CEM 485, Spring/2o1o

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Modern Nuclear Chemistry

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Course Information:

http:/www.chemistry.msu.edu/courses/CEM485/Index.html

Week 1 – Introduction

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Introduction
-- Goals, roll back the fog
-- Nomenclature
-- General Properties of Nuclei
-- Nuclear Processes, overview
--- decay equations
--- conservation laws
-- Nuclear “Activity”

Mass and Energy
-- Einstein’s cliché
-- Binding Energy viz. Separation Energy

Robert W. Cameron,
Aerial photographer

Nomenclature - 1

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Often misused: Nucleus vs. Nuclide; Atom vs. Ion

Atomic number = Proton number (Z)

Neutron number (N)

Electron number is not Charge state (q)

Atomic mass (u) is not Mass number (A=Z+N)

$$^{A}X^{q}$$

$$^{A}_{Z}X^{q}_{N}$$

For Example: ^{18}O has a mass of 17.99916 amu a.k.a. *"u"*
but the NSCL beam today: $^{18}O^{8+}$ has a lower mass

Nomenclature - 2

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Isotopes … constant Z … the chemical elements

Isotones … constant N

Isobars (have isotopic spin or isospin) … constant A

What isotopes exist?

Z,N	E-E	O-O	E-O	O-E
Stable	140	5	53	48
Long-lived	16	4	2	4
Terrestrial	156	9	55	52
Grand Total		272		

What limits the existence of isotopes? (Two important concepts …)

Chart of Nuclides

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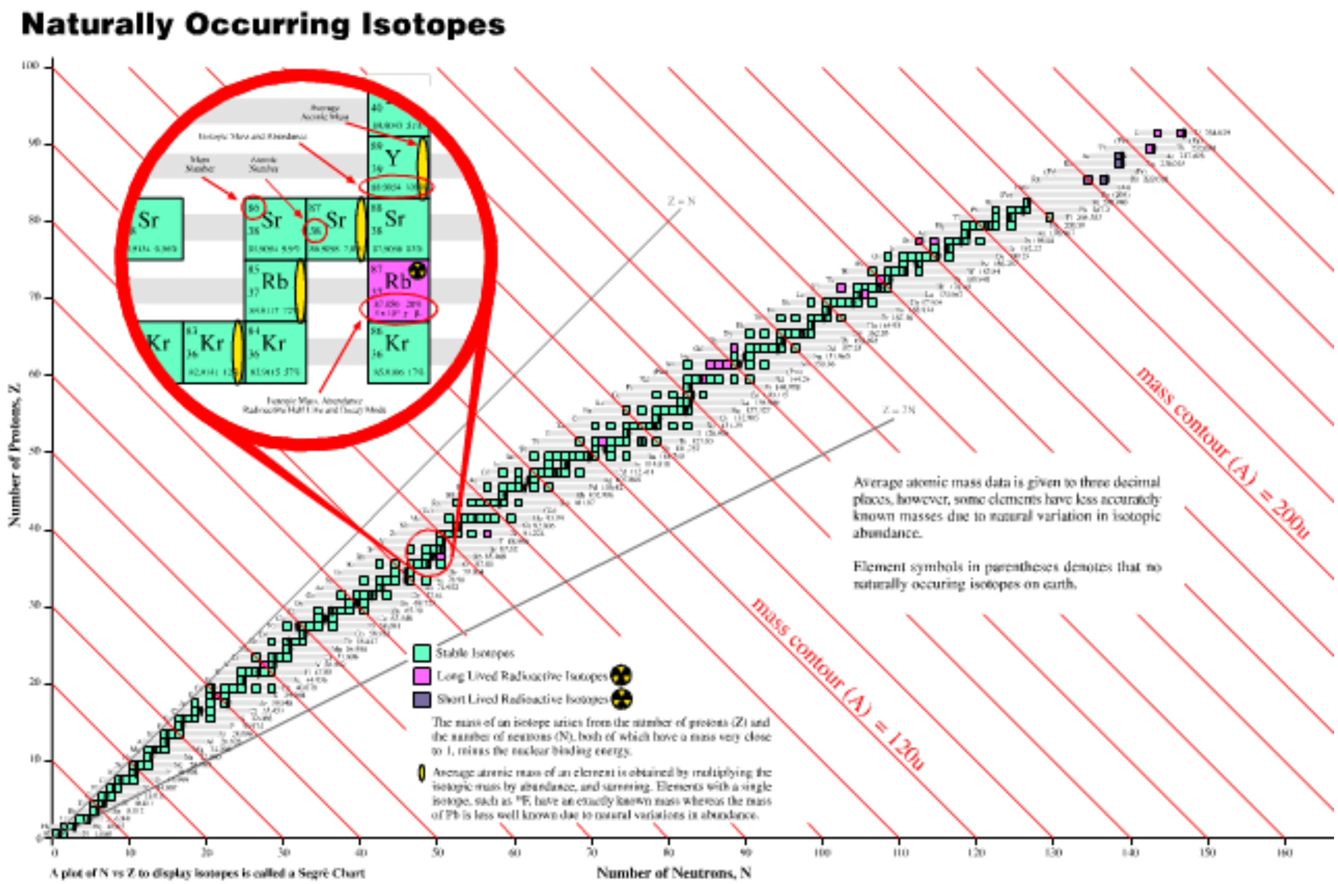
Segre Diagram … N by Z (cf. Fig. 2-3 in text)
More familiar chart … Z by N

http://www.meta-synthesis.com/webbook/33_segre/segre2.png



See also “Nucleus” Program for windoze:
http://amdc.in2p3.fr/web/nubdisp_en.html

http://www.nndc.bnl.gov/chart/

http://atom.kaeri.re.kr/ton/nuc1.html

Nuclear vs. Atomic

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Atomic

Sizes … atoms are spherical with radii in “angstroms”

Processes … electron excitation & relaxation, chemical reactions & bonding

E.g, solid Silicon:

Nuclear

Sizes … nuclear are spherical (or nearly so) with radii of “fermis”

in general, $r = r_0 A^{1/3}$ .. Packing nucleons with uniform density ..

Processes … proton & neutron excitation & relaxation

radioactive decay (often leads to nuclear and/or atomic excitation)

nuclear reactions (nuclear collisions, essentially all extraterrestrial)

Nuclear Processes - 1

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Internal Processes …

relaxation of excited states via photon emission:

e.g., proton, neutron excited states, nuclear vibration or rotation

E.g. $^{99m}Tc \rightarrow$ $^{99}Tc + \gamma$ (*gamma* is used to indicate that the photon is "nuclear")

two-bodies in final state, E_γ = 142.7 keV

1st order kinetics,

half-life is constant, $T_{½}$ =6.015 hr,

or mean-live = τ = $T_{½}$ / ln 2

or decay constant = λ = $1/\tau$ = ln $2/T_{½}$

This isomer is used extensively in nuclear medicine to highlight parts of the body that are biologically more active than surrounding tissue in a SPECT scan (single-photon emission computerized tomography).

Mayo Clinic link on SPECT scan

This material is in short supply at the moment due to a reactor problem in Canada.

http://www.nytimes.com/2009/07/24/science/24isotope.html

Nuclear Processes - 2

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Internal Processes …

relaxation of excited states via photon emission:

e.g., proton, neutron excited states, nuclear vibration or rotation

radioactive decay (often leads to nuclear and/or atomic excitation)

1) Nucleus has too much Coulomb energy
   nuclear conversion/change through the “strong force” … alpha decay, fission

$$^{252}_{98}Cf \rightarrow {}^{248}_{96}Cm + {}^{4}_{2}He + KE_{recoils} \qquad \left[{}^{252}_{98}Cf^{0} \rightarrow {}^{248}_{96}Cm^{2-} + {}^{4}_{2}He^{2+} + KE_{recoils}\right]$$

$$^{252}_{98}Cf \rightarrow {}^{107}_{42}Mo + {}^{141}_{56}Ba + 4n + KE_{f} \qquad [most\ likely\ split]$$

2) Nucleus is unbalanced with respect to neutron/proton number
   nuclear conversion/change through the “weak force” … beta-decay

The Conservation Laws

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(Natural) Law is a concise statement of observed facts in a natural process.

Quantities that are conserved in (all) nuclear reactions:

1) Total energy (including the mass al la Einstein, $E=mc^2$)

Total Energy = Kinetic Energy + Potential Energy + "Mass Energy"

2) Momentum, both linear and angular

Linear momentum, $\vec{p} = m\vec{\mathrm{v}}$

Angular momentum = orbital motion ($\vec{p} = m\vec{\mathrm{v}} \otimes \vec{\mathrm{r}}$) + spin

3) Electrical charge (protons and electrons are charged, of course)

4) The total number of nucleons and separately the total number of leptons

Nucleons: proton, neutron

Leptons: electron, electron-neutrino [anti-electron, anti-electron-neutrino]

Aside: Activity

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^{99m}Tc -- 800 MBq is typically administered during diagnostic procedures.

What does MBq refer to, how many atoms is this?

Radioactive sources are characterized in terms of the number of decays per unit time. This is thus called the ACTIVITY. The historical unit of activity is the "Curie" (Ci) that is defined as 3.700… $x10^{10}$ decays/s (the approximate decay rate of 1 gram of 'natural' radium separated from uranium ore).

The modern (SI) unit of activity is the "Becquerel" (Bq) that is 1 decay/s or simply 1 s^{-1}

Thus: 800 MBq (mega-Becquerel) = 800 $x10^{6}$ decays/s = 8.00 $x10^{8}$ /s

The activity: $A = \lambda N$

Week 2 – Masses & Binding

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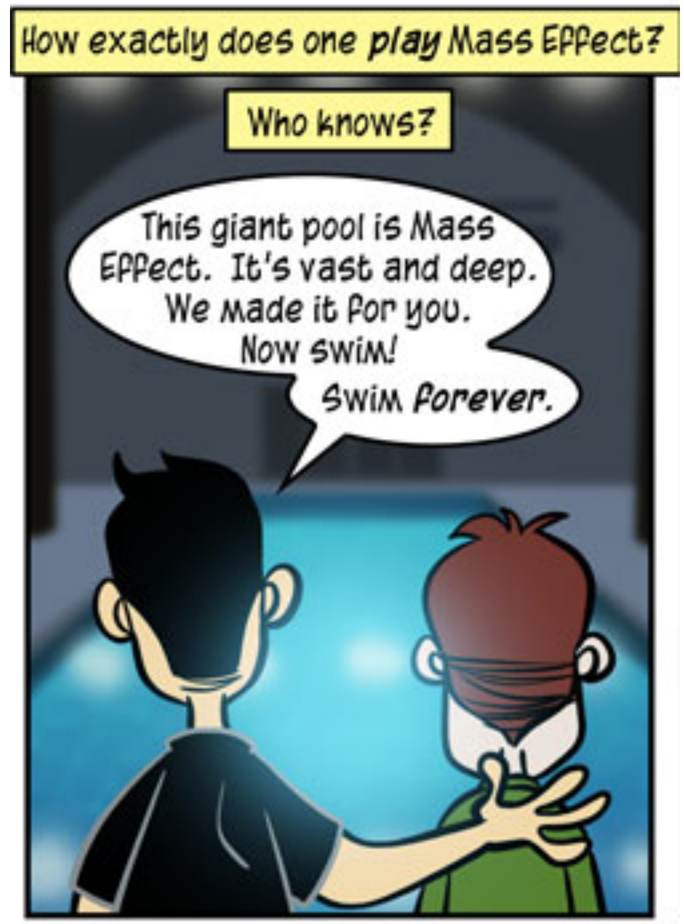
Mass and Energy
-- Einstein's cliché
-- Q values
-- Binding energy viz. Separation Energy
-- "Curve of the Binding Energy"
-- Mass systematics (E-E, E-O, O-E, O-O)
--- Isobaric masses (for beta decay)
-- Mass parameterizations
-- Mass surface
-- "Magic numbers" appear

Nuclear Sizes & Shapes
-- General behavior
-- Unusual behavior



Einstein's Mass

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More than a hundred years ago Einstein suggested a fundamental connection between the "energy" that we observe and the thing we call "mass": $E=mc^2$ The equation plays essentially no role in chemical reactions yet is central to nuclear reactions.

$$ {}^{252}_{98}Cf \rightarrow {}^{248}_{96}Cm + {}^{4}_{2}He + KE_{recoils} \qquad \left[{}^{252}_{98}Cf^{0} \rightarrow {}^{248}_{96}Cm^{2-} + {}^{4}_{2}He^{2+} + KE_{recoils} \right] $$

So the total "energy" on the LHS must equal the total "energy" on the RHS.

LHS = $(m_{nucleus} + 98\, m_{electron})c^2 + B_e(Z=98)$

Nuclear Binding & Separation Energies

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^{12}C 6 neutrons, 6 protons, 6 electrons

Chemistry:

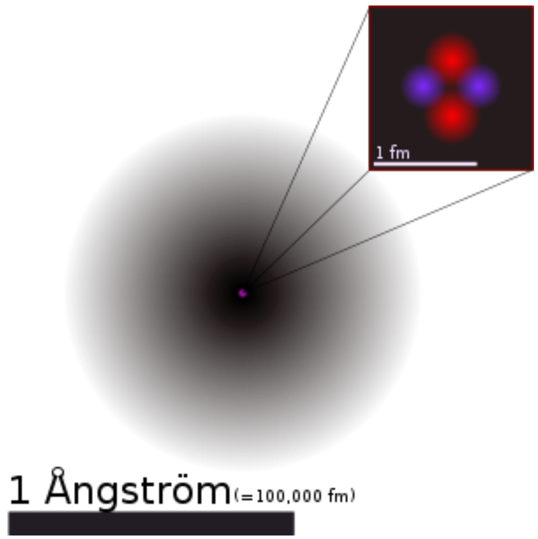
$^{12}C = {}^{12}C^{+} + 1\ e^{-}$ + First IP

$^{12}C^{+} = {}^{12}C^{2+} + 1\ e^{-}$ + Second IP

$^{12}C^{2+} = {}^{12}C^{3+} + 1\ e^{-}$ + Third IP

…

$^{12}C^{5+} = {}^{12}C^{6+} + 1\ e^{-}$ + Sixth IP



Total electron binding energy:

$$B_e(Z) = \sum_{i=1,6} IP_i$$

Approximate expression in text:

$$B_e(Z) \approx 15.73 Z^{7/3}\ eV$$

Nuclear Chemistry:

$^{12}C = {}^{11}C + 1\ n^{o}$ + Q

This Q value is called "S_n"

$^{12}C = {}^{11}B^{-} + 1\ p^{+} + S_p$

(for calculation)

$^{12}C = {}^{11}B + 1\ H + S_p$

Total "unbinding" …

$^{12}C = 6\ {}^{1}H + 6\ n^{o}$ + Energy Input

Total nuclear binding energy: $6\ {}^{1}H + 6\ n^{o} = {}^{12}C$ + BE

Curve of the Binding Energy (stable isotopes)

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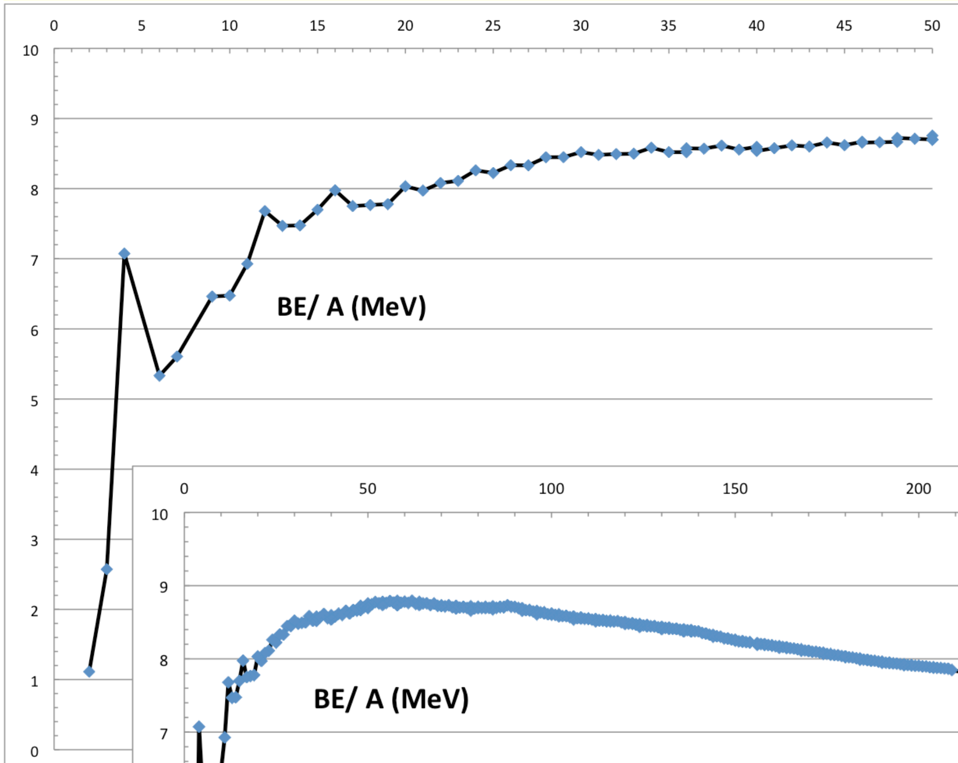

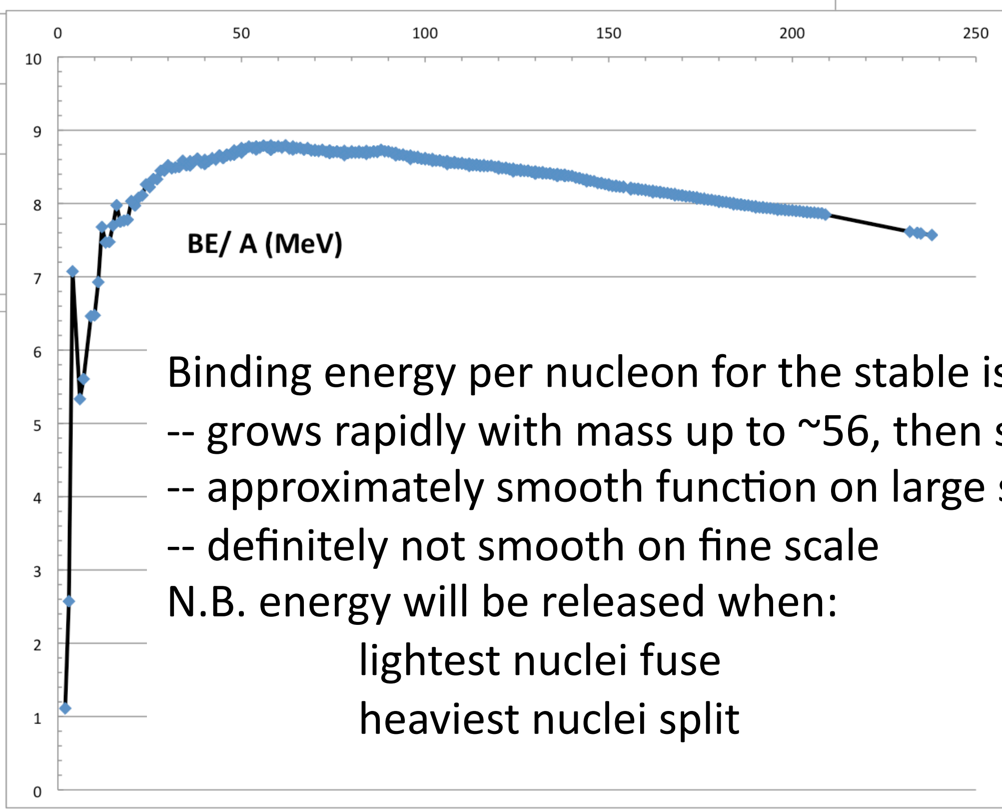

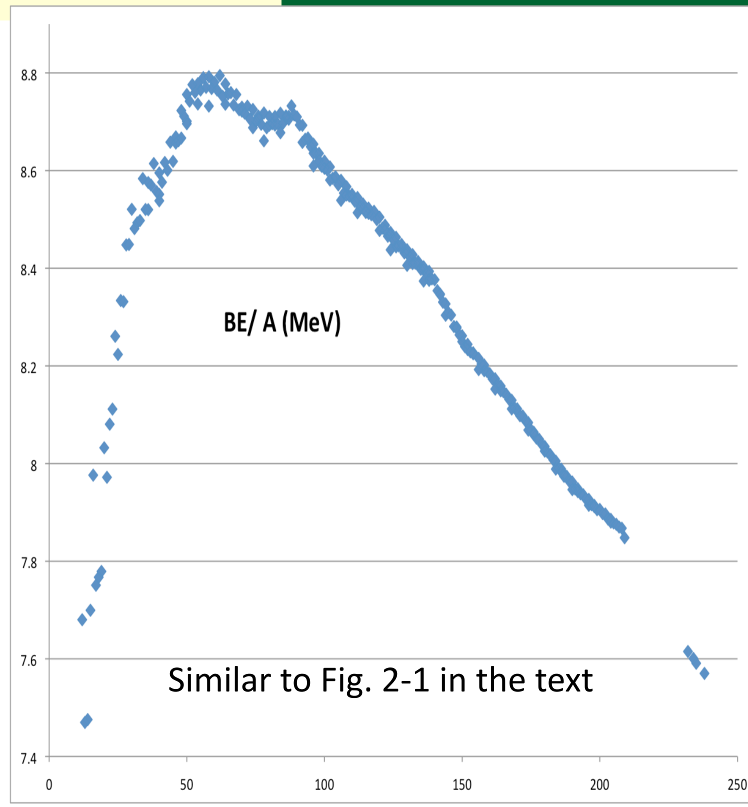

Similar to Fig. 2-1 in the text

Binding energy per nucleon for the stable isotopes:

-- grows rapidly with mass up to ~56, then slowly declines

-- approximately smooth function on large scale

-- definitely not smooth on fine scale

N.B. energy will be released when:

lightest nuclei fuse

heaviest nuclei split

Atomic Masses and Mass Defect (Δ)

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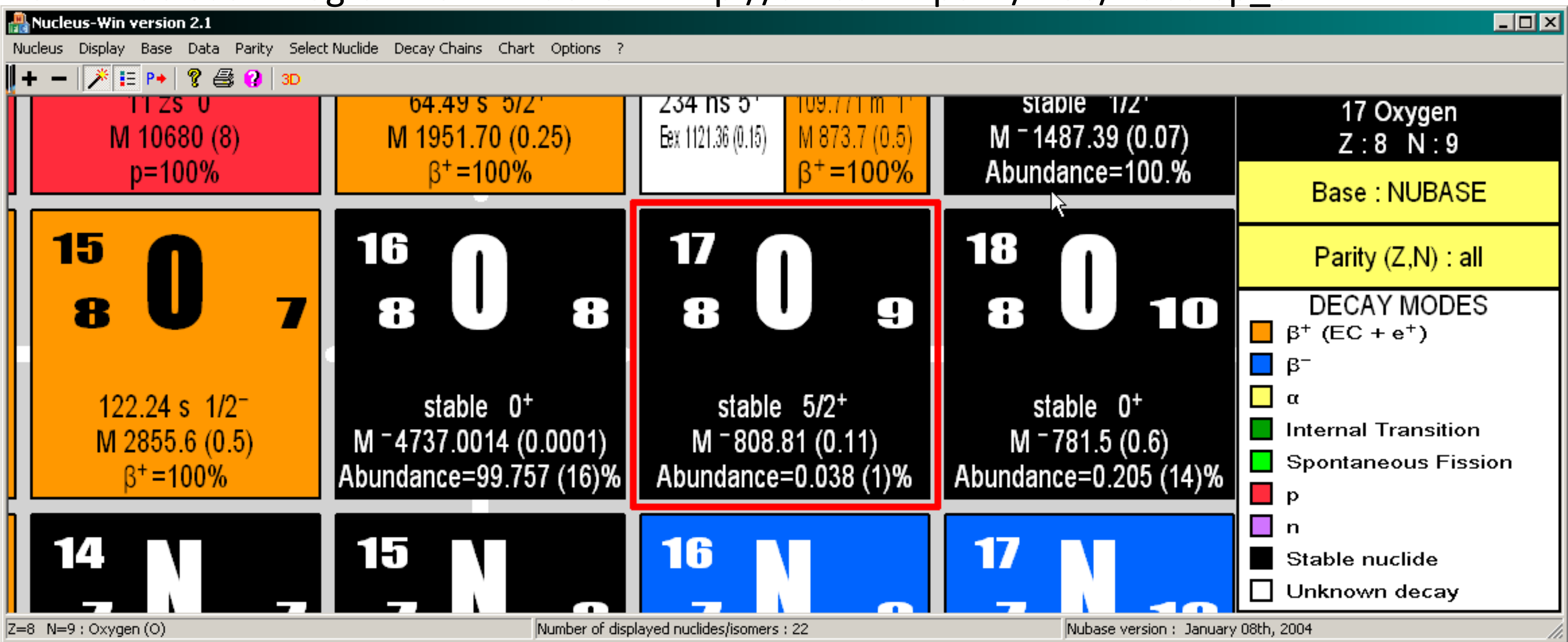
From “Nucleus” Program for windoze: http://amdc.in2p3.fr/web/nubdisp_en.html



Fact: the mass value (u) is always close to the integer mass number.
Reason: the binding energy is small compared to the (Einstein) rest-energy of a nucleon.
(Note that this is also true for electrons.)

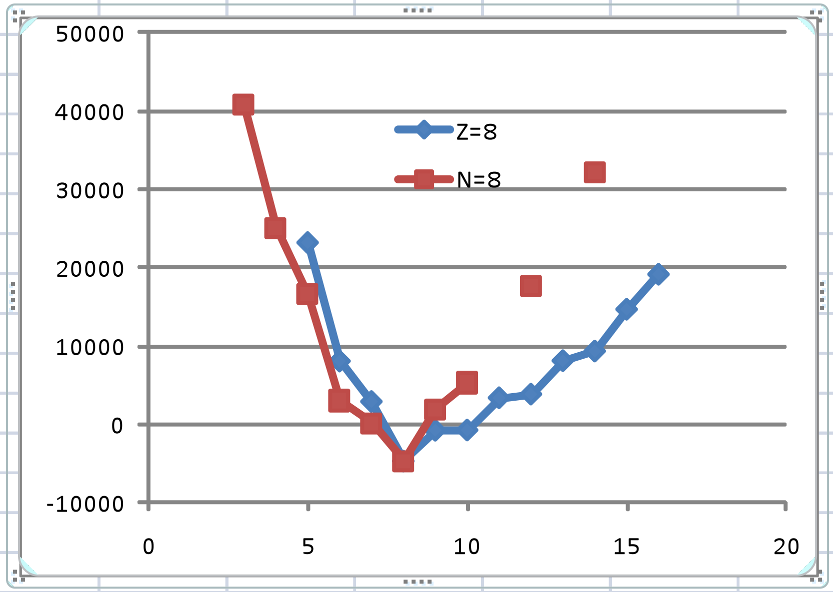
Practical use: Define the mass defect (Δ) as the difference from the integer mass number but use energy units (MeV or keV) instead of the traditional mass (u) or the SI unit (kg).

$\Delta = (m - A)\, c^2$ ^{18}O : $(17.999160 - 18)\,u\, c^2 * 931.494\ \mathrm{MeV}/u\, c^2 = -0.7825\ \mathrm{MeV}$

Systematics of Atomic Masses - 1

The set of all oxygen isotopes (Z=8): ^{13}O – ^{24}O
The set of all N=8 isotones: ^{11}Li – ^{18}Ne, ^{20}Mg, ^{22}Si

Z=8	Δ (keV)	N=8		Δ (keV)
5	23112	11-Li	3	40797
6	8007.36	12-Be	4	25077
7	2855.6	13-B	5	16562.2
8	-4737	14-C	6	3019.893
9	-808.81	15-N	7	101.438
10	-781.5	16-O	8	-4737
11	3334.9	17-F	9	1951.7
12	3797.5	18-Ne	10	5317.17
13	8063		11	
14	9280	20-Mg	12	17570
15	14610		13	
16	19070	22-Si	14	32160



Data from NUCLEUS-WIN (AME 2004)

Systematics of Atomic Masses – 2a

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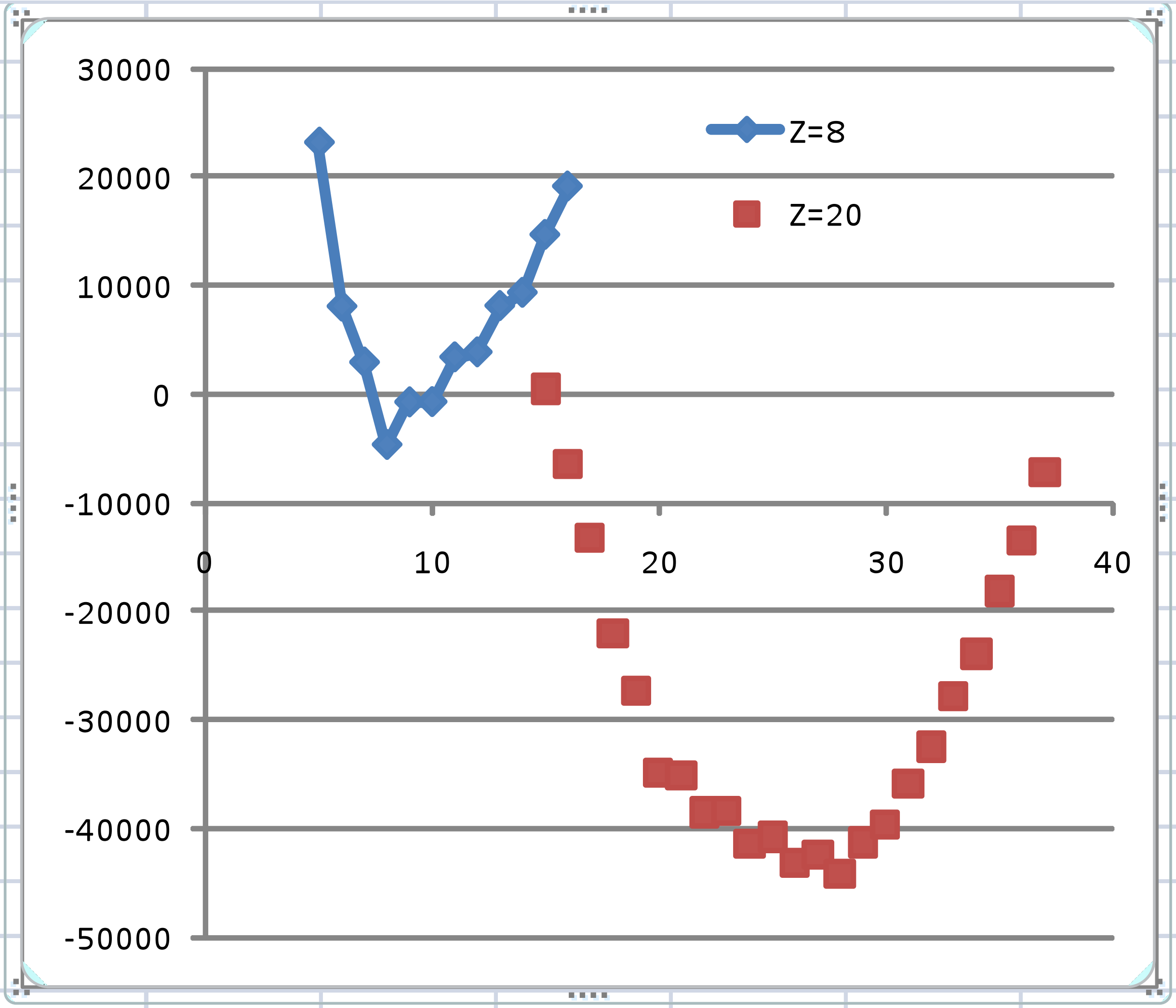
The set of all **calcium isotopes** (Z=20): ^{35}Ca – ^{57}Ca

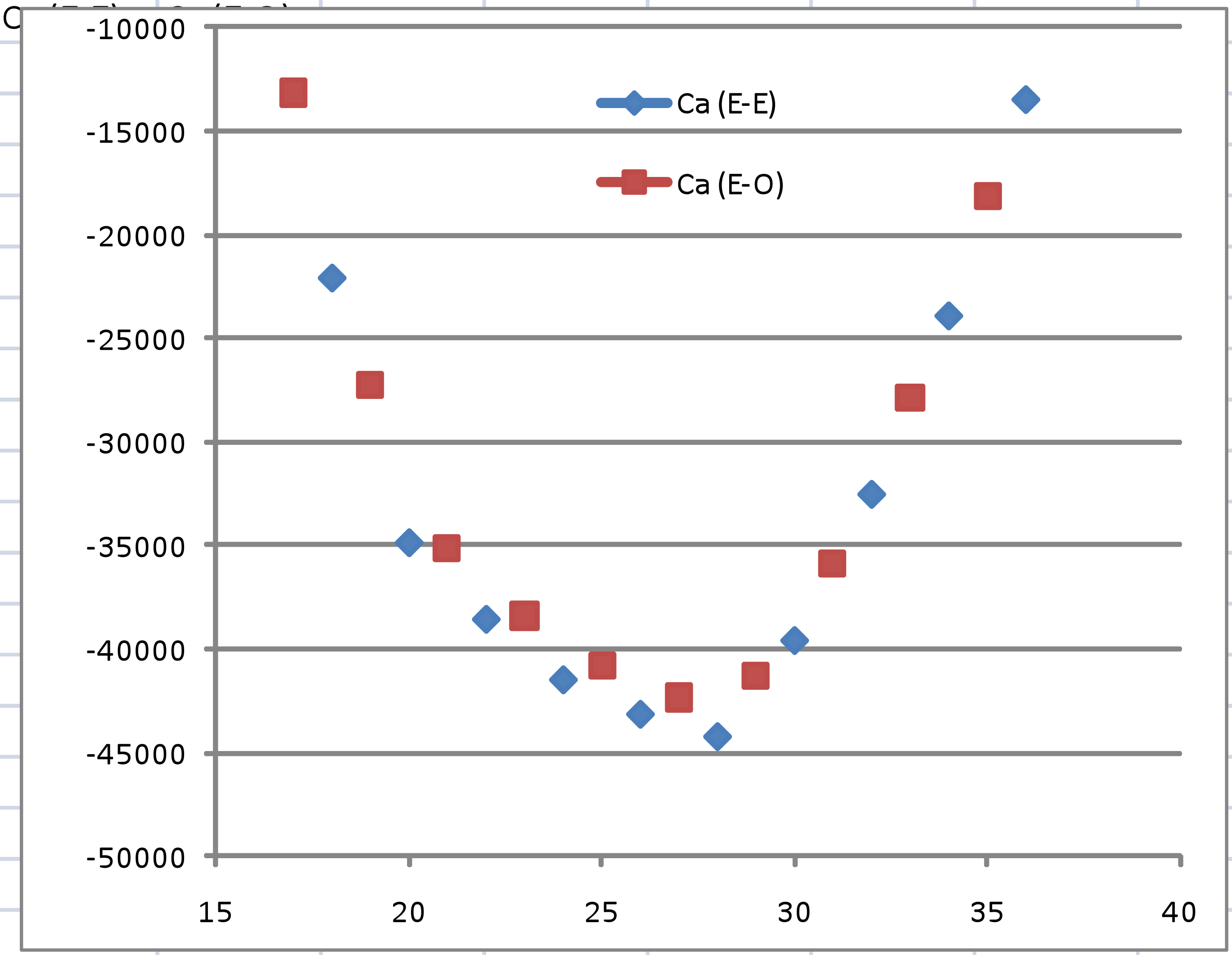
Z=20	Δ (keV)
15	460
16	-6440
17	-13162
18	-22059
19	-27274.4
20	-34846.3
21	-35137.8
22	-38547.1
23	-38408.6
24	-41468.5
25	-40812
26	-43135.1
27	-42340.1
28	-44214
29	-41289
30	-39571
31	-35860
32	-32510



Systematics of Atomic Masses – 2b

The set of all **calcium isotopes** (Z=20): ^{35}Ca – ^{57}Ca ; Separate by "type"

Z=20	Δ (keV)
15	460
16	-6440
17	-13162
18	-22059
19	-27274.4
20	-34846.3
21	-35137.8
22	-38547.1
23	-38408.6
24	-41468.5
25	-40812
26	-43135.1
27	-42340.1
28	-44214
29	-41289
30	-39571
31	-35860
32	-32510



Systematics of Atomic Masses – 3a

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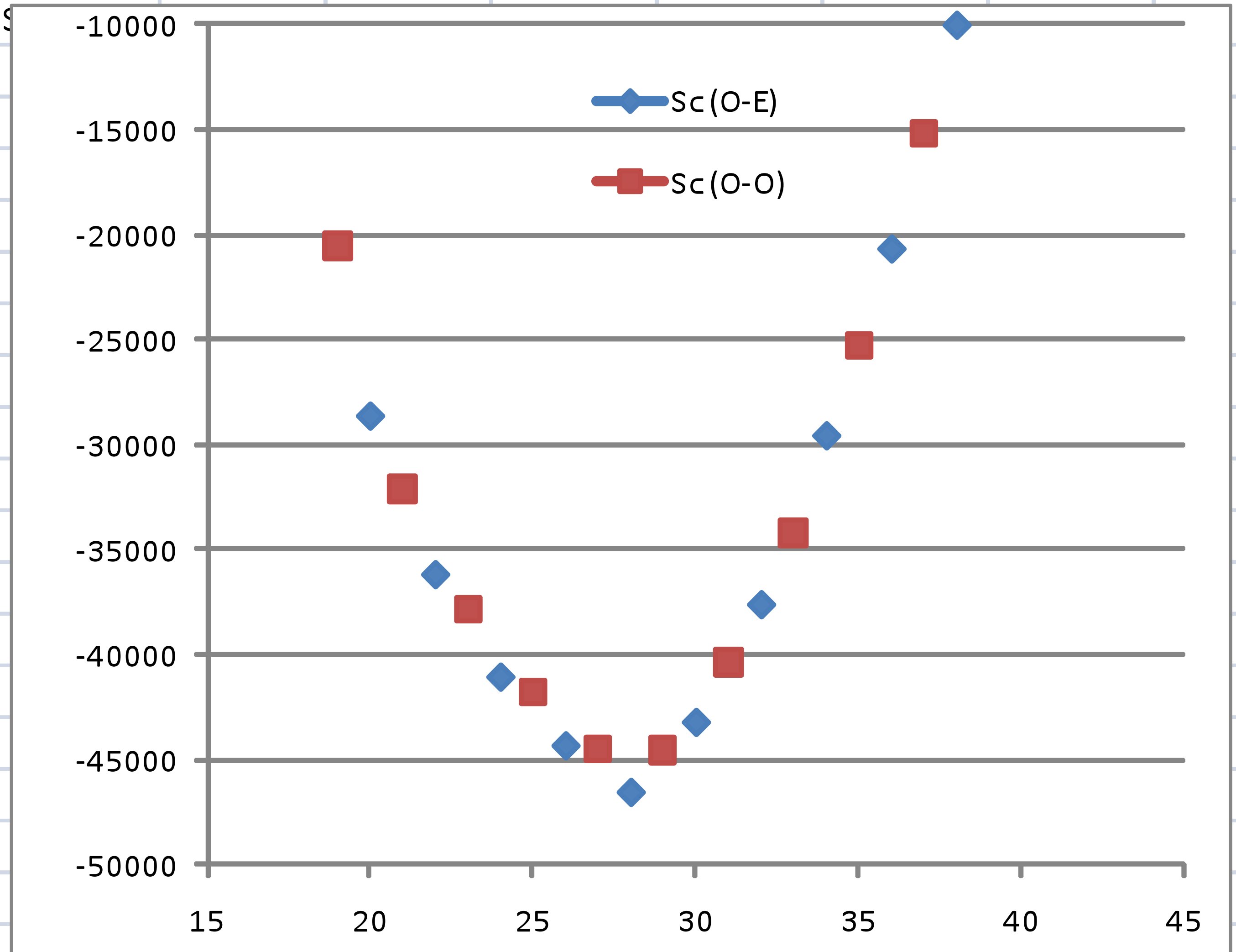
The set of all **scandium isotopes** (Z=21): ^{40}Sc – ^{60}Sc ;   Separate by "type"

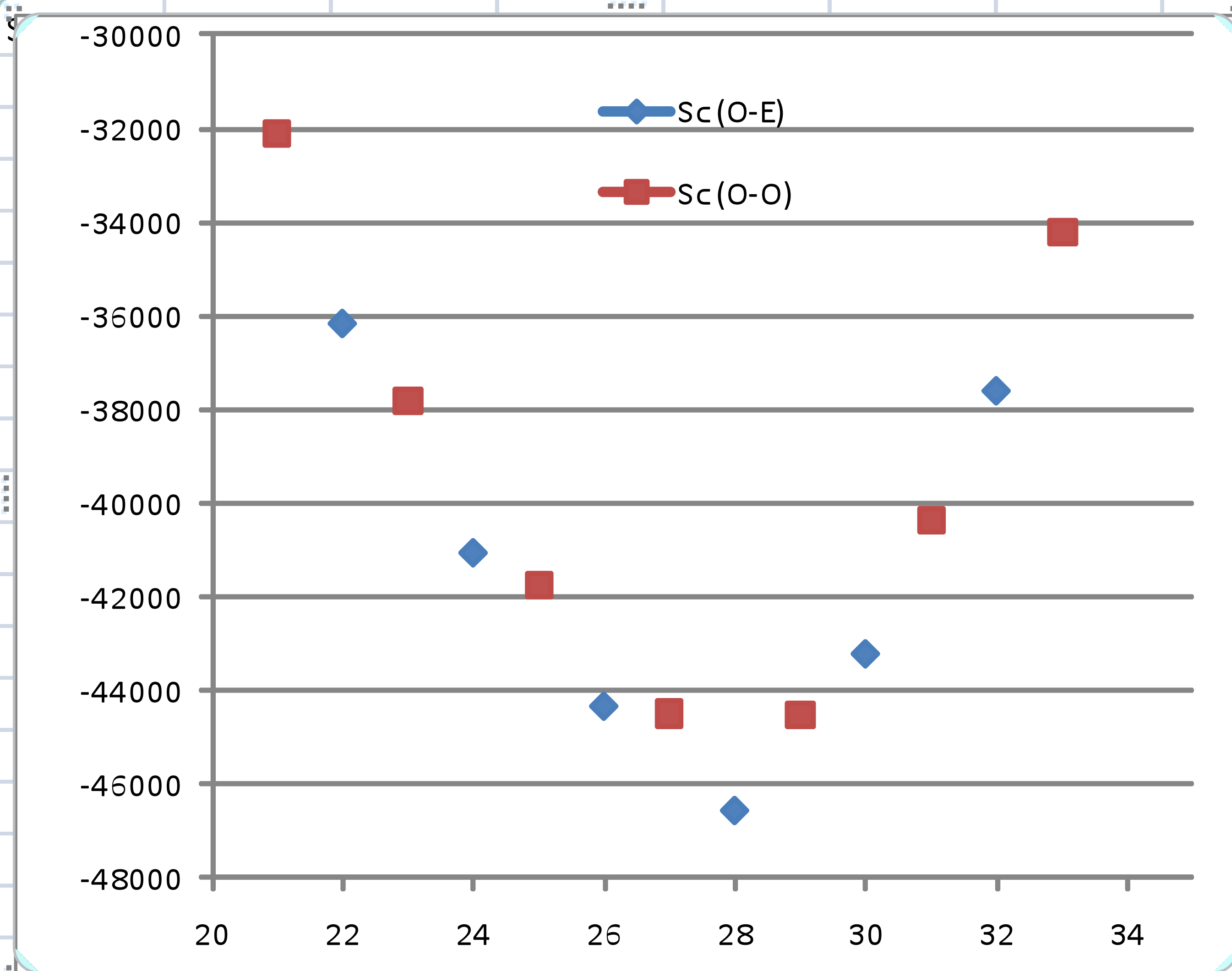
Z=21	Δ (keV)
19	-20523.2
20	-28642.4
21	-32121.2
22	-36187.9
23	-37816.1
24	-41067.8
25	-41757.1
26	-44332.1
27	-44496
28	-46552
29	-44537
30	-43218
31	-40360
32	-37620
33	-34220
34	-29580
35	-25270
36	-20690



Systematics of Atomic Masses – 3b

The set of all **scandium isotopes** (Z=21): ^{40}Sc – ^{60}Sc ; Separate by "type"

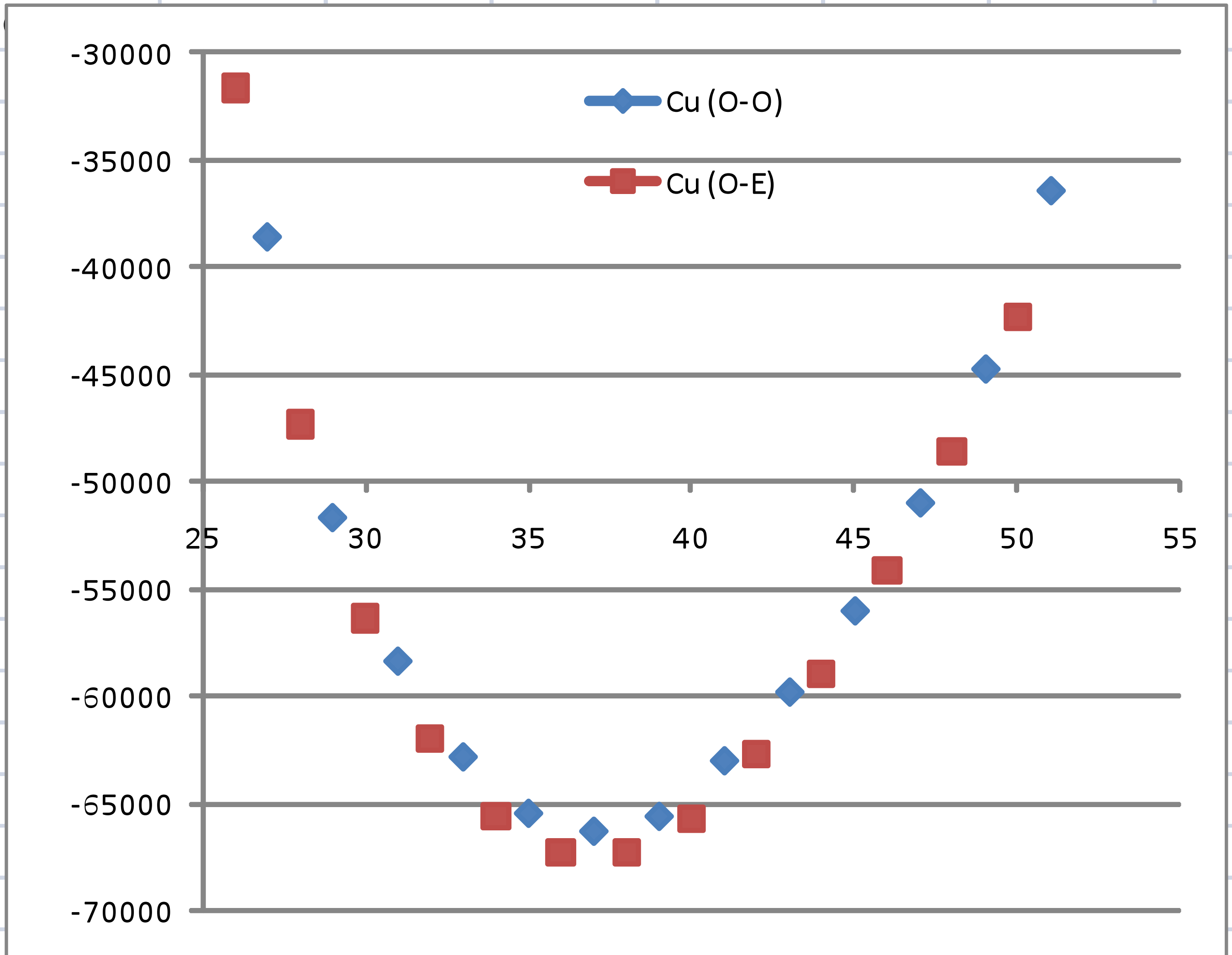
Z=21	Δ (keV)
19	-20523.2
20	-28642.4
21	-32121.2
22	-36187.9
23	-37816.1
24	-41067.8
25	-41757.1
26	-44332.1
27	-44496
28	-46552
29	-44537
30	-43218
31	-40360
32	-37620
33	-34220
34	-29580
35	-25270
36	-20690



Systematics of Atomic Masses – 4

The set of all **copper isotopes** (Z=29): $^{55}Cu - ^{80}Cu$;   Separate by "type"

Z=29	Δ (keV)
26	-31620
27	-38600
28	-47310
29	-51662
30	-56357
31	-58344
32	-61983
33	-62798
34	-65579.5
35	-65424.2
36	-67263.7
37	-66258.3
38	-67318.8
39	-65567
40	-65736.2
41	-62976.1
42	-62711.1
43	-59783



Week 3 – Radioactive Decay

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Nuclear Decay
-- Decay Law
-- Simplest form of kinetics
-- Sequential Decay (three classes)
-- Radioactive dating, Ages & Activities

Basics of Nuclear Structure
-- Nuclear potential well
-- Schematic shell model of nuclei