# Survey of Isobaric Analogue States (IAS) in NUBASE2012

# Isobaric Analogue States in Mass predictions / Mass modelling

Charge independent view of the nuclear mass, M ; nuclear states fully defined by

$$\mathrm{M(space, spin, isospin)}$$

**Isobaric Multiplet Mass Equation** [1] IMME (Wigner, 1958)

$$\mathrm{M}\ (T, T_Z) = \ a + bT_Z + \ cT_Z^2$$

interpreted as being

$$\mathrm{M}(T, T_Z) = \ \mathrm{scalar} + \mathrm{vector} + \ \mathrm{tensor} \qquad \text{parts of the Hamiltonian}$$

- addition of cubic and quartic terms as necessary (to include higher order effects)

## Coulomb Displacement Energy [2] CDE

Energy differences between analog pairs

$$\Delta E_c = M_{>Z} - M_{<Z} + \Delta_{np}$$

where $M_{>Z}$ and $M_{<Z}$ masses of greater and lower Z content, $\Delta_{np}$ the neutron-proton mass difference.

CDE accessible via β decay measurements

$$\Delta E_c = E_\beta + \Delta_{np}$$

where $E_\beta$ is the β endpoint energy.

## Electroweak theory: test of the standard model via super-allowed β decay[3]

Test of the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix

Accessed via the measurement of isospin non-conserving transitions to T=1 ground states along N=Z.

## Astrophysics

Masses of unstable nuclei are critical inputs for nucleosynthesis calculations.

# Isobaric Analogue States (IAS)

IAS : subset of M(space, spin, isospin)

same space structure (isobars, A=cte)

same spin (and parity) states ($J^{\pi}$ = cte)

same isospin multiplet but different isospin projections (T = cte, $T_Z$)

→ only $T_Z$ changes

Isospin multiplet, $T = \left|\frac{N - Z}{2}\right|$

of the most neutron-rich nuclide

and

Isospin projections, $T_z \in [-T, +T]$

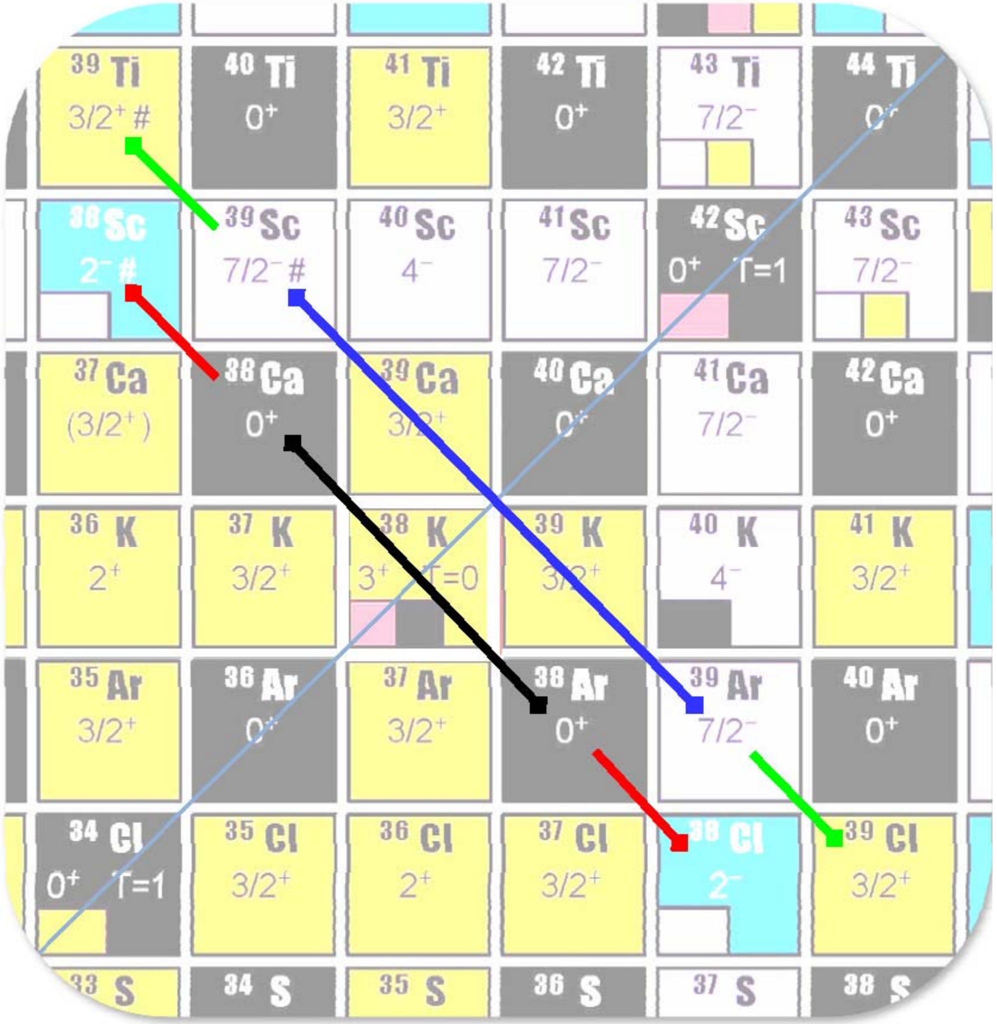
Special IAS notation

*i* or *j* superscripts indicate IAS states

$^{62}Cu^{i}$

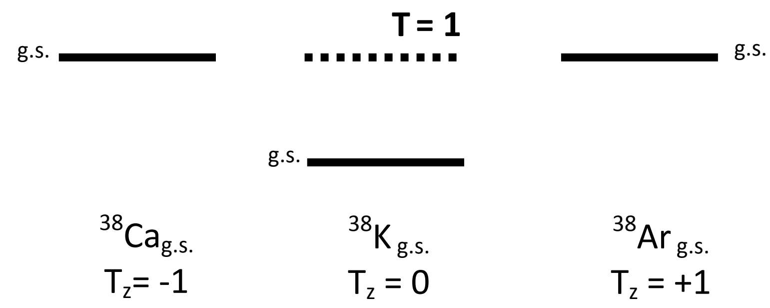
# Idealized (charge independent) view

## On the chart of nuclides

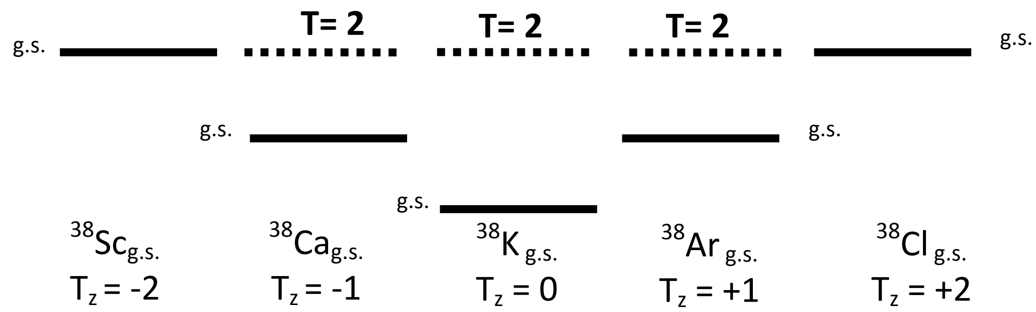



## Relative Energy levels

**T=1** isobar multiplet members, IAS same spin-parity




**T=2** isobar multiplet members, IAS same spin-parity



# ENSDF – AME evaluation methods

## ENSDF vertical relationships

|Q| = E* = K.E. available in the CM

Typically high precision gamma-decay measurements

→ Best evaluation when decay data is available.

## AME horizontal relationships

Nuclear reactions: Q-values

Reaction A(b,c)D $Q = \Delta M_A + \Delta M_b - \Delta M_c - \Delta M_D$

Typical measurement resolution ~ $10^{-6}$

Final mass resolution will depend on the precision of projectile and target masses.

→ Keeps track of original experimental data

# IAS recalibrations in NUBASE2012

$$Q = \Delta M_A + \Delta M_b - \Delta M_c - \Delta M_D$$

Change in target mass value/precision

=> automatic change in $M_b$-value OK

Equipment recalibration: change in "well known" experimental reference nuclides

=> manual adjustment required Ongoing

Use reaction data or single- double- proton emission data when available:

$^{27}P^{i}(2p)^{25}Al$

Also includes IT data when decay is not direct to g.s. (selection rules) :

E(2p)=5315(60) to 3/2+ level at 944.9 keV

944.9 keV to g.s. from ENSDF evaluation

→ Optimized mass evaluation

# Example: $^{60}Cu^{i}$

## Reaction Q data (input data)

| | | | | | | |
|---|---|---|---|---|---|---|
| Data: | 060 870294800c1 | HMIT | 68Yo01,W | 3210 | 10 | 58Ni(3He,p)60Cui |
| Comment : | 060 870294800c2 | Wh | 68Yo01*W | Q given in paper, and IT=2536(15) deduced by authors | | |

## Data generated during the evaluation (mid-analysis)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 58Ni**(3He,p)**60Cui | 3210 | 10 | 3217.511 | 5.145 | .8 | 1 | **26** | 26 | 60CuiHMIT | 68Yo01,W |
| 60Ni**(3He,t)**60Cui | -8685 | 6 | -8687.704 | 5.145 | -.5 | 1 | **74** | 74 | 60CuiH | 71Be29,* |

→ Mass of $^{60}Cu^{i}$ is evaluated from two principal reactions

26% via ($^{3}$He,p) and 74% via ($^{3}$He,t)

→ Masses of p, t, $^{3}$He, $^{58}$Ni and $^{60}$Ni (and their relation to other masses) are included in the final mass evaluation

## Evaluated Atomic Mass (output result)

2 31 29 60 Cui **-55803.419 5.167 2541.132 5.380**

→ Evaluated Mass Excess for $^{60}Cu^{i}$ is $-55803.419 \pm 5.167$ keV and E* is $2541.132 \pm 5.380$ keV

# NUBASE2012 IAS Statistics

Each isospin multiplet includes two g.s. masses, already included in AME2012

There are 8 isomer states which are also IAS. Not discussed here.

$^{16}N^{m}$, $^{26}Al^{m}$, $^{34}Cl^{m}$, $^{38}K^{m}$, $^{46}V^{m}$, $^{50}Mn^{m}$, $^{54}Co^{m}$, $^{72}Ga^{m}$

107 IAS nuclides in NUBASE2012, including

5 cases where there is no data in ENSDF:

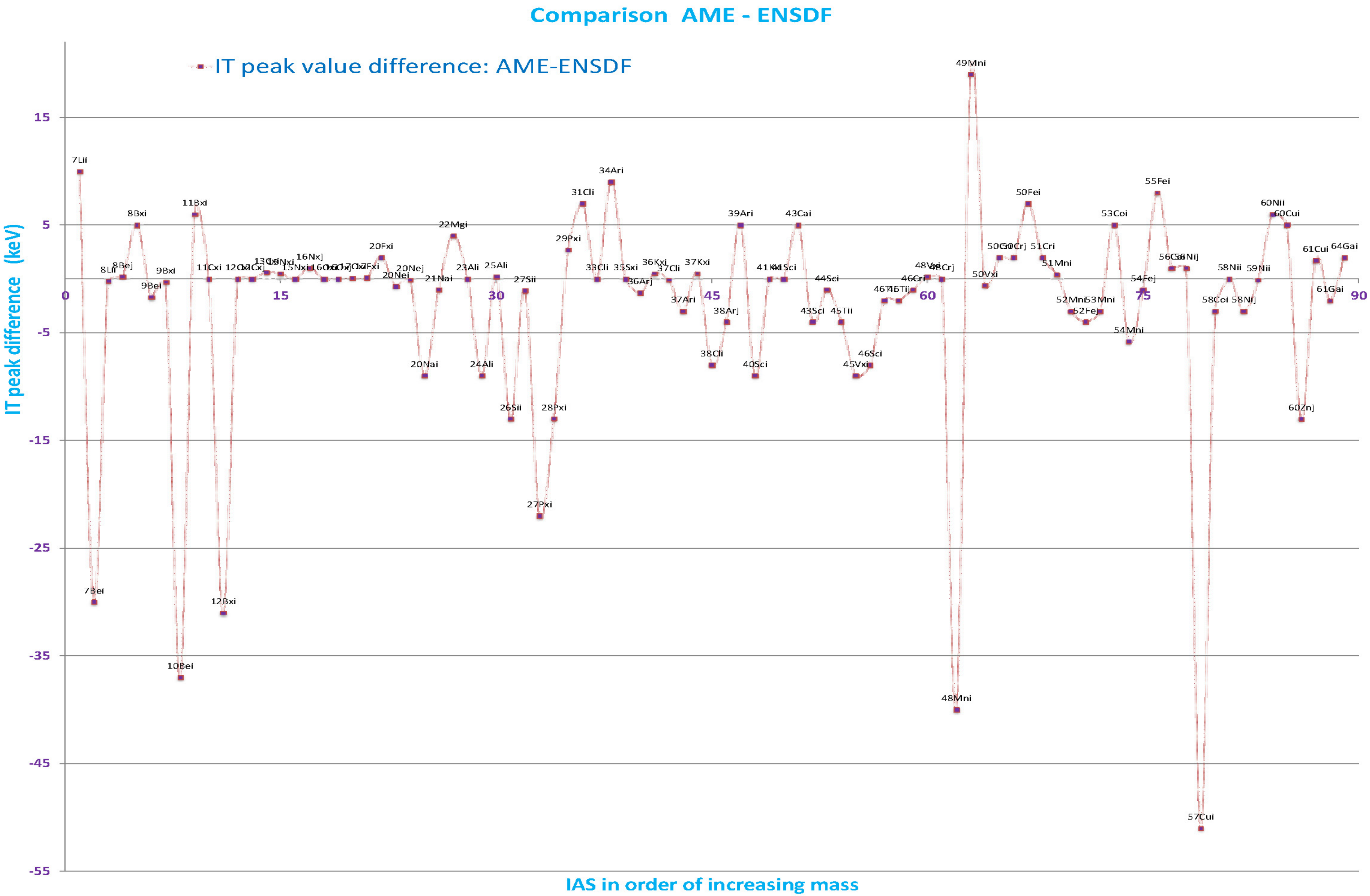
$^{35}K^{i}$, $^{44}V^{i}$, $^{51}Co^{i}$, $^{56}Cu^{i}$, $^{69}Br^{i}$

5 cases where no error is given and peak is generally an estimate

$^{49}V^{i}$, $^{52}Co^{i}$, $^{53}Co^{i}$, $^{63}Zn^{i}$, $^{66}Ga^{i}$

3 cases where there is a disagreement in the attributed level

$^{57}Co^{i}$, $^{62}Cu^{i}$, $^{65}As^{i}$


Comparison AME - ENSDF
IT peak value difference: AME-ENSDF
IT peak difference (keV)
IAS in order of increasing mass
15
5
-5
-15
-25
-35
-45
-55
0
15
30
45
60
75
90

## References and further reading

**[1]** E.P. Wigner in the Proceedings of the Robert A. Welch Foundation Conference on Chemical Research
edited by W.0. Milligan, Welch Foundation, Houston, 1958, Vol. 1, p. 88.

**[2]** Isobaric mass equation for A=1-45 and systematics of Coulomb displacement energies.
M. S. Antony, J. Britz, J. B. Bueb, and A. Pape
Atomic Data and Nuclear Data Tables 33 (1985) 447**;**
**and also**
M.S. Antony, J. Britz and A. Pape, Atomic Data and Nuclear Data Tables 34 (1985) 279;
A. Pape and M.S. Antony, Atomic Data and Nuclear Data Tables 39 (1988) 201;
M.S. Antony, J. Britz and A. Pape, , Atomic Data and Nuclear Data Tables 40 (1988) 9.

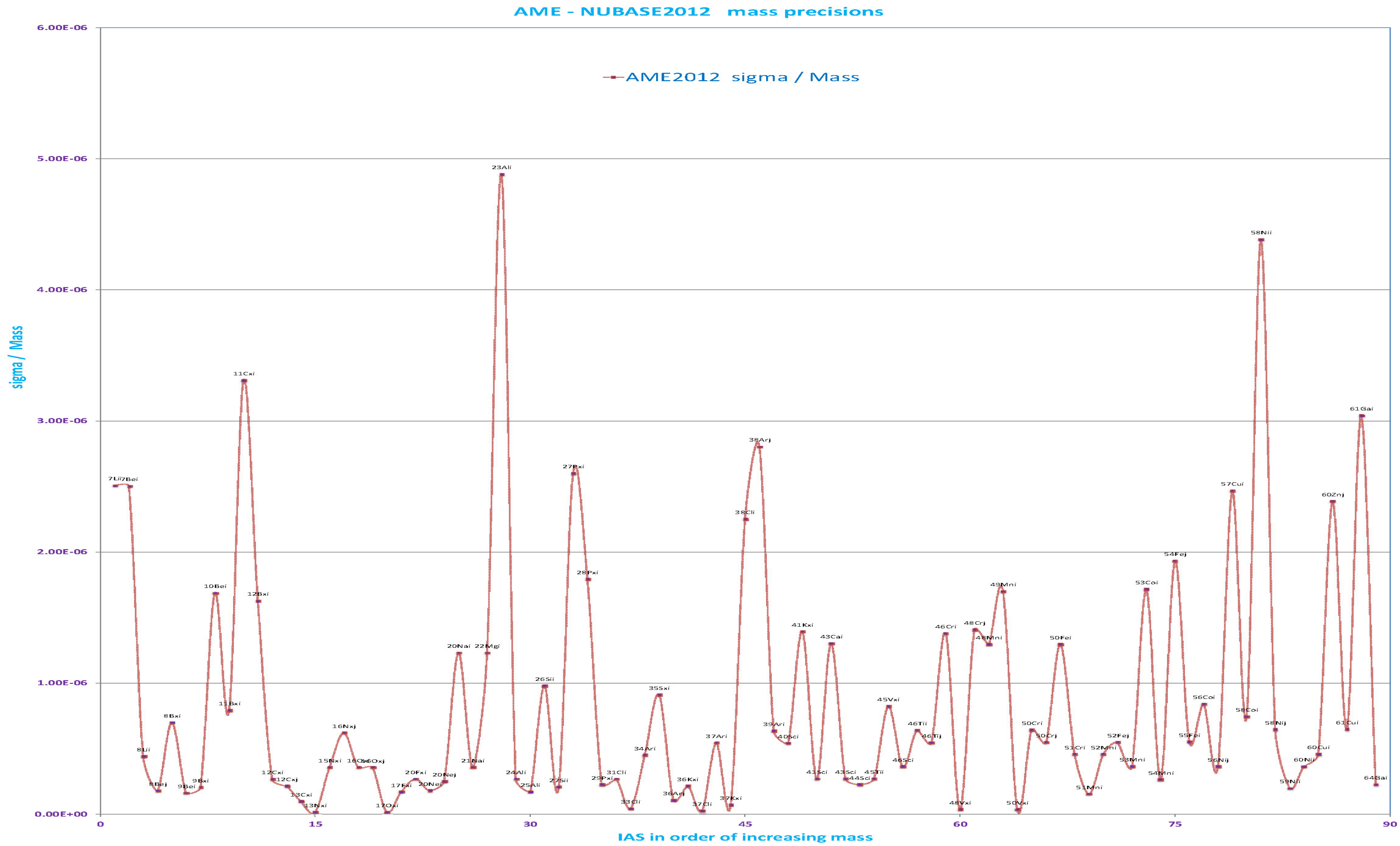
**[3]** Superallowed 0+ → 0+ nuclear β decays: A new survey with precision tests of the conserved vector current hypothesis and the standard mode
J. C. Hardy and I. S. Towner
PHYSICAL REVIEW C 79, 055502 (2009)

## NUBASE 2012 and AME2012

**The NUBASE2012 evaluation of nuclear properties**
G. Audi, F.G.Kondev, M.Wang, B.Pfeiffer, X.Sun, J. Blachot, M. MacCormick
Chinese Physics C, vol. 36 December 2012 (pp. 1157 – 1286)
http://amdc.impcas.ac.cn/evaluation/data2012/nubase.html

**The AME2012 atomic mass evaluation (I) Evaluation of input data, adjustment procedures**
G. Audi, M. Wang, A.H.Wapstra, F.G.Kondev, M.MacCormick, X.Xu, B. Pfeiffer
Chinese Physics C, vol. 36 December 2012 (pp. 1287 – 1602)
http://amdc.impcas.ac.cn/evaluation/data2012/ame.html

**The AME2012 atomic mass evaluation (II) Tables, graphs and references**
M. Wang, G. Audi, A.H. Wapstra, F.G. Kondev, M. MacCormick, X. Xu, B. Pfeiffe
Chinese Physics C, vol. 36 December 2012 (pp. 1603-2014)


AME - NUBASE2012 mass precisions
AME2012 sigma / Mass
sigma / Mass
6.00E-06
5.00E-06
4.00E-06
3.00E-06
2.00E-06
1.00E-06
0.00E+00
0
15
30
45
60
75
90
IAS in order of increasing mass
7Lii
7Bei
8Lii
8Bej
8Bxi
9Bei
9Bxi
10Bei
11Bxi
11Cxi
12Bxi
12Cxi
12Cxj
13Cxi
13Nxi
15Nxi
16Nxj
16Oxi
16Oxj
17Oxi
17Fxi
20Fxi
20Nei
20Nej
20Nai
21Nai
22Mgi
23Ali
24Ali
25Ali
26Sii
27Sii
27Pxi
28Pxi
29Pxi
31Cli
33Cli
34Ari
35Sxi
36Arj
36Kxi
37Cli
37Ari
37Kxi
38Cli
38Arj
39Ari
40Sci
41Kxi
41Sci
43Cai
43Sci
44Sci
45Tii
45Vxi
46Sci
46Tii
46Tij
46Cri
48Vxi
48Crj
48Mni
49Mni
50Vxi
50Cri
50Crj
50Fei
51Cri
51Mni
52Mni
52Fej
53Mni
53Coi
54Mni
54Fej
55Fei
56Coi
56Nij
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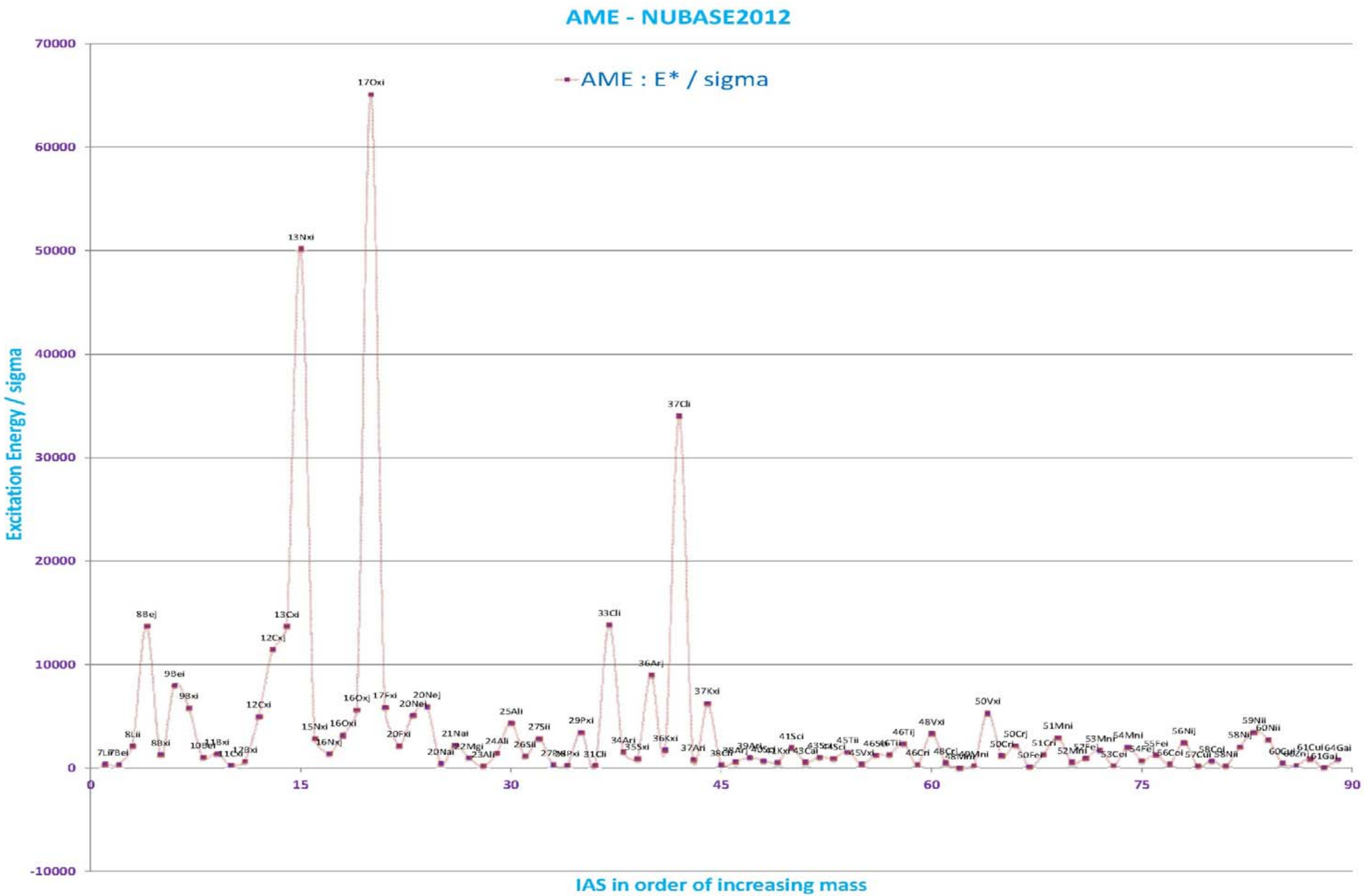
60Znj
61Cui
61Gai
64Gai


AME - NUBASE2012
AME : E* / sigma
Excitation Energy / sigma
IAS in order of increasing mass
17Oxi
13Nxi
37Cli
33Cli
8Bej
13Cxi
12Cxj
36Arj
9Bei
37Kxi
50Vxi