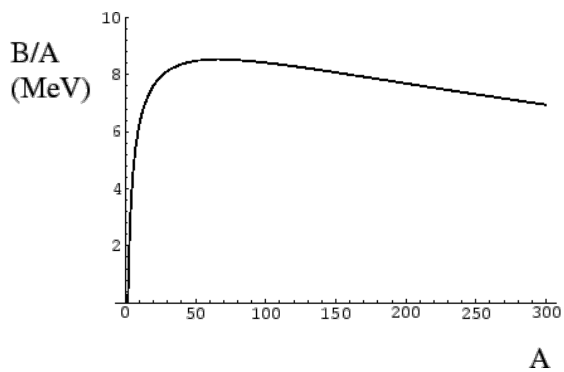
Problem 1

The binding energy per nucleon is described by the following curve:



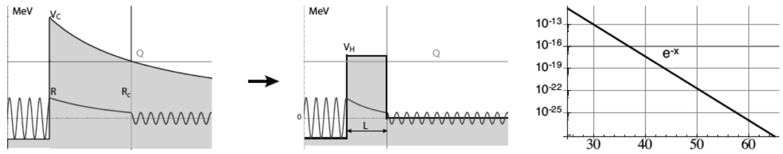
- What is the name of the formula we can use to estimate binding energies?
- This formula consists of several terms. Write up all the terms in the formula and sketch the individual curves corresponding to the terms (together they will make up the curve above).
- Explain the physical principles behind each term. Which term is the most important?

Problem 2

- In a scattering experiment it was found that ^{12}C has a nuclear radius of 2.7 fm. The same experiment is then repeated using a different, unknown element. The result shows that the nuclear radius is twice as big. What is the mass number of the unknown element?
- Which experiment was the first to measure the size of the nucleus? Briefly describe this experiment.

Problem 3

The isotope Europium-131 ($^{131}_{63}Eu$) with rest mass 121919.966 MeV/c^2 is an unstable isotope and a possible decay channel is proton emission. We want to analyze this decay mode following the same theory as we used for alpha decay and in particular estimate the half-life of $^{131}_{63}Eu$. The following questions will guide you through the estimation.



3a

- How can we see that this isotope is unstable?
- What is the Q value for the reaction ${}^{131}_{63}Eu \rightarrow {}^{130}_{62}Sa + {}^{1}_{1}H$?
  The rest mass of Samarium-130 is 120980.755 MeV/c^2.
- What is the frequency $f = \frac{v}{R}$ for the proton at the edge of the Coulomb potential? R is the Samarium radius and v is the proton speed when Q is the (classical) kinetic energy. Useful quantity: $R_0 = 1.2fm$

3b

- What is the Coulomb potential, $V_C(R)$, at the distance R?
- What is the distance R_C where the Coulomb potential is equal to the Q value?

3c

- To estimate the tunnelling probability we replace the Coulomb barrier with a rectangular barrier of height $V_H = V_C(R)/2$ and length $L = (R_C - R)/2$ (see figure). What is the tunnelling probability?
- Finally, find the decay rate λ and the half-life $t_{1/2}$ for the proton emission decay of ${}^{131}_{63}Eu$.

Problem 4

1 MeV photons and 100 MeV protons traverse water.

- Assuming charged particle equilibrium (CPE), what is the expression for dose from the photons and protons?
- What are two main conditions that must be fulfilled to achieve CPE?
- Further assume that the two different beams give identical dose to water at a given point. Compare the fluence and energy fluence from the photons and protons required to give this dose. Discuss the result.

Useful numbers: proton stopping power in water = 7.286 cm^2/g and photon mass energy absorption coefficient in water = 0.031 cm^2/g

Problem 5

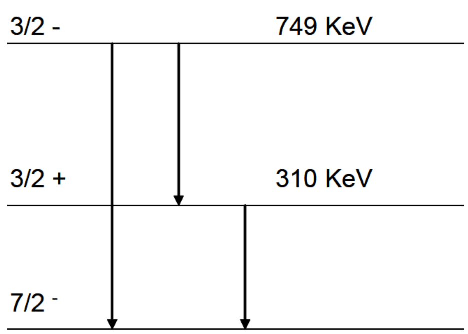
From the second project (posters) two of the topics presented were nuclear fission reactors and Rutherford backscattering spectrometry. For both of these:

- Describe the basic principles for how they work/operate
- Describe their pros and cons
- Name one application/example use of each

Problem 6

6a

- Write up the angular momentum and parity selection rules for γ decay
- The scandium isotope, ^{43}Sc, with a ground state spin and parity of $7/2^-$ has the excited states shown below in the figure (energy numbers are approximate). Determine the angular momentum, parity and type (magnetic or electric; also known as multipolarity) of the γ ray photons that are emitted to get from the $3/2^-$ excited state at 749 keV to the ground state. Which transition will be dominating?



Low lying states of ^{43}Sc.

6b

- Describe and sketch the experimental setup to measure attenuation of a γ ray. Name the different components in the setup.
- What difference does it make whether the detector is placed close to the absorber or more distant?

- Which detector can be used in this situation? Sketch a typical output from this detector (for example using the spectrum you got from one of the measurements in the lab exercises). Describe what you see in such a spectrum and the physical explanation.

6c

- A γ ray interacts with matter through three primary processes. Name these three processes.
- How is the cross section for each of these processes related to the Z number of the material?
- Calculate the thickness of concrete (density 2200 kg/m^3) needed to attenuate a 1 MeV γ ray by a factor of 10^6.

  The mass attenuation coefficient of concrete is 0.064 cm^2/g.

CONSTANTS

Speed of light	c	2.99792458×10^{8} m/s
Charge of electron	e	1.602189×10^{-19} C
Boltzmann constant	k	1.38066×10^{-23} J/K
		8.6174×10^{-5} eV/K
Planck's constant	h	6.62618×10^{-34} J · s
		4.13570×10^{-15} eV · s
	$\hbar = h/2\pi$	1.054589×10^{-34} J · s
		6.58217×10^{-16} eV · s
Gravitational constant	G	6.6726×10^{-11} N · m²/kg²
Avogadro's number	N_A	6.022045×10^{23} mole^{-1}
Universal gas constant	R	8.3144 J/mole · K
Stefan-Boltzmann constant	σ	5.6703×10^{-8} W/m² · K⁴
Rydberg constant	R_∞	1.0973732×10^{7} m^{-1}
Hydrogen ionization energy		13.60580 eV
Bohr radius	a_0	5.291771×10^{-11} m
Bohr magneton	μ_B	9.27408×10^{-24} J/T
		5.78838×10^{-5} eV/T
Nuclear magneton	μ_N	5.05084×10^{-27} J/T
		3.15245×10^{-8} eV/T
Fine structure constant	α	1/137.0360
	hc	1239.853 MeV · fm
	$\hbar c$	197.329 MeV · fm
	$e^2/4\pi\epsilon_0$	1.439976 MeV · fm

PARTICLE REST MASSES

	u	MeV/c^2
Electron	5.485803×10^{-4}	0.511003
Proton	1.00727647	938.280
Neutron	1.00866501	939.573
Deuteron	2.01355321	1875.628
Alpha	4.00150618	3727.409
$\pi^\pm$	0.1498300	139.5669
π^0	0.1448999	134.9745
μ	0.1134292	105.6595

CONVERSION FACTORS

1 eV = 1.602189×10^{-19} J

1 u = 931.502 MeV/c^2
= 1.660566×10^{-27} kg

1 b = 10^{-28} m²

1 Ci = 3.7×10^{10} decays/s

$$
\begin{aligned}
F &= \frac{|q_1 q_2|}{4\pi\epsilon_0 r^2} \\
P &= \frac{q_1 q_2}{4\pi\epsilon_0 r} \\
\vec{F} &= q\vec{E} + q\vec{v} \times \vec{B} \\
\\
\vec{p} &= m\vec{v} \\
\vec{L} &= \vec{r} \times \vec{p} \\
F &= ma \\
F &= \frac{mv^2}{r} \\
\\
U(\vec{r}) &= -\int_{\infty}^{\vec{r}} \vec{F} \cdot d\vec{r} \\
\Delta\vec{p}(t) &= \int_0^t \vec{F} d\tau \\
\\
T &= \frac{1}{2}mv^2 \\
p &= \frac{mv}{\sqrt{1 - v^2/c^2}} \\
E &= \sqrt{p^2c^2 + m^2c^4} \\
T &= E - mc^2 \\
E_0 &= mc^2 \\
\lambda &= \frac{h}{p} \\
\Delta p \Delta x &\geq \frac{\hbar}{2} \\
\Delta E \Delta t &\geq \frac{\hbar}{2} \\
\text{Plane wave } \psi(x) &= e^{i\vec{p}\cdot\vec{r}/\hbar} \\
\langle l^2 \rangle &= \hbar^2 l(l+1) \\
\langle l_z \rangle &= \hbar m_l
\end{aligned}
$$

$$
\begin{aligned}
B &= a_v A - a_s A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_{sym} \frac{(A-2Z)^2}{A} + \delta \\
Q &= \sum_i m_i c^2 - \sum_f m_f c^2
\end{aligned}
$$

$$
\begin{aligned}
N(t) &= N_0 e^{-\lambda t} \\
A(t) &\equiv \lambda N(t) \\
t_{1/2} &= \frac{ln2}{\lambda} = \tau ln2 \\
N_1(t) &= \frac{R}{\lambda_1}(1 - e^{-\lambda_1 t}) \\
N_2(t) &= N_0 \frac{\lambda_1}{\lambda_2 - \lambda_1}(e^{-\lambda_1 t} - e^{-\lambda_2 t})
\end{aligned}
$$

$$
\begin{aligned}
P_T &= 4e^{-2\kappa L} \\
\kappa &= \frac{\sqrt{2m(V(x)-E)}}{\hbar} \\
\lambda &= \frac{2\pi}{\hbar}|V_{fi}|^2 \rho(E_f) \\
V_{fi} &= \int \psi_f^* V \psi_i d\nu \\
\lambda &= \frac{g^2 |M_{fi}|}{2\pi \hbar^7 c^3} \int_0^{p_{max}} F(Z', p) p^2 (Q - T_e)^2 dp
\end{aligned}
$$

$$
\begin{aligned}
\pi(ML) &= (-1)^{L+1} \\
\pi(EL) &= (-1)^L
\end{aligned}
$$

$$
\begin{aligned}
\sqrt{T_b} &= \frac{\sqrt{m_a m_b T_a}\cos\theta \pm \sqrt{m_a m_b T_a \cos^2\theta + (m_Y + m_b)\left[m_Y Q + (m_Y - m_a)T_a\right]}}{m_Y + m_b} \\
\sigma_{sc} &= \sum_{l=0}^{\infty} \pi \lambdabar^2 (2l+1)|1 - \eta_l|^2 \\
\sigma_r &= \sum_{l=0}^{\infty} \pi \lambdabar^2 (2l+1)(1 - |\eta_l|^2) \\
-\frac{dE}{dx} &= \left(\frac{ze^2}{4\pi\epsilon_0}\right)^2 \frac{4\pi Z \rho N_A}{Amv^2}\left[ln\left(\frac{2mv^2}{I}\right) - ln(1-\beta^2) - \beta^2\right] \\
n &= \frac{\rho N_A}{A} \\
N &= N_0 e^{-\mu x} \\
\mu &= n\sigma \\
\sigma &= \sigma_{PE} + Z\sigma_C + \sigma_{PP}
\end{aligned}
$$

$$
\begin{aligned}
\Phi &= \frac{dN}{dA} \\
\Psi &= \frac{dE}{dA} \\
D &\equiv \frac{d\bar{\varepsilon}}{dm} \\
\varepsilon &= R_{in} - R_{out} + \sum Q \\
K &= \frac{dE_{tr}}{dm} \\
K_C &= E\Phi\left(\frac{\mu_{en}}{\rho}\right) \\
S &= \frac{dE}{dx} \\
C &= \frac{dE_c}{dm} \\
D_m &= \Phi\frac{S_c}{\rho} \\
\Psi &= E\Phi \\
D(r_T, T_D) &= \sum_{r_S} \tilde{A}(r_S, T_D) S(r_T \leftarrow r_S) \\
S(r_T \leftarrow r_S) &= \frac{1}{M(r_T)} \sum_i E_i Y_i \phi(r_T \leftarrow r_S, E_i) \\
\tilde{A}(r_S, T_D) &= \int_0^{T_D} A(r_S, t) dt \\
E &= \sum_T w_T \sum_R w_R D_R(r_T, T_D)
\end{aligned}
$$