## Physical constants

| | |
|---|---|
| neutron mass | $mc^2 = 939.565379(21)$ MeV |
| Planck conversion constant | $\hbar c = 197.3269718(44)$ MeV fm |
| Avogadro constant | $N_A = 6.02214129(27) \times 10^{23}$ mol$^{-1}$ |
| Boltzmann constant | $k_B = 1.3806488(13) \times 10^{-23}$ J/K |
| Atomic mass unit | $u = 931.494028(23)$ MeV/c$^2$ |

## Nuclear properties

| Nucleus | nat. ab. | b [fm] | $\sigma_a^{\mathrm{th}}$ [barn] | atomic mass [u] |
|---|---|---|---|---|
| $^1$H | 99.99% | -3.74 | 0.333 | 1.0078250322 |
| $^2$H | 0.015% | 6.67 | 0.00052 | 2.0141017781 |
| $^3$H | | 4.792 | 0 | 3.0160492779 |
| $^3$He | $10^{-4}$% | 5.74 | 5333 | 3.0160293201 |
| $^4$He | 100% | 3.26 | 0 | 4.0026032541 |
| $^6$Li | 7.5% | 2.00 | 940 | 6.0151228874 |
| $^7$Li | 92.5% | -2.22 | 0.0454 | 7.0160034366 |
| $^{10}$B | 20% | -0.1 | 3835 | 10.012936949 |
| $^{11}$B | 80% | 6.65 | 0.0055 | 11.009305355 |
| $^{14}$N | 99.6% | 9.37 | 1.91 | 14.003074004 |
| $^{19}$F | 100% | 5.654 | 0.0096 | 18.998403163 |
| $^{27}$Al | 100% | 3.449 | 0.231 | 26.981538531 |
| $^{54}$Fe | 5.8% | 4.2 | 2.25 | 53.9396105 |
| $^{56}$Fe | 91.7% | 9.94 | 2.59 | 55.934936326 |
| $^{57}$Fe | 2.2% | 2.3 | 2.48 | 56.935394 |

## Physical properties of materials

| material | $\rho$ [g/cm$^3$] | M [g/mol] |
|---|---|---|
| aluminum | 2.70 | 27.0 |
| boron | 2.34 | 10.8 |
| iron | 7.87 | 55.8 |

# 1 Lifetime of UCNs in a gas

Most of UCN experiments are performed in vacuum. To understand why this is necessary, let us discuss the behaviour of UCNs in a gas. Notice that the molecules in a gas at room temperature are much faster than UCNs.

**Absorption: the case of nitrogen** We want to calculate the lifetime $\tau$ of a neutron at rest in a nitrogen athmosphere (1 bar). We will consider only the neutron capture (n,$\gamma$). The cross section for this process, at a $N_2$ molecule, is given by $\sigma = 2\sigma_a^{\mathrm{th}} v_{\mathrm{th}}/V$, where $V$ is the relative velocity between the molecule and the neutron. What is the thermal velocity of the nitrogen moecules at room temperature? What is the number density $n$ of $N_2$ molecules? At what rate a UCN will be absorbed by the flux of nitrogen?

**Upscattering: the case of helium** In the case of $^4$He, the neutron absorption cross section is strictly zero. Still UCNs can be lost in helium at room temperature because of scattering. Now we consider a UCN bottle filled with 1 mbar of pure $^4$He. We assume that a UCN is lost when colliding with a helium nucleus. What is the thermal velocity of helium atoms at room temperature? What is the number density $n$ of $N_2$ molecules? At what rate a UCN will be upscattered by the flux of helium? Compare with the experimental result $P\tau = 418 \pm 2$ mbar s.

**Systematic effect in neutron lifetime measurements** In air, the UCN losses are quantified by $P\tau \approx 100$ mbar s. In UCN experiments measuring the neutron lifetime, the presence of air due to non-perfect vacuum is a source of systematic error. What residual pressure correspond to a systematic effect of $\Delta\tau_n = 1$ s?

# 2 UCN spin-analyser with a magnetized foil

We will discuss the optimal height of the analysing foil in the nEDM experiment. The analysing foil consists of a thin layer of magnetized iron. The precession chamber, situated at height $H$ above the analysing foil, stores neutrons in the energy range $0 < E < 120$ neV. Calculate the Fermi potential of non-magnetized iron. Suppose now that the foil is magnetized to a saturation field of $B_s =$ 2 T. Neutrons with spin aligned with the magnetic field are dubbed *low field seekers*, those with spin anti-parallel with the magnetic field are dubbed *high field seekers*. Calculate the Fermi potential of the magnetized foil for high and low field seekers. Discuss the optimal height $H$ to maximize the spin-analysis efficiency.

# 3 Kinetics of neutron induced reaction

Calculate the kinetic energy of the products for the following reactions induced by slow neutrons:

$$n + {}^3\text{He} \rightarrow t + p \quad (1)$$
$$n + {}^6\text{Li} \rightarrow \alpha + t \quad (2)$$
$$n + {}^{10}\text{B} \rightarrow {}^7\text{Li} + \alpha. \quad (3)$$

# 4 UCN detectors: boron conversion layer

The principle of a neutron detector using a Boron conversion layer is depicted in fig. 1. An incoming neutron is converted into charged particles according to

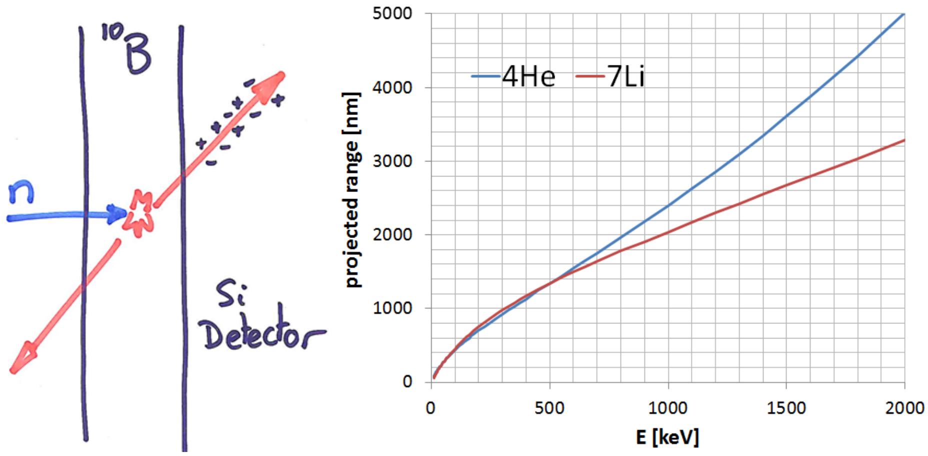


Figure 1: Principle of a boron conversion layer to detect neutrons (left) and Range of $^4$He and $^7$Li ions in Boron (right).

the following nuclear reactions:

$$^{10}\mathrm{B} + n \rightarrow \alpha(1.47 \text{ MeV}) + ^7\mathrm{Li}(0.84 \text{ MeV}) + \gamma(0.48 \text{ MeV}) \quad (94\%)$$
$$^{10}\mathrm{B} + n \rightarrow \alpha(1.78 \text{ MeV}) + ^7\mathrm{Li}(1.01 \text{ MeV}) \quad (6\%)$$

- Calculate the Fermi potential of (i) natural boron (ii) isotopically pure $^{10}$B. Is it necessary to use isotopically pure boron to detect UCNs?
- We consider a conversion layer of thickness 200 nm. We assume that the reaction products are produced uniformly in the depth of the conversion layer. Calculate the mean distance travelled by a reaction product inside the conversion layer.
- The range of the reaction products is shown in fig. 1. Calculate the mean energy of the reaction products at the exit of the conversion layer.
- Calculate the efficiency of the detector to UCNs (take $v = 3$ m/s), and to thermal neutrons ($v = 2200$ m/s).