Lecture on Ultracold neutrons

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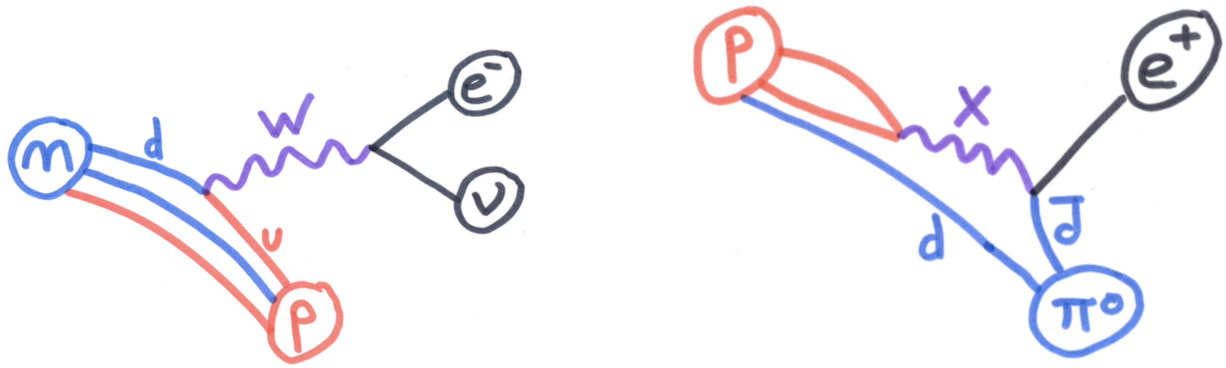

Figure 1: Left: diagram of the neutron β decay involving a virtual W boson. Right: hypothetical proton decay induced by a virtual X boson.

1. Neutrons at the precision frontier

1.1. The two frontiers of particle physics

Particle physics, in the hunt for new phenomena, progresses along two fronts: the **energy frontier** and the **precision frontier**. New physics is supposed to take the form of an extension of the Standard Model of particle physics with more particles, possibly heavier than the known particles. The existence of these new particles is required to explain the pending big mysteries about the Universe, in particular the microscopic nature of the dark matter and the origin of the matter-antimatter asymmetry. Detecting these new heavy particles from the proton collisions at the Large Hadron Collider is the program of the energy frontier. There is a great hope to produce at the LHC the particle making up the dark matter. Instead, at the precision frontier, one aims at detecting the virtual effects of the heavy particles.

1.2. Virtual particles, real effects

As an example, consider the β decay of the neutron $n \to p + e + \bar{\nu}$. The Standard Model describes this process as shown in fig. 1, via a quark transition $d \to u$ radiating a W transforming into a electron - antineutrino pair. This is in fact an interaction between quantum fields, the W boson field is coupled to the quarks and lepton fields. No real W boson is created in this process since its mass $m_W = 80.4$ GeV is larger than the available energy in the decay $m_n - m_p - m_e = 782$ keV. It is said that the decay proceeds via the exchange of a virtual boson. Even without creating the particle, we learn a lot about the W boson by studying such virtual processes. In fact the basic structure of the Standard Model was inferred from detailed investigation of β decays, in particular with the observation of parity violation. Later in this lecture we will describe modern experiments measuring the neutron β decay, as it is still an active field of research.

Consider now the case of a new hypothetical heavy boson X, much heavier than the W and therefore impossible to materialize at the LHC. Depending on the specific interactions of the new boson to standard particles, it can be revealed by looking at very rare decays. For example if it violates the conservation of baryon and lepton numbers, it could induce proton decay as shown on fig. 1. The proton lifetime would then be $\tau_p \approx \frac{m_X^4}{\alpha^2 m_p^5}$, where α is the fine structure constant. The current limit on the proton lifetime, $\tau_p > 10^{33}$ years, translates into a limit on the mediator mass of $m_X > 10^{15}$ GeV, which is far beyond the LHC reach. Similarly, if new particles mediate interactions connecting different lepton flavors, they can induce an exotic decay of the muon $\mu \to e\gamma$. This rare decay has never been observed, so far the upper limit on the branching ratio is $B(\mu^+ \to e^+\gamma) < 4 \times 10^{-13}$, but experiments are progressing in the precision in order to probe the existence of heavier virtual particles. We should also mention the search for rare decays of K and B mesons, and the search for neutrinoless double beta decays, which are the other ongoing experimental programs to search for new physics with rare decays.

Another powerful way to probe new virtual effects consists in measuring precisely the **electric dipole moment** of known particles such as the neutron. The electric dipole moment quantifies the coupling between the particle spin and the electric field, it can be generated by virtual effects induced by heavy particles as shown in fig. 2. This is interesting because such a coupling, if it exists, would **violate time reversal symmetry** and is connected to the matter antimatter asymmetry of the Universe. We will elaborate on that topic later in the lecture.

Experiments at the precision frontier of particle physics (also called the **intensity frontier**) are quite diverse, different measurements are based

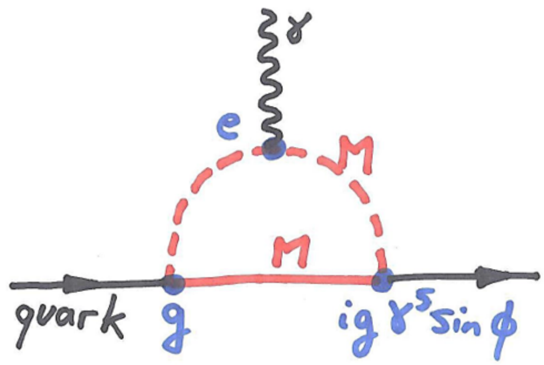

Figure 2: Virtual effects generating an EDM (electric dipole moment) for a quark, therefore generating a neutron EDM.

on very different experimental techniques, including:

- Low background particle detectors. The search for neutrinoless double beta decay requires shielding from natural radioactivity and cosmic rays in underground laboratories. Similar constraints, although less severe, apply for searching proton decays.

- Particle colliders as B factories. To search for rare decays of B mesons one needs to produce them copiously with electron positron colliders or the LHC, this is the program of the LHCb experiment.

- Intense beams of unstable particles. Precision experiments with kaons or muons needs copious production of these particles by sending an intense proton beam on a fixed target.

- And of course: intense sources of neutrons.

In this lecture we will cover the production of neutrons, in particular ultracold neutrons, and their detection. We will also describe important experiments with neutrons: the measurement of the neutron lifetime and the electric dipole moment.

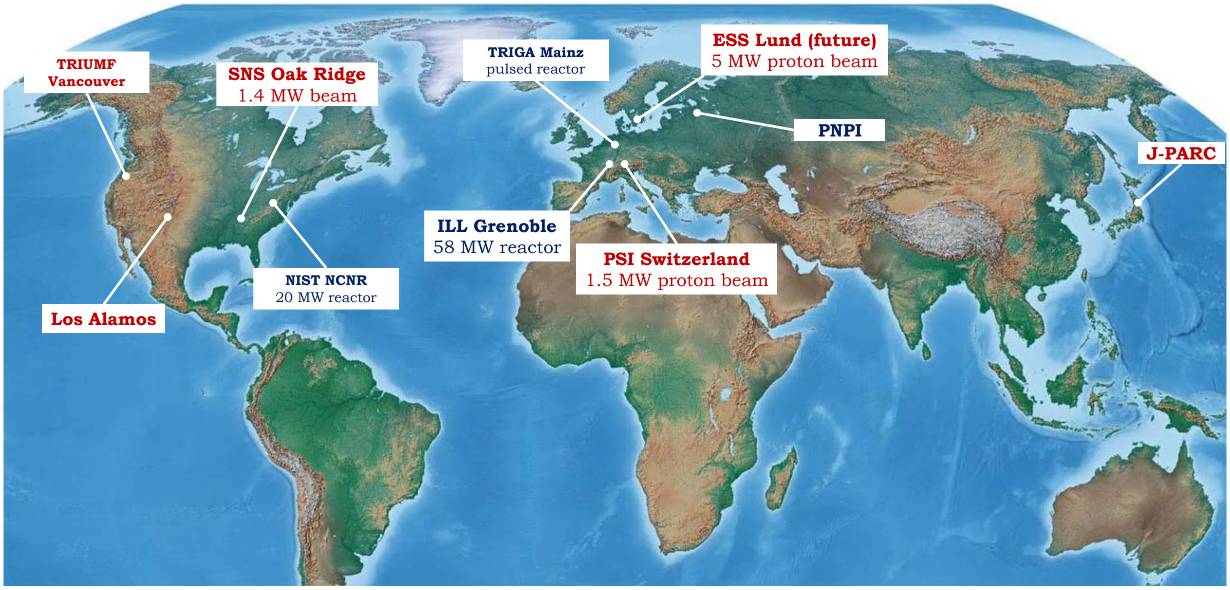

Figure 3: A selection of the big neutron factories in the world. Fission reactors in blue and spallation sources in red.

2. NEUTRON FACTORIES

2.1. Setting neutrons free

When neutrons are produced by a nuclear reaction they have a kinetic energy of a few MeV, the characteristic binding energy of nucleons in nuclei. To set neutrons free, practical possibilities are

- Bombarding beryllium (or other few light elements) by α particles produce neutrons according to the nuclear reaction $\alpha + {}^9\mathrm{Be} \rightarrow n + {}^{12}\mathrm{C}$. Chadwick used this reaction to discover the neutron in 1932. This process is still widely used for small size, laboratory neutron sources.

- A beam of protons or deutons (with an energy of a few MeV) may be used to produced neutrons using targets of light elements, such as $d + t \rightarrow \alpha + n$. This process is employed for intermediate-size neutron sources.

- Fission chain reaction of ^{235}U, each fission frees in average $\nu = 2.6$ neutrons.
- A high energy proton beam (of the order of 1 GeV) hitting a target made of heavy nuclei (in practice Pb, W or Hg), emits neutrons along with other fragments. This process, called nuclear spallation, liberates up to 20 neutrons for a single proton.

Figure 3 shows a world map with the big neutron factories in operation and in construction, these are either fission reactors or spallation sources.

2.2. Thermalisation of fast neutrons

Neutrons with a kinetic energy E close to 1 MeV are called **fast neutrons**. In a fission reactor or a spallation source, the neutrons released from the nuclei are fast neutrons. Note that they are non-relativistic ($E \ll mc^2 = 939.6$ MeV). Then, neutrons are usually slowed down in a moderator surrounding the primary source. In a nuclear reactor, the slowing down, also called moderation, is necessary in order to sustain the chain reaction, because the fission cross section is larger for slower neutrons. For precision experiments with neutrons, we need slow neutrons anyway, as it will become clear later. The moderation simply proceeds by elastic scattering of neutrons on the nuclei forming the moderation material. Remind that **elastic scattering** means that the total kinetic energy of the system neutron + target is the same before and after the collision, however there is indeed some energy exchanged between the neutron and the target. For a target nucleus at rest, considering the conservation of energy and momentum, the final energy E' is related to the to the incoming energy E :

$$E' = \left(1 - \frac{4A\sin^2(\theta/2)}{(A+1)^2}\right)E, \tag{1}$$

where θ is the collision angle, and A is the mass number of the nucleus. An efficient moderator is a material with low A to maximize the energy transfer per collision as apparent in eq. 1, and low absorption cross section to minimize the neutron losses during the slowing down. In particularr, heavy water is a good moderator because deuterium is a light nucleus with a small absorption cross section. The scattering cross section on deuterium is $\sigma \approx 6 \times 10^{-24}$ cm^2. Given the number density of deuterium in liquid heavy water, $n = 7 \times 10^{22}$ cm^{-3}, the mean free path between two elastic collisions is $\frac{1}{n\sigma} \approx 2$ cm. The moderation process stops when the kinetic energy of the neutron reaches the kinetic energy of the molecules ($kT = 25$ meV at room temperature). In heavy water it takes about 35 collisions to cool from ≈ 1 MeV down to ≈ 25 meV. At the end the moderator produces **thermal neutrons**, that is, neutrons with a kinetic energy of $E \approx 25$ meV.

The design of the big neutron sources is generally optimized to maximize the flux of thermal neutrons in the core. The high flux reactor of the Institut Laue Langevin (ILL) in Grenoble, France, produces a maximal thermal flux of 1.5×10^{15} n/s/cm^2. The future European Spallation Source (ESS) will have a similar performance. As a comparison, the thermal flux in a power nuclear reactor is typically 10^{14} n/s/cm^2 an order of magnitude lower.

3. Neutron optics and ultracold neutrons

Let us now discuss the wave nature of the neutron. For a non-relativistic massive particle, the De Broglie wavelength λ reads

$$\lambda = \frac{2\pi\hbar}{mv} = \frac{2\pi\hbar}{\sqrt{2mE}} \tag{2}$$

Fast neutrons have a wavelength of $\lambda \approx 30$ fm, very small compared to the typical distance between atoms in normal matter. They behave as point particle and interact with a single atom at a time. Thermal neutrons have a much larger wavelength, $\lambda_{\text{thermal}} = 0.18$ nm and neutrons even slower than thermal neutrons (they are called **cold neutrons**) have even bigger wavelength. Having wavelengths larger than the typical distances between atoms in solids, cold neutrons could undergo optical phenomena such as reflection and refraction at surfaces. It was E. Fermi who first realized that cold neutrons could behave like waves.

3.1. Neutron scattering at a single nucleus.

Let us consider the scattering of a neutron at a nucleus of atomic mass A. Following the quantum theory about the scattering of a non-relativistic particle by a potential well, the neutron wave function takes the form:

$$\psi(\vec{r}) = e^{ikx} + f(\theta)\frac{e^{ikr}}{r} \tag{3}$$

where $r = 0$ is the position of the nucleus, $k = mv/\hbar$ is the wave number, x is the direction of the incident neutron, $f(\theta)$ is the scattering amplitude. Now we assume that the wavelength of the neutron is much larger that the size of the nucleus. It is a reasonable assumption for fast neutrons, and an even better approximation for slower neutrons. In this case (i) the scattering amplitude is independent of the energy of the incident particle, (ii) the scattering is isotropic *i.e.* $f(\theta)$ is independent of θ. Therefore we can write

$$f(\theta) = -b \tag{4}$$

where b is a constant called the **bound scattering length** [1].

Given the complexity of the strong interaction, it is impossible to perform *ab initio* calculations of the scattering lengths of the nuclei. One must refer to tabulated values. However, as a rule of thumb, the neutron scattering length is of the order of magnitude of the nuclear radius:

$$b \approx 1.45 \text{ fm} \times A^{1/3}. \tag{5}$$

3.2. *Neutron interaction with a collection of nuclei.*

Consider a collection of nuclei, with positions $\vec{R}_j$ (j is the index of the nuclei). The wavefunction ψ for an incident neutron, with a kinetic energy $E = \hbar^2 k^2/2m$ should satisfy the self-consistency equation :

$$\psi(\vec{r}) = e^{ikx} - \sum_j \psi(\vec{R}_j) b \frac{e^{ik|\vec{r}-\vec{R}_j|}}{|\vec{r}-\vec{R}_j|} \tag{6}$$

Using the relation

$$\left(\Delta + k^2\right) \frac{e^{ik|\vec{X}|}}{|\vec{X}|} = -4\pi\delta(\vec{X}), \tag{7}$$

we find that the wavefunction satisfies

$$\left(\Delta + k^2\right) \psi(\vec{r}) = 4\pi b \sum_j \delta\left(\vec{r} - \vec{R}_j\right) \psi(\vec{r}). \tag{8}$$

If the wavelength of the neutron is much larger than the distance between the nuclei, we can make the approximation

$$\sum_j \delta\left(\vec{r} - \vec{R}_j\right) = n \tag{9}$$

where n is the number density of the nuclei in the medium. In this case, the wavefunction satisfies the following equation:

$$-\frac{\hbar^2}{2m}\Delta\psi + V_F\psi = E\psi \tag{10}$$

[1] It is assumed that the target nucleus is rigidly bound, like in a solid, or in a large molecule. The scattering is treated in the frame where the nucleus is at rest. If the nucleus is free to recoil, then the scattering must be treated in the center of mass frame and the bound scattering length must be replaced by the free scattering length $a = \frac{A}{A+1} b$.

where

$$V_F = \frac{2\pi\hbar^2}{m}\, b\, n \tag{11}$$

is called the *Fermi potential*. Notice that Eq. (10) is in fact the Schrödinger equation in the potential energy V_F. The Fermi potential plays the role of an optical index for the neutron wave. The discussion above applies if the material is constituted by a single species of nuclei. If the material is heterogeneous one must sum the potentials of all nuclear species composing the material.

For most materials the Fermi potential is positive, i.e. repulsive [2]; it is of the order of 10^{-7} eV, much smaller than the kinetic energy of thermal neutrons. For example, natural nickel is a material with a relatively high Fermi potential which amounts to 250 neV.

Neutrons approaching a surface at grazing incidence could be reflected by the Fermi potential of the material. Total reflection occurs when the kinetic energy associated with the velocity normal to the surface is smaller than the potential barrier (11). This condition is called the **Fermi-Zinn condition**:

$$E \sin^2\theta < V_F, \tag{12}$$

where E is the kinetic energy and θ is the angle complementary to the incidence angle. In practice this phenomenon is at play in neutron guides. It is possible to transport neutrons from the core of the reactor where they are produced to an experimental hall situated at a distance of up to 100 m, using evacuated rectangular tubes, with a cross section of typically 100 cm^2, made up of plates coated with nickel or with a multilayer of nickel and titanium.

3.3. Ultracold neutrons.

In 1959, Zeldovich realized that neutrons with total kinetic energy lower than 250 neV should be reflected at any angle of incidence and therefore could be stored in material bottles. These storable neutrons were called *ultracold neutrons (UCNs)* by the pioneer workers in the field. It is not easy to get ultracold neutrons, because their proportion in the energy spectrum of thermal neutrons (when neutrons are thermalised in a moderator at

[2] This is surprising because the strong nuclear interaction responsible for the Fermi potential is attractive: it holds neutrons inside nuclei. For an explanation of this apparent paradox, see for example Pignol2009.

room temperature) is only 10^{-11}. The first storage of ultracold neutrons was reported by Groshev1971. The group of Russian physicists stored on average 2 neutrons at a time in a copper cylindrical bottle (diameter 14 cm and length 174 cm). The capacity of the bottle to store neutrons was quantified by a storage time of about 30 s (compare to the neutron beta decay lifetime of 880 s).

The kinetic energy of ultracold neutrons corresponds to a temperature as low as a few mK. However, it is important to understand that ultracold neutrons can be stored in bottles at room temperature. The neutrons do not thermalise with the walls of the bottle, like photons of visible light do not thermalise when reflecting off a mirror. In fact the specular (i.e. mirror) reflection of ultracold neutrons and visible photons share many similarities, because the wavelength of UCNs is of the order of 100 nm, very close to the wavelength of visible light. In both cases the wavelength is much larger than the lattice spacing of atoms in the matter of the walls. It means that the particle interacts with a large number of atoms in the wall, it is almost blind to the thermal motion of individual atoms. Using appropriate wall materials, UCNs can undergo as many as 10^4 specular reflections before being inelastically scattered or captured by a single nucleus.

The ability to store neutrons for a long period was immediately recognized as a great opportunity for fundamental physics, for two main reasons. First, ultracold neutrons provide a direct method to measure the neutron lifetime by simply storing neutrons for a certain time and counting the survivors. Second, longer observation times enhance the sensitivity of detection schemes like the Rabi or Ramsey resonance techniques, following the uncertainty relation $\delta E \times T \geq \hbar$, where δE is the precision of the measured energy and T is the observation time. A 1 m long apparatus observes a neutron spin in a cold beam for typically 10 ms, whereas in a storage experiment observation times longer than 100 s could be achieved. The measurement of the neutron electric dipole moment (nEDM) could thus benefit from an improvement of the sensitivity by four orders of magnitude. Since 1970 the techniques to produce and handle ultracold neutrons were greatly improved to pursue these two goals: a precise measurement of the neutron lifetime and the search for the nEDM.

4. Neutron detection

Detection of neutrons is used for a wide variety of purposes. First, neutron detectors are omnipresent in civilian and military applications of nuclear technology: for radiation safety, for monitoring the power of nuclear reactors, or even for border security to detect fissile materials such as ^{233}U and ^{239}Pu. A less known application concerns the monitoring of cosmic rays striking the Earth. The neutron flux on the ground is constantly detected by extensive arrays of "neutron monitors" to measure the variations in time of the flux of cosmic rays (it fluctuates with the solar activity, in particular). Finally, physics experiments using neutrons for the investigation of matter or to study the fundamental properties of the neutron obviously need neutron detectors.

Since neutrons have no electric charge, they do not directly cause ionization. The detection process needs an interaction with a nucleus releasing energetic charged particles. One can think of the elastic collision with a proton (or another light target nucleus). The incident neutron transfers parts of its kinetic energy to target and the recoil can be detected. While this is a valid method to detect fast neutrons, it does not work for slow neutrons because the energy of the proton recoil is too small. To detect slow neutrons (in particular thermal, cold and ultracold neutrons), an inelastic reaction is required. It is important to notice that the detection process will necessarily be destructive for the neutron.

Let us now discuss the possible inelastic reactions for a neutron incident on a nucleus ^{A}X.

Neutron radiative capture (n,γ). In a radiative capture, the nucleus absorbs the incoming neutron, the final nucleus ends up in a highly excited state and emits a single gamma or gamma cascade:

$$n + {}^{A}\mathrm{X} \rightarrow {}^{A+1}\mathrm{X} + \gamma. \tag{13}$$

The Q value of the reaction is simply

$$Q = \left(m({}^{A}\mathrm{X}) - m({}^{A+1}\mathrm{X}) - m_n\right) c^2 \tag{14}$$

In figure 4 we show the Q value for all stable nuclei sorted by atomic number. It shows that all materials, with the notable exception of ^{4}He, can absorb

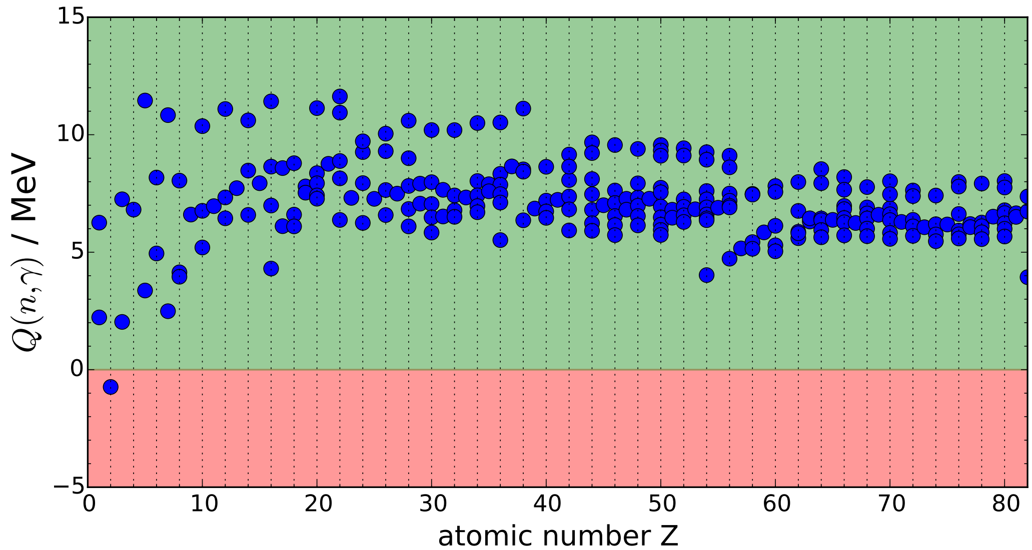

Figure 4: Q value for the radiative capture reaction for all stable nuclei as a function of the atomic number. They are all exothermic ($Q > 0$) with the notable exception of ^{4}He.

slow neutrons.

Neutron-induced fragmentation or fission

5. The neutron lifetime

Work in progress.

6. The neutron electric dipole moment

Work in progress.

References

[1] G. Pignol, "Probing Dark Energy models with neutrons," Int. J. Mod. Phys. A **30**, no. 24, 1530048 (2015) [arXiv:1503.03317 [astro-ph.CO]].

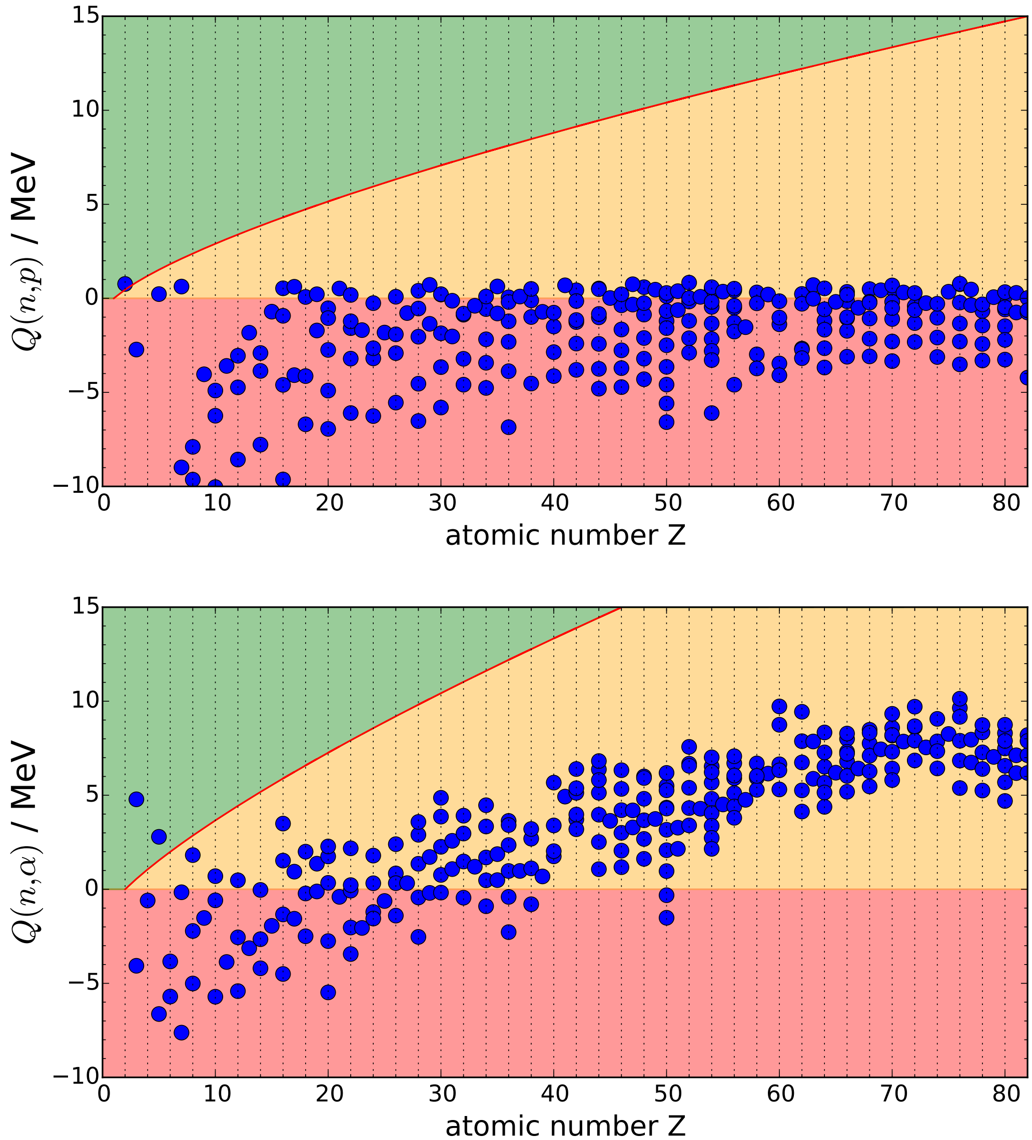

Figure 5: $Q(n,p)$ (Top) and $Q(n,\alpha)$ (Bottom).