Can the Neutrino tell us its Mass by Electron Capture?

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University of Tuebingen;

Heidelberg, MPI 20. May 2015

1)Faessler, Gastaldo, Simkovic, J. Phys. G 42, 015108 (2015)

2)Faessler, Simkovic, Phys. Rev C91, 045505 (2015)

3)Faessler, Enss, Gastaldo, Simkovic, arXiv: 1503.2282

Not about Experiment, the Calorimetric Detector.

Popular Public Resonance of Paper 2:

Die Chemie-News hat eine Meldung mit Artikel auf Ihre Internetseite gesetzt:
http://www.chemie.de/news/152561/wird-das-neutrino-beim-einfang-eines-elektrons-sein-gewicht-verraten.html

Das Physikportal Pro-Physik der DPG hat einen Artikel unter:
http://www.pro-physik.de/details/news/7865871/Verraten_Neutrinos_beim_Einfang_ihre_Masse.html

Popular Public Response for second Paper:

Chemie-News:

Wird das Neutrino beim Einfang eines Elektrons sein Gewicht verraten?

Forscher halten nach neuen Berechnungen die Lösung einer großen Frage der Elementarteilchenphysik für möglich

22.04.2015

Physik-Portal:

Verraten Neutrinos beim Einfang ihre Masse?

21. April 2015

Neuen Berechnungen zufolge kann Projekt ECHo eine der großen Fragen der Elementar-teilchen-physik klären.

Some open problems for neutrinos:

- 1) The absolute value of the anti-neutrino mass?
- 2)The absolute value of the neutrino mass? (Topic of this talk)
- 3)Dirac or Majorana particle?
- 4)The Neutrino Hierarchy problem?

2) Determination of the electron neutrino mass by electron capture in

$$^{163}_{67}\text{Holmium} + e^-_{\text{bound}} \rightarrow {}^{163}_{66}\text{Dysprosium}^* + \nu_e$$

Gamow-Teller:

bound electron(s1/2,p1/2) + proton [523] $[h_{11/2}]7/2$

$\rightarrow$ neutron [523] $[h_{9/2}+f_{7/2}]$ $5/2^-$ + neutrino

2) Determination of the electron neutrino mass by electron capture in

$$^{163}_{67}\text{Holmium} + e^-_{\text{bound}} \rightarrow {}^{163}_{66}\text{Dysprosium}^* + \nu_e$$

roposed by De Rujula and Lusignoli, Phys. Lett. 118B, 429 (1982).

Competing Experiments with 163 Holmium in preparation:

) ECHo: Heidelberg, Mainz, Tübingen, … ;

Christian Enss, Loredana Gastaldo, Blaum, Düllmann, …

) HOLMES: Milano Biccoca; Stefano Ragazzi, Angelo Nucciotti, …

) NuMECS: Los Alamos, Michigan State Univ. (NSCL), Central Michigan University, Stanford Univ. ; Gerd Kunde, …

Determination of the electron neutrino mass by electron capture in $^{163}_{67}\text{Holmium} + e^-_{\text{bound}} \rightarrow ^{163}_{66}\text{Dysprosium}^* + \nu_e$

$Q(\text{ECHo}) = (2.843 \pm 0.009^{stat} \pm 0.06^{syst})\ [\text{keV}] \approx 2.8\ [\text{keV}]$

Loredana Gastaldo et al.

$Q = E^*(\text{excited Dy-Atom}) + E_\nu$

$= E^*(\text{Dy}) + \sqrt{(T_\nu)^2 + m_\nu^2}$

Upper end of spectrum:

$E^*(\text{Dy, max}) = Q(\text{value}) - m_\nu$

For Electron Capture (in Holmium 163)

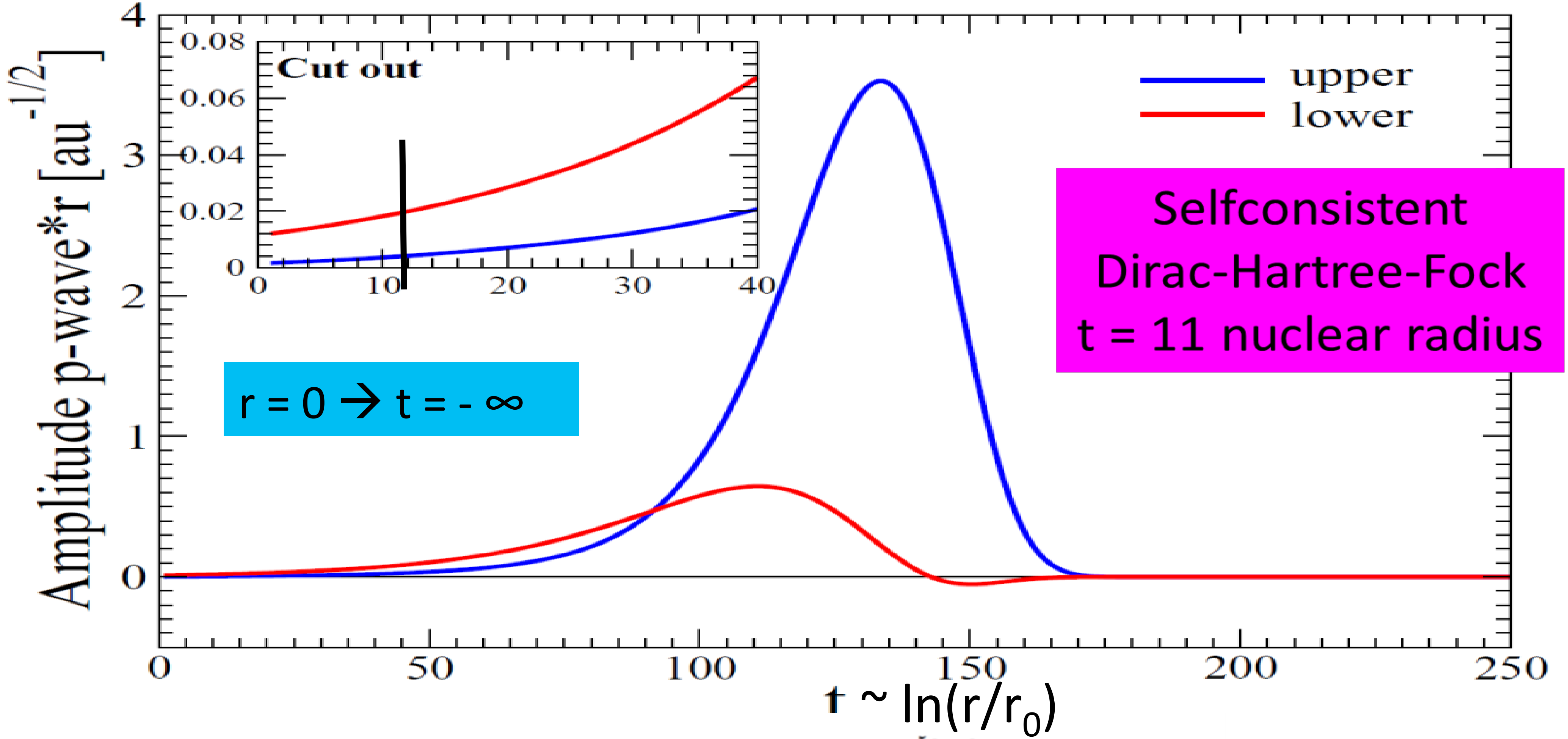
1) Electron at nucleus → s1/2 and p1/2

2) Electron binding energy < Q-value ≈ 2.8 [keV]

$(1s_{1/2}$, K,Ho) = 55.6 keV
$(2s_{1/2}$, L1,Ho) = 9.4 keV
$(2p_{1/2}$,L2,Ho) = 8.9 keV
$(2p_{3/2}$,L3,Ho) = 8.1 keV

E($3s_{1/2}$,M1,Ho) = 2.0 keV
E($3p_{1/2}$,M2,Ho) = 1.8 keV
E($4s_{1/2}$, N1,Ho) = 0.4 keV
E($4p_{1/2}$, N2,Ho) = 0.3 keV
E($5s_{1/2}$,O1,Ho) = 0.05 keV

The upper and lower relativistic amplitude of the 2p1/2 wave function in Ho multiplied by r



$t = \ln(r/r_0)/h; \quad h = 0.05; \quad r_0 = 7.1469 \cdot 10^{-5}[au]. \quad t = 1, 2, ...251$

Selfconsistent Dirac-Hartree-Fock [Grant, Desclaux and Ankudinov et al. Comp. Phys. Com. 98 (1996) 359] for $_{67}$Ho and $_{66}$Dy*

$$|G> = a_1^\dagger a_2^\dagger a_3^\dagger \ldots a_Z^\dagger |0>$$

Holmium

Dysprosium

$$|A'_f> = a_1'^\dagger a_2'^\dagger \ldots a_{f-1}'^\dagger a_{f+1}'^\dagger \ldots a_Z'^\dagger |0>$$

A. Faessler, E. Huster, O. Krafft, F. Krahn, Z. Phys. 238 (1970)

eexcitation Spectrum (X-rays, Auger- electron by a Calorimeter) of excited Dy* (Atom)

$$\frac{d\Gamma}{dE_c} \propto (Q - E_c)\sqrt{(Q - E_c)^2 - m_\nu^2} \sum_{f=f'} \lambda_0 B_f \frac{\Gamma_{f'}}{2\pi} \frac{1}{(E_c - E_{f'})^2 + \Gamma_{f'}^2/4}$$

λ_0 \propto $G^2_{weak}\,\xi$

$$B_f \approx |\psi_f(R)|^2 / |\psi_{3s1/2}(R)|^2$$

$$\psi_A(r) = \frac{1}{r}\begin{pmatrix} P_A \\ Q_A \end{pmatrix}$$

$$< A|B' >= \int_{0,\infty} \left(P_A(r) \cdot P_{B'}(r) + Q_A(r) \cdot Q_{B'}(r)\right) \cdot dr = overlap(A, B')$$

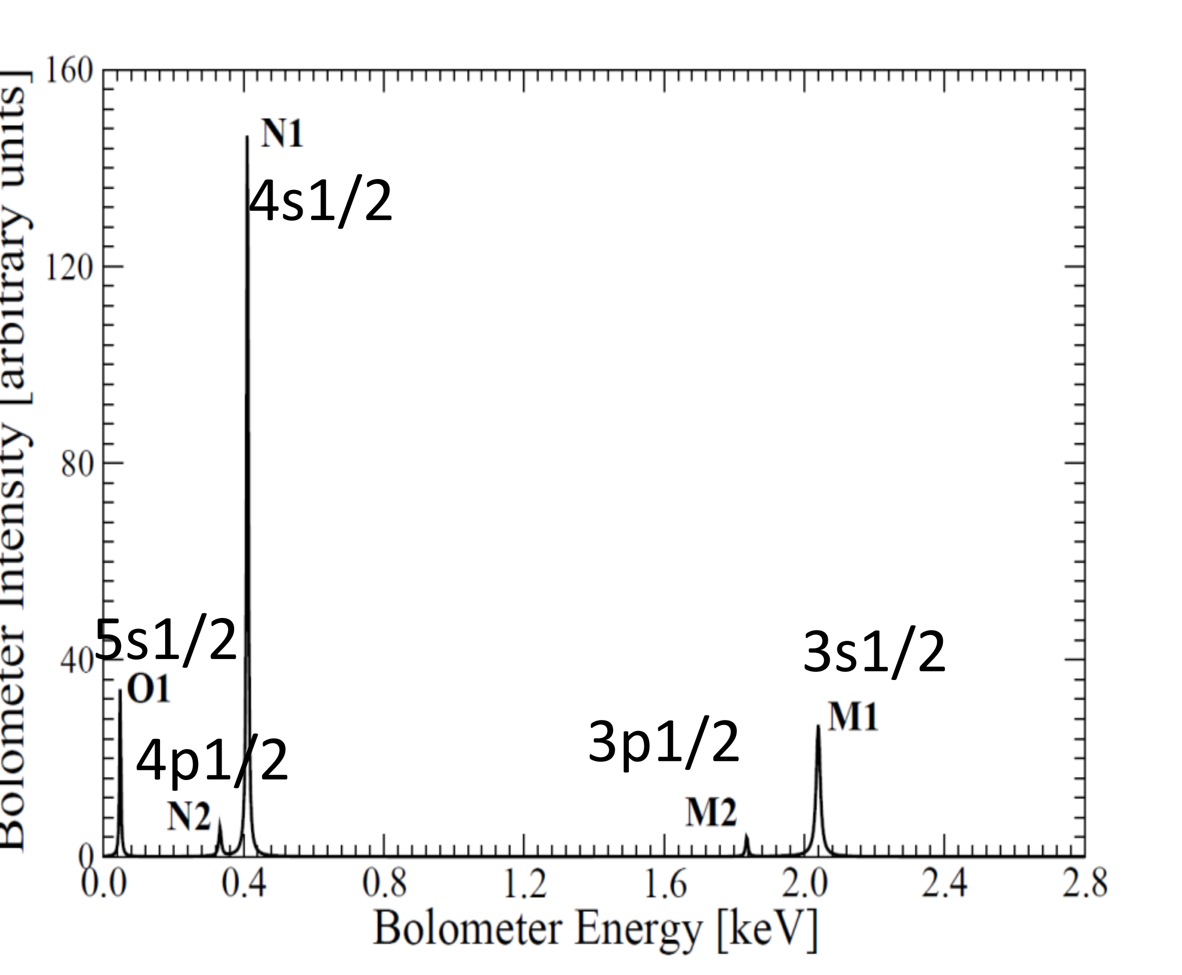
Spectrum of the deexcitation of one-, two- and three-hole states in ^{163}Dysprosium*

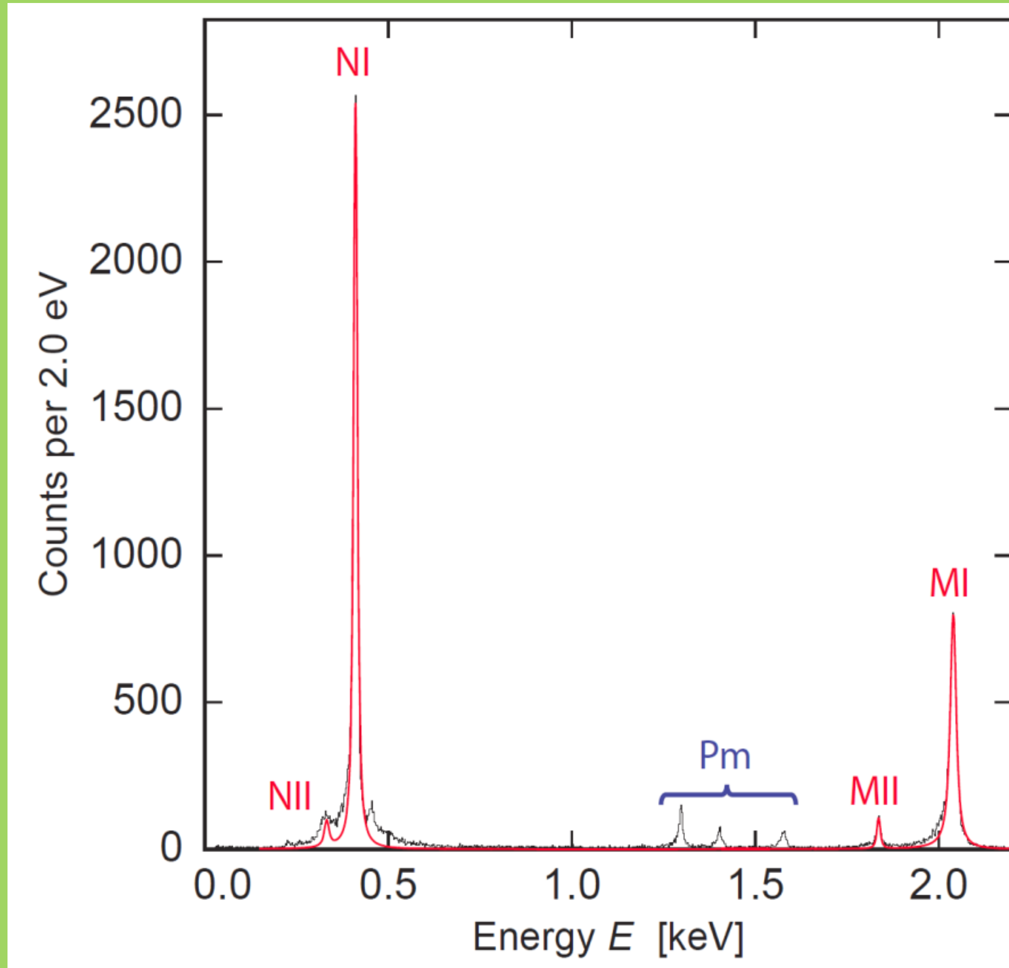
$$\frac{d\Gamma}{dE_c} \propto \sum_{i=1,\ldots N_\nu} (Q - E_c) \cdot U_{e,i}^2 \cdot \sqrt{(Q - E_c)^2 - m_{\nu,i}^2}$$

$$\sum_{h'=b',b'(p^{-1'}q'),b'(p_{1'}^{-1}q_{1'})(p_{2'}^{-1}q_{2'})} \lambda_0 B_h \frac{\Gamma_{h'}}{2\pi} \frac{1}{(E_c - E_{h'})^2 + \Gamma_{h'}^2/4}$$

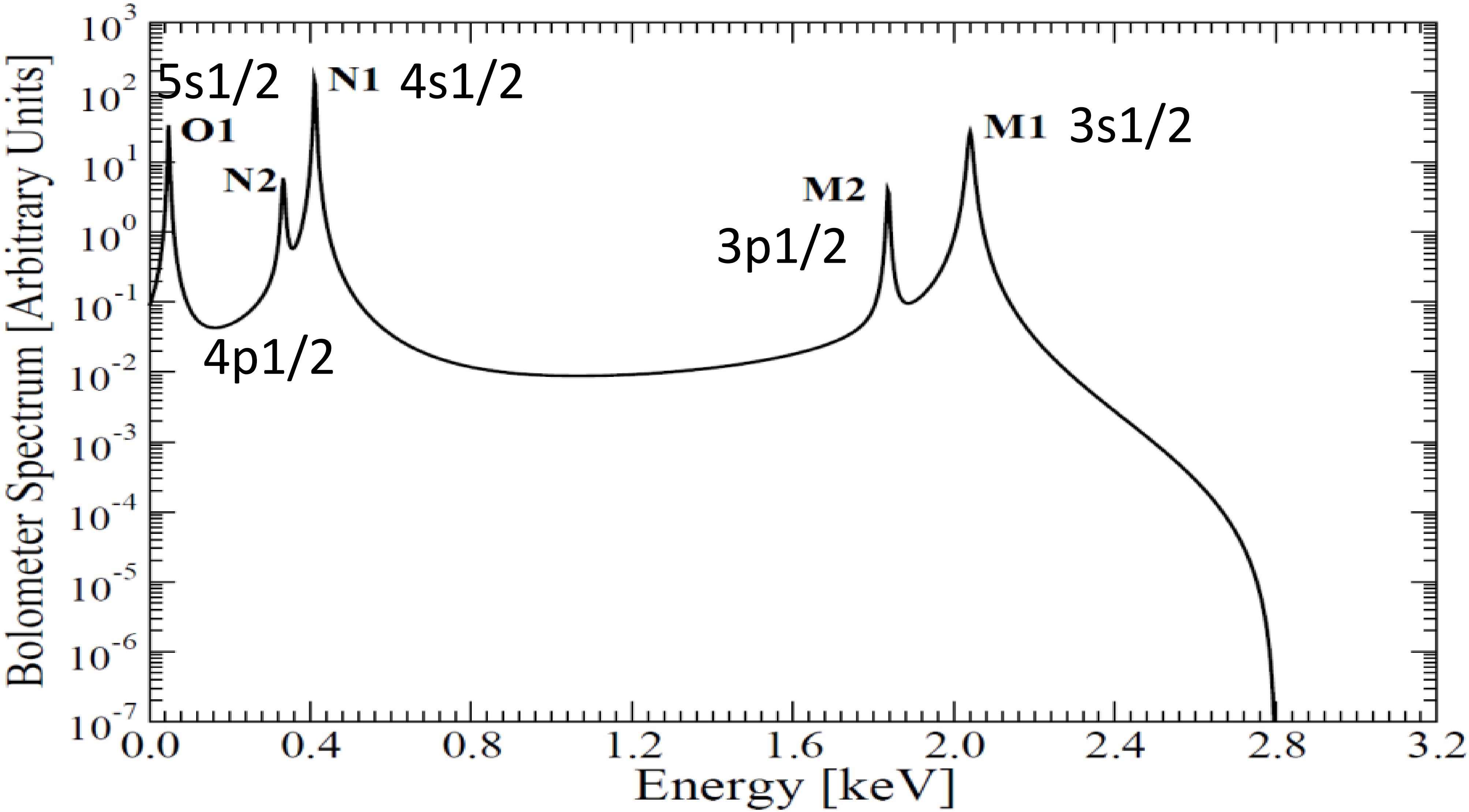
Importance = $B_f \Gamma_f / ((Q-E_f)^2+\Gamma_f^2/4) \approx B_f \Gamma_f / (Q-E_f)^2$

Theoretical and experimental (ECHo) one-hole deexcitation of Dy.





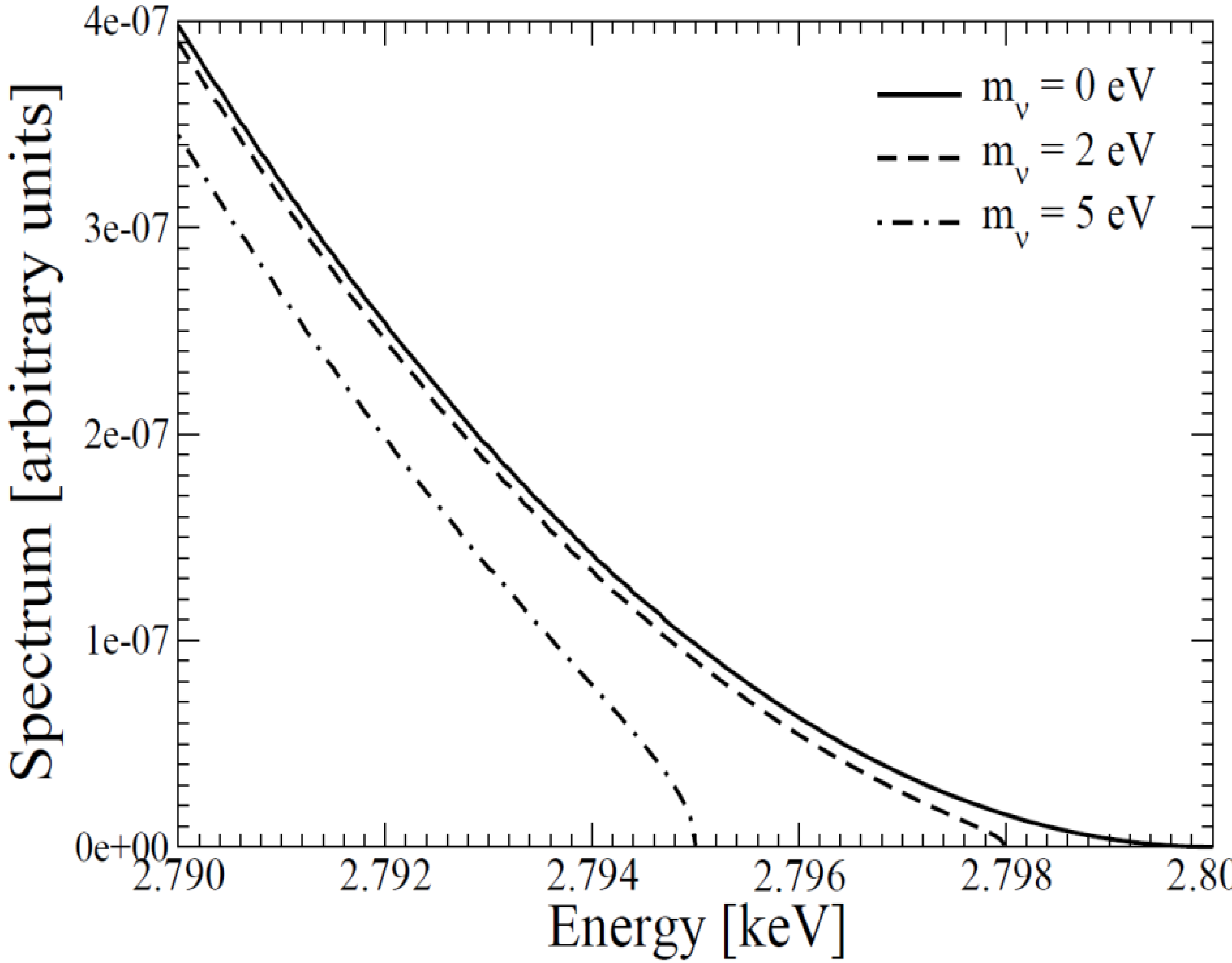
Logarithmic10 one-hole Deexcitation Spectrum



Last 10 eV below the Q-value

ne –resonance only
ortant at Q after folding
n detector response
heory as function of
r parameters:
m_ν (neutrino mass)
Q-$E_{f'}$ (Q-value – reson.)
$\Gamma_{f'}$ (width of resonance)
I_f (intensity of resonan.)

Two Resonances : fit 7 parameters



Robertson [Phys. Rev. C91 (2015) 03504] takes the Two-Hole probability from Carlson and Nestor, Phys. Rev. A 8, 2887 (1973) calculated for ${}_{54}^{132}Xe$ and not for ${}_{67}^{163}Ho \rightarrow {}_{66}^{163}Dy$

- Sudden approximation; probability for an empty (hole) state in Dy:

$<\psi_{(nlj)}(Ho)|\psi_{(nlj)'}(Dy^*)> \approx 0.999$ Always less than 1; j = ½; 2j+1 = 2

Hole-probability: $P_{1-h} \approx 1 - [<\Psi_{(nlj)}(Ho)|\Psi_{(nlj)'}(Dy^*)>]^{2(2j+1)} =$

$1-0.999^4 = 0.004 \rightarrow 0.4$ %; $1- 0.98^4 = 0.077 \rightarrow 7.7$ % (19 *larger)

[Overlap |Z> with |Z-1>] largest difference for outside electrons.

In addition to ${}_{54}Xe$ in ${}_{66}Dy$: $(6s_{1/2})^2, (4f_{5/2})^6, (4f_{7/2})^4$,

Difference between $_{54}$Xenon and $_{67}$Holmium (Literatur)

$_{67}Ho = [_{54}Xe](6s_{1/2})^2 (4f_{5/2})^6 (4f_{7/2})^5$

-	$E\ [eV]\ Xenon$	$E\ [eV]\ Holmium$
$5s_{1/2}$	23.3	49.9
$5p_{1/2}$	13.4	26.3 (30.8)
$5p_{3/2}$	12.1	26.3 (24.1)
Overlap	*for* (−2 %) 0.979; P(2-hole)	*for* 0.999; P(2-hole)
$j = 1/2$	8.1 %	0.4 %
$j = 3/2$	15.6 %	0.8 %

ur and the Robertson (arXiv: 1411.2906v1) 2-hole probabilities in D

1. hole	2. hole	$E_c[eV]$	$\Gamma[eV]$	$P-Fae[\%]$	$P-Rob[\%]$
4s1/2	——	409.0	5.4	24.40	23.29
4s1/2	4s1/2	841.4	5.4	0.021	0.001
4s1/2	4p1/2	752.5	5.4	0.052	0.004
4s1/2	4p3/2	717.2	5.4	0.091	0.01
4s1/2	4d3/2	569.0	5.4	0.088	0.077
4s1/2	4d5/2	569.0	5.4	0.125	0.123
4s1/2	4f5/2	417.6	5.4	0.027	0.0
4s1/2	4f7/2	414.2	5.4	0.023	0.0
4s1/2	5s1/2	458.3	5.4	0.066	0.254
4s1/2	5p1/2	439.8	5.4	0.039	0.629
4s1/2	5p3/2	433.1	5.4	0.058	1.502

Numerical values of Ho-Dy overlaps with holes in the selfconsitent Dirac-Hartree-Fock.

A. Faessler, E. Huster, O. Krafft, F. Krahn, Z. Phys. 238 (1970) 352.

hole in 3s1/2: $< Ho, 3s1/2|Dy, 3s1/2 > = 0.999390;$

$$< Ho, 4s1/2||Dy, 4s1/2 > = 0.999332;$$

Probability(Hole 4s1/2) = 0.27 %

hole in 4s1/2: $< Ho, 3s1/2|Dy, 3s1/2 > = 0.999377;$

$$< Ho, 4s1/2|Dy, 4s1/2 > = 0.998870;$$

Probability(Hole 4s1/2) = 0.45 %; 66% larger

Improvement in our work over Robertson: Faessler + Simkovic, Phys. Rev. C91, 045505 (2015)

-hole probabilities in $_{67}$Ho and $_{66}$Dy and not in $_{54}{}^{132}$Xe; Carlson+Nestor 1973

he electron holes $ns_{1/2}$ and $np_{1/2}$ selfconsistently in Dy (Dirac-HF).

$_{6}{}^{163}$Dy has more than 8 additional 2-hole states compared to $_{54}$Xe and not in Carlson, Nestor.

or the 1-hole states the exchange and overlap corrections are included. (Bahcal 1965, Faessler 1970; not included in Vatai approximation.)

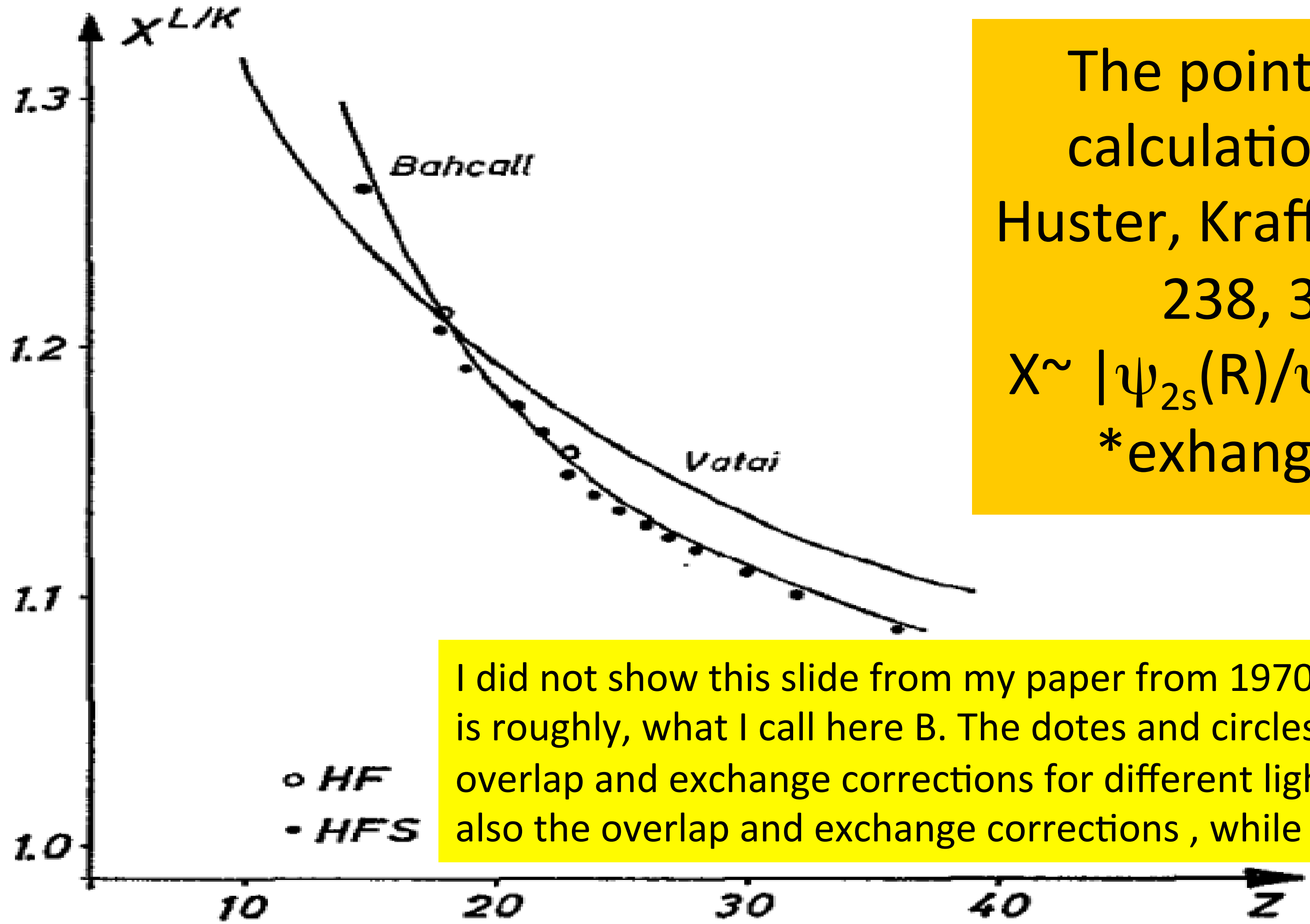
irac-Hartree-Fock includes finite charge distribution of the nucleus.

robability for hole states $\sim \psi_{(n,l,j)}(R) * R^2$ and not at $r = 0.0$.

erived in second quantization: automatic antisymmetrization.

lew Q-value: Q = 2.8 keV.

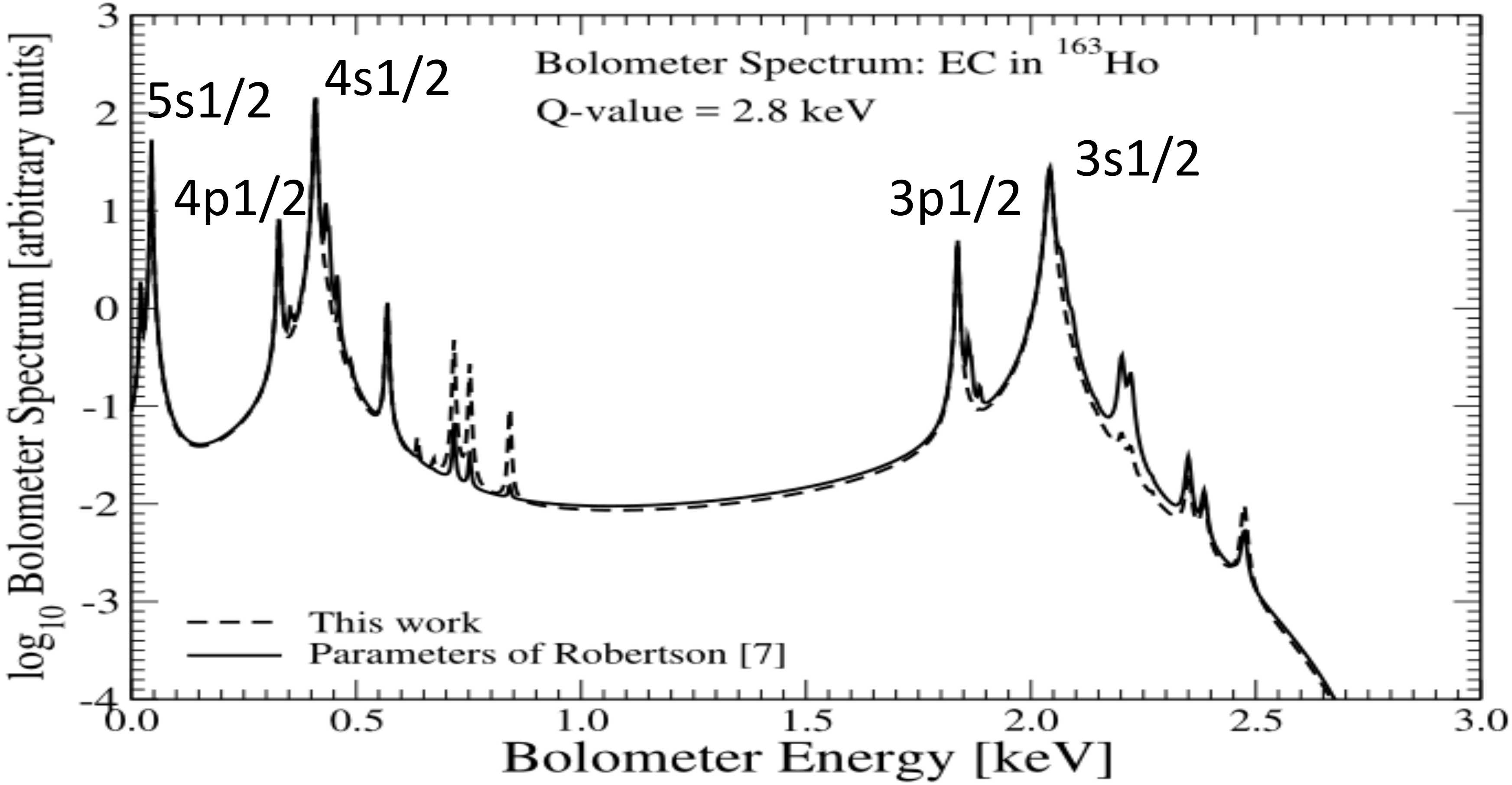
A. Faessler, E. Huster, O. Krafft and F. Krahn:



The points are different calculations of Faessler, Huster, Krafft, Krahn: Z. Phy 238, 352 (1970);
X~ $|\psi_{2s}(R)/\psi_{1s}(R)|^2$ *overla
*exhange corrections

I did not show this slide from my paper from 1970 in the talk. The quanti is roughly, what I call here B. The dotes and circles are my calculation of overlap and exchange corrections for different light atoms. Bahcall incluc also the overlap and exchange corrections , while Vatai neglected it.

1- and 2-hole excitations of our work; Q =2.8 keV



Probabilities for the formation of 1- and 2-hole states in $_{66}$Dy after electron capture in $_{67}$Ho.

$$P_f = |< A'_f|a_i|G>|^2 = |<0|a'_Z a'_{Z-1}...a'_{f+1}a'_{f-1}...a'_1 \cdot a_f \cdot a^\dagger_1 a^\dagger_2 a^\dagger_3 ... a^\dagger_Z|0>|^2$$

$$P_{p/f} = |< A'_{p',f'}|a_f|G>|^2 = \sum_{q'>F} |<0|a'_{q'}a'_Z...a'_{p'+1}a'_{p'-1}...a'_{f+1}a'_{f-1}...a'_1 \, a_f \cdot a^\dagger_1 a^\dagger_2 a^\dagger_3 ... a^\dagger_Z|0>|^2$$

Faessler, Huster, Krafft, Krahn, Z. Phys. 238 1, 352 (1970)

Probability for two-hole States:

Completness relation:

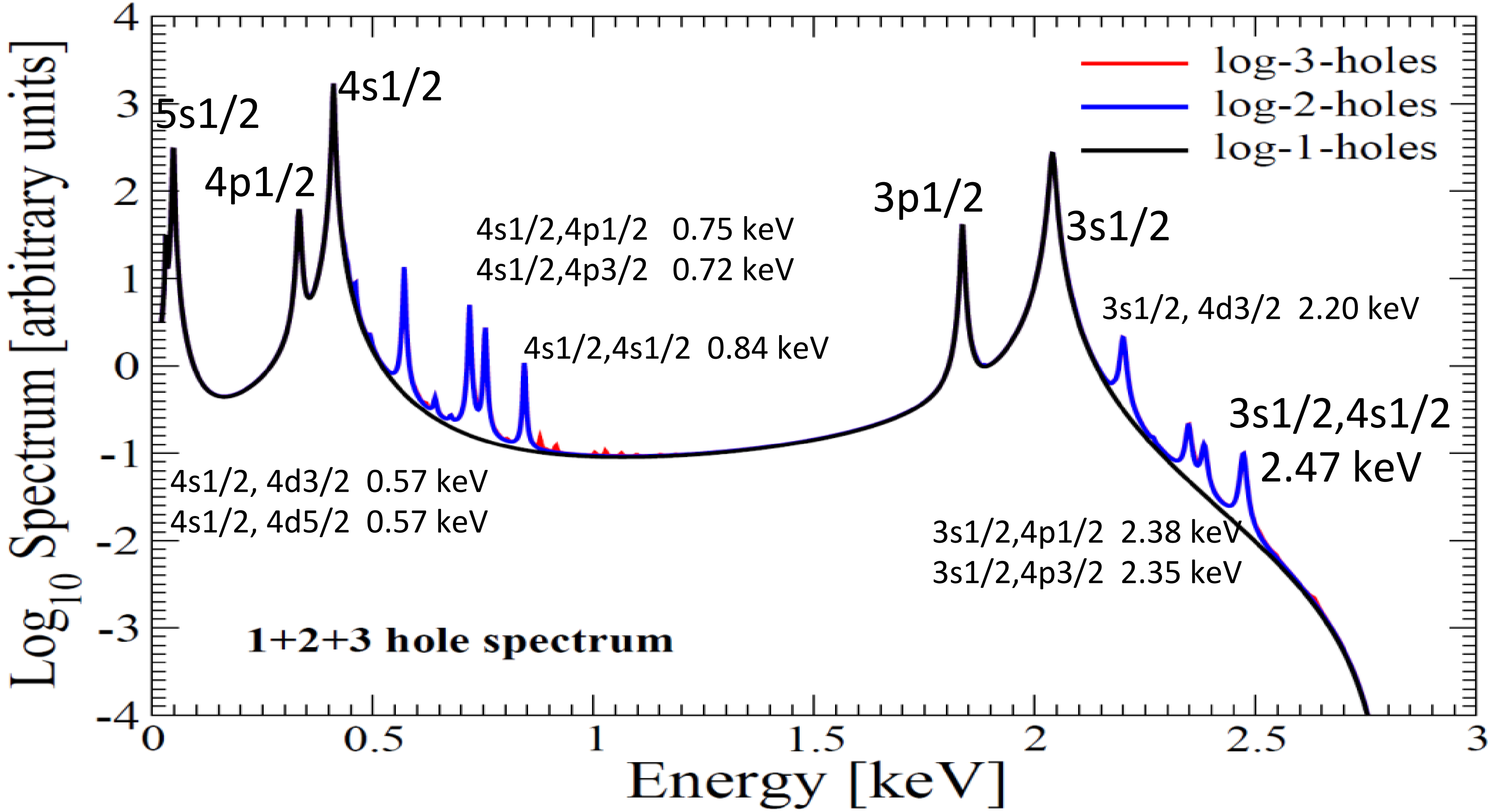
$$1 = \sum_{q'<F} < p|q' >< q'|p > + \sum_{q'>F} < p|q' >< q'|p >$$

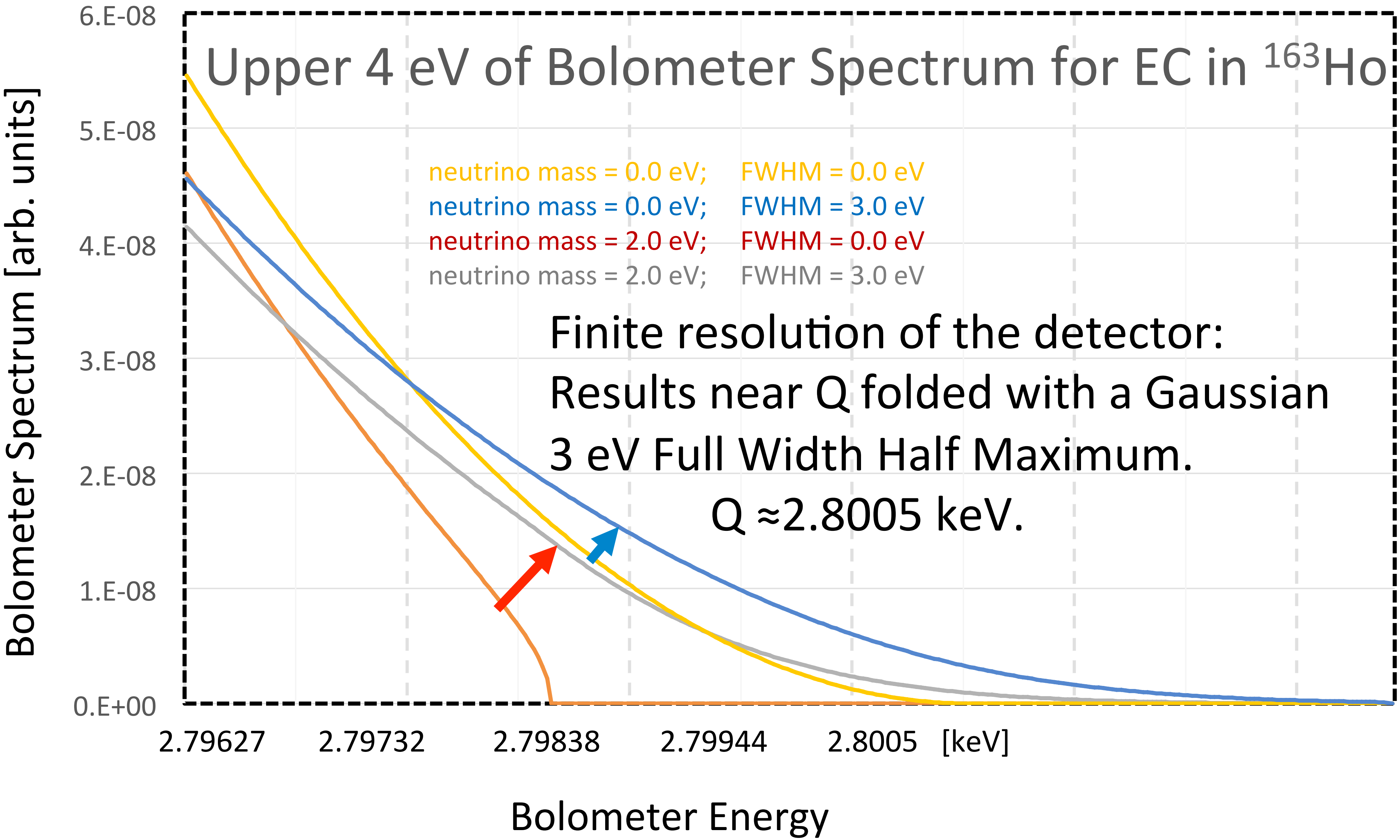
$$P_{p/f} = \left(1 - \sum_{q'<F} < p_{Ho}|q'_{Dy} >< q'_{Dy}|p_{Ho} >\right) =$$

$$\left(1 - < p_{Ho}|p'_{Dy} >< p'_{Dy}|p_{Ho} > - \sum_{q'<F, \neq p'} < p_{Ho}|q'_{Dy} >< q'_{Dy}|p_{Ho} >\right)$$

apply the Vatai approximation, we obtain the same formulas for $_{54}$Xe as Carlson and or.

One-, two- and three-hole state deexcitation in Dy*




Upper 4 eV of Bolometer Spectrum for EC in ¹⁶³Ho
neutrino mass = 0.0 eV; FWHM = 0.0 eV
neutrino mass = 0.0 eV; FWHM = 3.0 eV
neutrino mass = 2.0 eV; FWHM = 0.0 eV
neutrino mass = 2.0 eV; FWHM = 3.0 eV
Finite resolution of the detector:
Results near Q folded with a Gaussian
3 eV Full Width Half Maximum.
Q ≈2.8005 keV.
6.E-08
5.E-08
4.E-08
3.E-08
2.E-08
1.E-08
0.E+00
Bolometer Spectrum [arb. units]
2.79627
2.79732
2.79838
2.79944
2.8005
[keV]
Bolometer Energy

Importance of different resonance deexcitations of Dy* at the Q value for the determination of the neutrino mass.

$$\frac{d\Gamma}{dE_c} \propto \sum_{i=1,\ldots N_\nu} (Q - E_c) \cdot U_{e,i}^2 \cdot \sqrt{(Q - E_c)^2 - m_{\nu,i}^2}$$

$$\sum_{h'=b',b'(p^{-1'}q'),b'(p_{1'}^{-1}q_{1'})(p_{2'}^{-1}q_{2'})} \lambda_0 B_{h'} \frac{\Gamma_{h'}}{2\pi} \frac{1}{(E_c - E_{h'})^2 + \Gamma_{h'}^2/4}$$

Importance $\approx B_{h'} \Gamma_{h'} / (Q - E_{h'})^2$

Importance of highest two-hole state $(3s_{1/2}, 4s_{1/2})^{-1}$ at 2.47 keV relative to the highest one-hole state at 2.04 keV

$\Delta E_C = Q - E_C$;
$\Delta_{f'} = Q - E_{f'}$

r folding theory with the
tral function of the detector
he following 4 parameters, if
one resonance is important:

eutrino mass
Q value: $\Delta_{f'} = Q - E_{f'}$
Width of resonance $\Gamma_{f'}$
trength S ~ B_f

$$\frac{d\Gamma}{dE_c} \propto (Q - E_c) \cdot \sqrt{(Q-E_c)^2 - m_\nu^2} \cdot \frac{S}{(E_c - E_{f'})^2 + \Gamma_{f'}^2/4}$$
$$= \Delta E_C \cdot \sqrt{\Delta E_C^2 - m_\nu^2} \cdot \frac{S}{(\Delta_{f'} - \Delta E_C)^2 + \Gamma_{f'}^2/4}$$

$(3s_{1/2})^{-1}$

$$Relative\ weight \propto \frac{P_{1-hole}\ \%}{(Q - E_{f'})^2} = \frac{100\ \%}{(2.80 - 2.04)^2} = 174$$

$(3s_{1/2}, 4s_{1/2})^{-1}$

$$Relative\ weight \propto \frac{P_{2-hole}\ \%}{(Q - E_{f'})^2} = \frac{0.167\ \%}{(2.80 - 2.47)^2} = 1.6$$

omparison
with the
CHo data.

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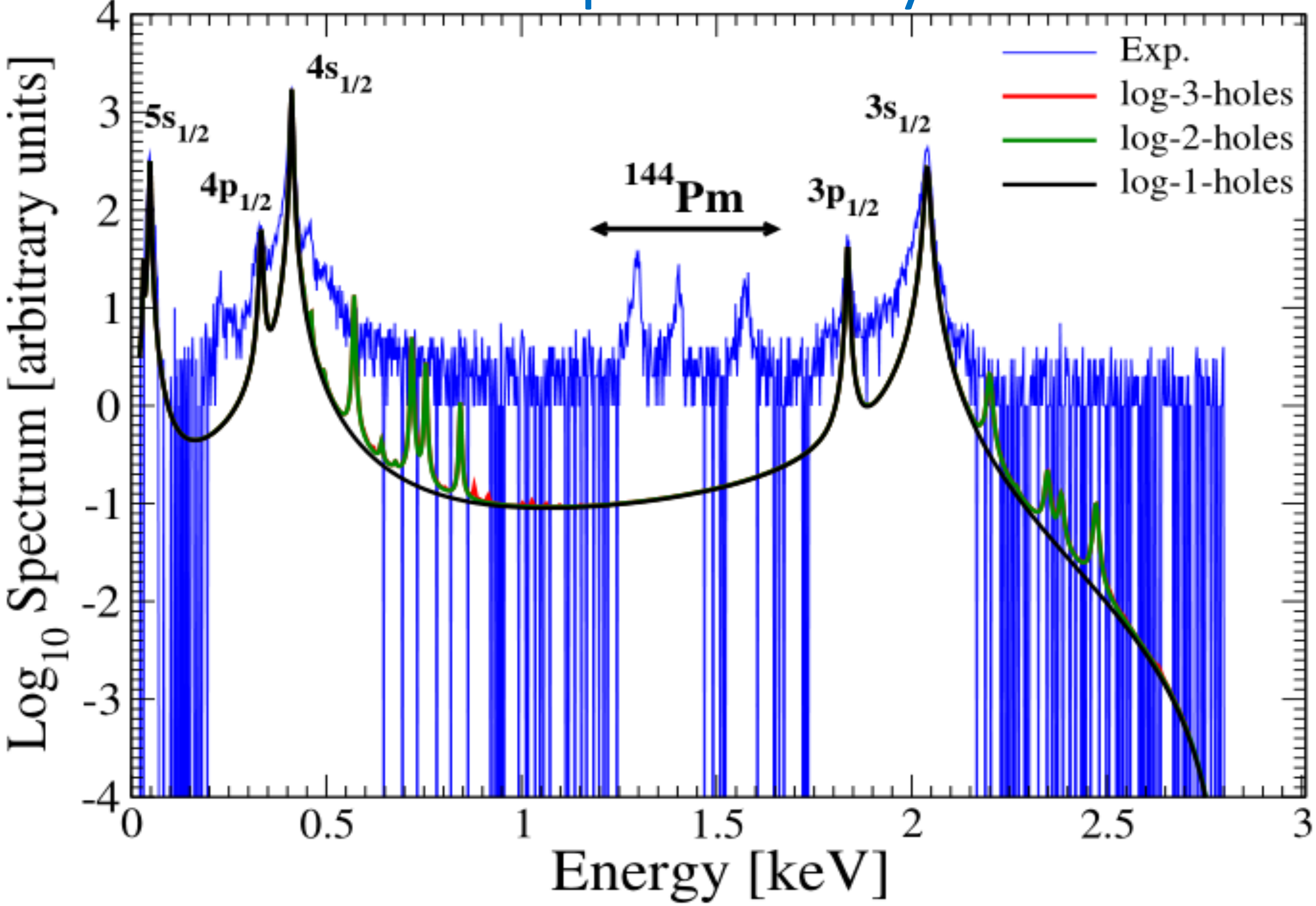
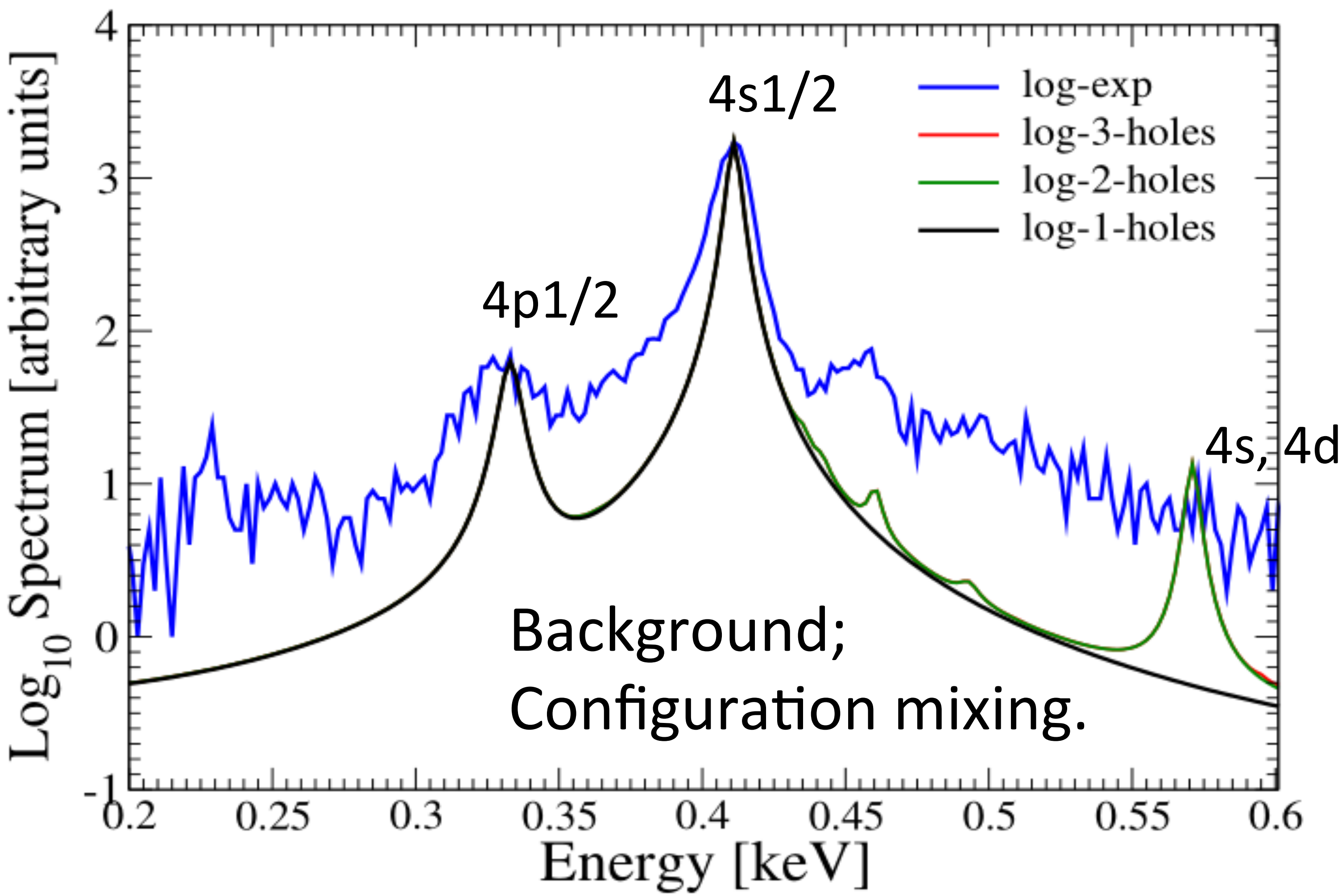
eatment.

ECHo Exp binned by 2 eV



etailled
omparison
round the
o1/2 and
s1/2
ne-hole
xcitations.



Summary: THE END

Determination of the electron neutrino mass by electron capture in 163Holmium?

One-hole, the two-hole (for the first time correctly) and the three hole (for the first time) deexcitation of 163 Dysprosium.

Measured by the Bolometer (X-rays, Auger-electrons)

Fold with Spectral Function of detector and fit 4 parameters to data one resonance: m_ν, Q, $\Gamma_{f'}$, B_f. More resonances important? Background? Conf. mixing?

m_ν determination seems to be (very) difficult but (perhaps) not impossible.