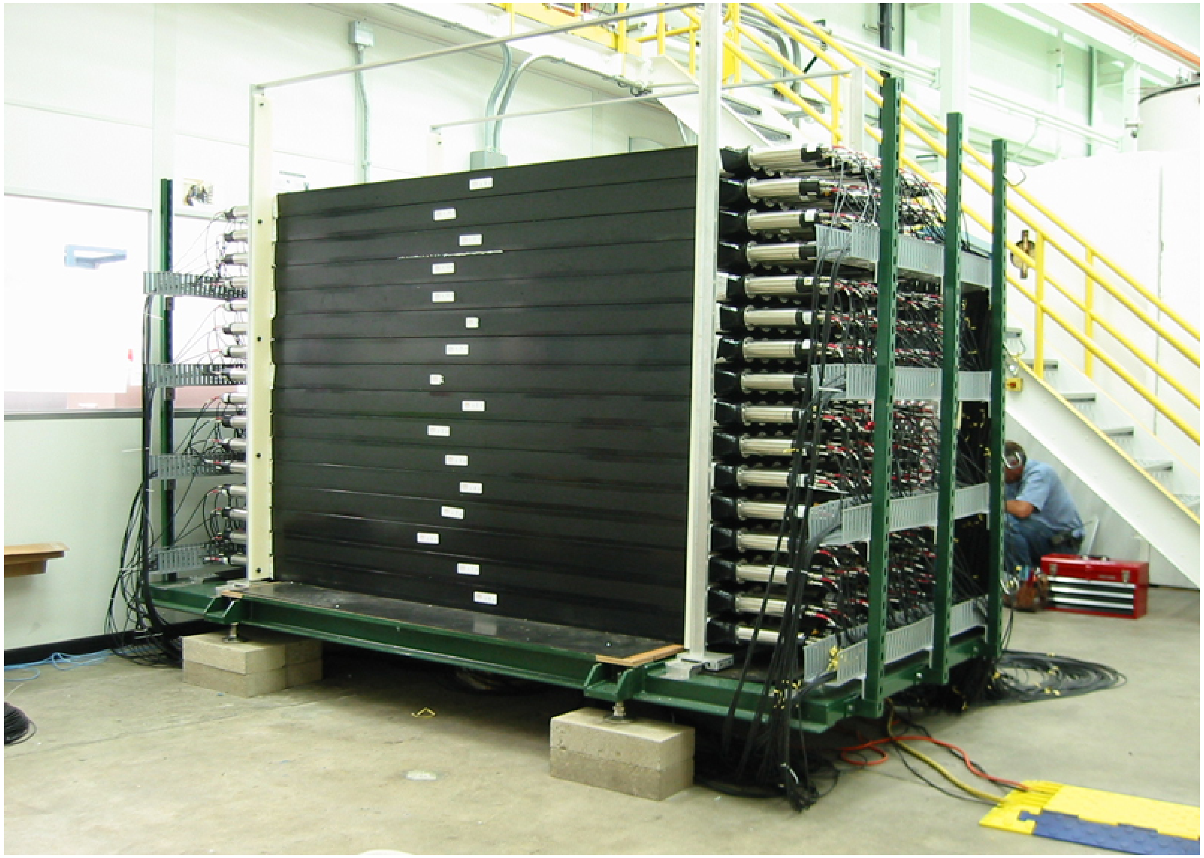
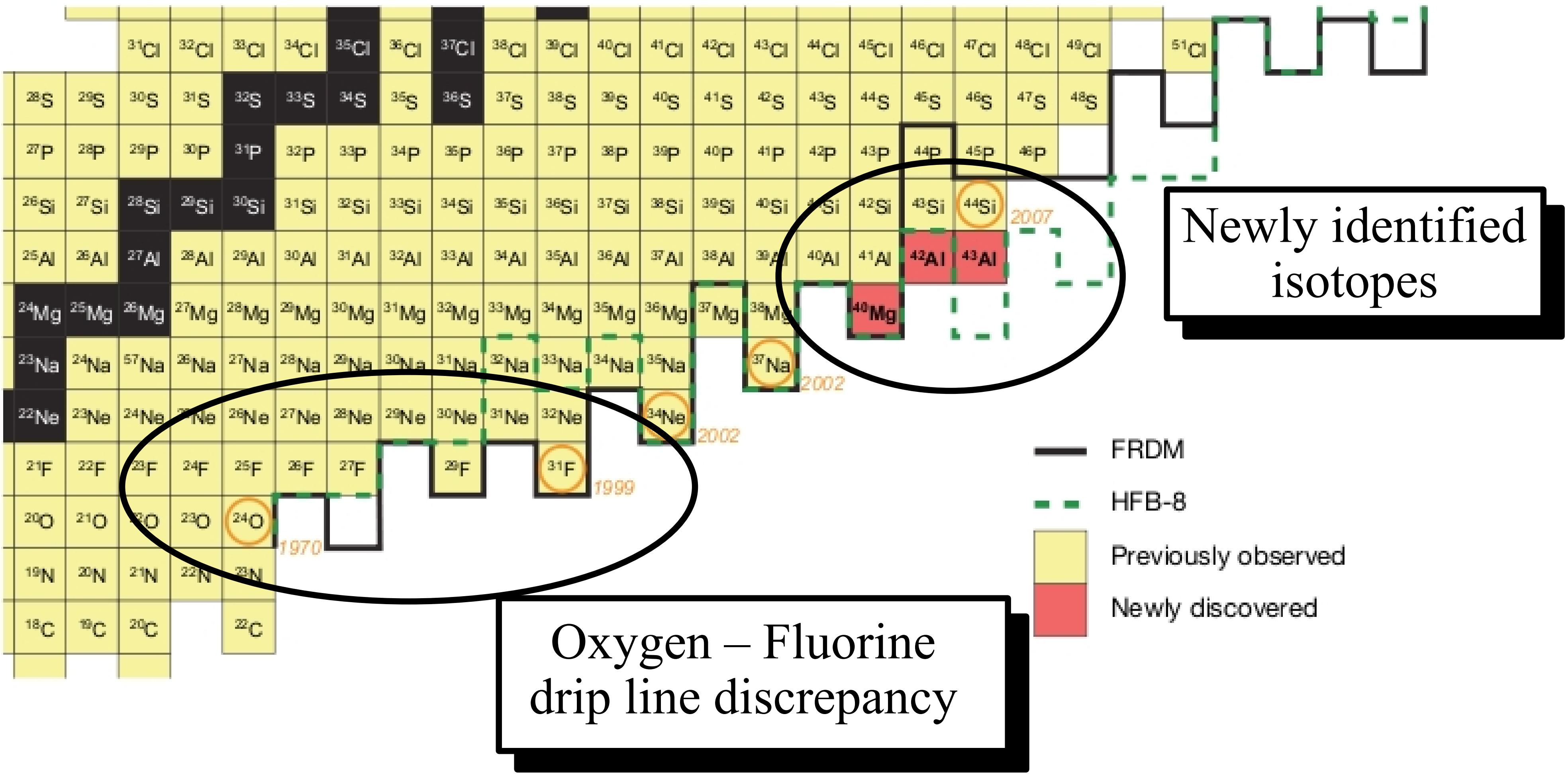
Spectroscopy of Unbound States at the Oxygen Drip-Line



Outline

- States in ^{24}O and ^{25}O
  - Motivation
  - Results
  - Discussion
- Other MoNA-Sweeper Experiments
  - Completed
  - Under Analysis

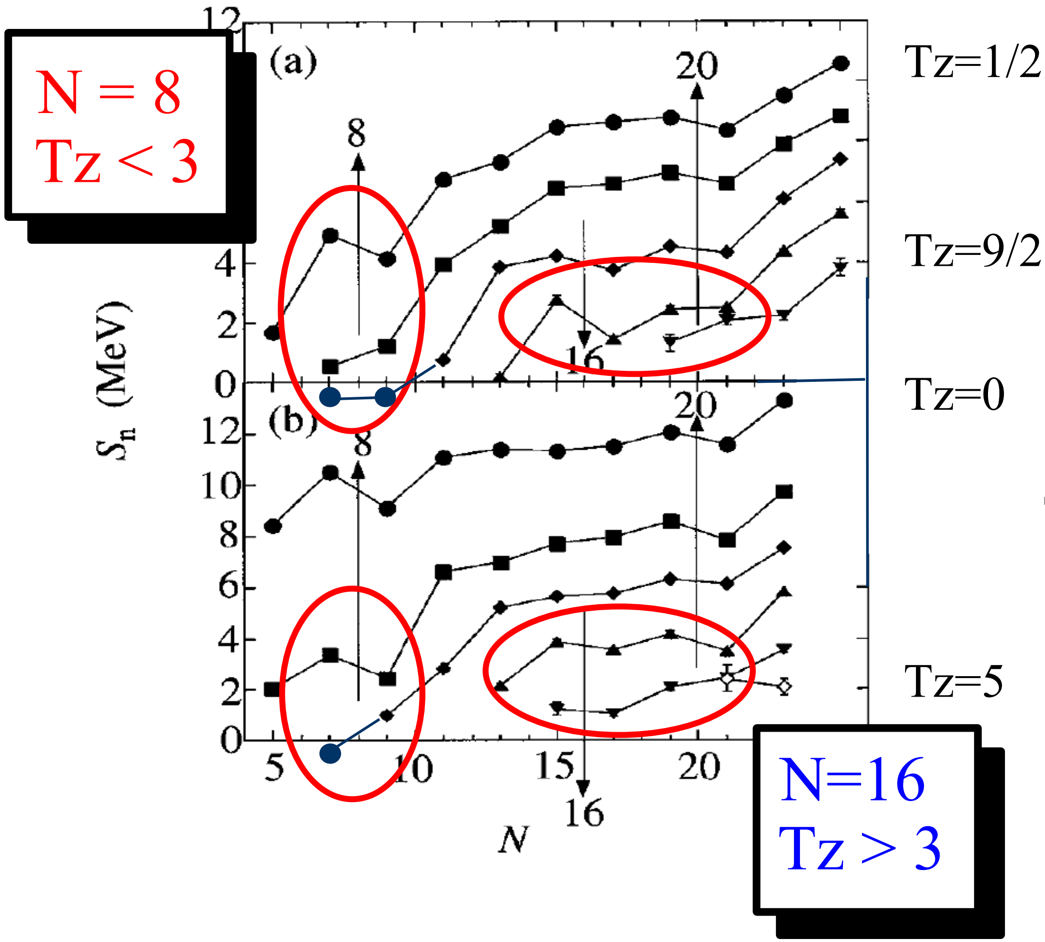
New Mg and Al Isotopes



T. Baumann et al., Nature (London) **449,** 1022 (2007)

New Magic Number at N = 16

Systematics of S_n values for different Isospins

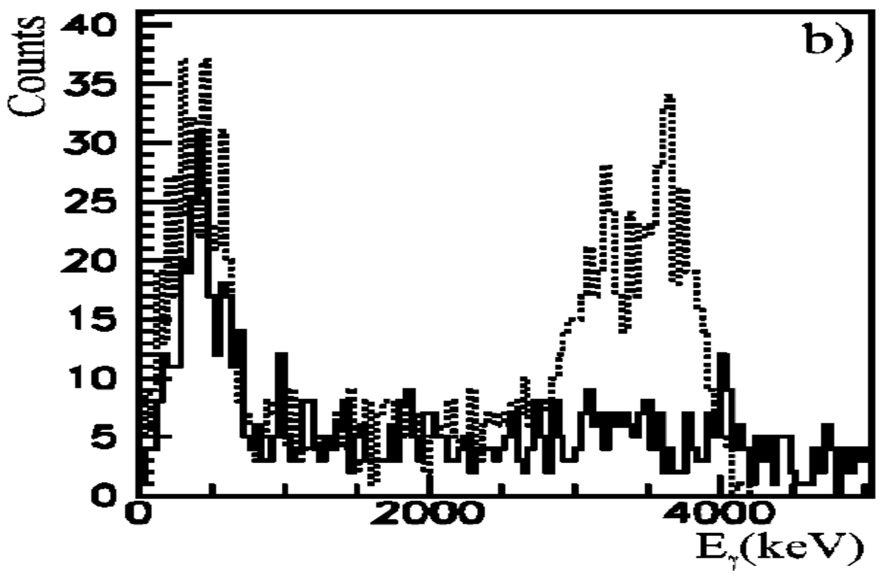


Taken from: Ozawa *et al.*, Phys. Rev. Lett. **84**, 5493 (2000)

Search for excited bound states in $^{23,24}O$

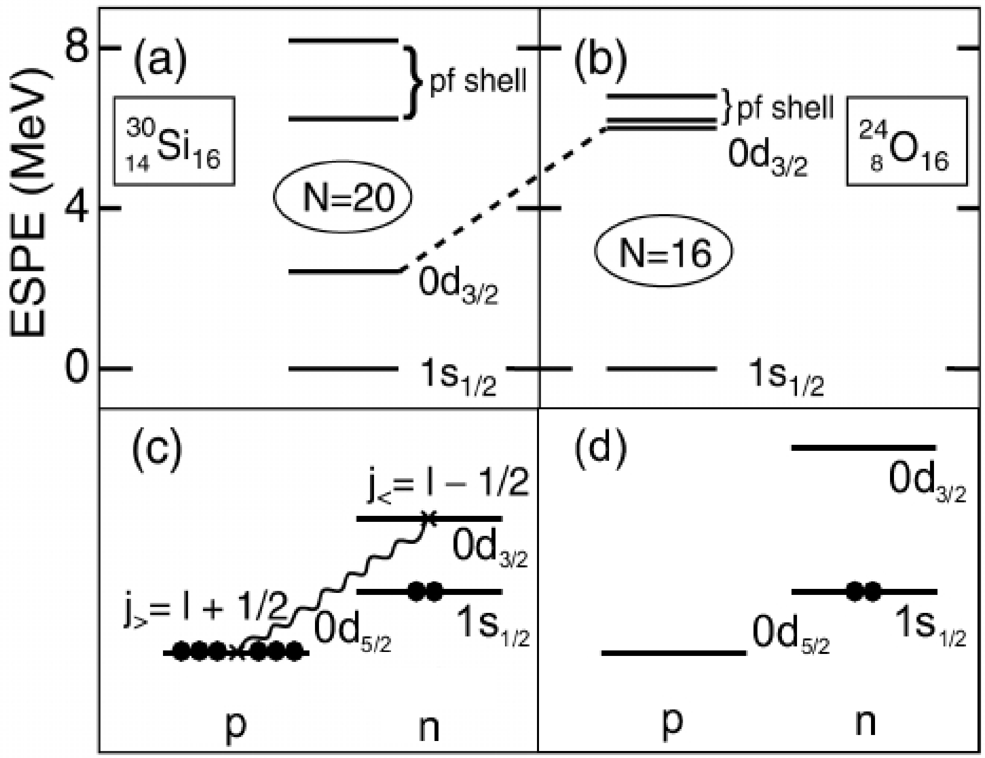
No gamma-rays observed

$^{24}O\ 2^+ > S_n = 4.09(10)$ MeV

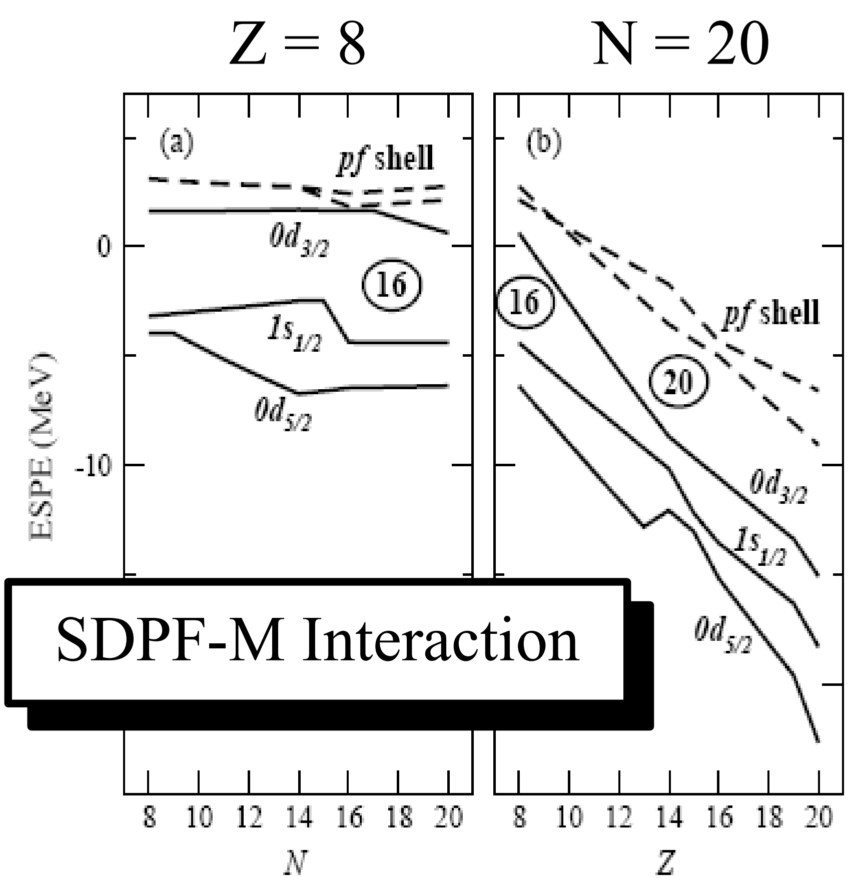


Taken from: Stanoiu *et al.*, Phys. Rev. C **69**, 034312 (2004)

Evolution of Effective Single-Particle Energies



SPEs show N = 16 shell gap for Z = 8

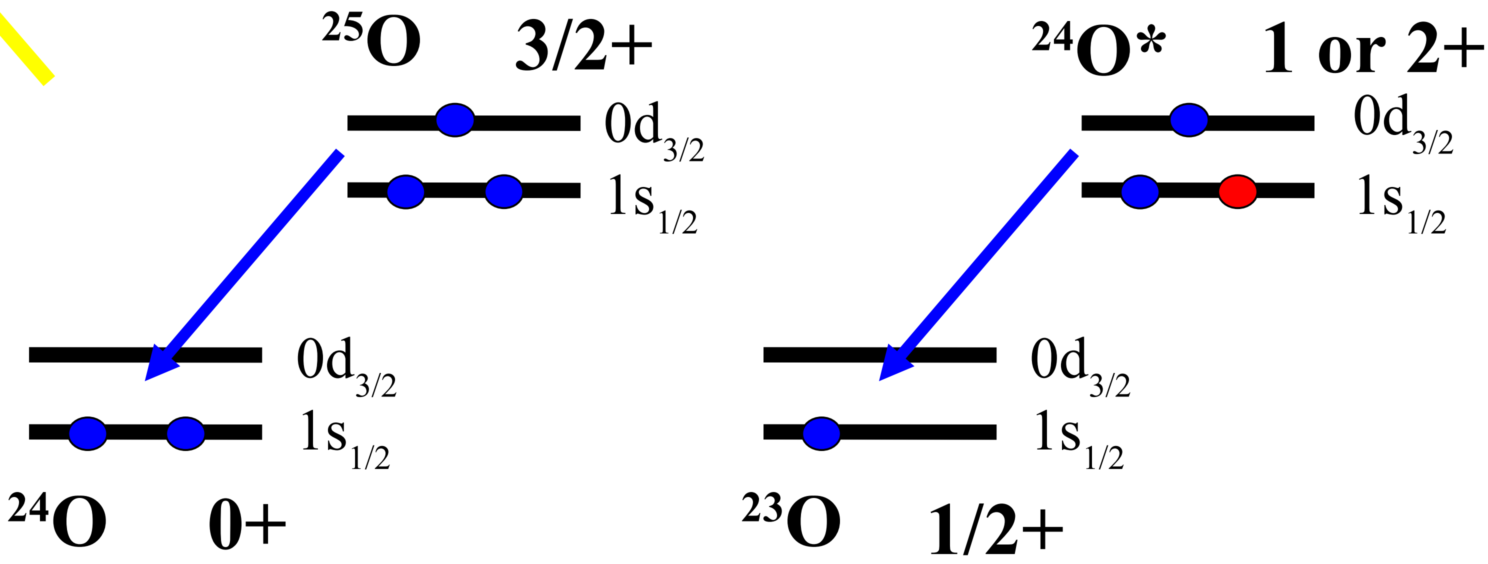


SDPF-M Interaction

- **Tensor Force**
  - Spin-isospin component
  - Migration of $0d_{3/2}$

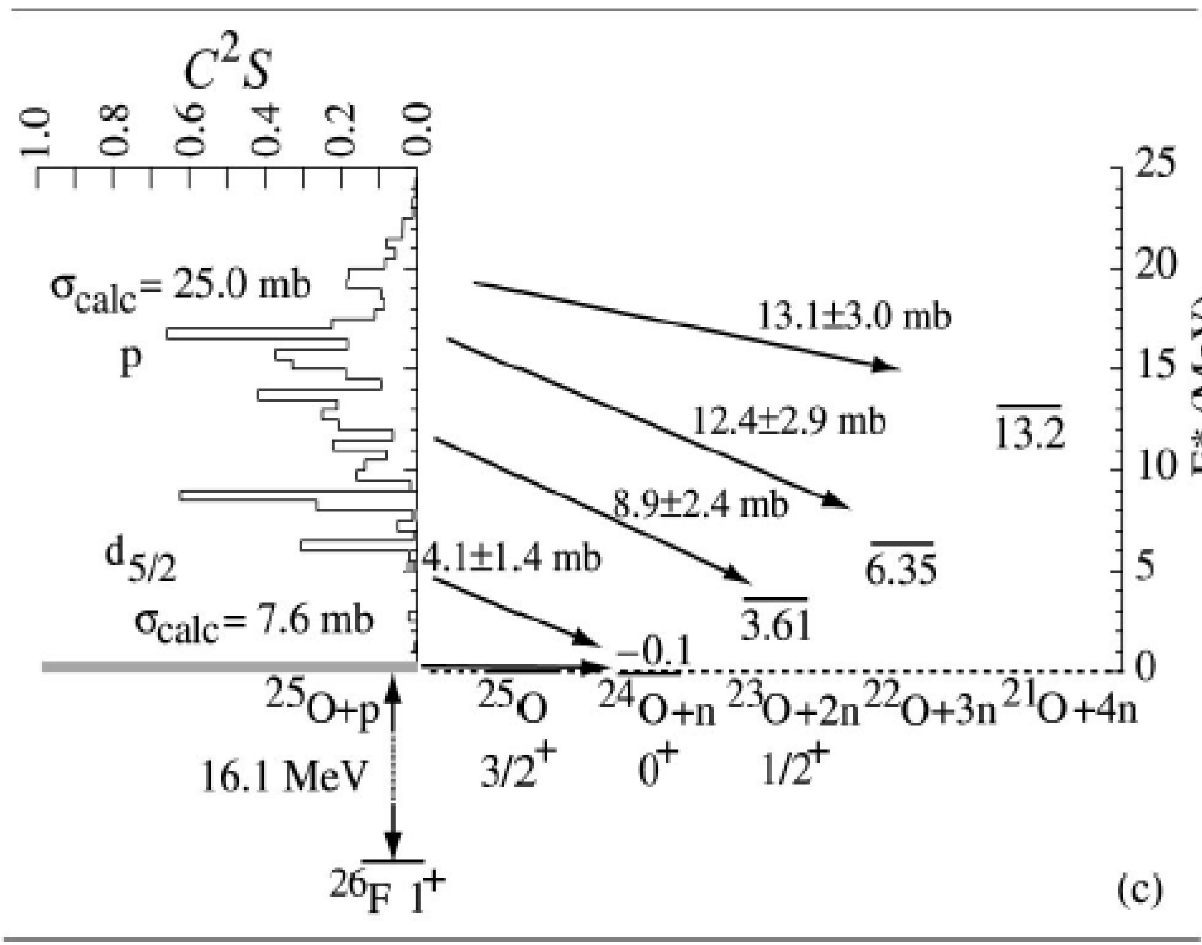
Taken from: T. Otsuka *et al.*, Eur. Phys. J. A **15**, 151 (2002)

^{24,25}O Measurement

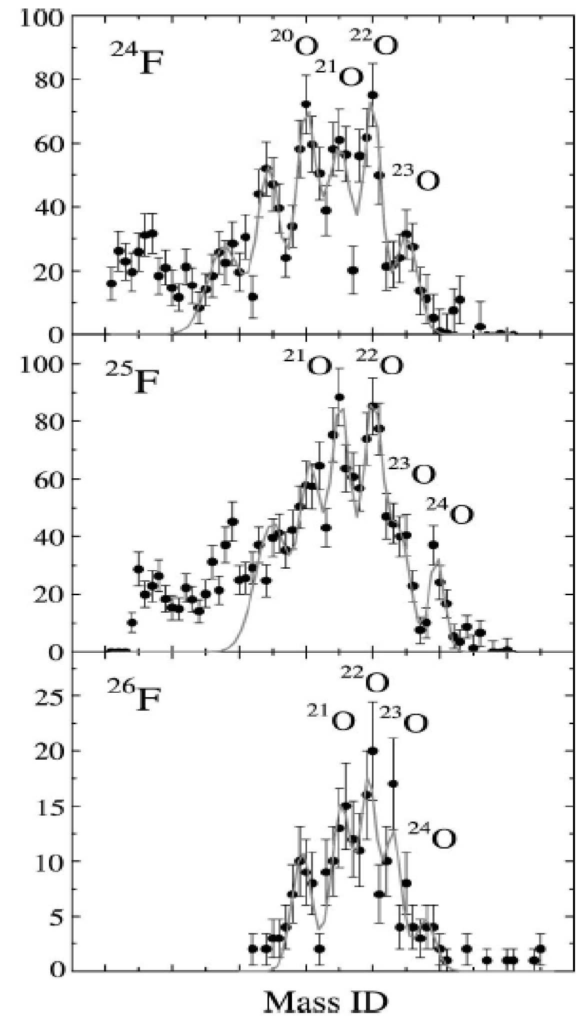


- Observe the size of the N=16 shell gap
  - Measure the ^{25}O (N=17) ground state and determine $\nu 0d_{3/2}$ orbital location
- Determine the spherical nature of ^{24}O
  - Find the location of the lowest excited states and the size of the N=16 shell gap

^{24,25,26}F Single Proton Knock-Out Reactions



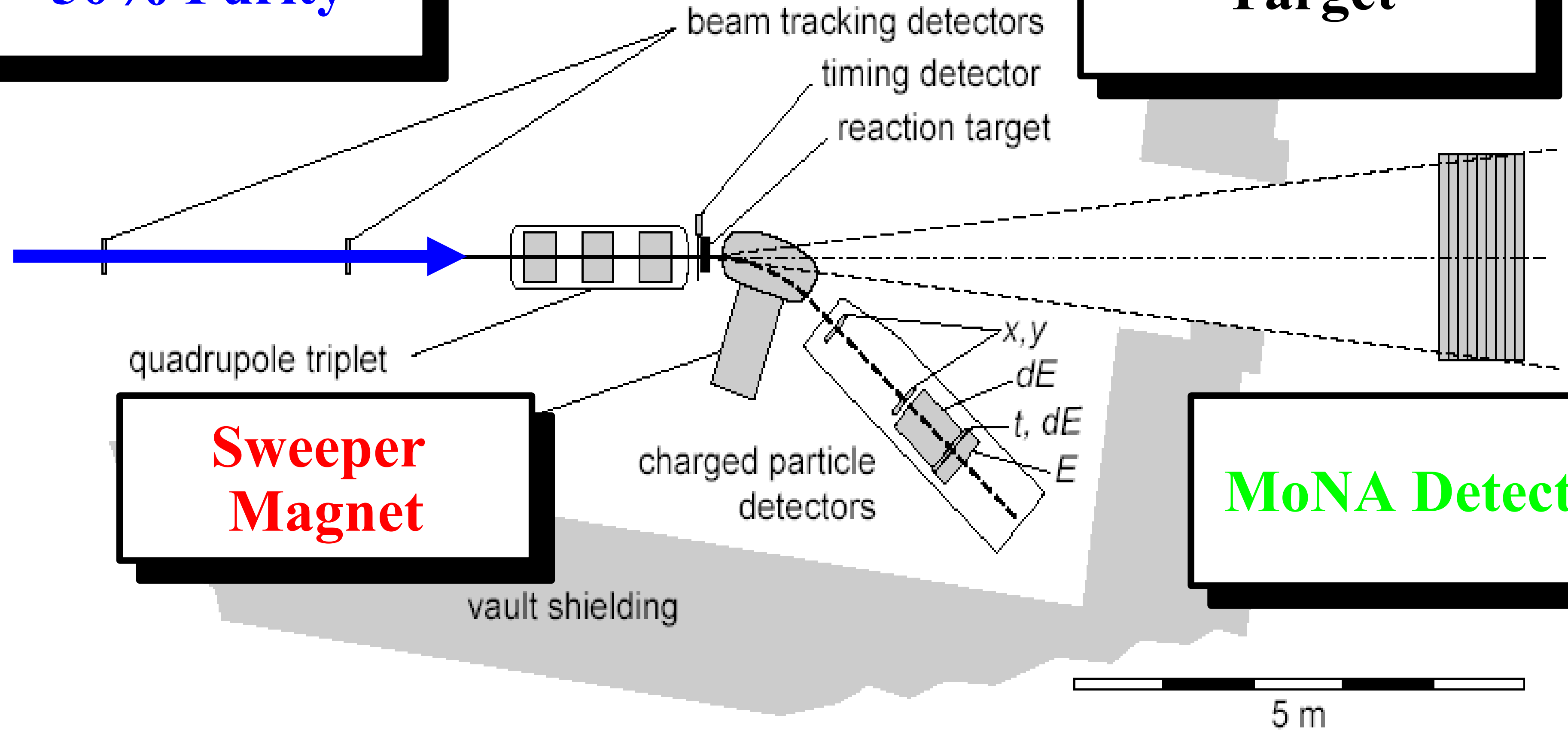
Thoennessen et al., Phys. Rev. C **68**, 044318 (2003)



Experimental Setup

85 MeV/u ^{26}F
50% Purity

470 mg/cm² Be Target

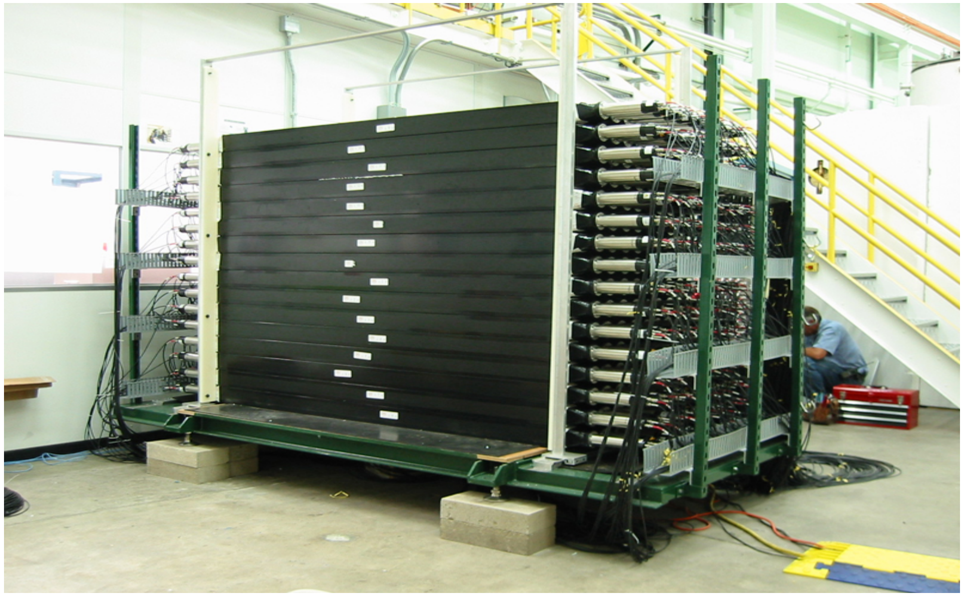


Sweeper Magnet

MoNA Detector

The Modular Neutron Array (MoNA)

- ToF Neutron Detector
- 10 X 10 X 200 cm Bar of Plastic Scintillator
- 9 Layers of 16 Stacked Bars
- Time Resolution < 1 ns
- Position Resolution ~ 10 cm
- Detection Efficiency ~ 70 % for 85 MeV/A Neutrons



Central Michigan University
Hope College
IUSB Indiana University South Bend
Concordia College Moorhead, Minnesota
Florida State University 1851
Western Michigan University 1903
Westmont College
Wabash College
Marquette University
Michigan State University

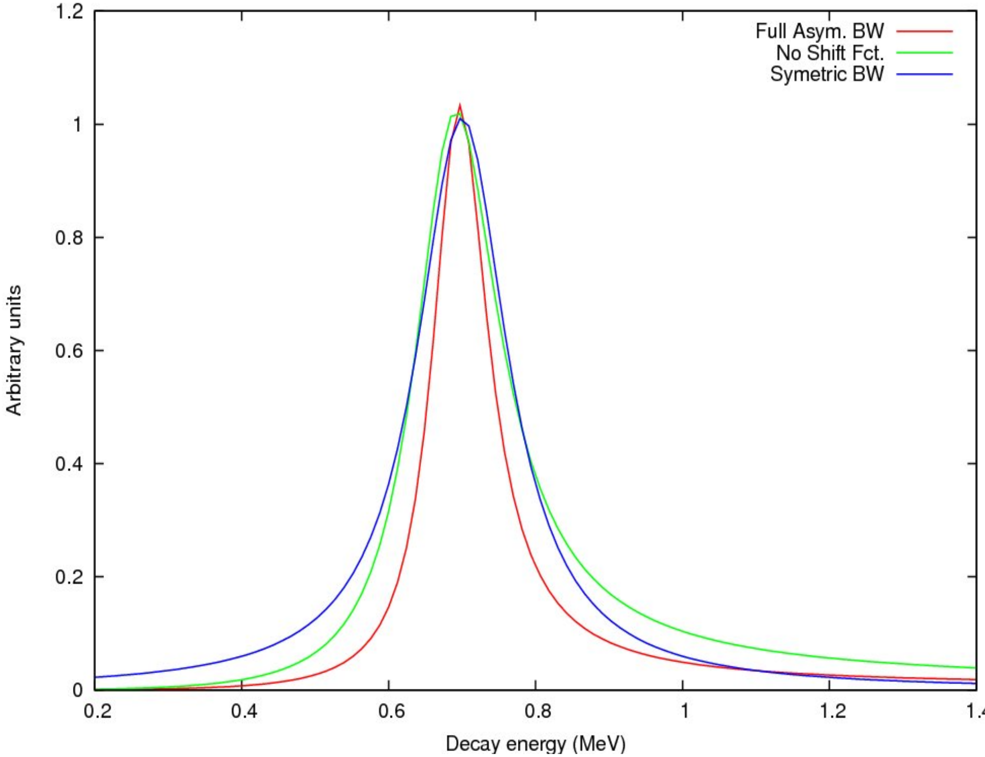
Breit-Wigner Single-Level Line-Shape

$$B.W. \sim \frac{\Gamma}{(E_{decay} + \Delta - E)^2 + \frac{\Gamma^2}{4}}$$

$$\Gamma = 2P_l(E)\gamma^2$$

$$\Delta = -(S_l(E) - B)\gamma^2$$

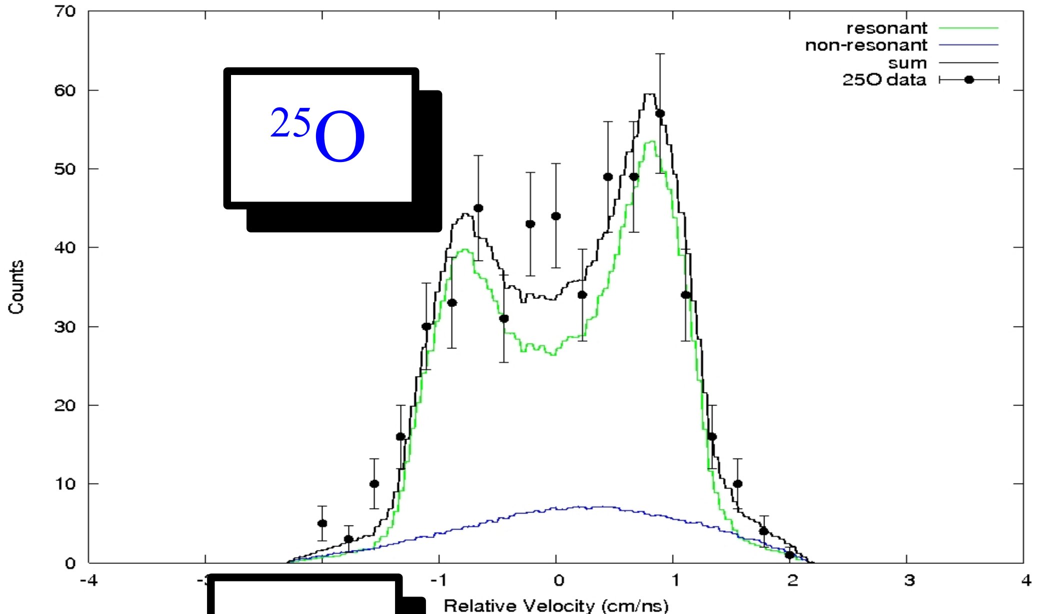
$$B = S_l(E_{decay})$$

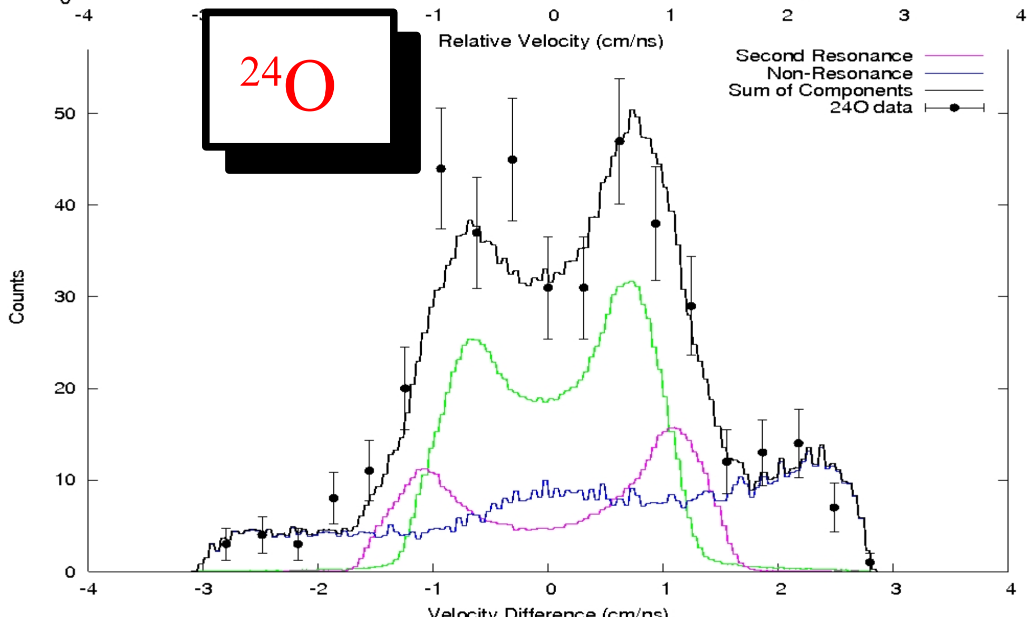


- Full energy-dependent BW single-level equation
- Lacking the shift function
- No energy dependence

[1] A. M. Lane and R. G. Thomas, Rev. Mod. Phys. 30, 257 (1958)

Non-Resonance Distributions





- 2 Non-Resonant distributions:
  - ^{25}O – Maxwellian distribution of beam velocity neutrons T=1.75 MeV
  - ^{24}O – Gaussian distribution Centroid=10 MeV Sigma=5 MeV
- The resulting shapes do not differ much in the relative decay spectrum
- Do produce different line-shapes for large relative velocity differences

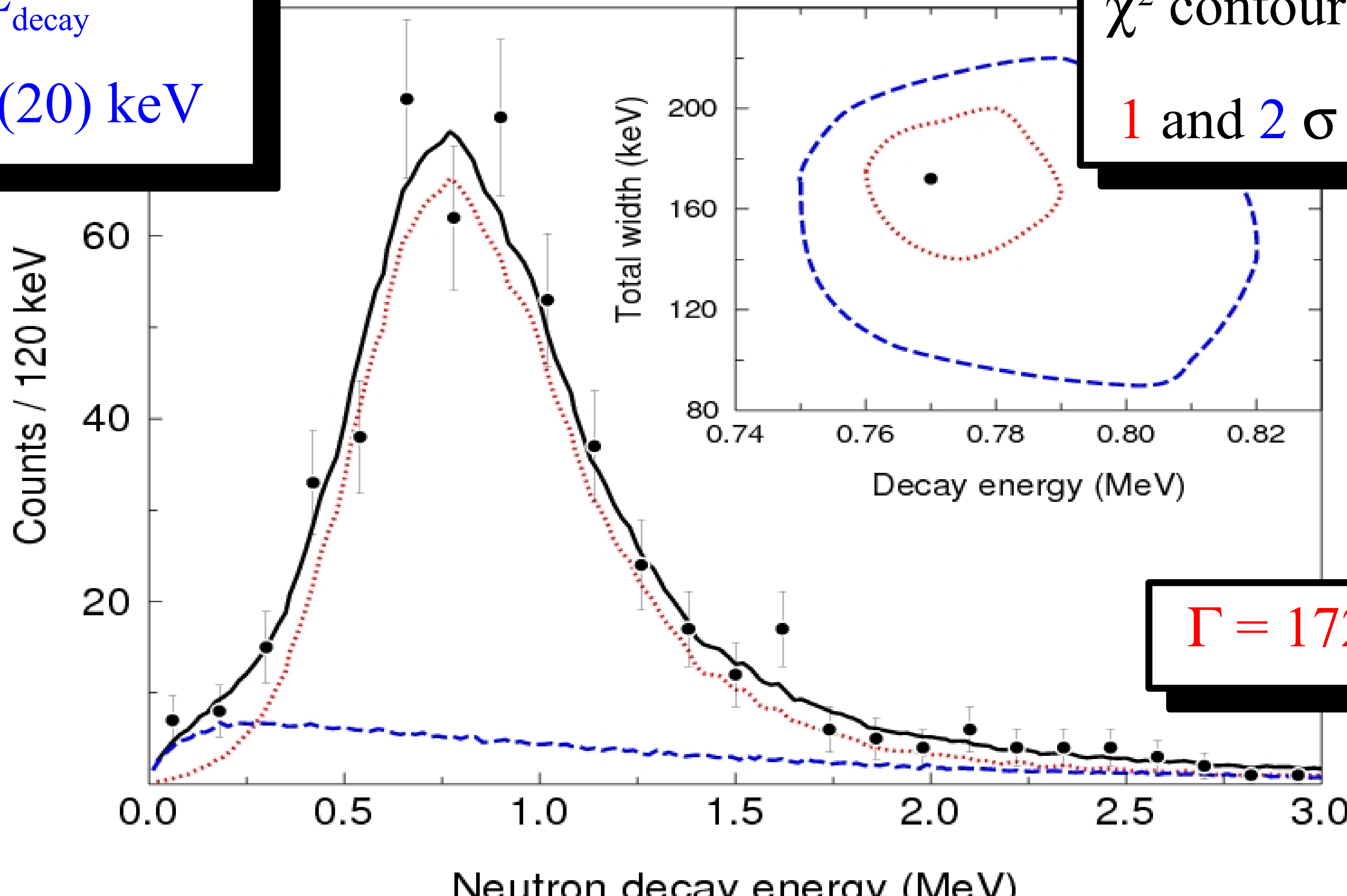
^{25}O Decay Spectrum

E_{decay} =

770(20) keV

χ^2 contours

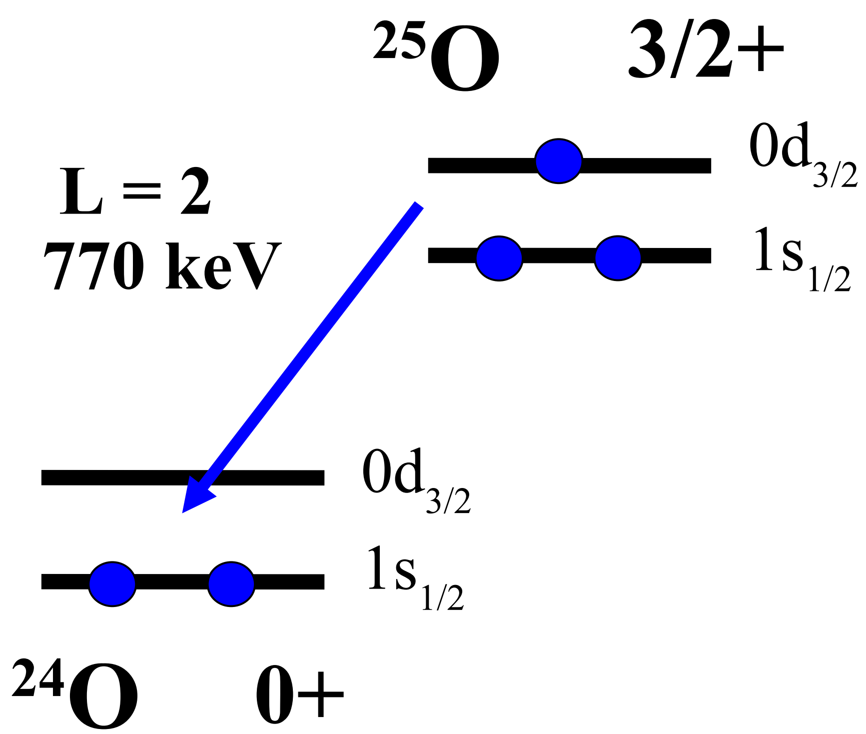
1 and 2 σ



Γ = 172(30) keV

Simulated line-shapes: (black) Sum of the Resonance (red) and non-resonance (blue) contributions (Maxwellian distribution)

^{25}O Results



Mass excess of 27440(110) keV

Assuming 0p-0h ^{24}O configuration

- ^{25}O (g.s.) - ^{24}O (g.s.)

  $\varepsilon 0d_{3/2} = 770(20)$ keV

- ^{24}O (g.s.) - ^{23}O (g.s.)

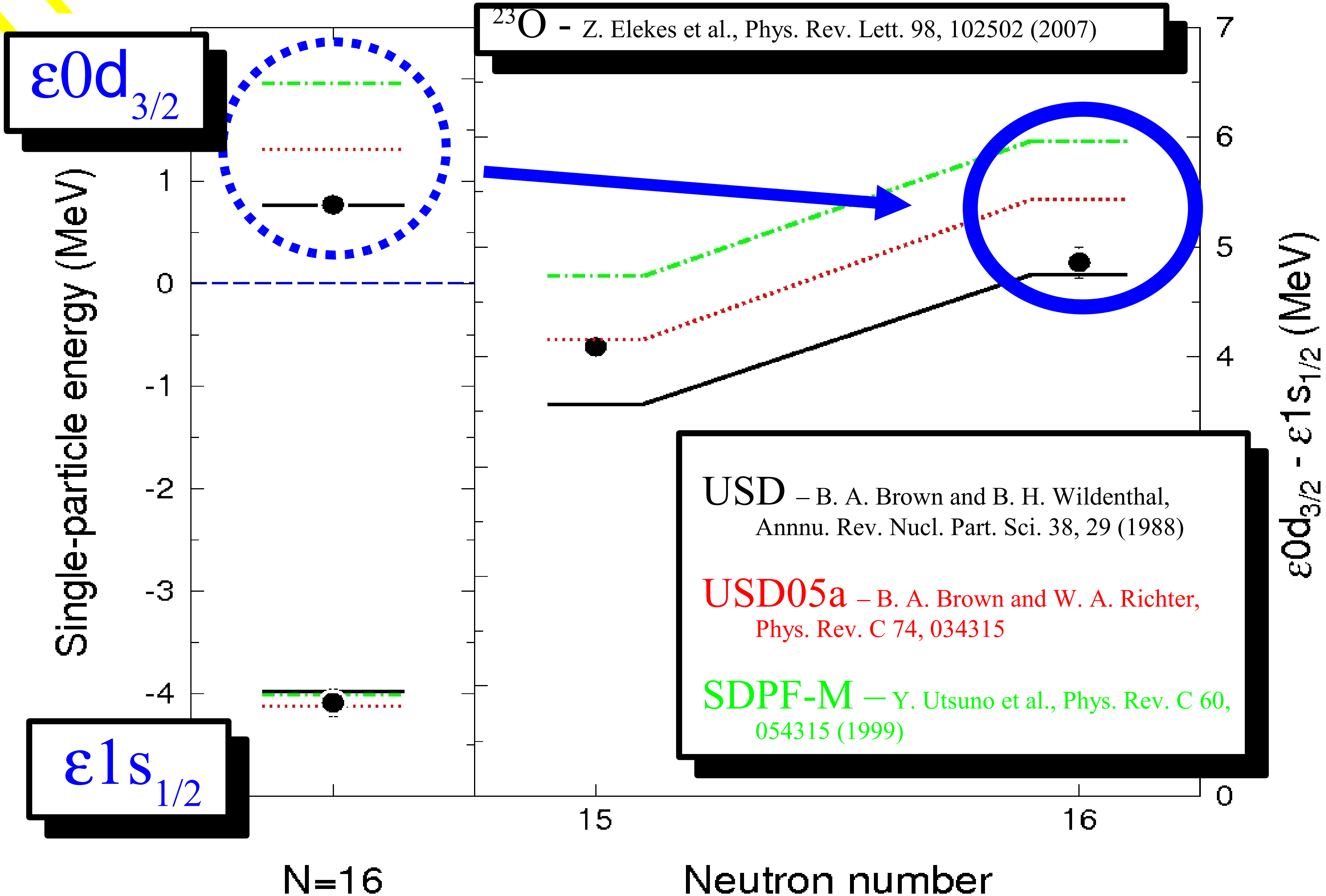
  $\varepsilon 1s_{1/2} = -4.09(13)$ MeV[1,2]

- N=16 shell gap size:

  $\varepsilon 0d_{3/2} - \varepsilon 1s_{1/2} = 4.86(13)$ MeV

[1] B. Jurado *et al.*, Phys. Lett. B **649**, 43 (2007) [2] G. Audi *et al.*, Nucl. Phys. *A729*, 2 (2003)

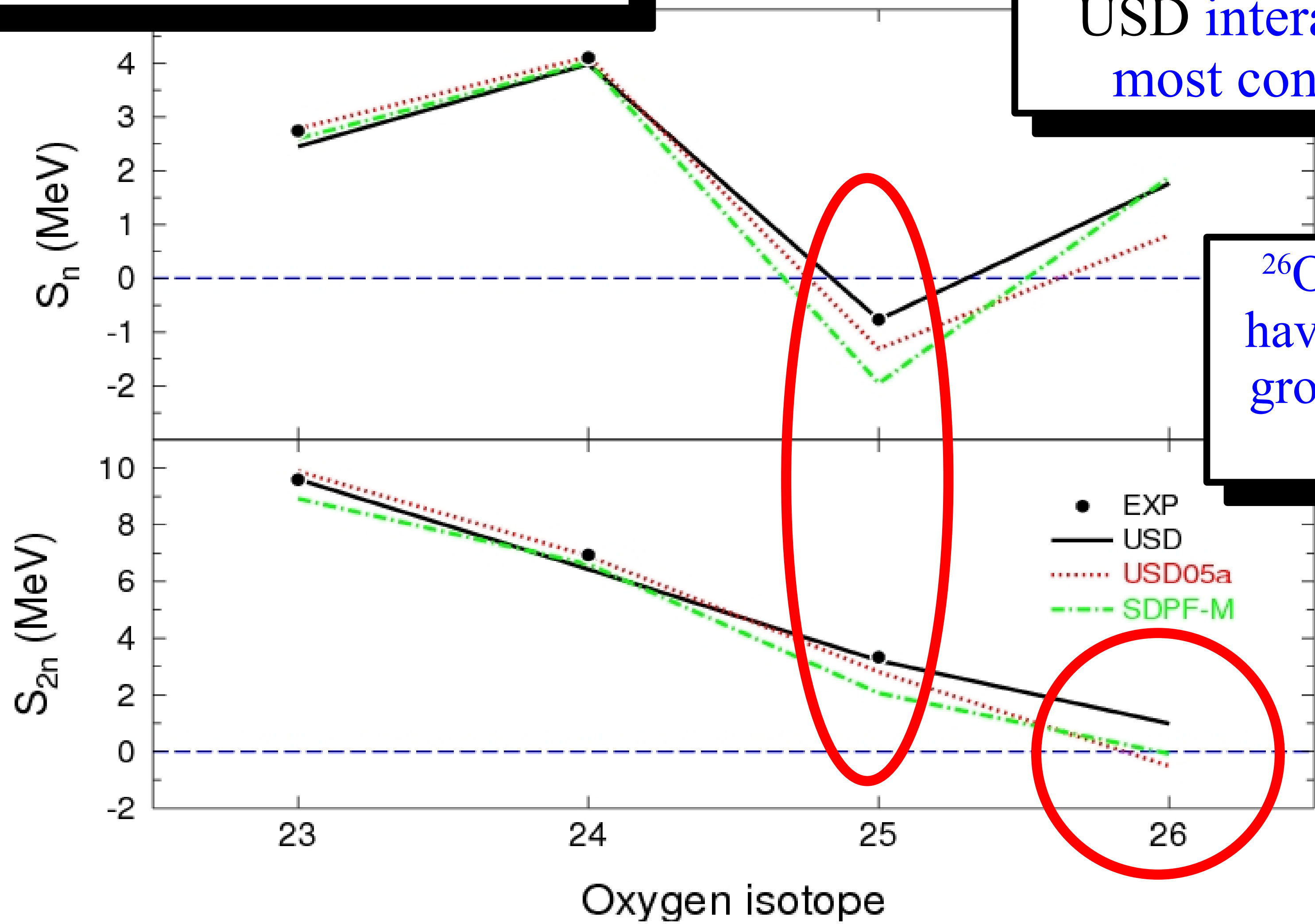
N=16 Shell gap size from SPEs



1- and 2- Neutron Separation Energies

$S_n = M(N-1,Z) - M(N,Z) + n$

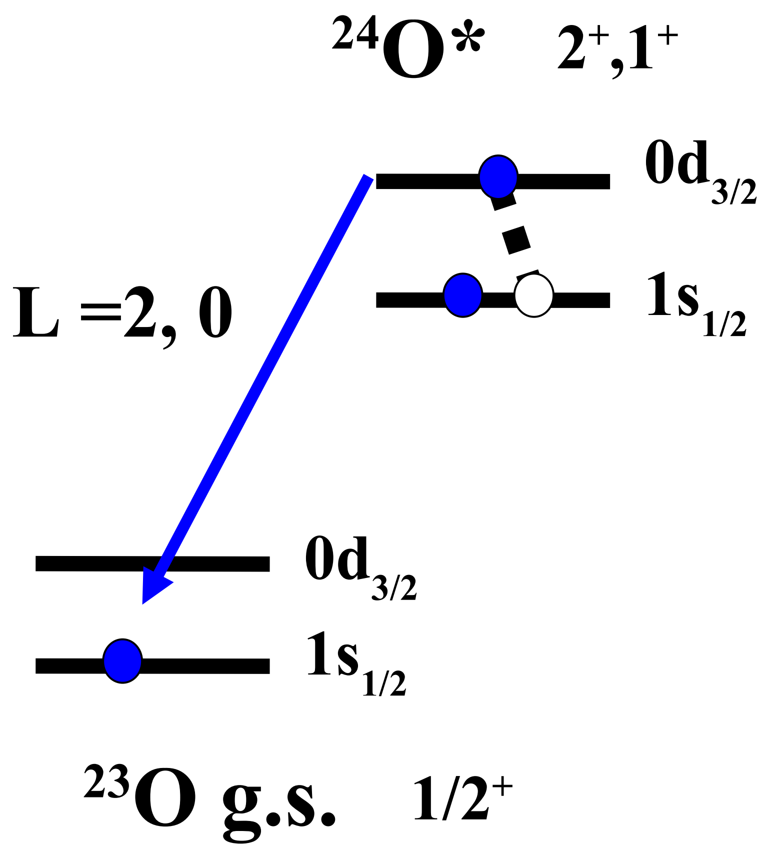
USD interaction is most consistent



^{26}O observed to have an unbound ground state (Sn < 0)

$^{24}O^*$ Results

- Single-particle configuration for first excited state gives 1^+ and 2^+
- Decay to ^{23}O $1/2^+$ g.s. by either L=0,2 inside the sd shell
- All theories predict 2^+ (L=2) as lowest
- USD, USD05a, USD05b – spectroscopic factors consistent with ZERO for L=0 decay
- One and two single-level Breit-Wigner distributions fit to data

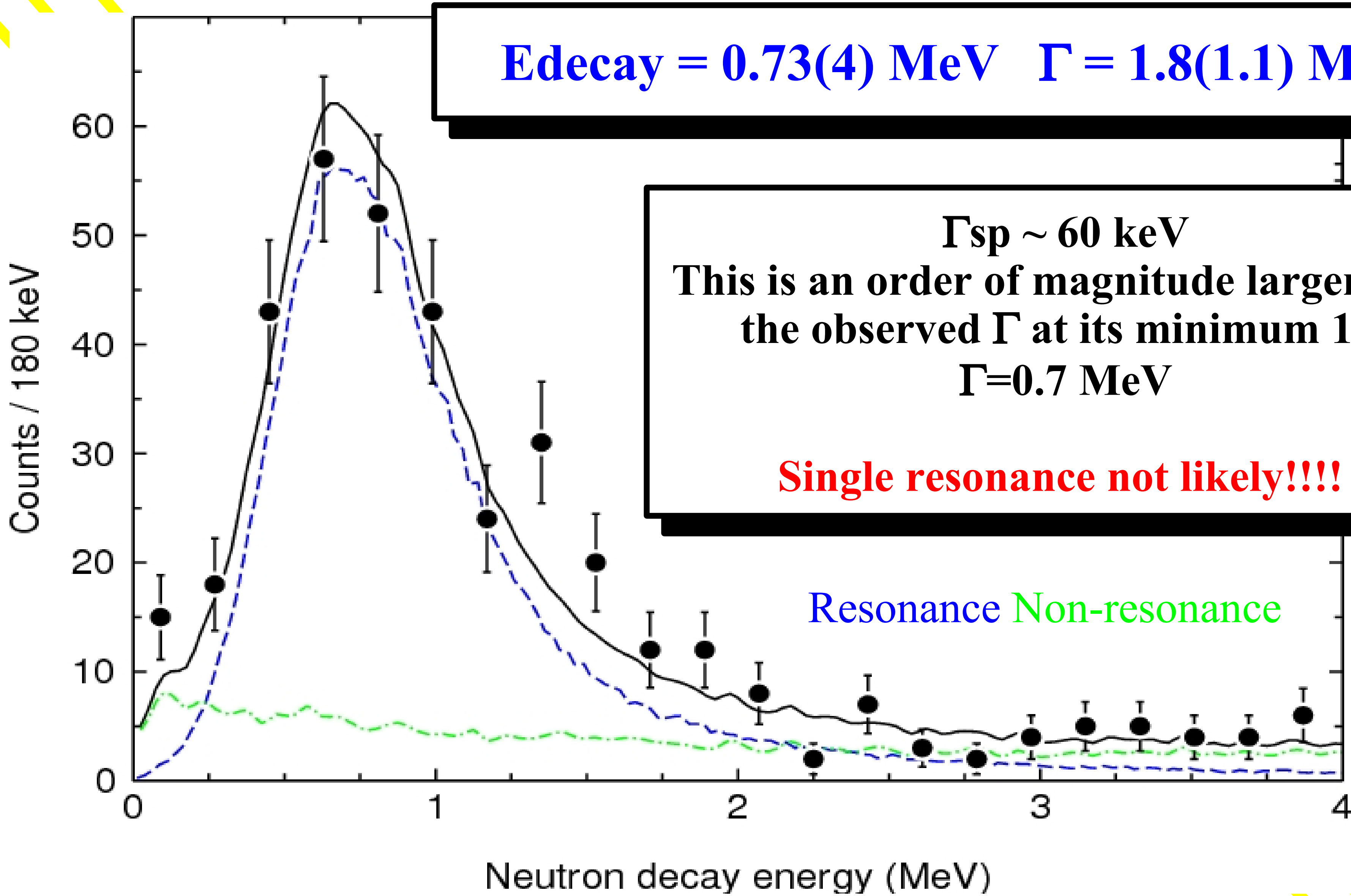


$^{24}O^*$ Measurement: Single Resonance

Edecay = 0.73(4) MeV   Γ = 1.8(1.1) MeV

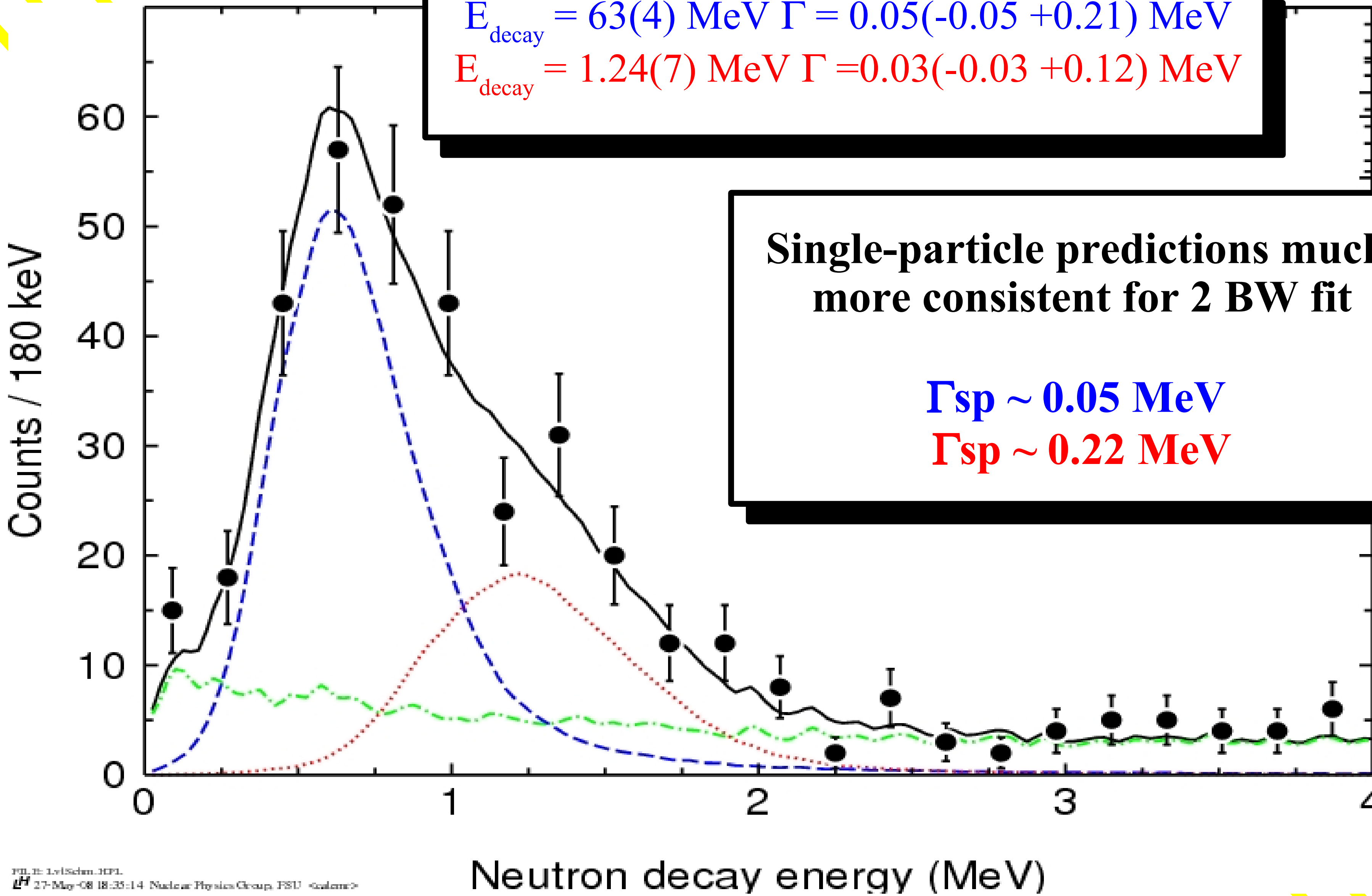
Γsp ~ 60 keV
This is an order of magnitude larger than the observed Γ at its minimum 1 σ
Γ=0.7 MeV

Single resonance not likely!!!!



$^{24}O^*$ Measurement: Two Resonances

E_{decay} = 63(4) MeV Γ = 0.05(-0.05 +0.21) MeV
E_{decay} = 1.24(7) MeV Γ =0.03(-0.03 +0.12) MeV



Single-particle predictions much more consistent for 2 BW fit

Γsp ~ 0.05 MeV
Γsp ~ 0.22 MeV

Excitation Energy of Observed States

- Excitation energy for the states

$$E^* = E_{decay} + S_n\ (^{24}O)$$

- Sensitive to ^{23}O – ^{24}O ground state masses
  - New measurement[1] gives $Sn = 4.09(10)$ MeV
  - Atomic Mass Evaluation[2] $Sn = 3.62(25)$ MeV
- Using new mass measurements decay levels are:

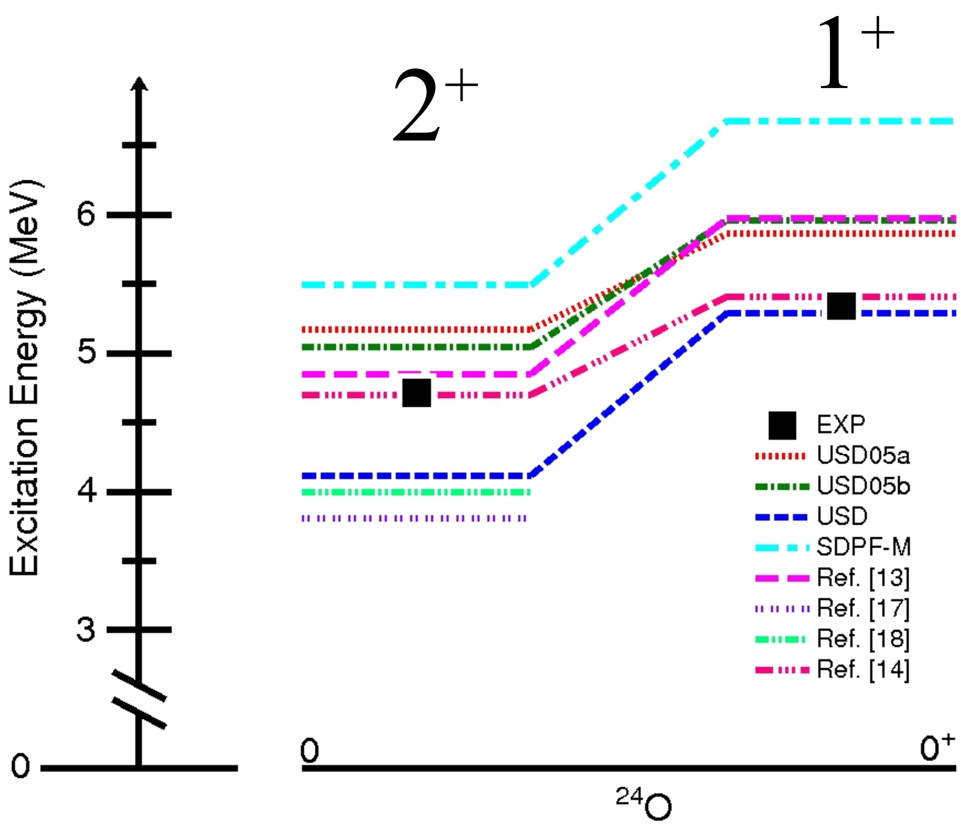
$$E^*_{2+} = 4.72(10) \qquad E^*_{1+} = 5.33(11)$$

- Ratio of contribution from 2^+ to 1^+ consistent with statistical value $(2J_{2+} + 1) / (2J_{1+} + 1)$:

~1.4 to ~1.67

[1]B. Jurado et al., Phys. Lett. B **649** (2007) [2]G. Audi et al., (2003)

^{24}O Level Scheme: Theoretical Predictions of Excited States



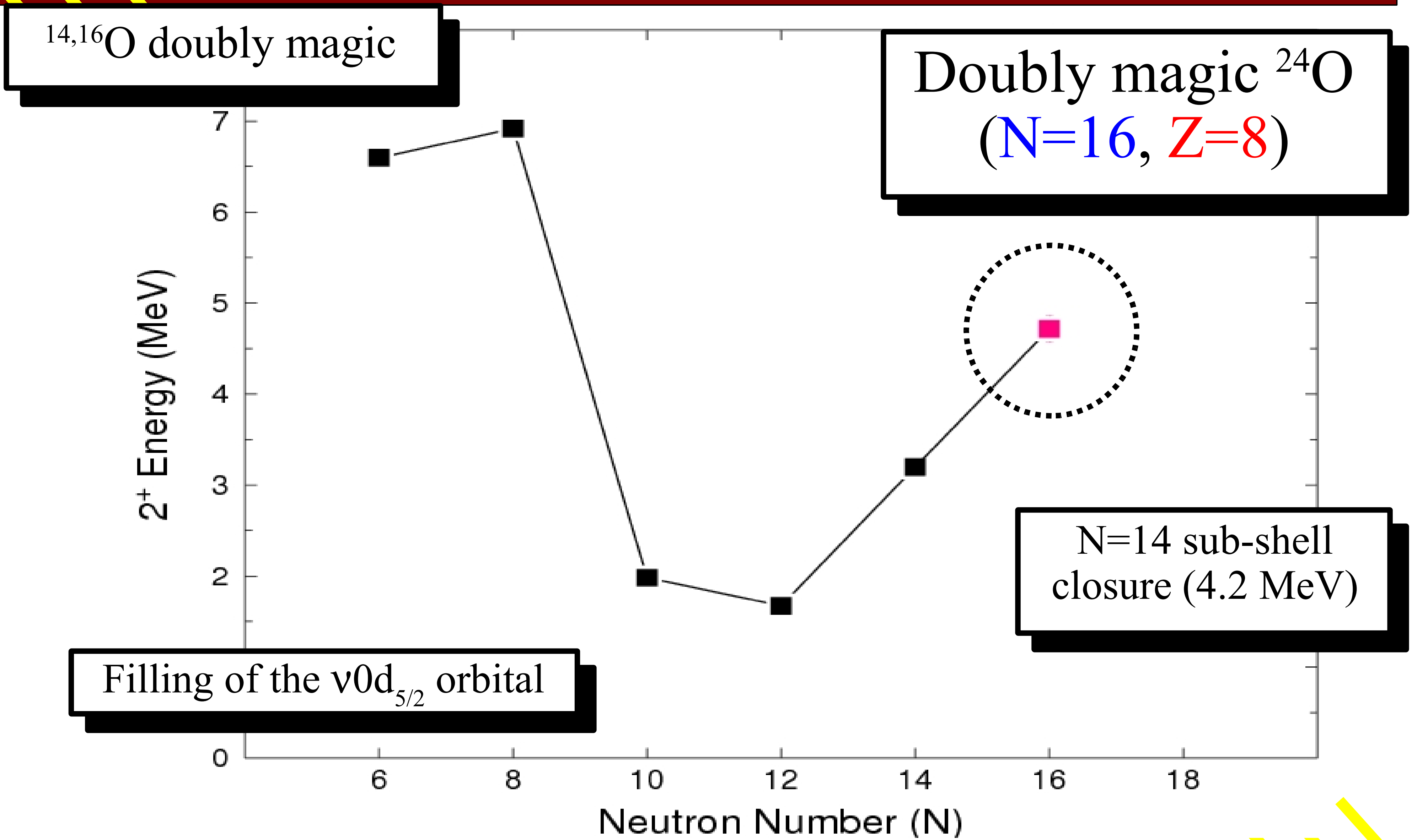
- No bound state calculation reproduces both states well
  - USD05a interaction gets level (1p – 1h residual) splitting correct
- Continuum prediction of Tsukiyama *et al.,* is the most consistent
  - Includes continuum $\nu 0d_{3/2}$ orbital in the wave function directly

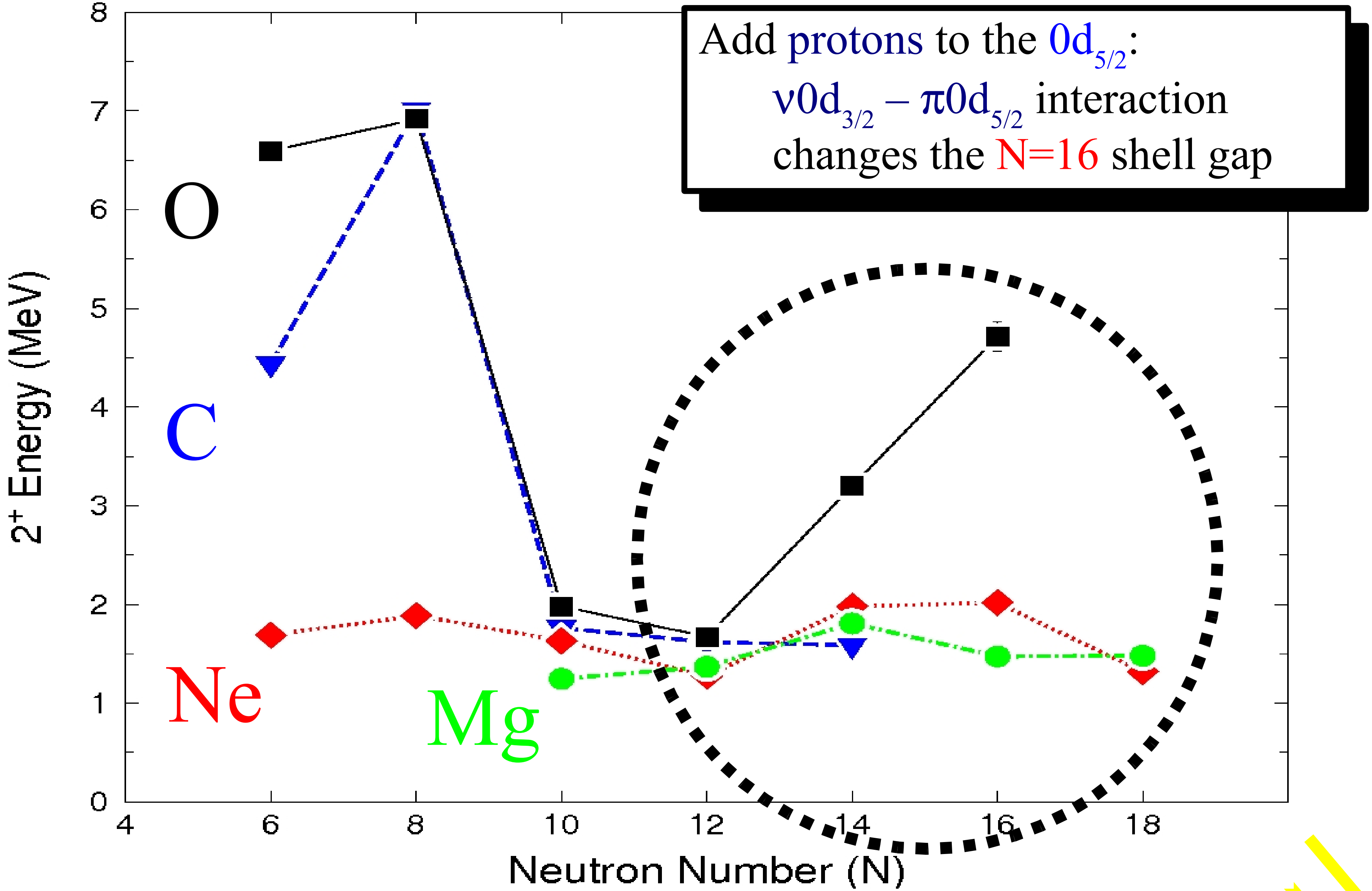
USD – B. A. Brown and B. H. Wildenthal, Annnu. Rev. Nucl. Part. Sci. **38**, 29 (1998)
USD05a,b – B. A. Brown and W. A. Richter, Phys. Rev. C **74**, 034315
SDPF-M – Y. Utsuno et al., Phys. Rev. C **60**, 054315 (1999)
A. Volya and V. Zelevinsky, Phys. Rev. Lett. **94**, 052501 (2005)
A. Obertelli et al., Phys. Rev. C **71**, 024304 (2005)
E. Khan et al., Phys. Rev. C **66**, 024309 (2002)
K. Tsukiyama and T. Otsuka, Private communication.

N = 16 Shell Gap Size

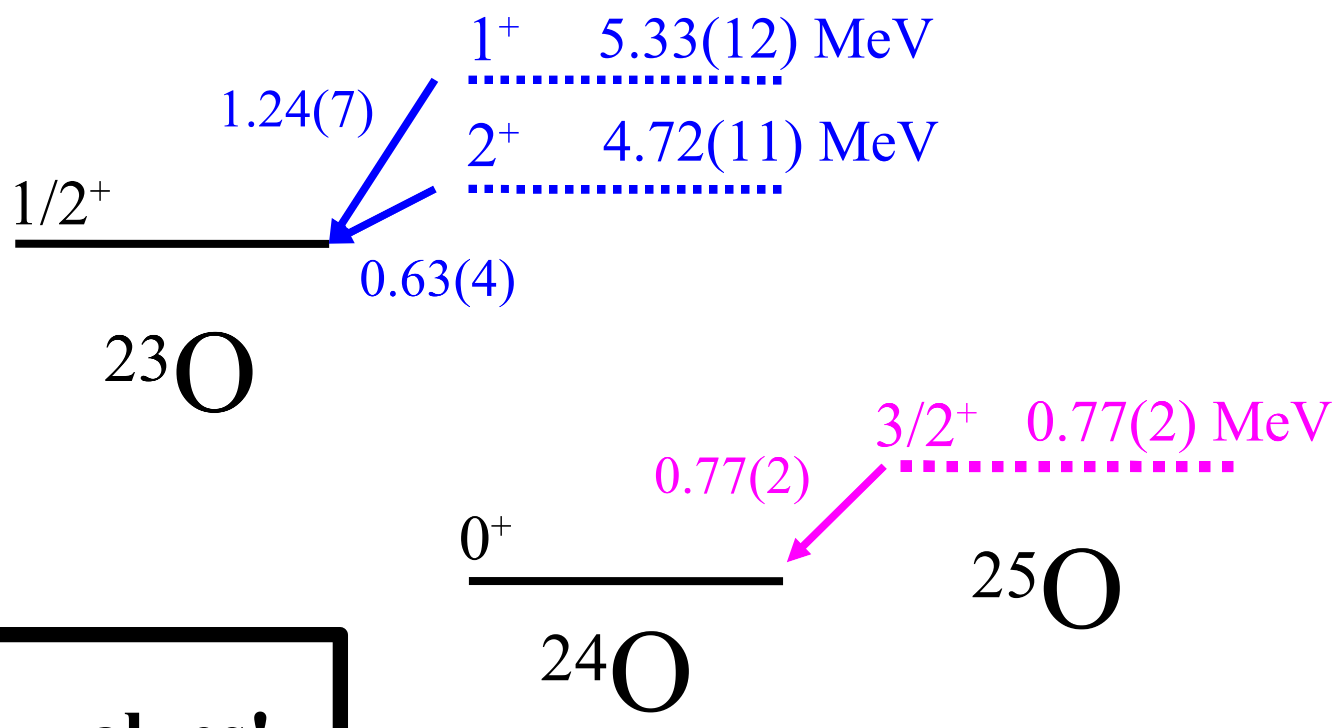
- Taking a closed ^{24}O g.s. (0p-0h)
  - Filled neutron $\nu 1s_{1/2}$
- 2^+ and 1^+ states possible from a 1p-1h excited configuration $(\nu 1s_{1/2})^1(\nu 0d_{3/2})^1$
- Weighted average of the 1^+ and 2^+ energies gives N=16 shell gap of 4.95(16) MeV
- In agreement with 4.89(13) MeV from ^{25}O ground state mass measurement[1]

^{24}O 2^+ Systematics




Add protons to the 0d5/2:
ν0d3/2 – π0d5/2 interaction
changes the N=16 shell gap
O
C
Ne
Mg
2+ Energy (MeV)
Neutron Number (N)
0
1
2
3
4
5
6
7
8
4
6
8
10
12
14
16
18

Decay results



New S_n values!

^{24}O S_n = 4.09(13) MeV

Conclusions on $^{24,25}O$

- The size of N=16 shell gap has been determined
  - ^{25}O mass measurement - 4.89(13) MeV
  - ^{24}O excited states - 4.95(16) MeV
- ^{24}O shows evidence of a doubly magic nucleus
  - Relatively large shell gap at N=16
  - Very high 2^+ energy
- Possible by neutron spectroscopy using a knock-out reaction

C. R. Hoffman *et al.*, Phys. Rev. Lett. **100**, 152502 (2008)

Completed MoNA-Sweeper Experiments

PRL **99,** 112501 (2007) PHYSICAL REVIEW LETTERS week ending 14 SEPTEMBER 2007

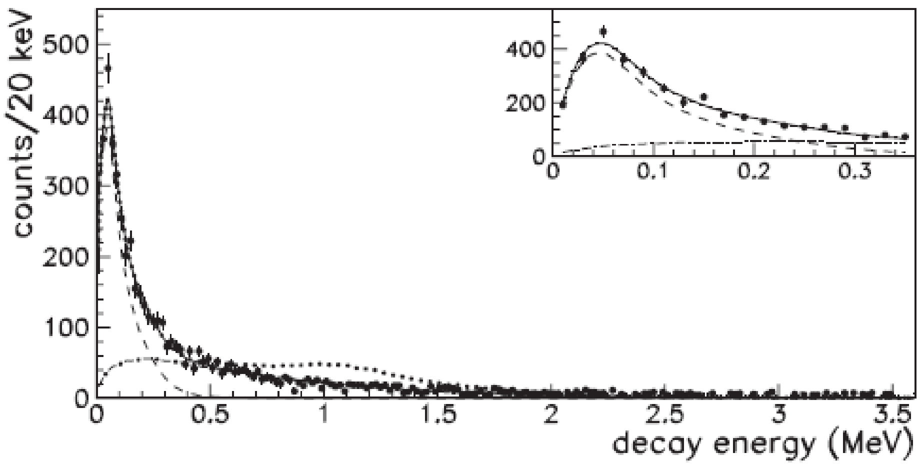
Selective Population and Neutron Decay of an Excited State of ^{23}O

A. Schiller,[1,*] N. Frank,[1,2,3] T. Baumann,[1] D. Bazin,[1] B. A. Brown,[1,2] J. Brown,[4] P. A. DeYoung,[5] J. E. Finck,[6] A. Gade,[1,2] J. Hinnefeld,[7] R. Howes,[8] J.-L. Lecouey,[1,†] B. Luther,[3] W. A. Peters,[1,2] H. Scheit,[1] M. Thoennessen,[1,2] and J. A. Tostevin[1,2,9]

^{26}Ne + Be Target

-2p1n ^{23}O*

First excited hole state ($0d_{5/2}$) strongly populated



E_{decay} = 0.45(2) MeV T=0.7 MeV

Completed MoNA-Sweeper Experiments

PHYSICAL REVIEW C **78**, 044303 (2008)

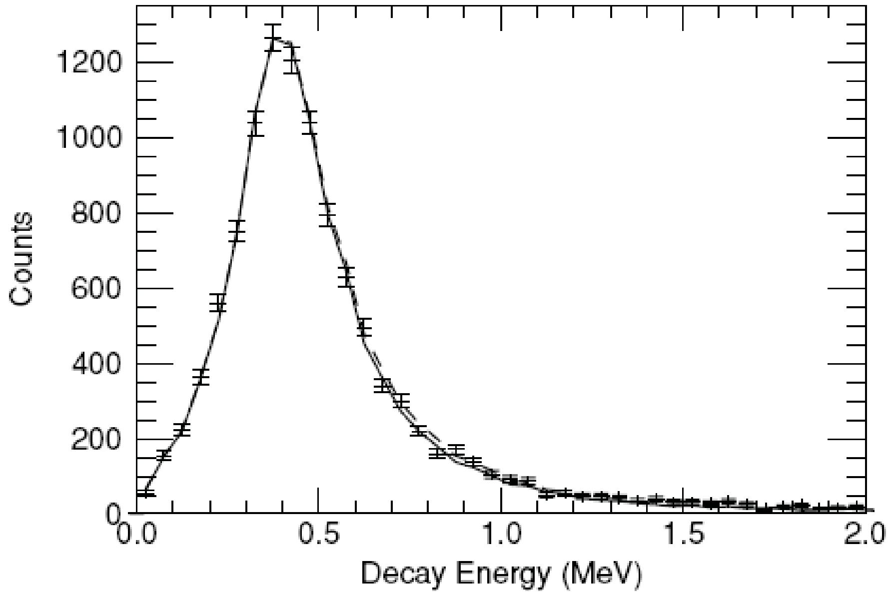
Ground state energy and width of ^{7}He from ^{8}Li proton knockout

D. H. Denby,[1] P. A. DeYoung,[1] T. Baumann,[2] D. Bazin,[2] E. Breitbach,[3] J. Brown,[4] N. Frank,[2,5,*] A. Gade,[2,5] C. C. Hall,[1] J. Hinnefeld,[6] C. R. Hoffman,[7] R. Howes,[3] R. A. Jenson,[8] B. Luther,[8] S. M. Mosby,[2,5] C. W. Olson,[8] W. A. Peters,[2,5] A. Schiller,[9] A. Spyrou,[2] and M. Thoennessen[2,5]

^{8}Li on Be Target @ 41 MeV/u

-p ^{7}He

No evidence for low lying $1/2^-$ excited state



E_{decay} = 400(10) keV $\Gamma = 160^{+40}_{-15}$ keV

Completed MoNA-Sweeper Experiments

Available online at www.sciencedirect.com

ScienceDirect

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Nuclear Physics A 801 (2008) 101–113

NUCLEAR PHYSICS A

www.elsevier.com/locate/nuclphysa

^{48}Ca + Be @ 60 MeV/u

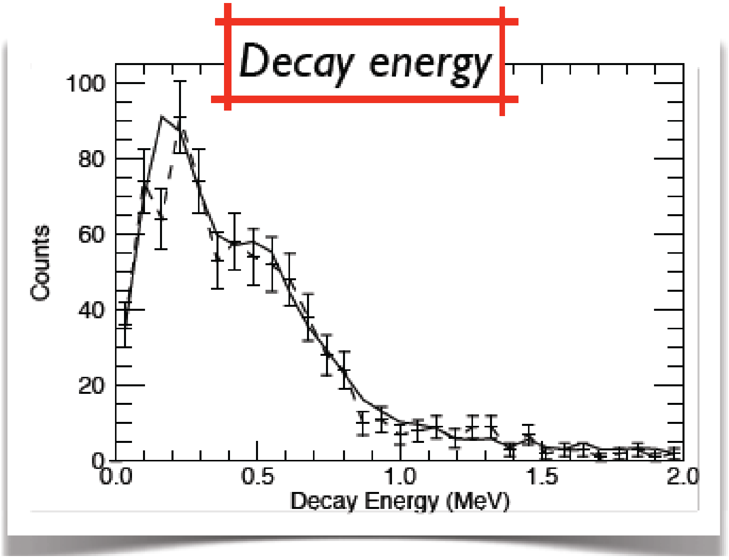
Production of nuclei in neutron unbound states via primary fragmentation of ^{48}Ca

G. Christian [a,b], W.A. Peters [a,b,1], D. Absalon [c], D. Albertson [a,b], T. Baumann [a], D. Bazin [a], E. Breitbach [c], J. Brown [d], P.L. Cole [e], D. Denby [f], P.A. DeYoung [f], J.E. Finck [g], N. Frank [a,b,2], A. Fritsch [d], C. Hall [f], A.M. Hayes [a,b], J. Hinnefeld [h], C.R. Hoffman [i], R. Howes [c], B. Luther [e], E. Mosby [j], S. Mosby [j], D. Padilla [f], P.V. Pancella [k], G. Peaslee [f], W.F. Rogers [j], A. Schiller [l], M.J. Strongman [a,b], M. Thoennessen [a,b,*], L.O. Wagner [e]

Ongoing and Future MoNA-Sweeper Experiments

- ^{12,13}Li
  - ^{14}B and ^{14}Be Beams
- ^{16}Be, ^{16}B
  - ^{17}C and ^{17}B Beams
- ^{24}N g.s.
  - ^{26}F Beam
- ^{26}O g.s.
  - ^{27}F Beam

All Under Analysis!!!



Taken from: Spyrou et al., DNP 2008

Acknowledgments

Florida State: S. L. Tabor, G. V. Rogachev and A. Volya

MoNA Collaboration: M. Thoennessen[a], D. Bazin[a], T. Baumann[a], G. Christian[a],P. Deyoung[b], N. Frank[a], J. Hinnefeld[c], W. A. Peters[a], A. Schiller[a], and H. Scheit[a]

[a] NSCL / Michigan State University

[b] Hope College

[c] Indiana University at South Bend

University of Tokyo: K. Tsukiyama and T. Otsuka