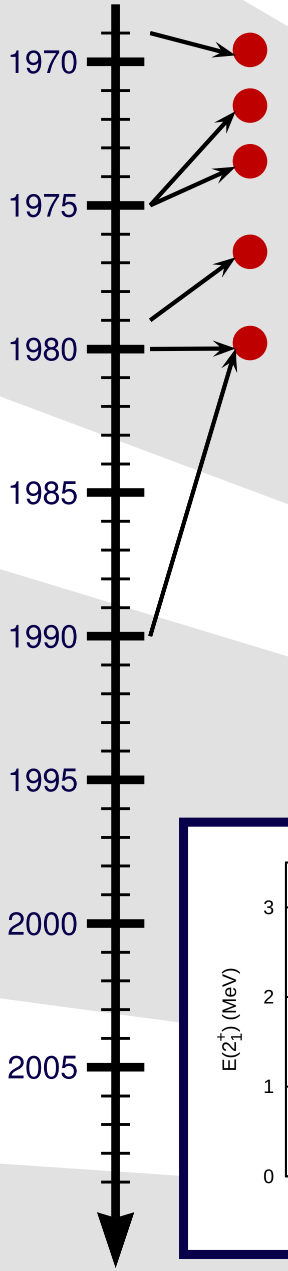


- First observation of $^{27\text{-}32}$Na isotopes R. Klapisch *et al.*, PRL 23, 652 (1969)
- Mass measurement C. Thibault *et al.*, PRC 12, 644 (1975)
- Explanation of "unusual" masses
  X. Campi *et al.*, NPA 251, 193 (1975)
- Low $E(2^+)$ in ^{32}Mg
  C. Dètraz *et al.*, PRC 19, 164 (1979)





Time Line (1969-2000)

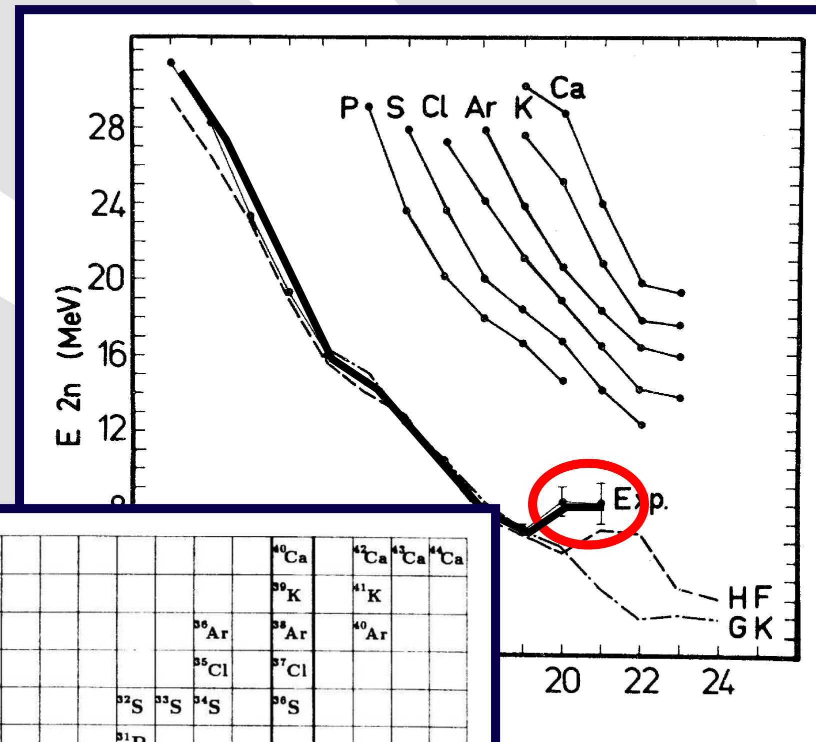


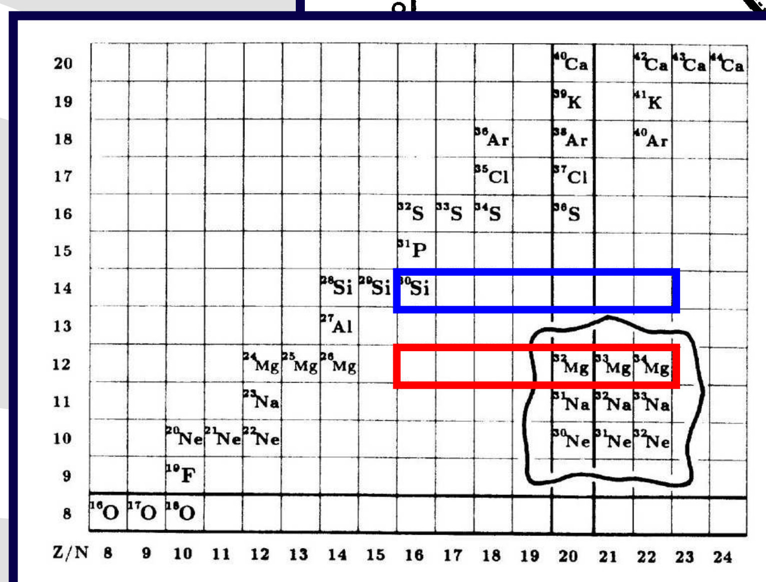
- First observation of $^{27\text{-}32}$Na isotopes R. Klapisch *et al.*, PRL 23, 652 (1969)
- Mass measurement C. Thibault *et al.*, PRC 12, 644 (1975)
- Explanation of "unusual" masses
  X. Campi *et al.*, NPA 251, 193 (1975)
- Low $E(2^+)$ in ^{32}Mg
  C. Dètraz *et al.*, PRC 19, 164 (1979)
- "Island of inversion"

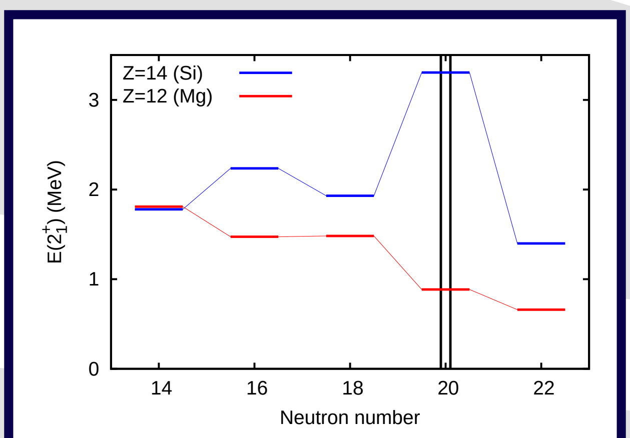
  B.H. Wildenthal, W. Chung, PRC 22, 2260 (1980)

  E.K. Warburton, J.A. Becker, B.A. Brown,

  PRC 41, 1147 (1990)







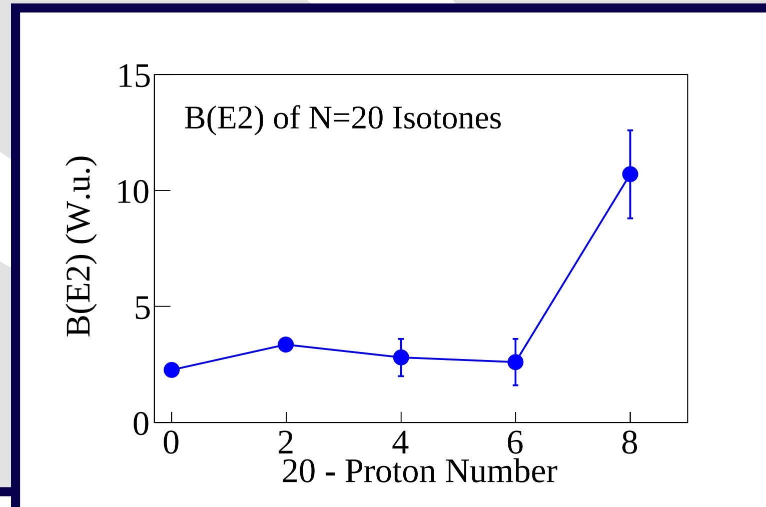
Time Line (1969-2000)

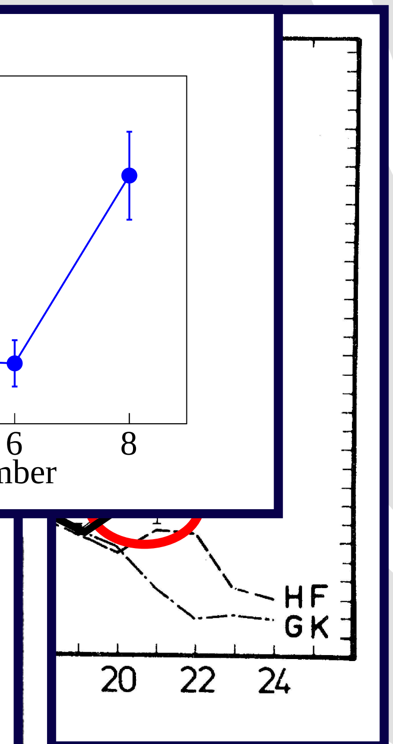
1970, 1975, 1980, 1985, 1990, 1995, 2000, 2005

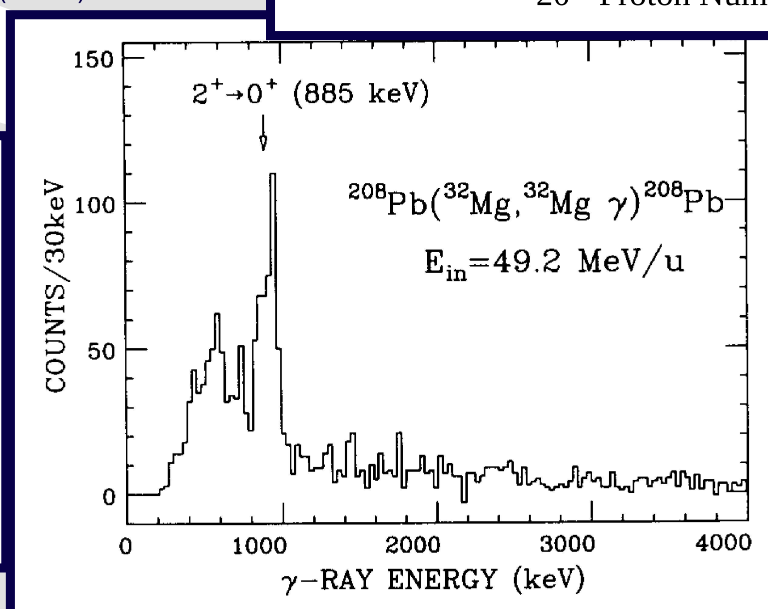
- First observation of $^{27\text{-}32}$Na isotopes R. Klapisch *et al.*, PRL 23, 652 (1969)
- Mass measurement C. Thibault *et al.*, PRC 12, 644 (1975)
- Explanation of "unusual" masses
  X. Campi *et al.*, NPA 251, 193 (1975)
- Low $E(2^+)$ in ^{32}Mg
  C. Dètraz *et al.*, PRC 19, 164 (1979)
- "Island of inversion"

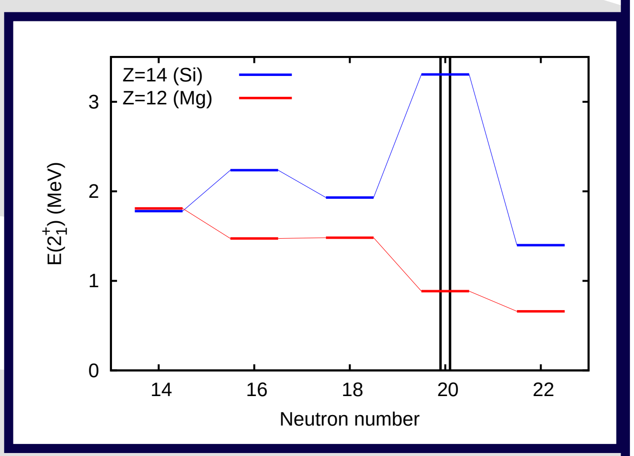
  B.H. Wildenthal, W. Chung, PRC 22, 2260 (1980)

  E.K. Warburton, J.A. Becker, B.A. Brown, PRC 41, 1147 (1990)
- $B(E2)\uparrow$ of ^{32}Mg
  T. Motobayashi *et al.*, PLB 346, 9 (1995)



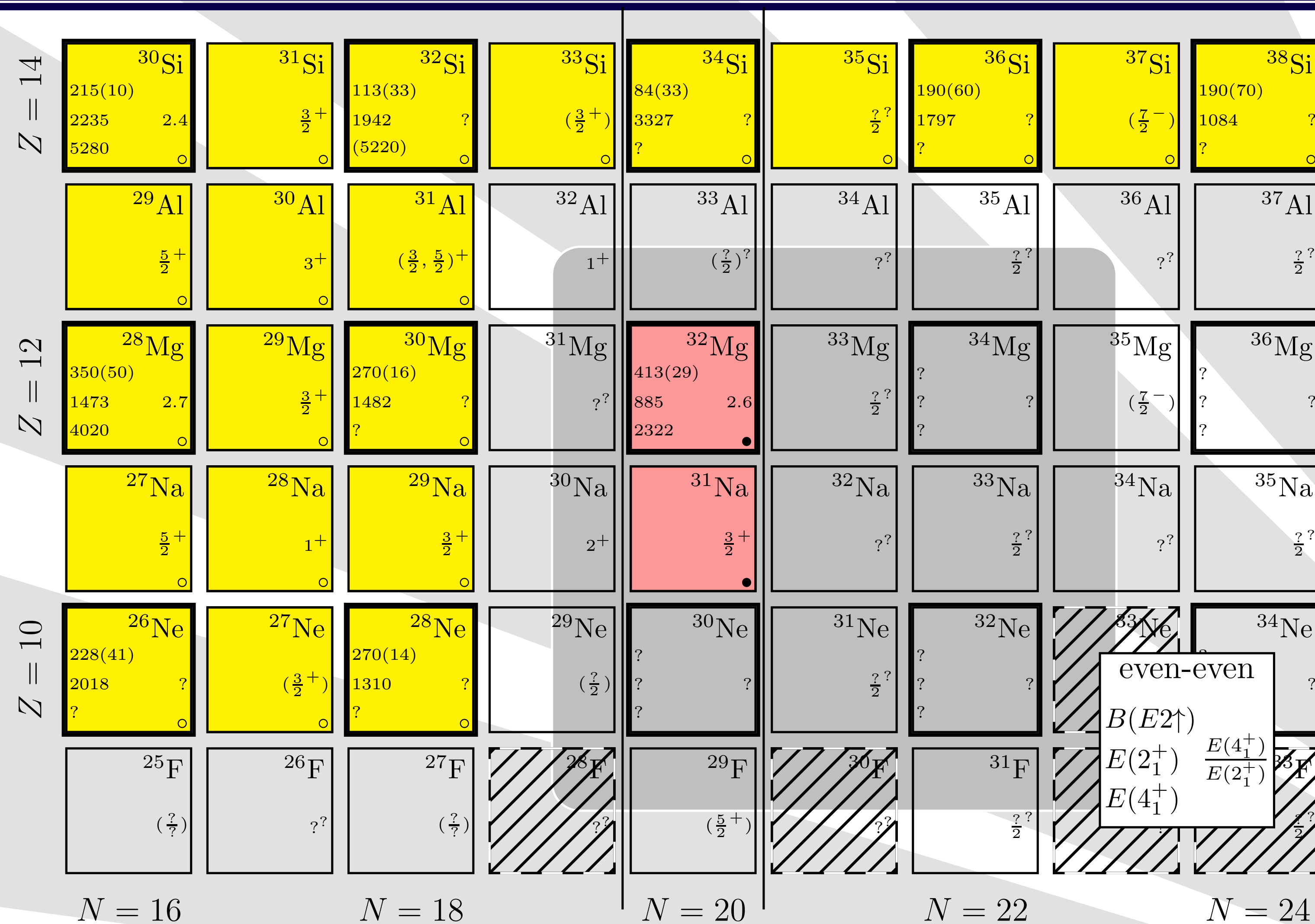






$E(2_1^+)$ and $E(4_1^+)$ Systematics

Status in 2000 from Gamma-ray Spectroscopy

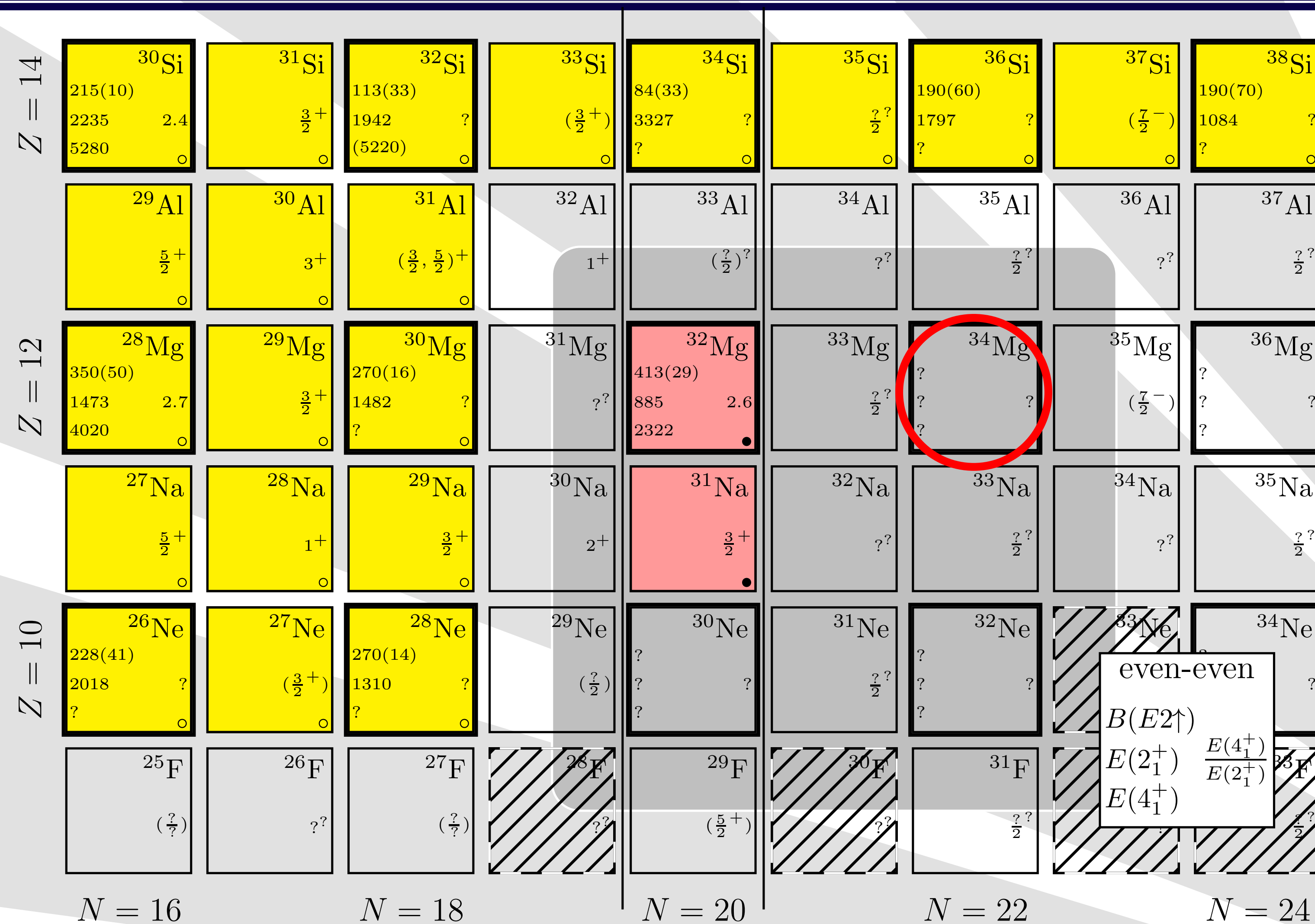


Prediction by E. K. Warburton *et al.*, Phys. Rev. C **41**, 1147 (1990).

^{26,28}Ne, ^{30,32}Mg Coulex: B. Pritychenko *et al.*, Phys. Lett. B **461**, 322 (1999).

^{31}Na Coulex: B. Pritychenko *et al.*, Phys. Rev. C **63**, 011305(R) (2000).

Status in 2000 from Gamma-ray Spectroscopy

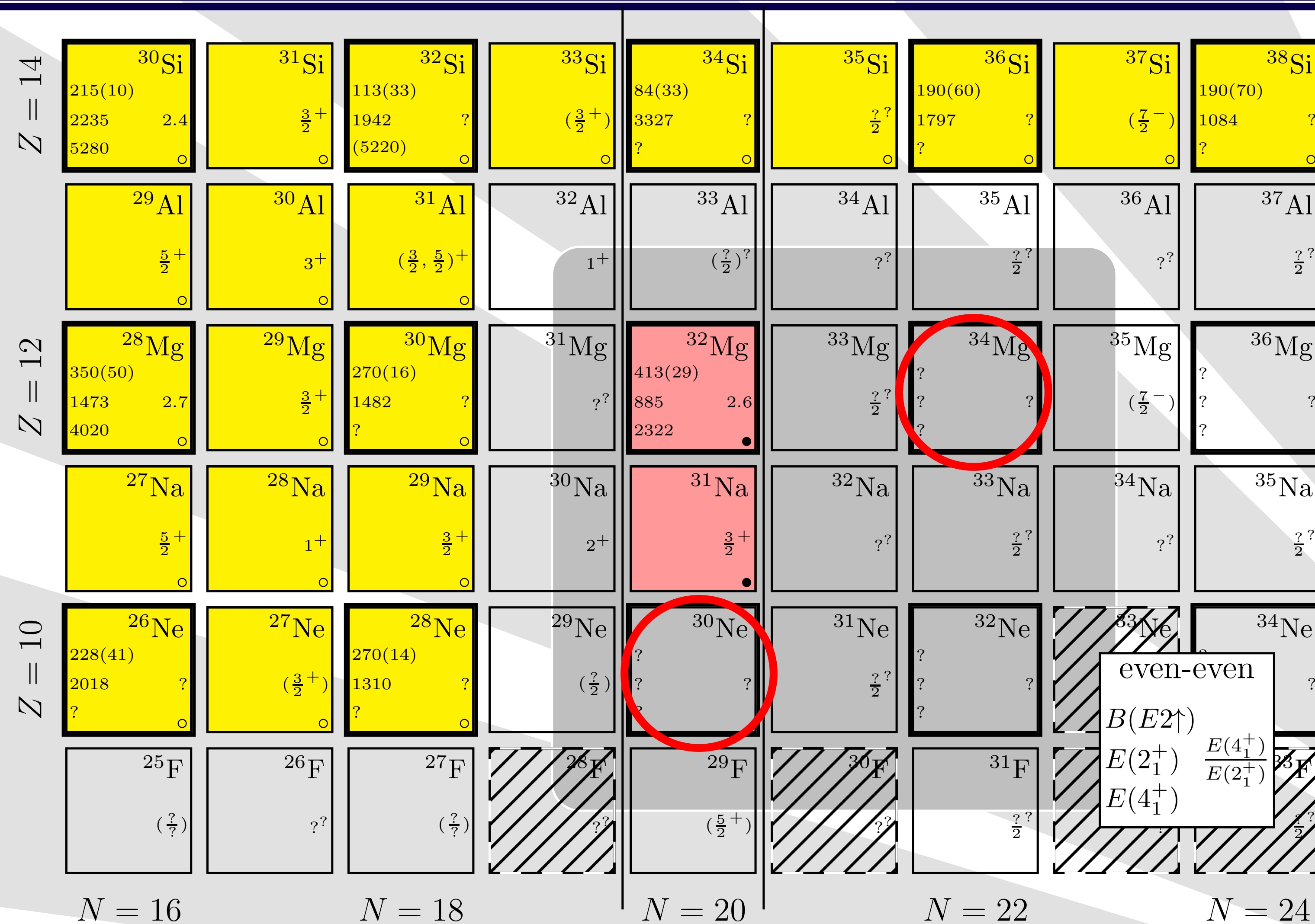


Prediction by E. K. Warburton *et al.*, Phys. Rev. C **41**, 1147 (1990).

^{26,28}Ne, ^{30,32}Mg Coulex: B. Pritychenko *et al.*, Phys. Lett. B **461**, 322 (1999).

^{31}Na Coulex: B. Pritychenko *et al.*, Phys. Rev. C **63**, 011305(R) (2000).

Status in 2000 from Gamma-ray Spectroscopy



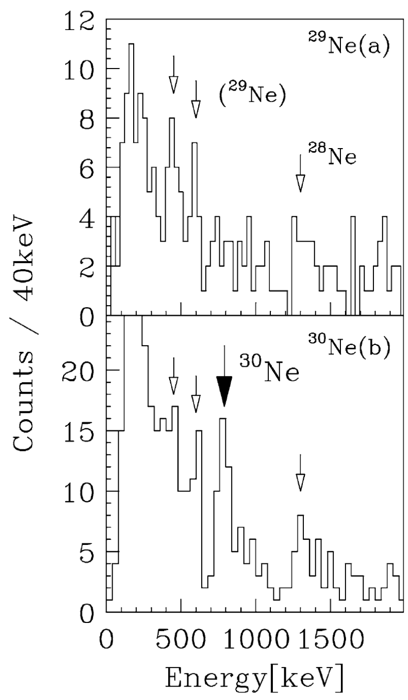
Prediction by E. K. Warburton *et al.*, Phys. Rev. C **41**, 1147 (1990).

^{26,28}Ne, ^{30,32}Mg Coulex: B. Pritychenko *et al.*, Phys. Lett. B **461**, 322 (1999).

^{31}Na Coulex: B. Pritychenko *et al.*, Phys. Rev. C **63**, 011305(R) (2000).

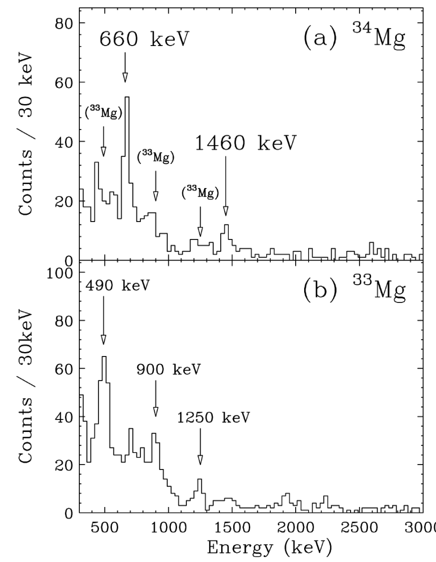
Inelastic Scattering on lH2 and Two-Step Fragmentation of ^{30}Ne and ^{34}Mg at Intermediate Energies with RIPS

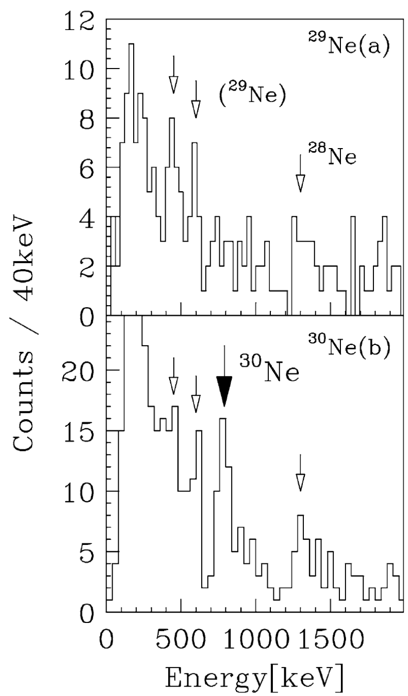
- ^{40}Ar at 95 MeV/u, 60 pnA
- $\approx$ 0.2 pps of ^{30}Ne
- 48 MeV/u at mid-target
- 0.19 g/cm^2 H
- (p,p')



Inelastic Scattering on lH2 and Two-Step Fragmentation of ^{30}Ne and ^{34}Mg at Intermediate Energies with RIPS

- ^{40}Ar at 95 MeV/u, 60 pnA
- $\approx$ 0.2 pps of ^{30}Ne
- 48 MeV/u at mid-target
- 0.19 g/cm^2 H
- (p,p')

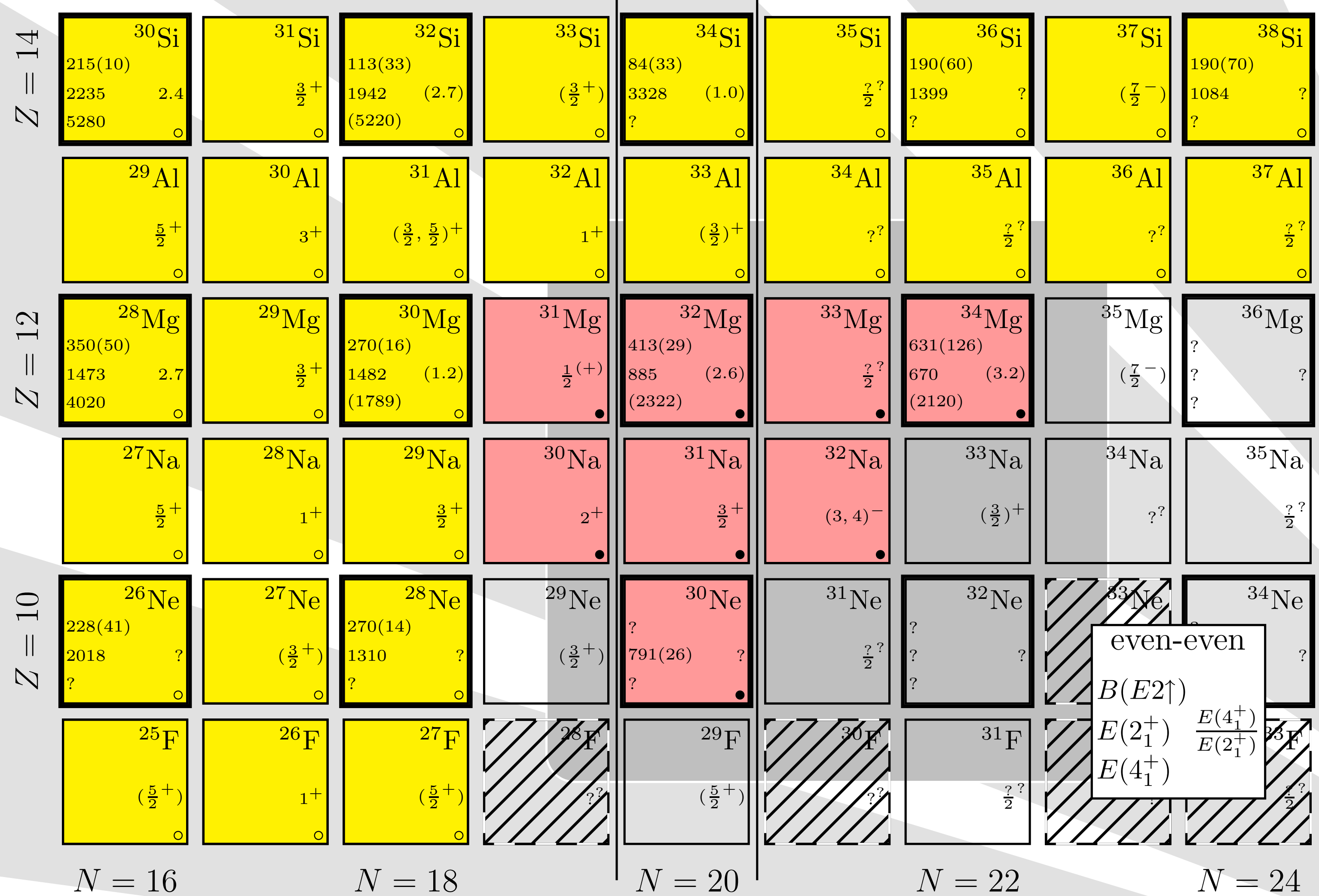




- ^{40}Ar at 95 MeV/u, 60 pnA
- $\approx 2 \times 10^4$ pps of ^{36}Si
- 38 MeV/u at mid-target
- 0.39 g/cm^2 Be
- ^{9}Be(^{36}Si,^{34}Mg+γ)

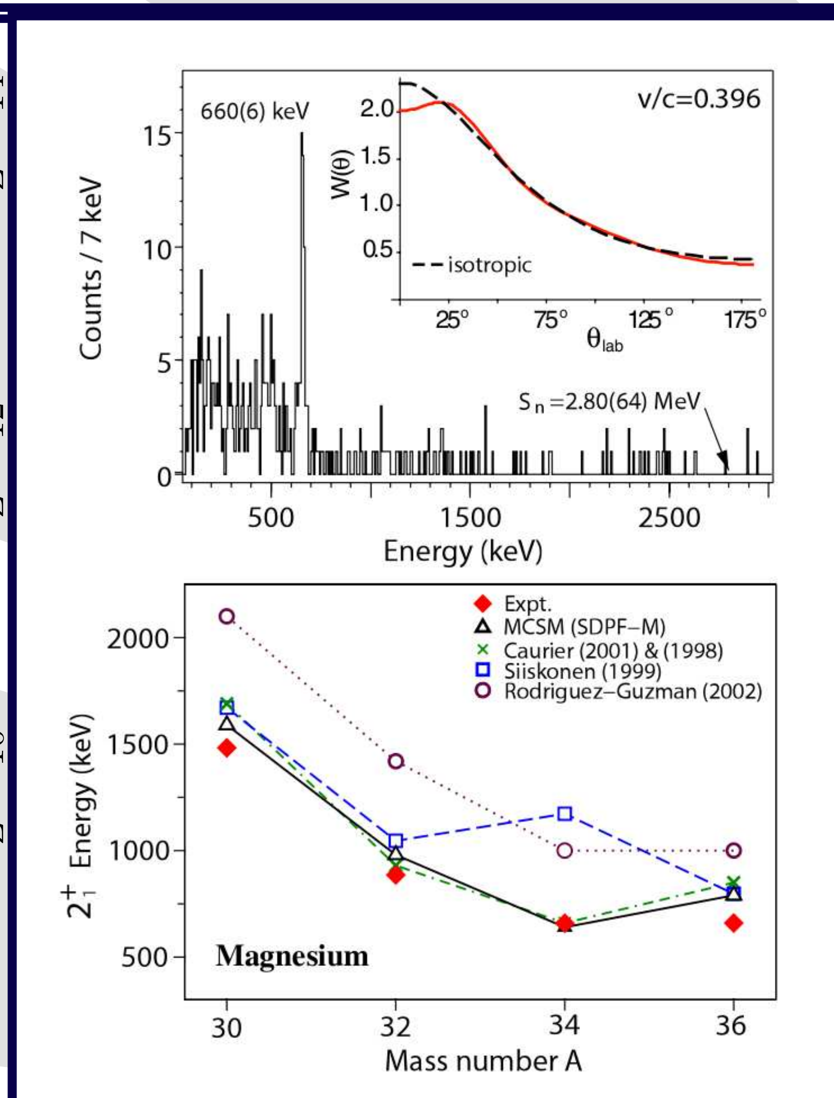
^{30}Ne: Y. Yanagisawa *et al.*, PLB **566**, 322 (2003).
^{34}Mg: K. Yoneda *et al.*, PLB **499**, 233 (2001).

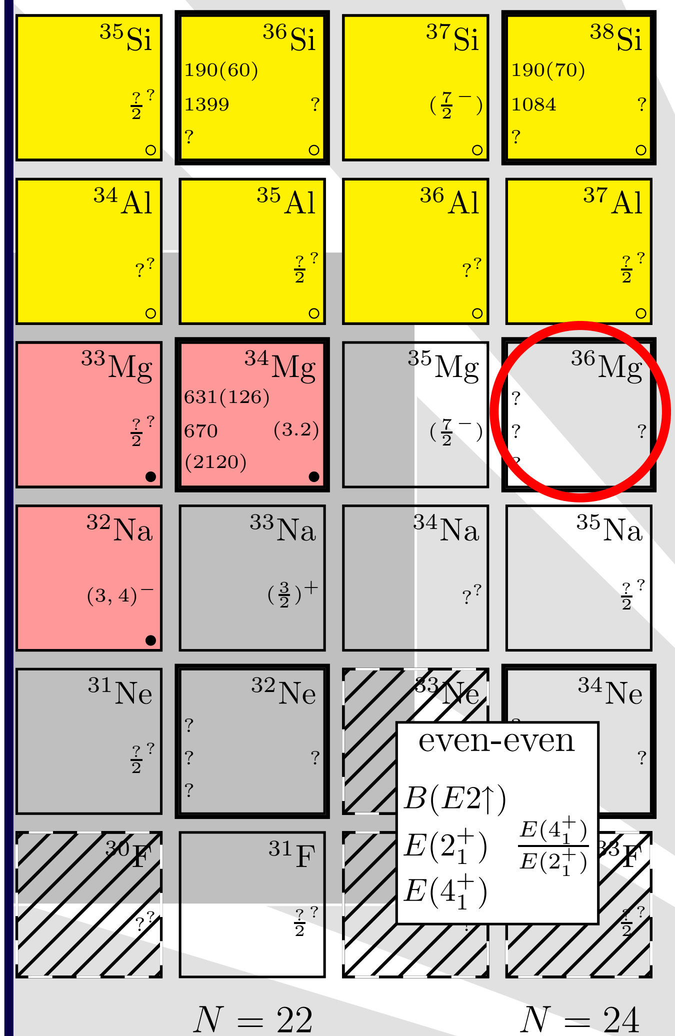
Satus in 2005



Prediction by E. K. Warburton *et al.*, Phys. Rev. C **41**, 1147 (1990)

Satus in 2005

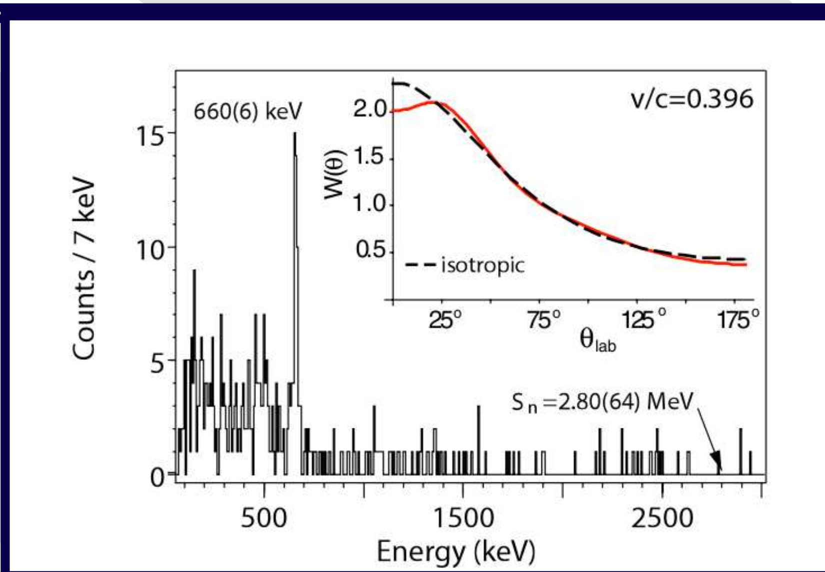




Prediction by E. K. Warburton *et al.*, Phys. Rev. C **41**, 1147 (1990)

A. Gade *et al.*, PRL **99**, 072502 (2007).

Satus in 2005



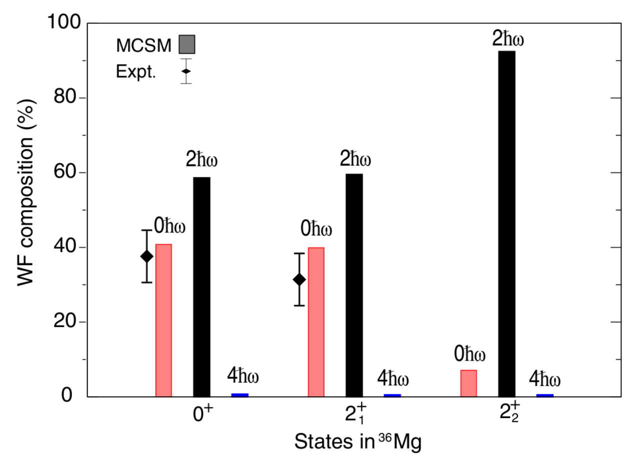
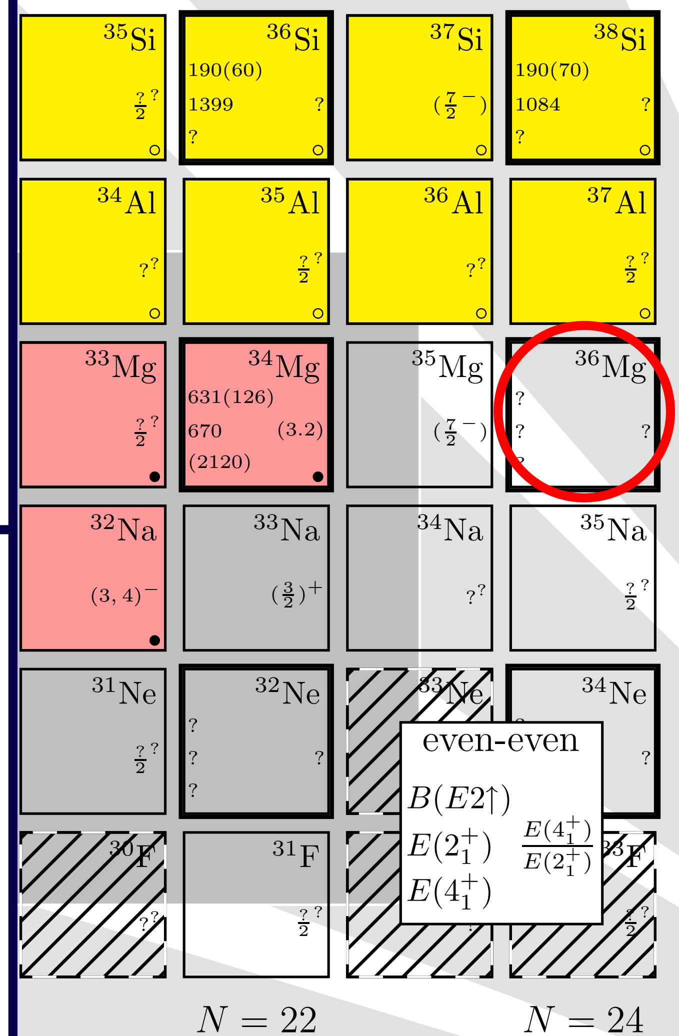


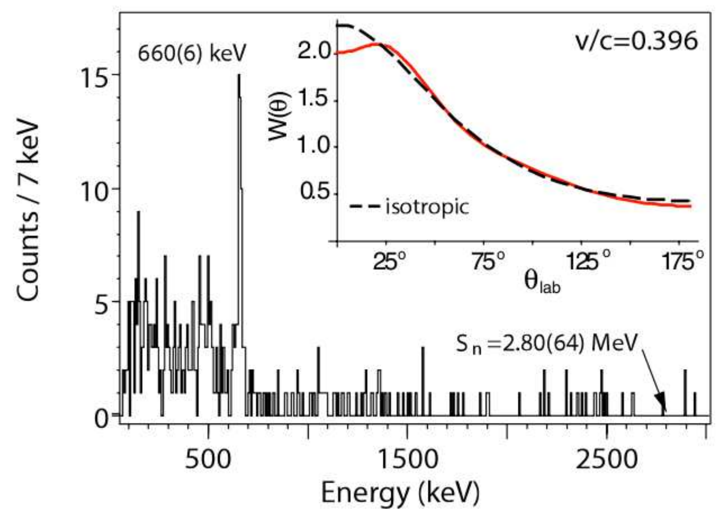
FIG. 3 (color online). Composition of the wave functions (WF) of the lowest-lying states of ^{36}Mg with respect to $n\hbar\omega$ components according to the MCSM calculation.



F… v. C **41**, 1147 (1990)

A. Gade *et al.*, PRL **99**, 072502 (2007).

Satus in 2005



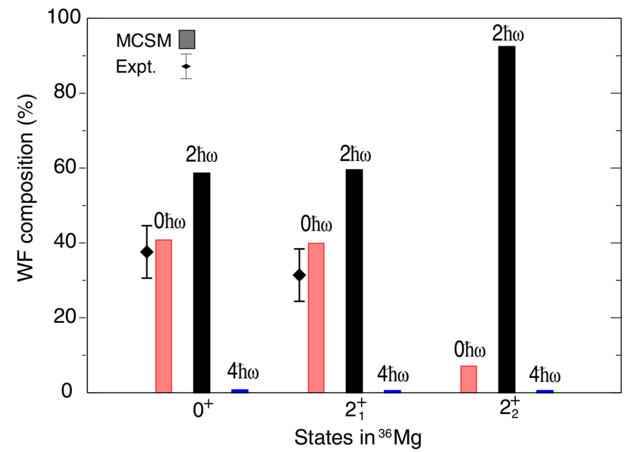
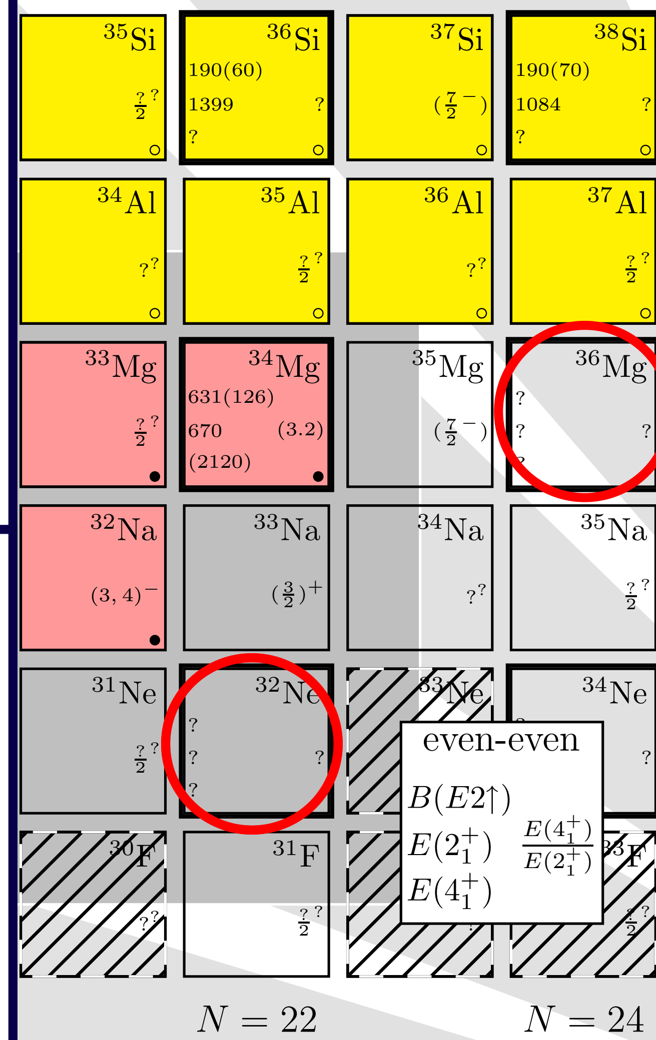


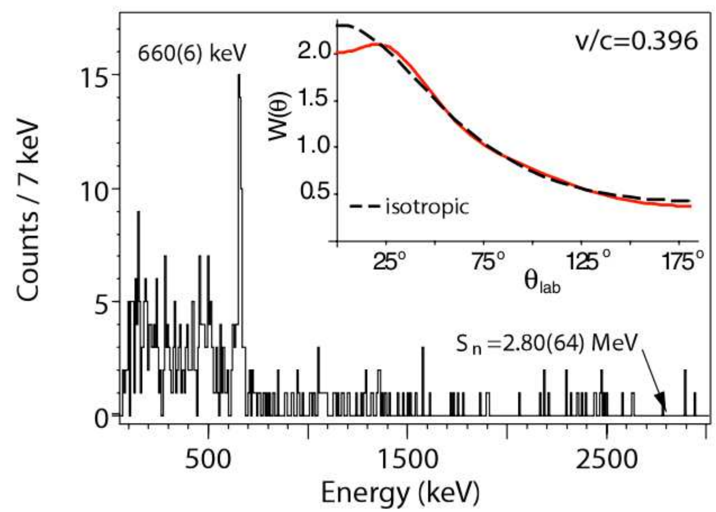
FIG. 3 (color online). Composition of the wave functions (WF) of the lowest-lying states of ^{36}Mg with respect to $n\hbar\omega$ components according to the MCSM calculation.



F… …v. C **41**, 1147 (1990)

A. Gade *et al.*, PRL **99**, 072502 (2007).

Satus in 2005



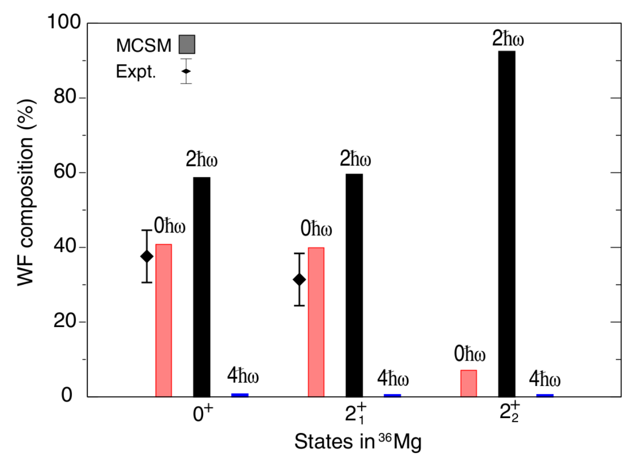
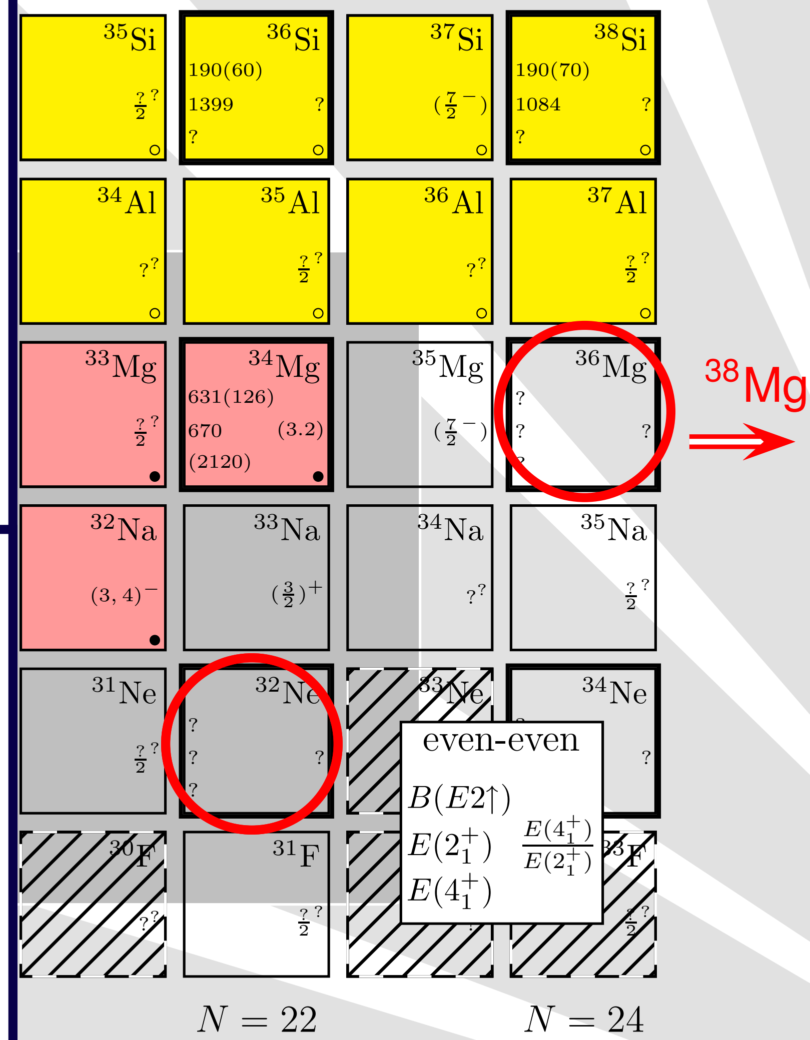


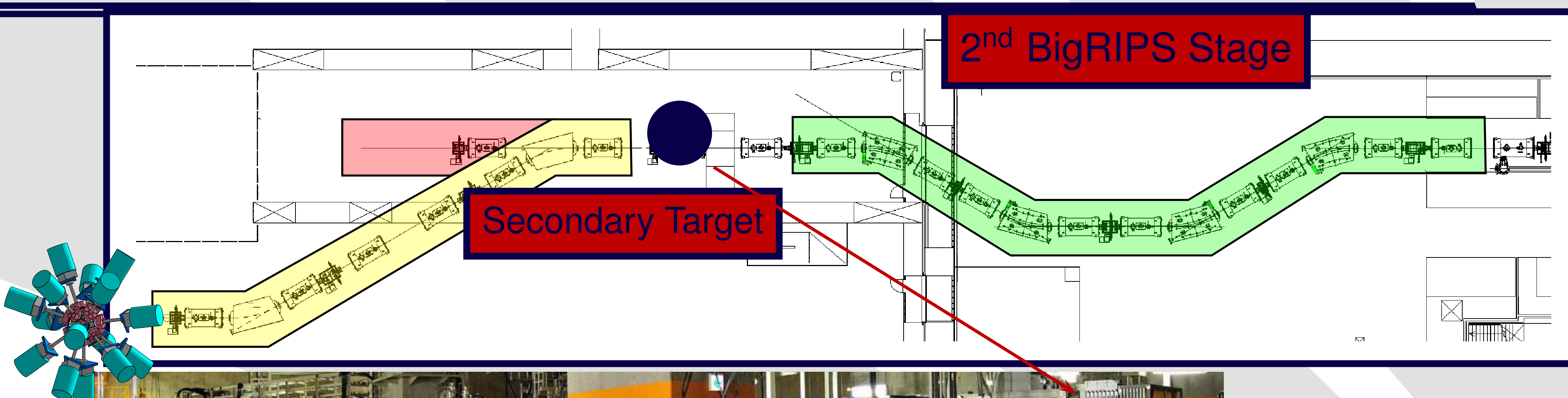
FIG. 3 (color online). Composition of the wave functions (WF) of the lowest-lying states of ^{36}Mg with respect to $n\hbar\omega$ components according to the MCSM calculation.



F... v. C **41**, 1147 (1990)

A. Gade *et al.*, PRL **99**, 072502 (2007).

ZeroDegree Spectrometer



0° Spectrometer ZeroDegree

- **Particle ID** after secondary target
- Fragment momentum distribution
- Various modes of operation

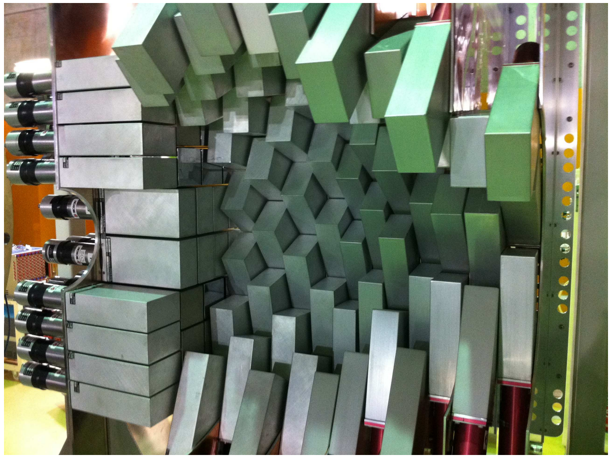
mode	$p/\Delta p$	Δp	Ang. Accep.
Large Accep.	**1240**	**± 3%**	**± 45 mrad(H) ± 30 mrad(V**
High res.(achrom)	2120	± 3%	± 20 mrad(H) ± 30 mrad(V)
Dispersive	4130	± 2%	± 20 mrad(H) ± 30 mrad(V)

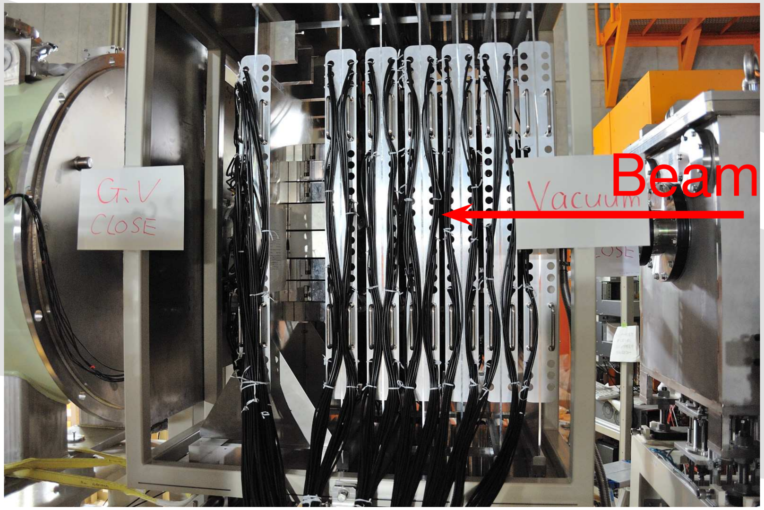
~ 3 m between Q-poles

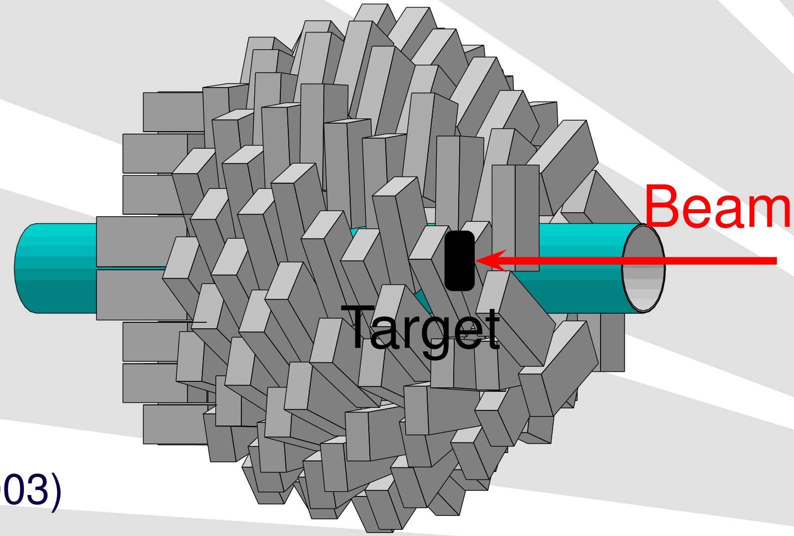
- DALI2 array, 186 NaI(Tl)
- GRAPE HPGe array
- $E_{\text{beam}} \sim 100 - 250$ MeV/u

DALI2 (2010–to Present)

- Forward-wall configuration
- 186 NaI(Tl) detectors
- ϑ coverage 11° to 165°
- Saint-Gobain: 16 × 8 × 4.5 cm^3
- Scionix: 16 × 8 × 4 cm^3
- 7 % intrinsic resolution at 1 MeV
- $\Delta E/E \approx$**10(11) % at 100(250) MeV/**u
- $\approx$ **20% FEP efficiency at 1 MeV**
- Simplified target holder and beam pipe
- 1mm Pb (+1mm Sn) shielding

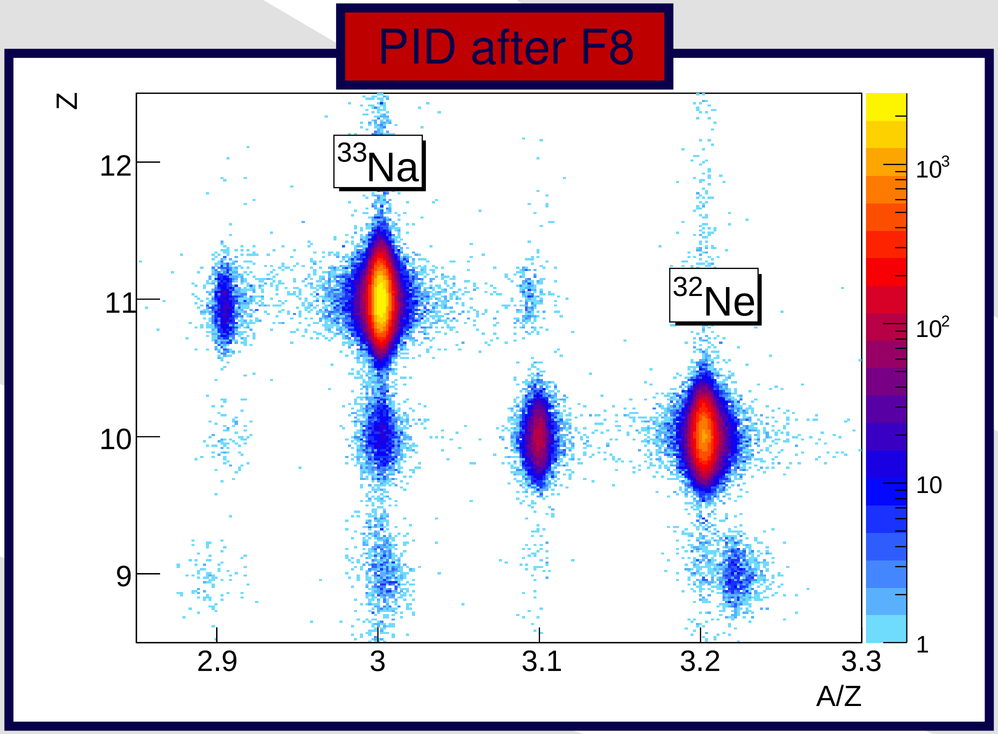






S. Takeuchi *et al.*, RIKEN Pr. Rep. 36, 148 (2003)

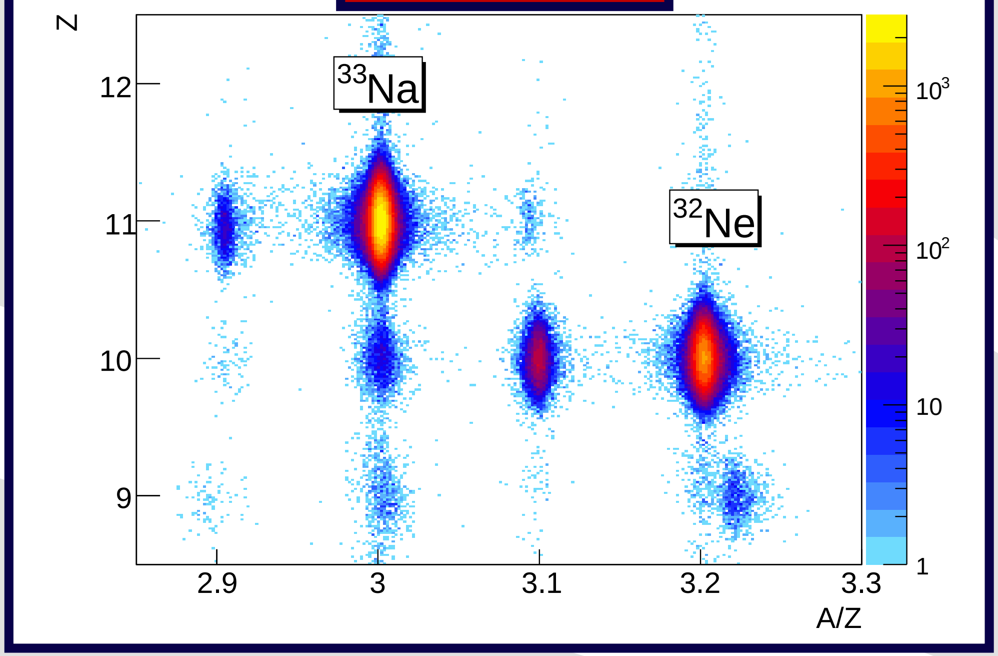
PID Behind Target and Gamma-Ray Spectra



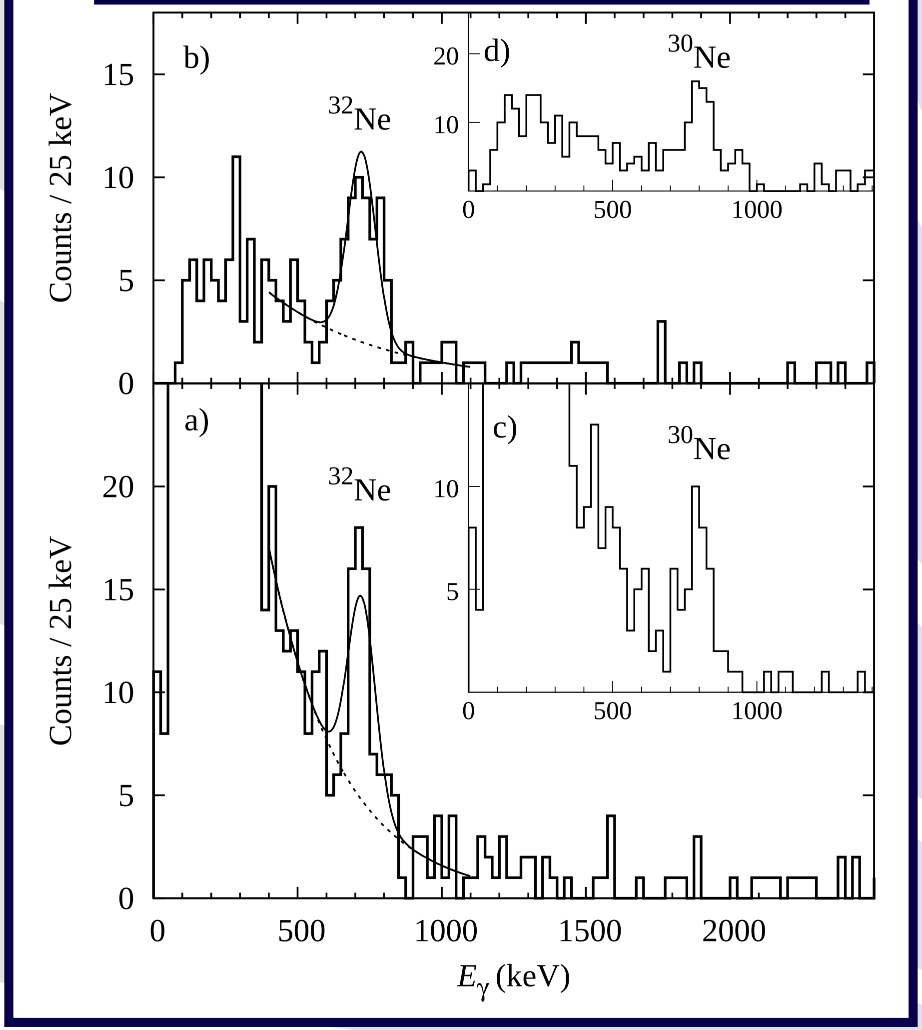
- ^{48}Ca 110 pnA
- C(^{32}Ne,^{32}Ne*), C(^{33}Na,^{32}Ne*)
- ^{32}Ne: 6 pps, 230 MeV/u
- F8 target: $^{nat.}$C (2.54 g/cm^2)
- DALI2 array: 180 NaI(Tl) detectors
- Total data taking: **8 hours**
- $E(2_1^+)$ at 722(9) keV

PID Behind Target and Gamma-Ray Spectra

PID after F8



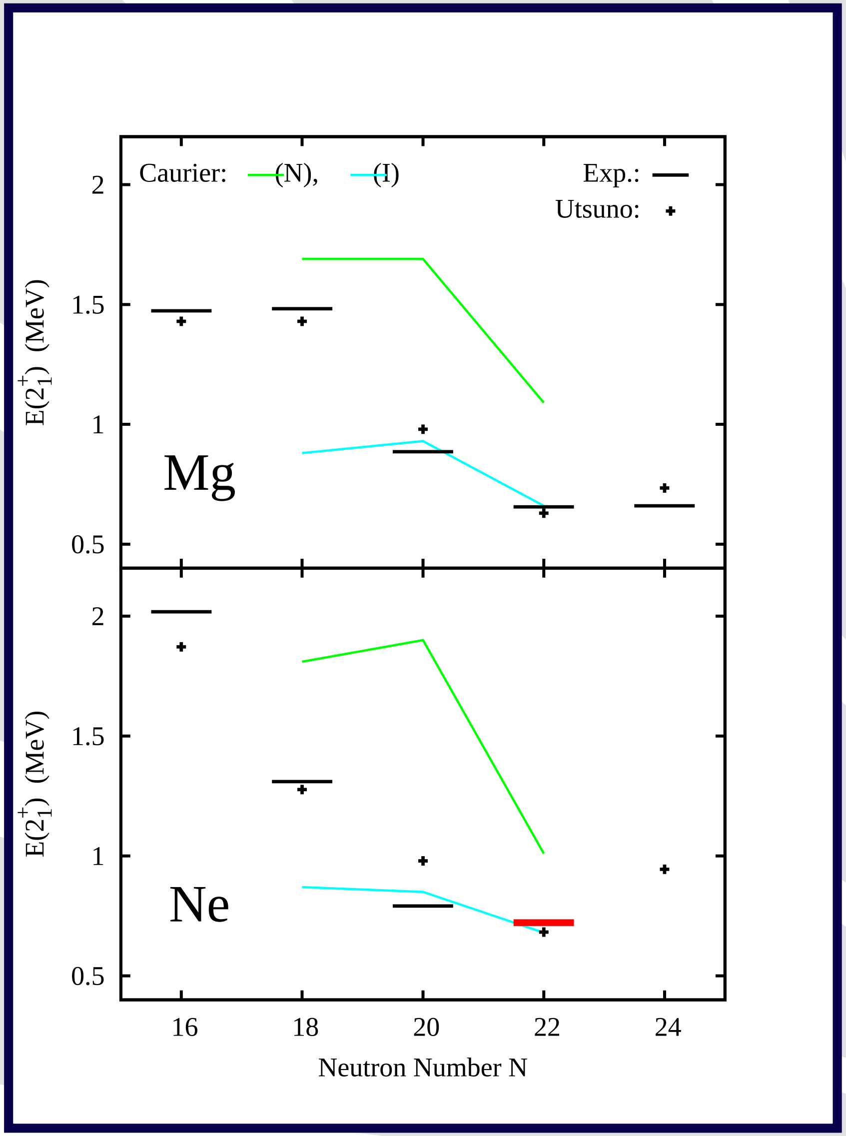
Doppler Corrected γ-Ray Energy



- ^{48}Ca 110 pnA
- C(^{32}Ne,^{32}Ne*), C(^{33}Na,^{32}Ne*)
- ^{32}Ne: 6 pps, 230 MeV/u
- F8 target: $^{nat.}$C (2.54 g/cm^2)
- DALI2 array: 180 NaI(Tl) detectors
- Total data taking: **8 hours**
- $E(2_1^+)$ at 722(9) keV

$E(2^+)$ as Function of N

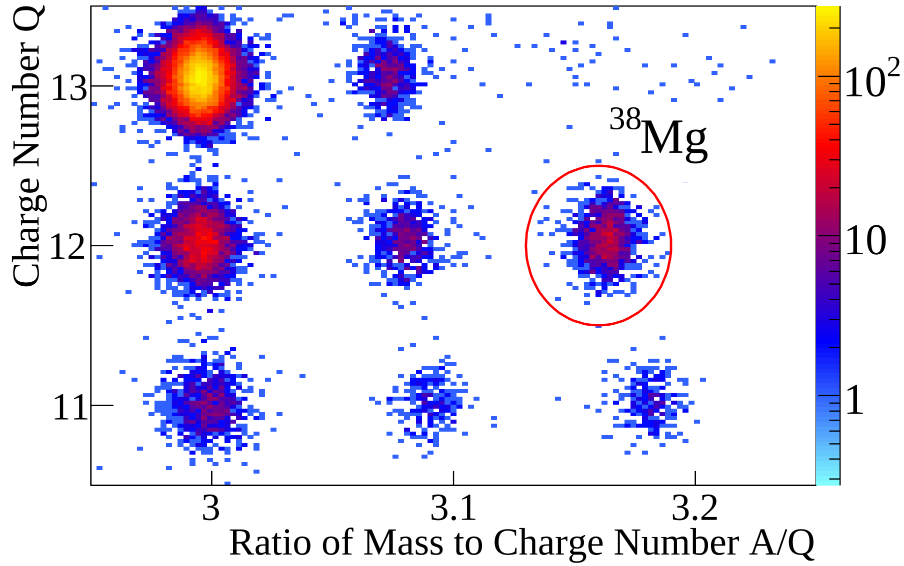
- Lowest $E(2^+)$ of Ne isotopes
- Very good agreement with Utsuno *et al.*, PRC 60, 054315 (1999)
- Very good agreement with Intruder calculation of Caurier *et al.*, NPA 693, 374 (2001)
- ^{32}Ne belongs to the "Island of Inversion"



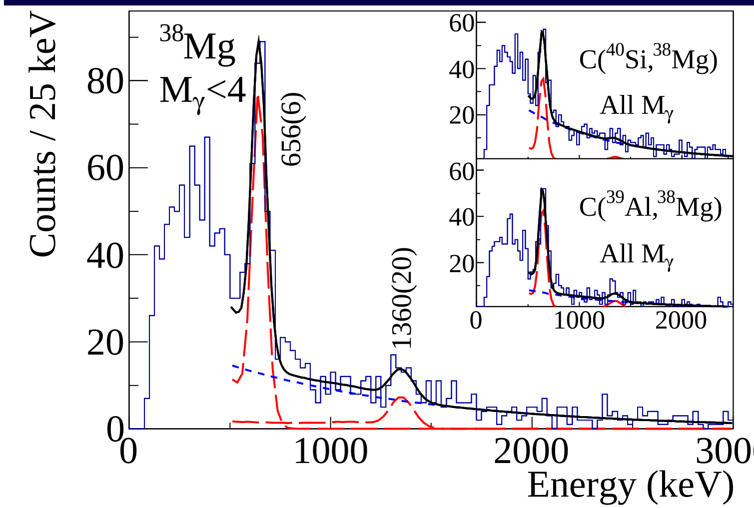
PD, H. Scheit *et al.*
Phys. Rev. Lett. 103, 032501 (2009)
arXiv:0906.3775

In-Beam γ-Ray Spectroscopy of ^{38}Mg

Particle Identification ZeroDegree



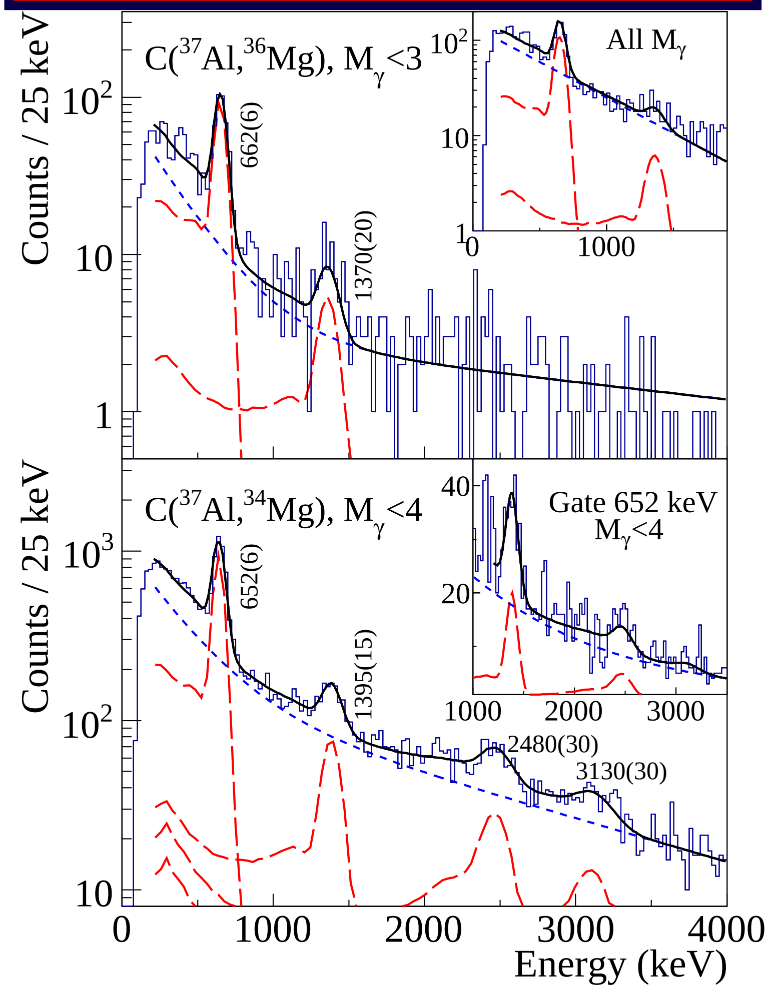
Doppler Corrected γ-Ray Energy



- ^{48}Ca, 70 pnA primary beam
- ^{40}Si: 3000 pps, 230 MeV/u
- ^{39}Al: 110 pps, 220 MeV/u
- F8 target: $^{nat.}$C, 2.54 g/cm^2
- **15 hours data taking**
- ^{38}Mg $E(2_1^+)$ 655(6) keV
- $E(4_1^+)/E(2_1^+) \approx 3$

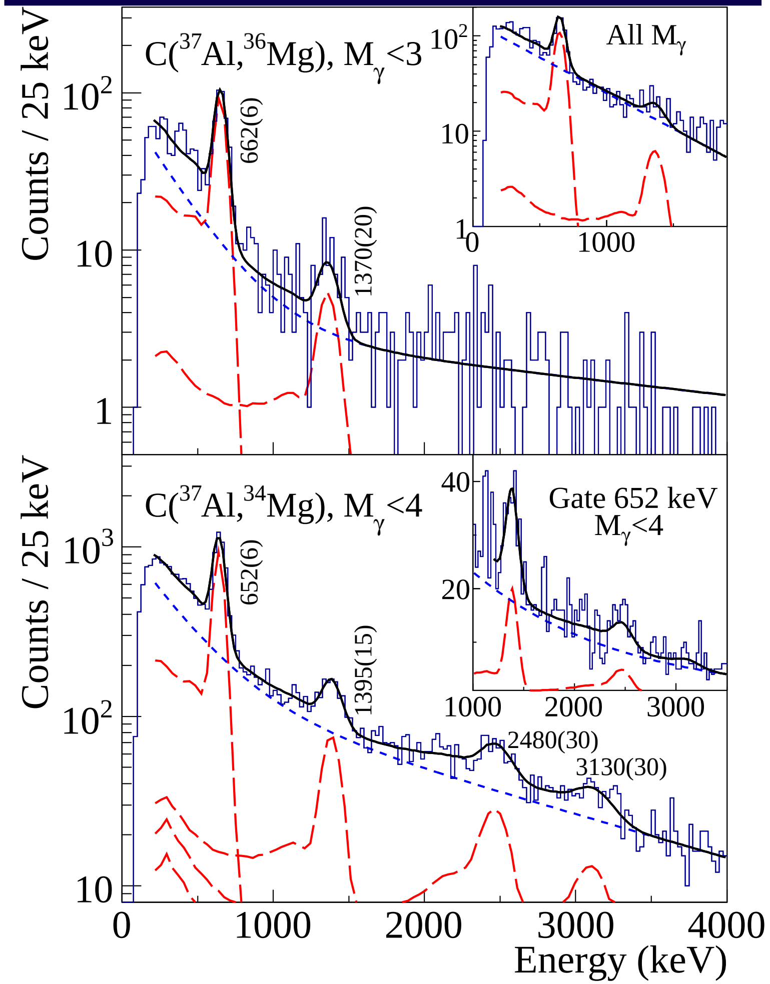
Systematics in Mg Isotopes

Doppler Corrected γ-ray Energy

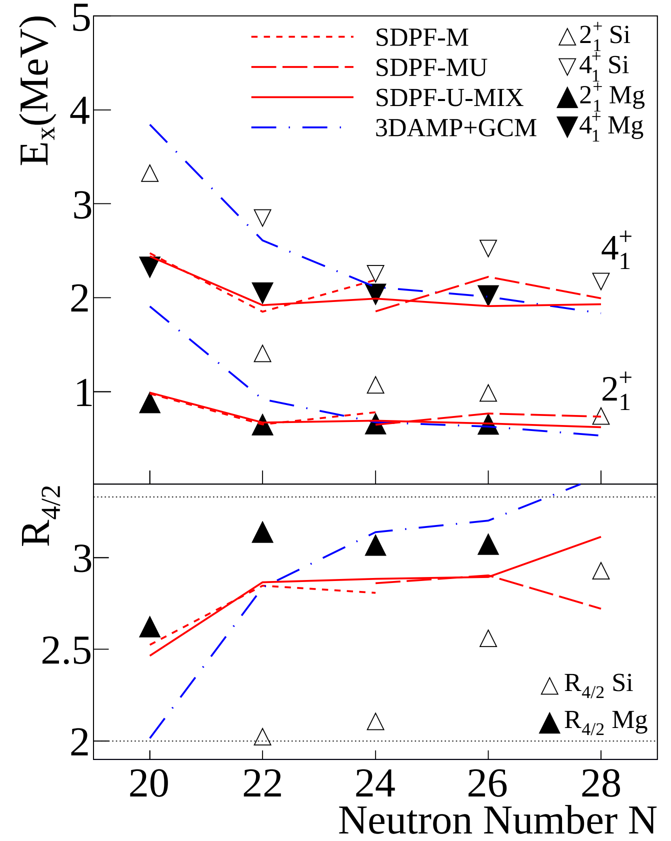


Systematics in Mg Isotopes

Doppler Corrected γ-ray Energy



Comparison with Si and Theory



SDPF-M: Y. Utsuno *et al.*, PRC 60, 054315 (1999).
SDPF-MU: Y. Utsuno *et al.*, PRC 86, 051301 (2012).
SPPF-U-MIX: A. Poves *et al.*, PST 150, 014030 (2012).
3DAMP+GCM: J. M. Yao *et al.*, PRC 83, 014308 (2011).
PD, H. Scheit, S. Takeuchi *et al.*, PRL 111, 212502 (2013).
$R_{4/2}$ in Si: S. Takeuchi *et al.*, PRL 109, 182501 (2012).
X. Liang *et al.*, PRC 74, 014311 (2006).

Summary of $E(2_1^+)$ and $E(4_1^+)$

Nucleus	Method	$E(2_1^+)$ MeV/u	Facility	Year	Method	$E(4_1^+)$ MeV/u	Facility	Year
^{28}Ne	Coulex	53	NSCL	1999	(p,p')	51	RIKEN	2006†
^{30}Ne	(p,p')	48	RIKEN	2003	2p-k.o.	87	NSCL	2010†
^{32}Ne	(C,C'),1p-k.o.	230	RIKEN	2009	2p-k.o	$\approx$ 230	RIKEN	$*$
^{30}Mg	β decay	–	CERN	1979	14C(18O,2p)	2.6	ANL	2010‡
^{32}Mg	β decay	–	CERN	1979	Inelastic	?	GANIL	2002$^{\diamond}$
^{34}Mg	2p-k.o.	38	RIKEN	2001	2p-k.o.	38	RIKEN	2001†
^{36}Mg	2p-k.o.	83	NSCL	2007	1p-k.o.	220	RIKEN	2013†
^{38}Mg	1,2p-k.o.	200	RIKEN	2013	1p-k.o.	200	RIKEN	2013†

†From systematics and comparison to theoretical calculations.
*Measured in NP0906-RIBF03 (D. Bazin *et al.*).
$^{\diamond}$Spin assignment via scattered particle angular distribution:
S. Takeuchi *et al.*, PRC **79**, 054319 (2009).
‡Spin assignment from γ-ray angular distribution:
A.N. Deacon *et al.*, PRC **82**, 034305 (2010).

Summary of $E(2^+_1)$ and $E(4^+_1)$

Nucleus	Method	$E(2^+_1)$ MeV/u	Facility	Year	Method	$E(4^+_1)$ MeV/u	Facility	Year
^{28}Ne	Coulex	53	NSCL	1999	(p,p')	51	RIKEN	2006†
^{30}Ne	(p,p')	48	RIKEN	2003	2p-k.o.	87	NSCL	2010†
^{32}Ne	(C,C'),1p-k.o.	230	RIKEN	2009	2p-k.o	$\approx$ 230	RIKEN	*
^{30}Mg	β decay	–	CERN	1979	14C(18O,2p)	2.6	ANL	2010‡
^{32}Mg	β decay	–	CERN	1979	Inelastic	?	GANIL	2002$^\diamond$
^{34}Mg	2p-k.o.	38	RIKEN	2001	2p-k.o.	38	RIKEN	2001†
^{36}Mg	2p-k.o.	83	NSCL	2007	1p-k.o.	220	RIKEN	2013†
^{38}Mg	1,2p-k.o.	200	RIKEN	2013	1p-k.o.	200	RIKEN	2013†

†From systematics and comparison to theoretical calculations.
*Measured in NP0906-RIBF03 (D. Bazin *et al.*).
$^\diamond$Spin assignment via scattered particle angular distribution:
S. Takeuchi *et al.*, PRC **79**, 054319 (2009).
‡Spin assignment from γ-ray angular distribution:
A.N. Deacon *et al.*, PRC **82**, 034305 (2010).

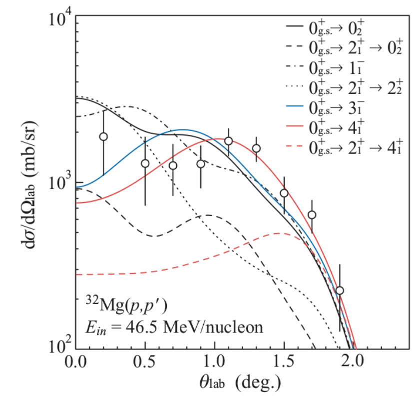
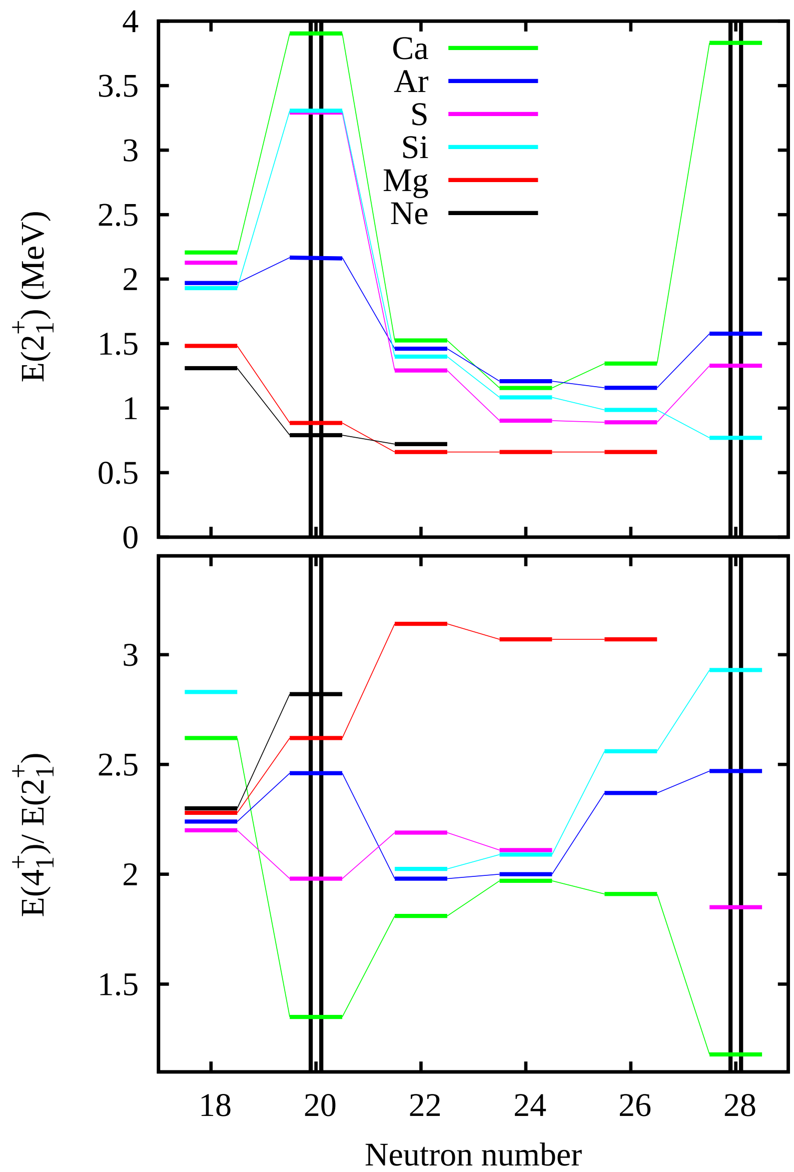


FIG. 6. (Color) Angular distributions for the excitation to the 2321-keV states in ^{32}Mg. The black curves show the calculations with $J^\pi = 0^+, 1^-$, and 2^+ assumed. The blue and red curves show the calculations for $J^\pi = 3^-$ and 4^+, respectively. For details see the text.

Summary of $E(2_1^+)$ and $E(4_1^+)$

Nuc	… r	Method	$E(4_1^+)$ MeV/u	Facility	Year
28 N	9	(p,p')	51	RIKEN	2006†
30 N	3	2p-k.o.	87	NSCL	2010†
32 N	9	2p-k.o	≈ 230	RIKEN	*
30 N	9	14C(18O,2p)	2.6	ANL	2010‡
32 N	9	Inelastic	?	GANIL	2002◇
34 N	1	2p-k.o.	38	RIKEN	2001†
36 N	7	1p-k.o.	220	RIKEN	2013†
38 N	3	1p-k.o.	200	RIKEN	2013†



† From s… …ations.
* Measu…
◇ Spin a… …tion:
S. Take…
‡ Spin a…
A.N. De…

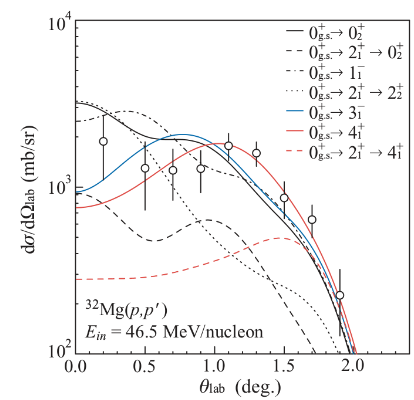
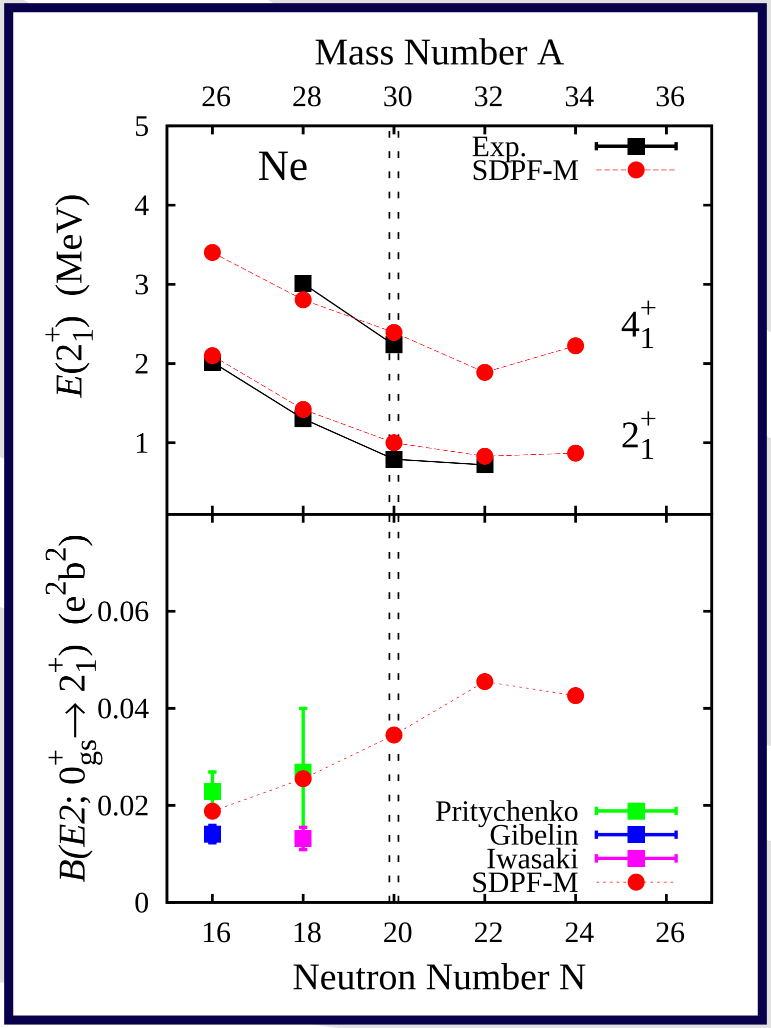
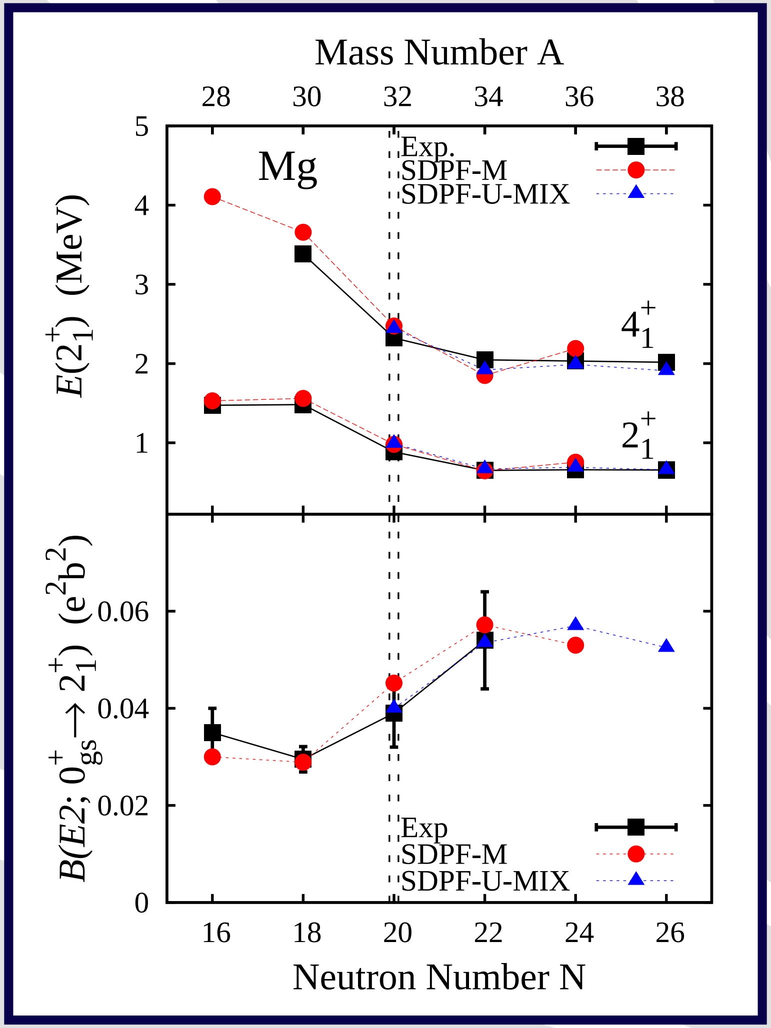


FIG. 6. (Color) Angular distributions for the excitation to the 2321-keV states in ^{32}Mg. The black curves show the calculations with $J^\pi = 0^+, 1^-$, and 2^+ assumed. The blue and red curves show the calculations for $J^\pi = 3^-$ and 4^+, respectively. For details see the text.

$B(E2)\uparrow$ *and* δ *inside the* *"Island of Inversion"*

Overview of Ne and Mg

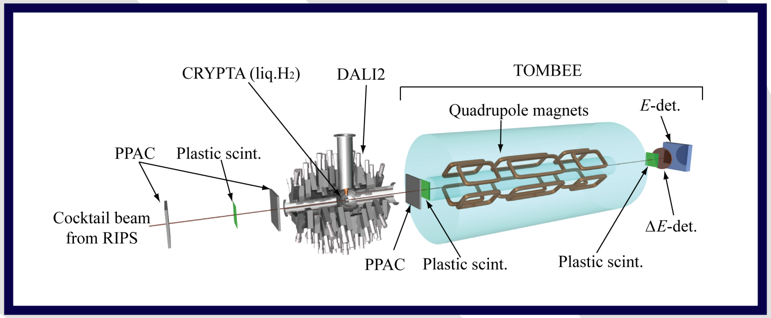


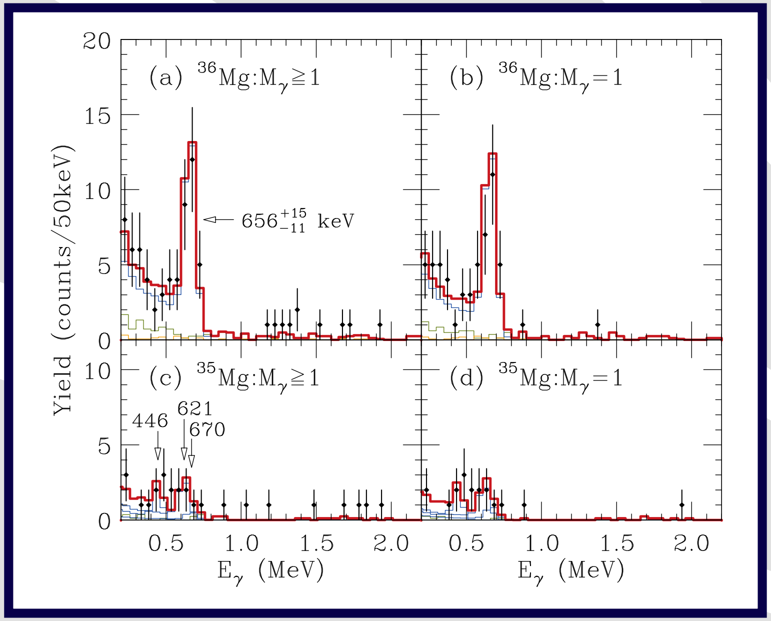


B. Pritychenko *et al.*, PLB **461**, 322 (2009).
H. Iwasaki *et al.*, PLB **620**, 118 (2005).
J. Gibelin *et al.*, PRC **75**, 057306 (2007).
SDPF-M: Y. Utsuno *et al.*, PRC **60**, 054315 (1999).
SDPF-U-MIX: E. Caurier *et al.*, arXiv:1309.6955.

Inelastic Scattering of Ne and Mg isotopes

- Inelastic scattering of ^{28,30}Ne and ^{34,36}Mg
- 0.095g/cm^2 liquid hydrogen target
- 45 MeV/u at center-of-target

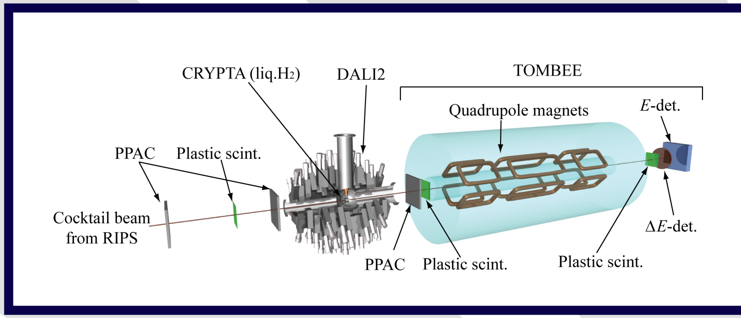


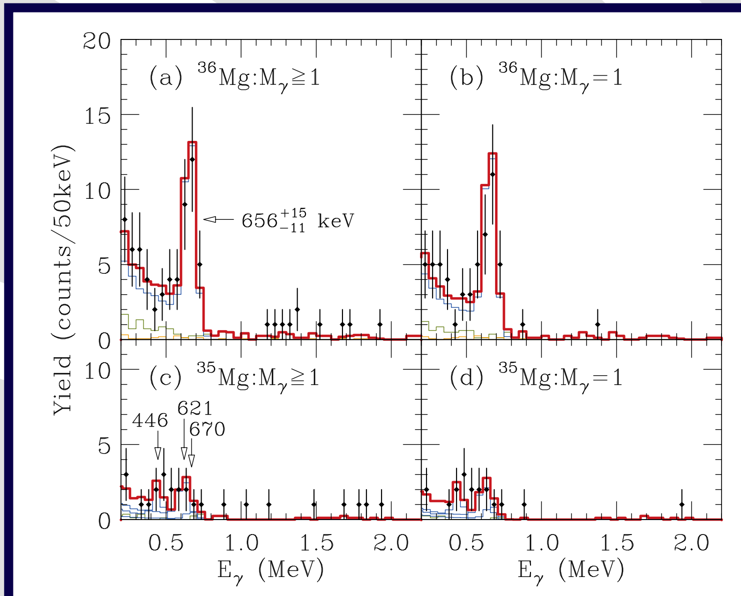


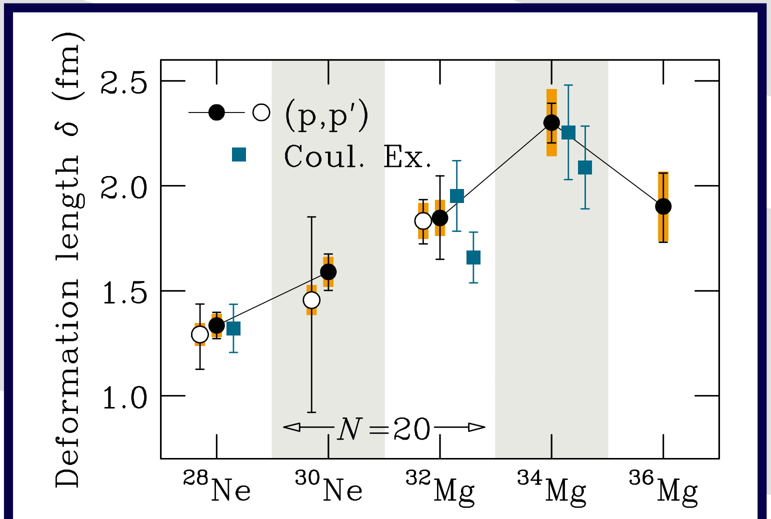
S. Michimasa *et al.*, PRC, accepted.

Inelastic Scattering of Ne and Mg isotopes

- Inelastic scattering of ^{28,30}Ne and ^{34,36}Mg
- 0.095g/cm^2 liquid hydrogen target
- 45 MeV/u at center-of-target
- $\delta_c = (4\pi/3eZR_0)B(E2)\uparrow^{1/2}$, $R_0 = 1.2A^{1/3}$ fm
- Maximum deformation lengths (and parameters $\beta_{(p,p')}$) in Mg isotopes



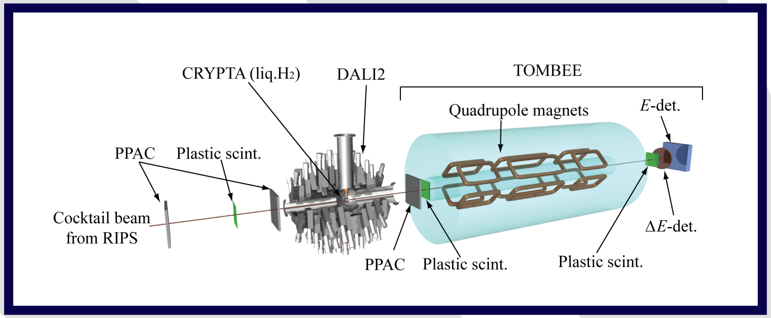


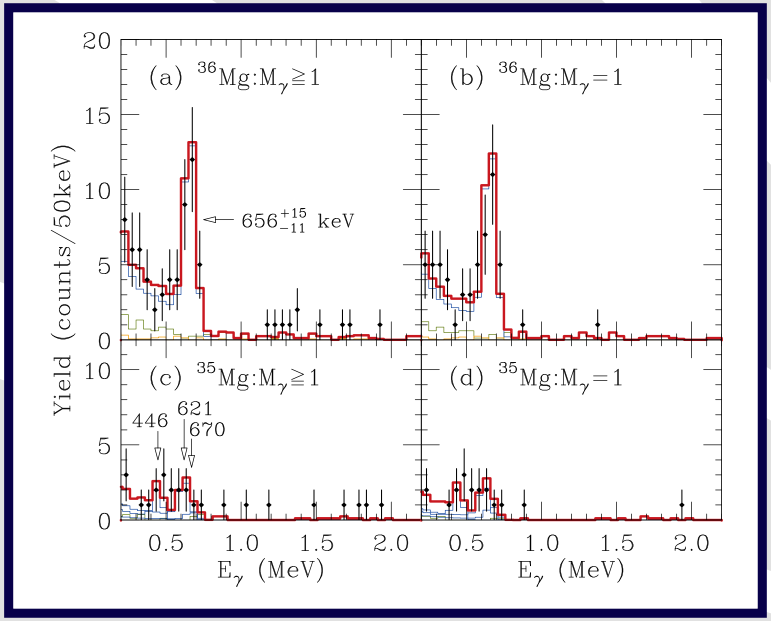


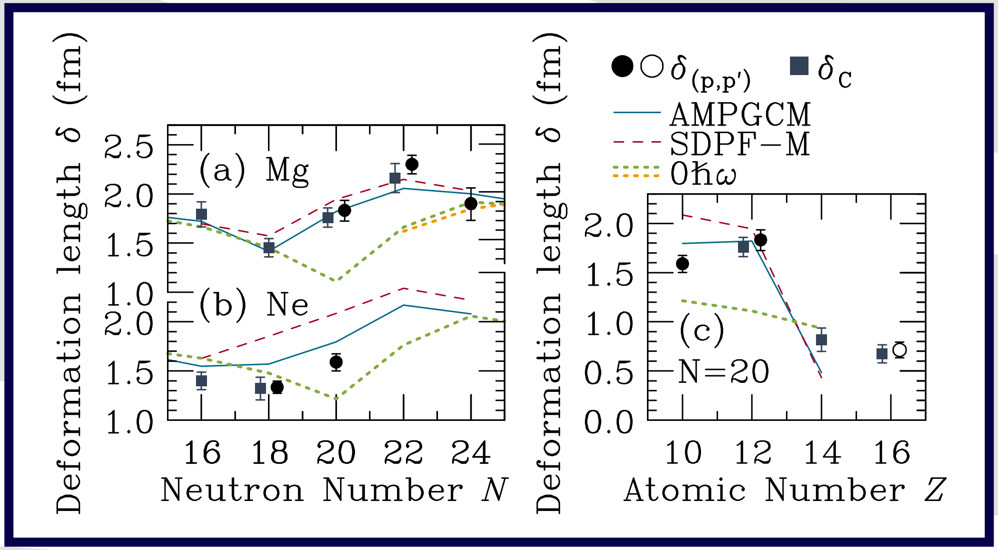
S. Michimasa *et al.*, PRC, accepted.

Inelastic Scattering of Ne and Mg isotopes

- Inelastic scattering of ^{28,30}Ne and ^{34,36}Mg
- 0.095g/cm^2 liquid hydrogen target
- 45 MeV/u at center-of-target
- $\delta_c = (4\pi/3eZR_0)B(E2)\uparrow^{1/2}$, $R_0 = 1.2A^{1/3}$ fm
- Maximum deformation lengths (and parameters $\beta_{(p,p')}$) in Mg isotopes
- Better theoretical agreement for Mg isotopes







S. Michimasa *et al.*, PRC, accepted.

Odd-Even Na Isotopes

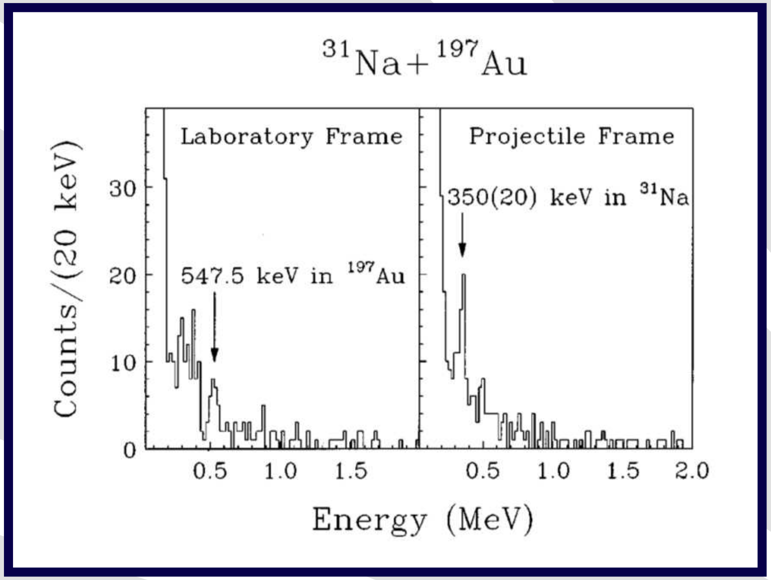
In-Beam Status on Na Isotopes

- Rather limited knowledge

B. Pritychenko *et al.*, PRC **63**, 011305(R) (2000).
PD, HS *et al.*, PRC **81**, 041305(R) (2010).
A. Gade *et al.*, PRC **83**, 044305 (2011).
PD, HS, ST, YU *et al.*, PTEP, accepted.

In-Beam Status on Na Isotopes

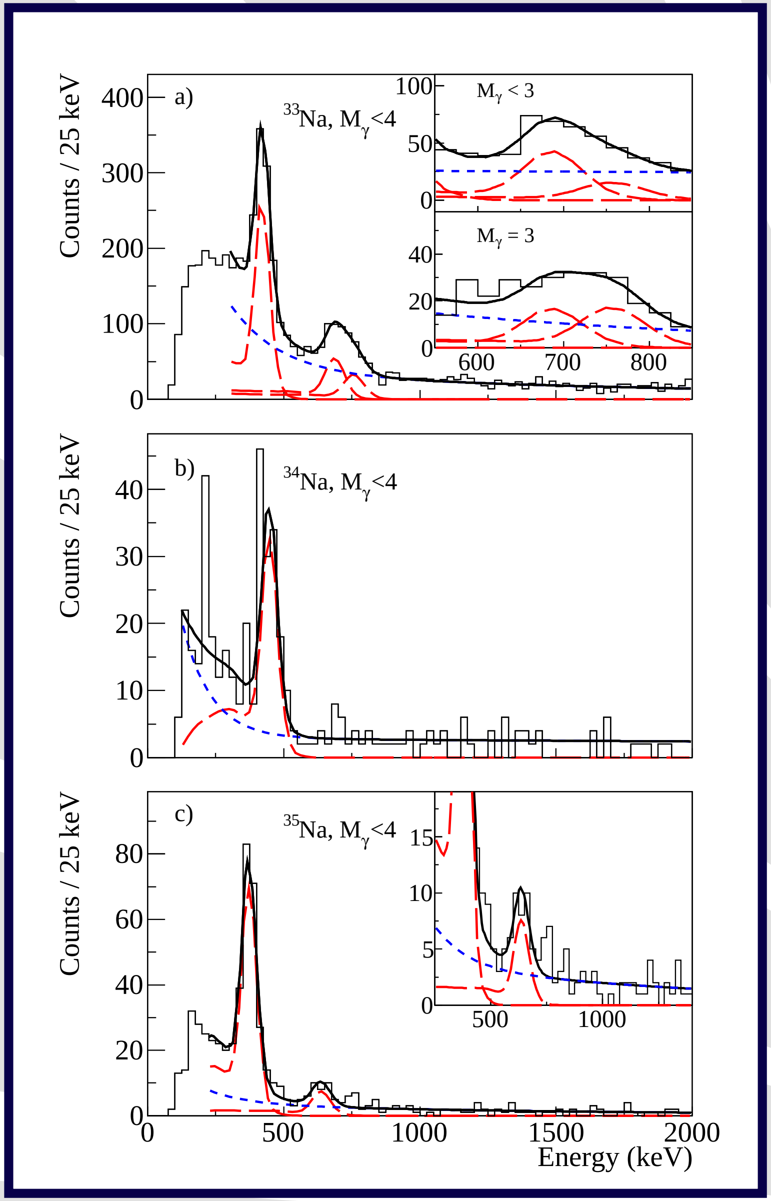
- Rather limited knowledge
- Intermediate-energy Coulex of ^{31}Na: $\beta_{C,A} = 0.59(10)$ for $3/2^+_{g.s.} \to 5/2^+$ and $3/2^+_{g.s.} \to 7/2^+$



B. Pritychenko *et al.*, PRC **63**, 011305(R) (2000).
PD, HS *et al.*, PRC **81**, 041305(R) (2010).
A. Gade *et al.*, PRC **83**, 044305 (2011).
PD, HS, ST, YU *et al.*, PTEP, accepted.

In-Beam Status on Na Isotopes

- Rather limited knowledge
- Intermediate-energy Coulex of ^{31}Na: $\beta_{C,A} = 0.59(10)$ for $3/2^+_{g.s.} \rightarrow 5/2^+$ and $3/2^+_{g.s.} \rightarrow 7/2^+$
- Extended spectroscopical information for ^{31,33,35}Na

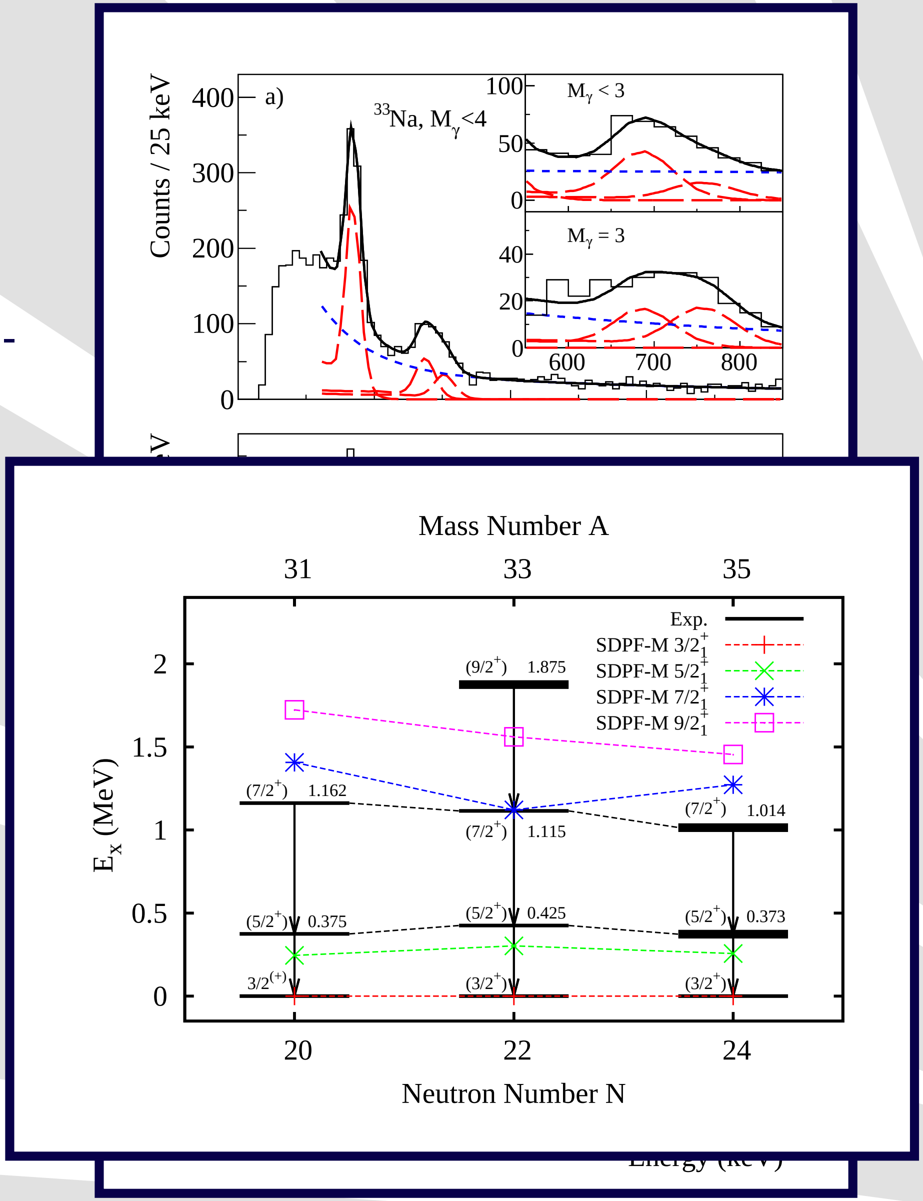


B. Pritychenko *et al.*, PRC **63**, 011305(R) (2000).
PD, HS *et al.*, PRC **81**, 041305(R) (2010).
A. Gade *et al.*, PRC **83**, 044305 (2011).
PD, HS, ST, YU *et al.*, PTEP, accepted.

In-Beam Status on Na Isotopes

- Rather limited knowledge
- Intermediate-energy Coulex of ^{31}Na: $\beta_{C,A} = 0.59(10)$ for $3/2^+_{g.s.} \to 5/2^+$ and $3/2^+_{g.s.} \to 7/2^+$
- Extended spectroscopical information for ^{31,33,35}Na

- Close-to-ideal $K = 3/2$ rotational bands in the strong-coupling limit

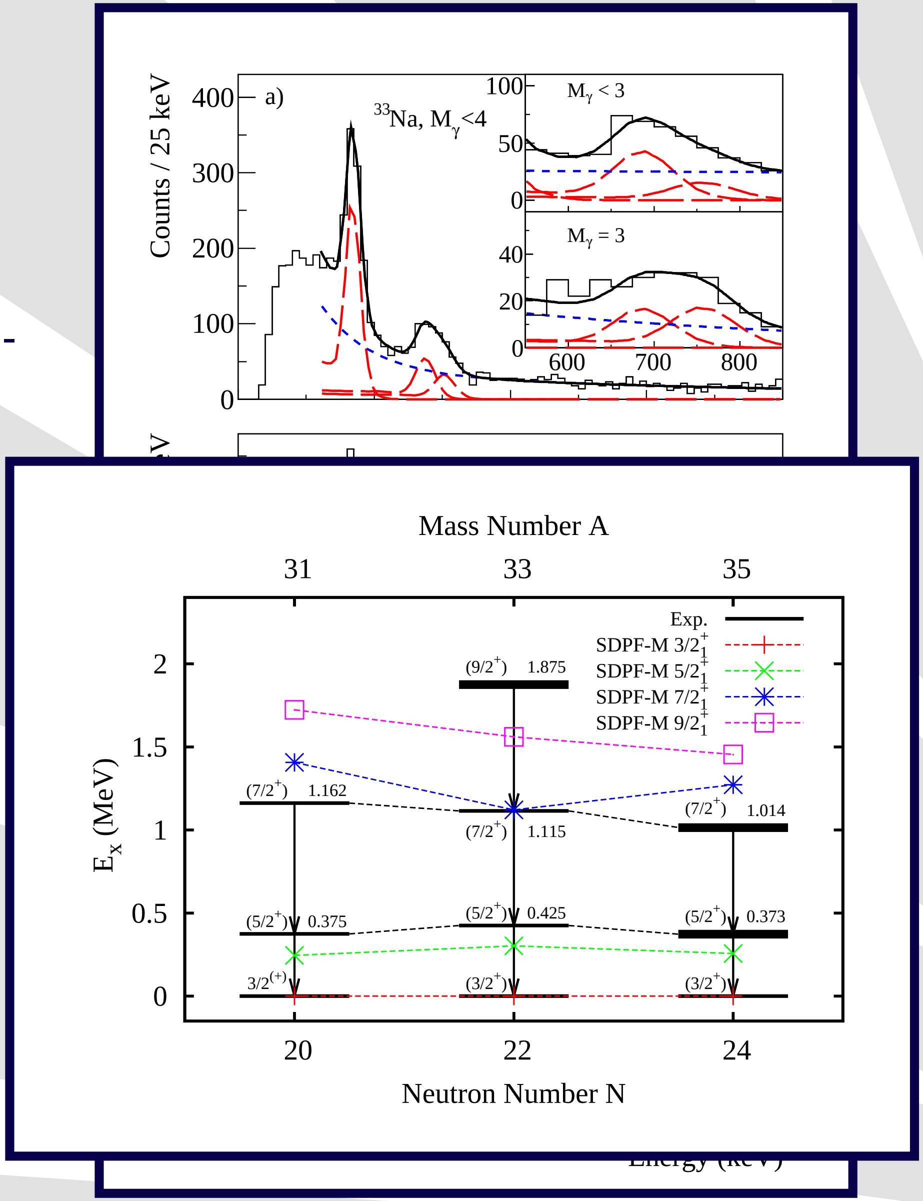


B. Pritychenko *et al.*, PRC **63**, 011305(R) (2000).
PD, HS *et al.*, PRC **81**, 041305(R) (2010).
A. Gade *et al.*, PRC **83**, 044305 (2011).
PD, HS, ST, YU *et al.*, PTEP, accepted.

In-Beam Status on Na Isotopes

- Rather limited knowledge
- Intermediate-energy Coulex of [31]Na: $\beta_{C,A} = 0.59(10)$ for $3/2^+_{g.s.} \rightarrow 5/2^+$ and $3/2^+_{g.s.} \rightarrow 7/2^+$
- Extended spectroscopical information for [31,33,35]Na

- Close-to-ideal $K = 3/2$ rotational bands in the strong-coupling limit
- $[E(7/2^+_1) - E(3/2^+_{gs})]/[E(5/2^+_1) - E(3/2^+_{gs})] = 2.4$ and $[E(9/2^+_1) - E(3/2^+_{gs})]/[E(7/2^+_1) - E(3/2^+_{gs})] = 1.75$

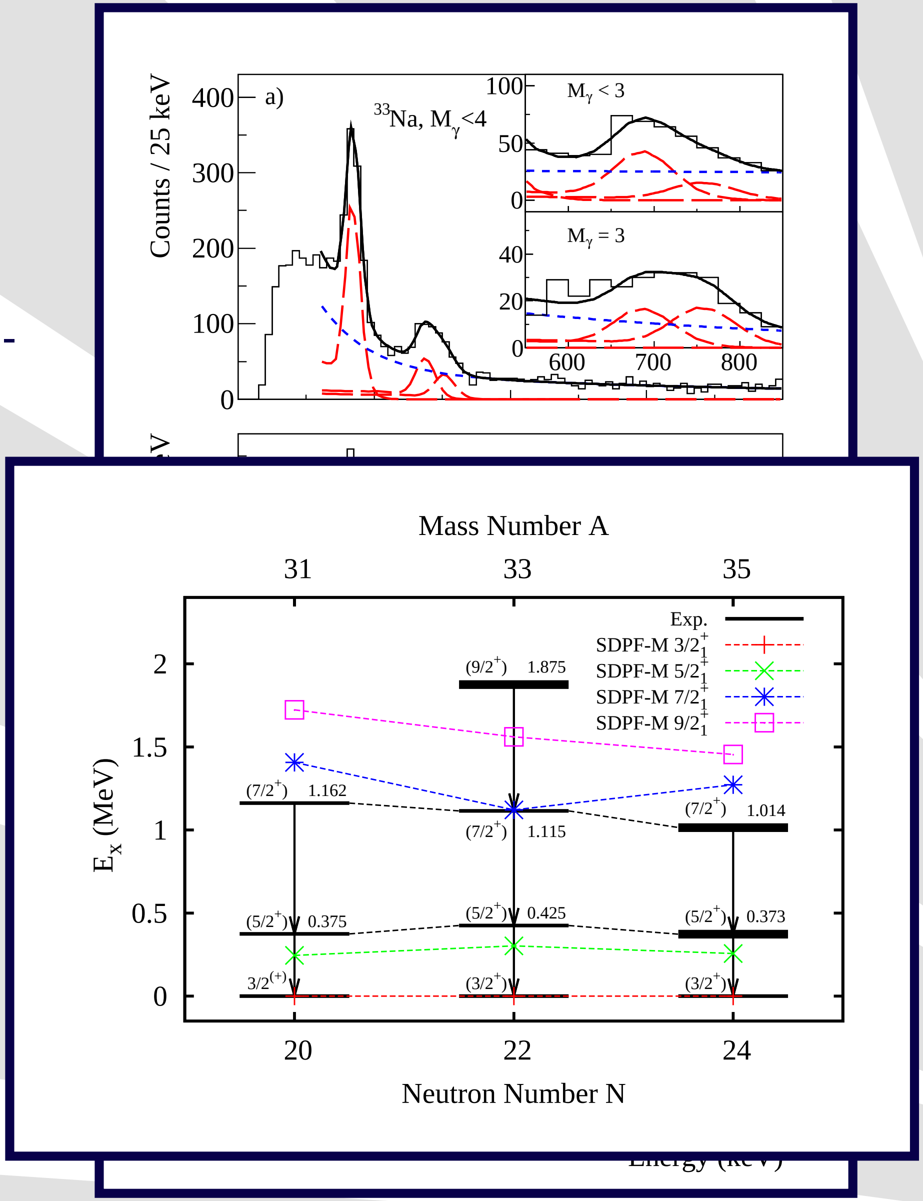


B. Pritychenko *et al.*, PRC **63**, 011305(R) (2000).
PD, HS *et al.*, PRC **81**, 041305(R) (2010).
A. Gade *et al.*, PRC **83**, 044305 (2011).
PD, HS, ST, YU *et al.*, PTEP, accepted.

In-Beam Status on Na Isotopes

- Rather limited knowledge
- Intermediate-energy Coulex of ^{31}Na: $\beta_{C,A} = 0.59(10)$ for $3/2^+_{g.s.} \rightarrow 5/2^+$ and $3/2^+_{g.s.} \rightarrow 7/2^+$
- Extended spectroscopical information for ^{31,33,35}Na

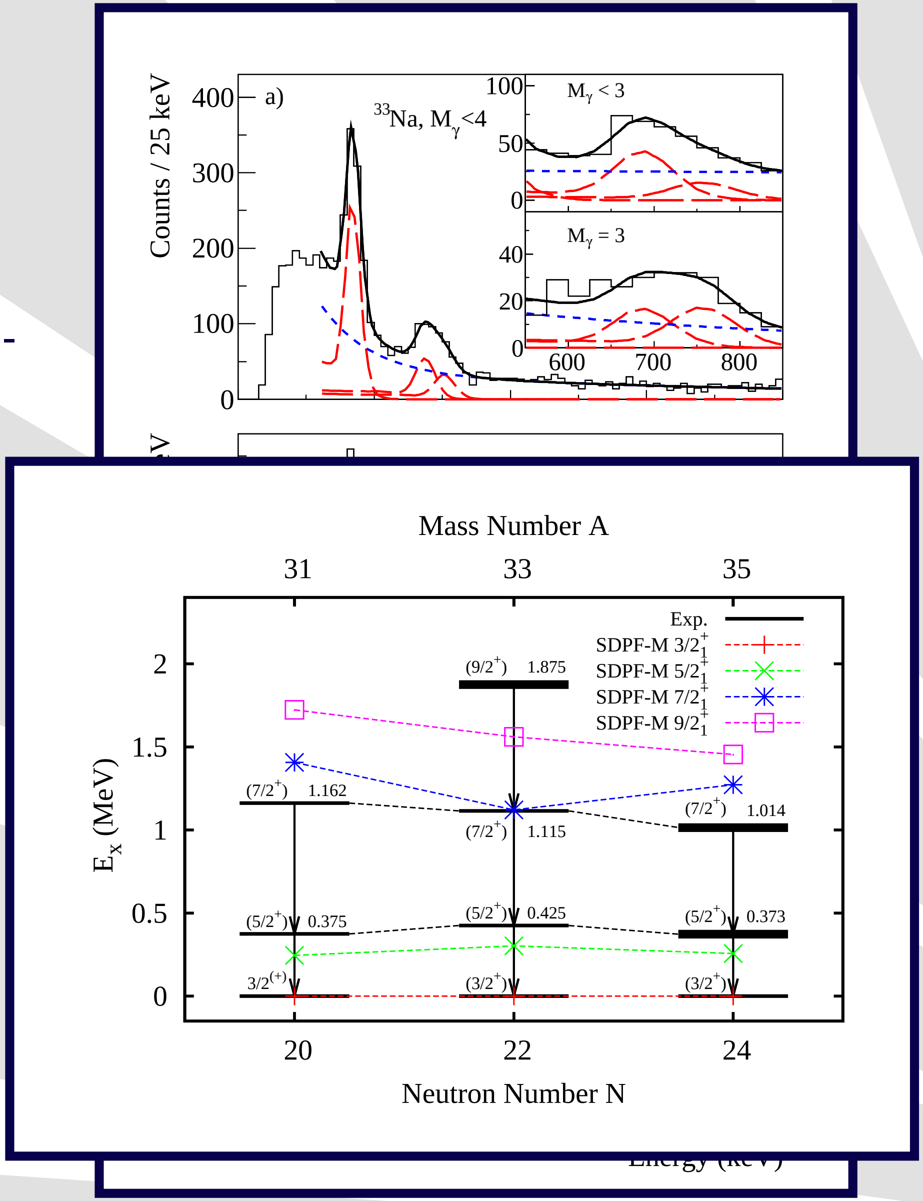
- Close-to-ideal $K = 3/2$ rotational bands in the strong-coupling limit
- $[E(7/2^+_1) - E(3/2^+_{gs})]/[E(5/2^+_1) - E(3/2^+_{gs})] = 2.4$ and $[E(9/2^+_1) - E(3/2^+_{gs})]/[E(7/2^+_1) - E(3/2^+_{gs})] = 1.75$
- Experiment: 3.10(4), 2.62(4), and 2.72(6) for ^{31,33,35}Na and 1.68(3) for ^{33}Na $9/2^+ \rightarrow 7/2^+$ decay



B. Pritychenko *et al.*, PRC **63**, 011305(R) (2000).
PD, HS *et al.*, PRC **81**, 041305(R) (2010).
A. Gade *et al.*, PRC **83**, 044305 (2011).
PD, HS, ST, YU *et al.*, PTEP, accepted.

In-Beam Status on Na Isotopes

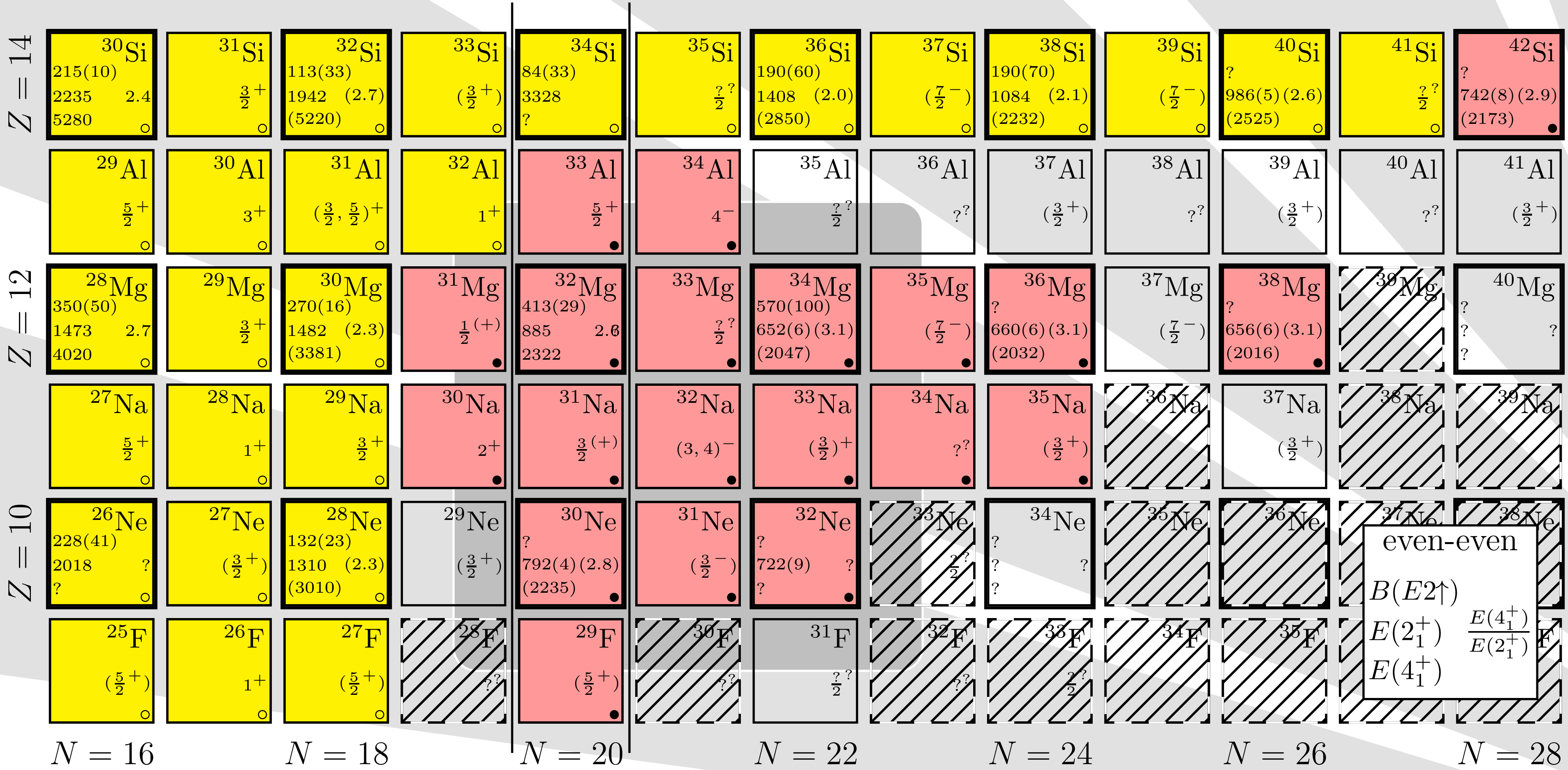
- Rather limited knowledge
- Intermediate-energy Coulex of [31]Na: $\beta_{C,A} = 0.59(10)$ for $3/2^+_{g.s.} \rightarrow 5/2^+$ and $3/2^+_{g.s.} \rightarrow 7/2^+$
- Extended spectroscopical information for [31,33,35]Na
- Close-to-ideal $K = 3/2$ rotational bands in the strong-coupling limit
- $[E(7/2^+_1) - E(3/2^+_{gs})]/[E(5/2^+_1) - E(3/2^+_{gs})] = 2.4$ and $[E(9/2^+_1) - E(3/2^+_{gs})]/[E(7/2^+_1) - E(3/2^+_{gs})] = 1.75$
- Experiment: 3.10(4), 2.62(4), and 2.72(6) for [31,33,35]Na and 1.68(3) for [33]Na $9/2^+ \rightarrow 7/2^+$ decay
- Good agreement with SDPF-M interaction



B. Pritychenko *et al.*, PRC **63**, 011305(R) (2000).
PD, HS *et al.*, PRC **81**, 041305(R) (2010).
A. Gade *et al.*, PRC **83**, 044305 (2011).
PD, HS, ST, YU *et al.*, PTEP, accepted.

Experimental Borders of “Island of Inversion”

Overview of Deformed Nuclei



Summary and Outlook

Summary and Outlook

- ^{40}Mg may be last 2_1^+ in this region of nuclear chart that can be accessed via in-beam γ-ray spectroscopy
  - ✦ AME2012: $S(2n)$ for ^{34}Ne = 300(100) keV
- All neutron-rich Na, Mg isotopes deformed
- Where is the maximum of deformation?
  - ✦ Data indicate Mg isotopes
  - ✦ Sparse information on Ne isotopes
  - ✦ Should remeasure $B(E2)\uparrow$ of ^{26,28}Ne at safe energies
- Most spin assignments follow systematics and comparison to calculations
  - ✦ Inelastic scattering at lower energies
  - ✦ 1-nucleon knockout reactions, e.g. ^{29}Ne

THE END

Backup slides from now