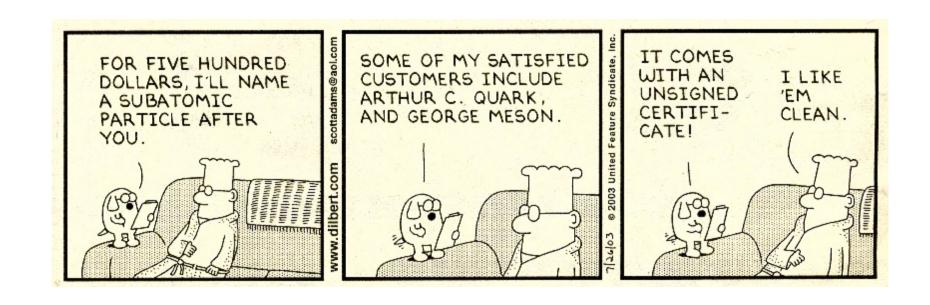
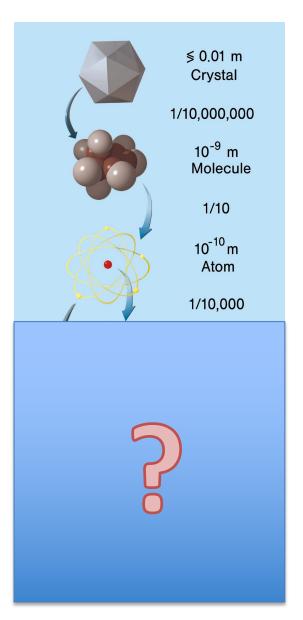
# PHYS415/515:

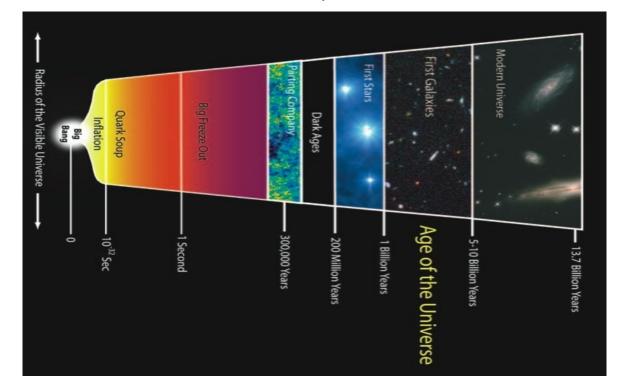
# Particle and Nuclear Physics Sebastian Kuhn



### The Structure of Matter



- What is the Universe made off?
- What are the most fundamental objects in Nature?
- ➤ What particles where there in the beginning (right after the big bang)?
- How do they interact? How do they form larger objects?
- Where does all matter in the present Universe come from?



# Hydrogen Atom Wave functions

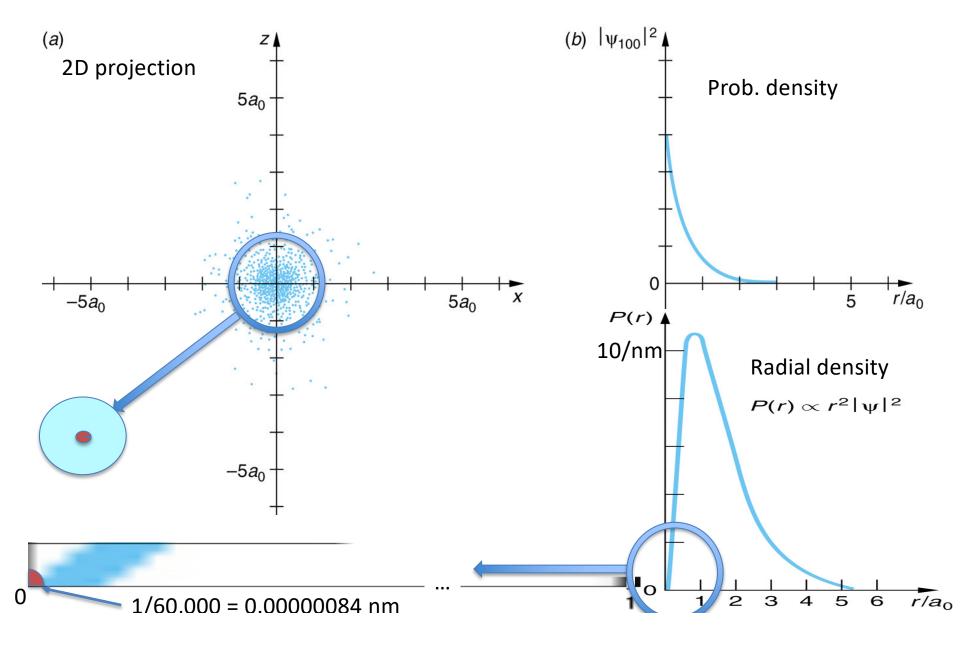
Remember Modern Physics / QM?

When n=1, l=0, m=0 : 1s 
$$\Psi_{1,0,0} = \sqrt{\frac{1}{a_0^3 \pi}} e^{-r/a_0}$$
 n=2, l=0, m=0 : 2s 
$$\Psi_{2,0,0} = \sqrt{\frac{1}{32a_0^3 \pi}} \left(2 - \frac{r}{a_0}\right) e^{-r/2a_0}$$
 l=1 m=0, ±1 : 2p 
$$\Psi_{2,1,0} = \sqrt{\frac{1}{32a_0^3 \pi}} \frac{r}{a_0} \cos \theta \, e^{-r/2a_0}, \Psi_{2,1,\pm 1} = \mp \sqrt{\frac{1}{64a_0^3 \pi}} \frac{r}{a_0} \sin \theta \, e^{\pm i\varphi} e^{-r/2a_0}$$

$$a_0=rac{4\piarepsilon_0oldsymbol{\hbar}^2}{e^2m_\mathrm{e}}=rac{oldsymbol{\hbar}}{m_\mathrm{e}clpha}$$
 = 0.0529 nm  $pprox$  0.53Å

- $\hbar$  is the reduced Planck constant,  $\approx 197.33 \frac{\text{nm eV}}{c}$
- $m_{\rm e}$  is the mass of an electron,  $\approx 511~{\rm keV/c^2}$
- *e* is the elementary charge,
- c is the speed of light in vacuum, and
- $\alpha$  is the fine-structure constant.  $\approx 1/137.036$

# H ground state



# Periodic Table

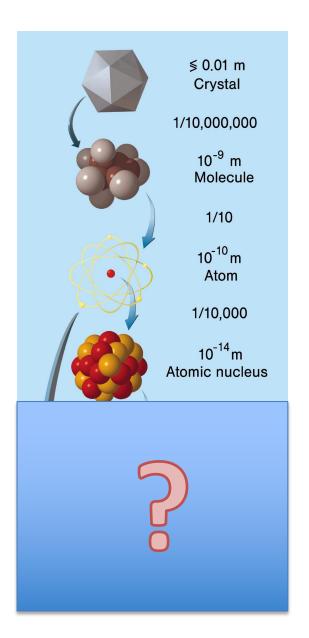
husba ann	1 -			75.1								-	Ato	mic	15.7	5.70		helium	
nydrogen 1		bo								boron		Number = Z							
H 1,0079						Atom	nic M	ASS			5							He	
lithium 3	beryllium <b>4</b>					(units: $u = 1/12$ the				-			boron 5	carbon 6	nitrogen 7	oxygen 8	fluorine 9	neon 10	
Li	Be					•		-		B			B	C	Ń	Ó	F	Ne	
6.941	9.0122					mass of 12C atom						10.811	12.011	14.007	15,999	18,998	20,18		
sodium 11	magnesium 12										10.811		aluminium 13	silicon 14	phosphorus 15	sulfur 16	chlorine 17	argor	
Na	Mg												Al	Si	Р	S	CI	Aı	
22.990	24.305	F						-					26.982	28.086	30.974	32.065	35.453	39.94	
otassium 19	calcium 20		scandium 21	titanium 22	vanadium 23	chromium 24	manganese 25	26	cobalt 27	nickel 28	copper 29	30	gallium 31	germanium 32	arsenic 33	selenium 34	bromine 35	krypto 36	
K	Ca		Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	K	
39.098	40.078		44.956	47.867	50.942	51,996	54.938	55.845	58.933	58,693	63,546	65.39	69.723	72.61	74.922	78.96 tellurium	79.904	83.80	
rubidium 37	strontium 38		yttrium 39	zirconium 40	niobium 41	molybdenum 42	technetium 43	ruthenium 44	rhodium 45	palladium 46	silver 47	cadmium 48	indium 49	50	antimony 51	52	iodine 53	xenor	
Rb	Sr		Υ	Zr	Nb	Мо	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	-	Xe	
85.468	87.62		88,906 lutetium	91.224 hafnium	92.906 tantalum	95.94	[98] rhenium	101.07	102.91 iridium	106.42	107.87	112.41	114.82 thallium	118.71	121.76 bismuth	127.60 polonium	126.90 astatine	131.2	
caesium 55	barium 56	57-70	71	72	73	tungsten 74	75	osmium 76	77	platinum 78	gold 79	mercury 80	81	lead 82	83	84	85	rador 86	
Cs	Ba	*	Lu	Hf	Ta	W	Re	Os	lr	Pt	Au	Hg	TI	Pb	Bi	Po	At	Rr	
132.91	137.33		174.97	178.49 rutherfordium	180.95 dubnium	183.84 seaborgium	186.21 bohrlum	190.23	192.22 meitnerium	195.08 ununnilium	196.97	200.59 ununbium	204.38	207.2	208.98	[209]	[210]	[222]	
randum 87	radium 88	89-102	103	104	105	106	107	hassium 108	109	110	unununium 111	112		ununquadium 114					
Fr	Ra	* *	Lr	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu			Uuq					
[223]	[226]		[262]	[261]	[262]	[266]	[264]	[269]	[268]	[271]	12721	[277]		[289]	l				

\*Lanthanide series

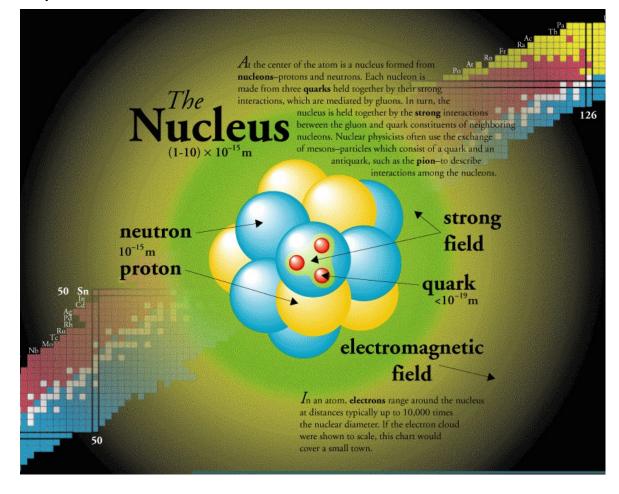
\* \* Actinide series

	lanthanum 57	cerium 58	praseodymium 59	neodymium 60	promethium 61	samarlum 62	europium 63	gadolinium 64	terbium 65	dysprosium 66	holmium 67	erbium 68	thulium 69	ytterbium 70
	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Но	Er	Tm	Yb
- 1	138.91	140.12	140.91	144.24	[145]	150.36	151.96	157.25	158.93	162.50	164.93	167.26	168.93	173.04
- [	actinium	thorium	protactinium.	uranium	neptunium	plutonium	americium	curium	berkelium	californium	einsteinium	fermium	mendelevium	nobelium
- 1	89	90	91	92	93	94	95	96	97	98	99	100	101	102
	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No
ı	[227]	232.04	231.04	238.03	[237]	[244]	[243]	[247]	[247]	[251]	[252]	[257]	[258]	[259]

### The Structure of Matter



99.97% of the mass of an atom (and hence of all visible matter) is concentrated in the nucleus. 0.000,000,000,024% of the atomic volume is occupied by the nucleus .



### Stable nuclei

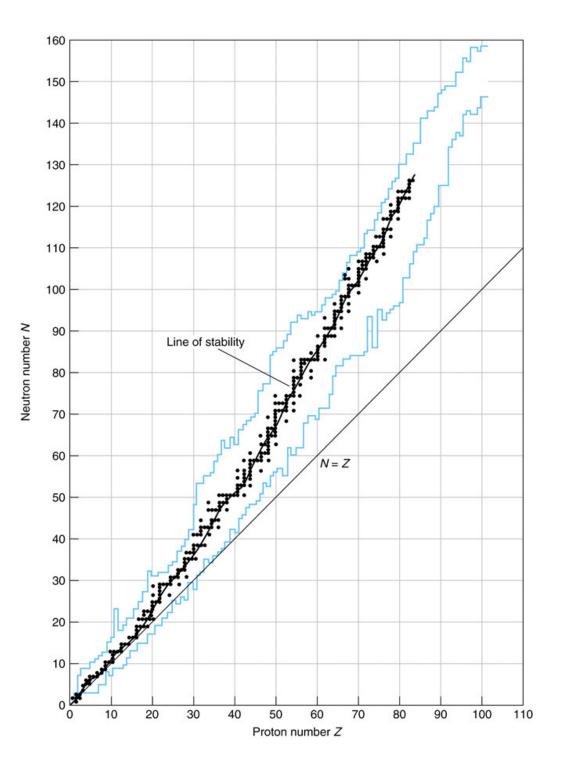
A = N + Z (all integers)

Isotopes: SAME Z

Isobars: SAME Z

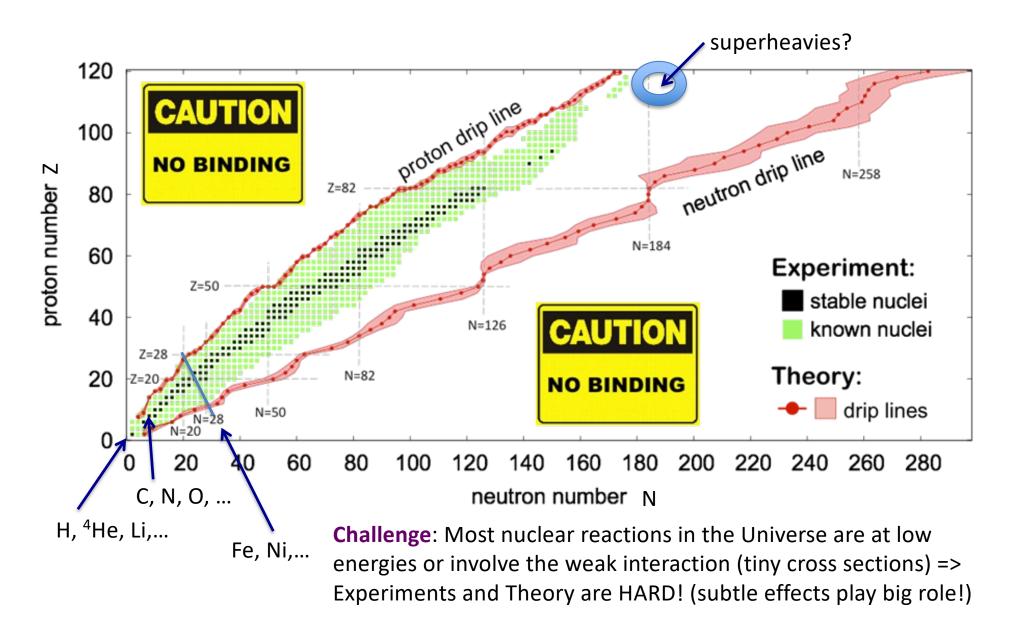
Nuclear mass is ROUGHLY proportional to A (see later)

ATOMIC mass can be fractional if the natural abundance of a given element has several stable isotopes





### All the nuclei in the universe



#### Atomic Binding energy

 $B_{\text{atomic}} M_{\text{At}} c^2 - M_{\text{Nuc}} c^2 - Z \cdot m_e c^2$ 

 $M_{\rm Nuc}$  = Mass of Nucleus  $M_{\rm At}$  = Atomic mass (single isotope) Z = Element Number

Typical values: few eV's ... keV's

#### Nuclear Binding energy

$$B_{\text{nuclear}} = M_{\text{N}}c^2 - Z \cdot m_{\text{p}}c^2 - N \cdot m_{\text{n}}c^2$$

 $m_p$  = Mass of Proton  $m_n$  = Mass of neutron

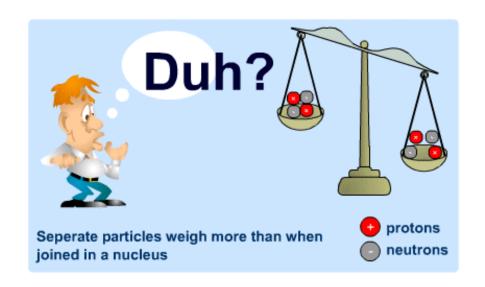
A= N + Z
A= Atomic Mass Number
N=Neutron Number
Z=Proton Number

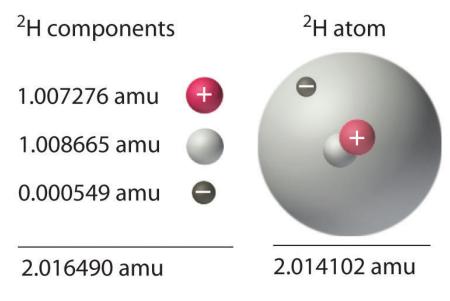
Typical values: keV's to 100's of MeV's

$$E = mc^2$$

In atomic and nuclear physics, masses are typically given in atomic mass units (u) 1 u = 1.66054 \*  $10^{-27}$  kg = 931.494 MeV/c<sup>2</sup>

Proton = 938.27 MeV Neutron = 939.51 Mev



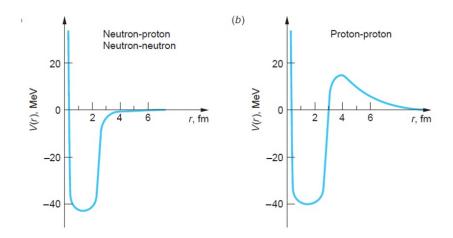


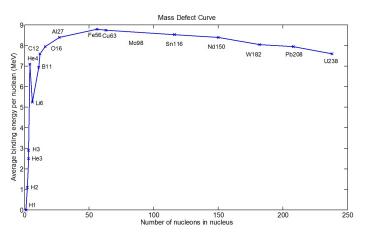
Mass defect = 0.002388 amu = 2.224 MeV

Note: amu = u (depending on who is talking)

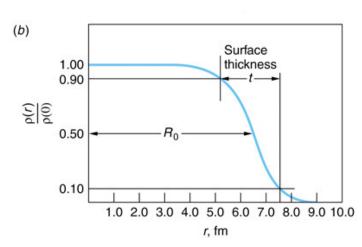
### **Nuclear Force**

- Charge independent.
- Highly dependent on distance
- Saturated force
- Coulomb Repulsion will overcome the Nuclear Force as atoms become larger.

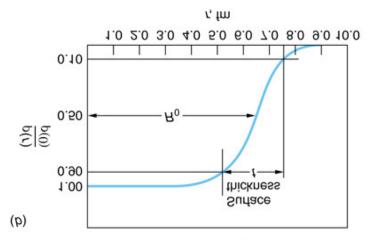




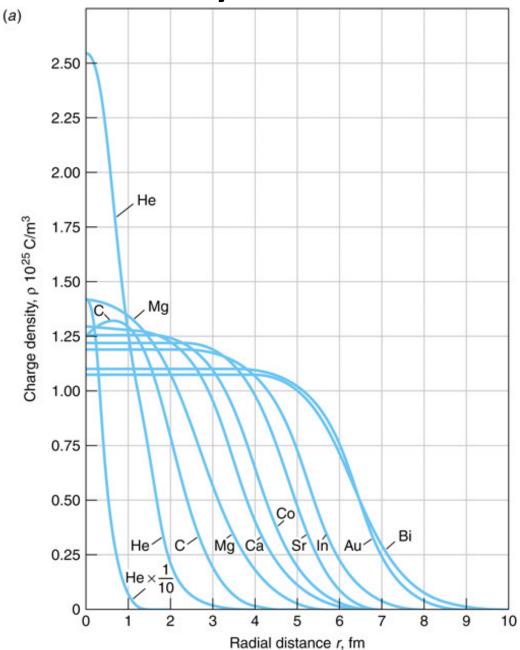
## **Nuclear Density**



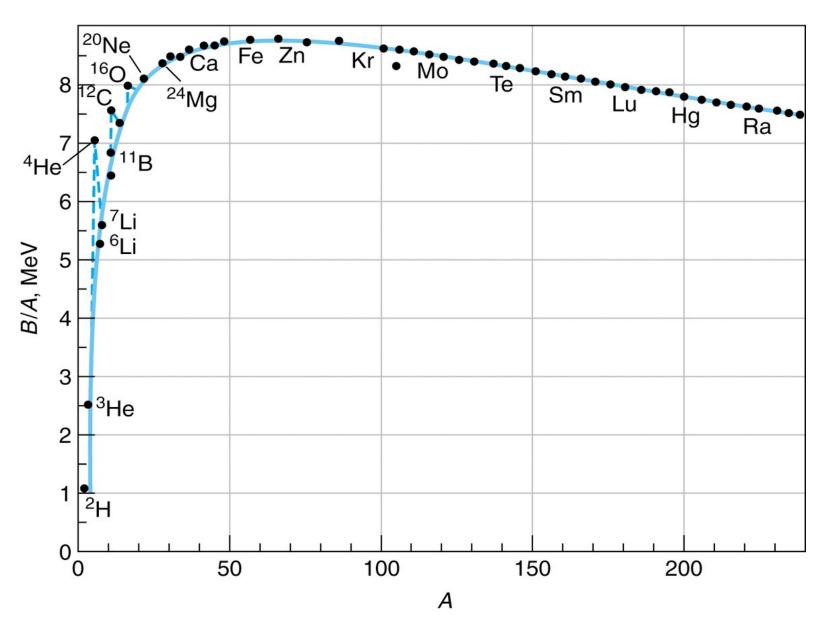
Typical Nuclear Density Profile (Cesium?)



=> Due to short range nuclear force, each nucleon "sees" THIS potential



# Nuclear Binding energies



### Liquid Drop Model

From previous slides, we find that nuclear density is roughly constant, and hence the nuclear radius goes like A<sup>1/3</sup>

$$R = 1.22 \text{ fm} \cdot A^{1/3}$$
Surface = 19 fm<sup>2</sup> ·  $A^{2/3}$ 

$$M(A, Z) = NM_{\rm n} + ZM_{\rm p} + Zm_{\rm e} - a_{\rm v}A + a_{\rm s}A^{2/3}$$

$$+ a_{\rm c}\frac{Z^2}{A^{1/3}} + a_{\rm a}\frac{(N-Z)^2}{4A} + \frac{\delta}{A^{1/2}}$$

$$a_{\rm v} = 15.67 \,\mathrm{MeV}/c^2$$

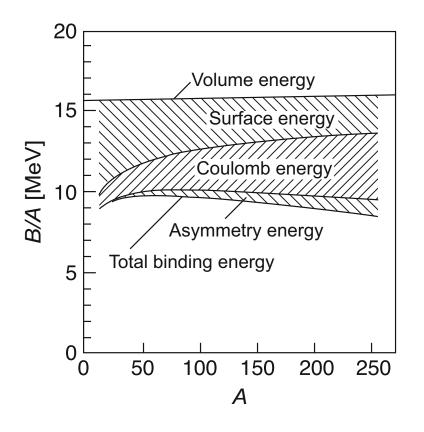
$$a_{\rm s} = 17.23 \,\mathrm{MeV}/c^2$$

$$a_{\rm c} = 0.714 \,\mathrm{MeV}/c^2$$

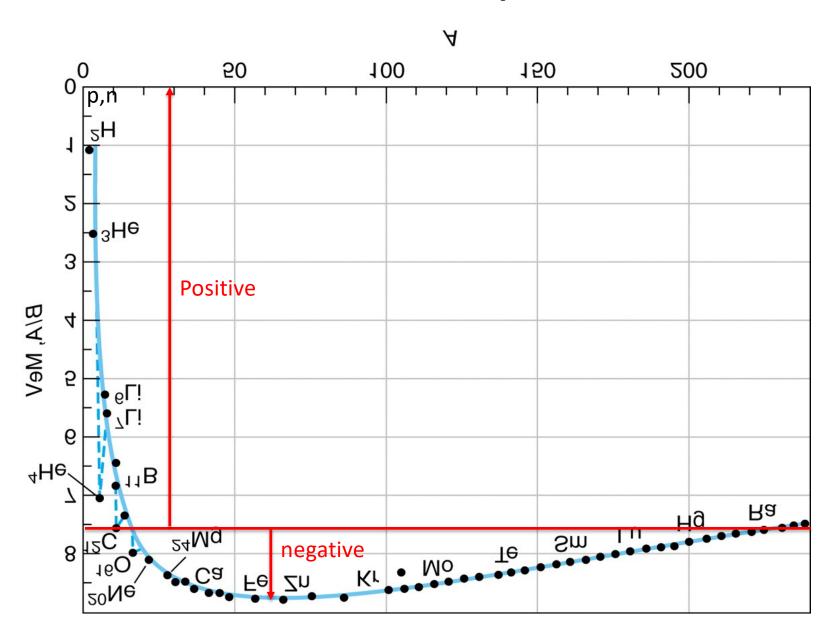
$$a_{\rm a} = 93.15 \,\mathrm{MeV}/c^2$$

$$\delta = \begin{cases} -11.2 \,\mathrm{MeV}/c^2 & \text{for even } Z \text{ and } N \text{ (even-even nuclei)} \\ 0 \,\mathrm{MeV}/c^2 & \text{for odd } A \text{ (odd-even nuclei)} \\ +11.2 \,\mathrm{MeV}/c^2 & \text{for odd } Z \text{ and } N \text{ (odd-odd nuclei)}. \end{cases}$$

Central (saturation) density:  $\varrho_0 \approx 0.17 \text{ nucleons/fm}^3 = 3 \cdot 10^{17} \text{ kg/m}^3$ Average density:  $0.13 \text{ nucleons/fm}^3$ 



## Nuclear Mass excess per nucleon



### Partially explains abundance of elements

**Fig. 2.2** Abundance of the elements in the solar system as a function of their mass number A, normalised to the abundance of silicon (=10<sup>6</sup>)

#### Full explanation requires:

- INITIAL ("primordial") abundance (nearly all <sup>1</sup>H and <sup>4</sup>He)
- 2) Reaction path from these to heavier elements (stars and their collapse, supernovae, neutron star mergers,...)

