Lecture on Ultracold neutrons

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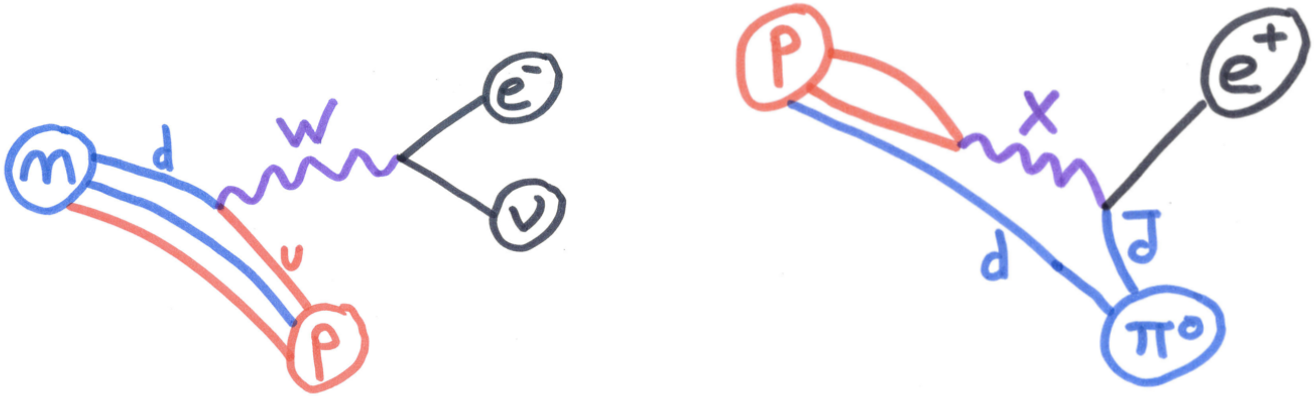

Figure 1: Left: diagram of the neutron β decay involving a virtual W boson. Right: hypothetical proton decay induced by a virtual X boson.

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 generally 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, such as the nature of the dark matter or the origin of the matter-antimatter asymmetry. Detecting these new heavy particles coming out of 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, one can 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 and the observation that they violate parity. 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 on very different experimental techniques, including:

- Low background particle detectors. The search for neutrinoless double

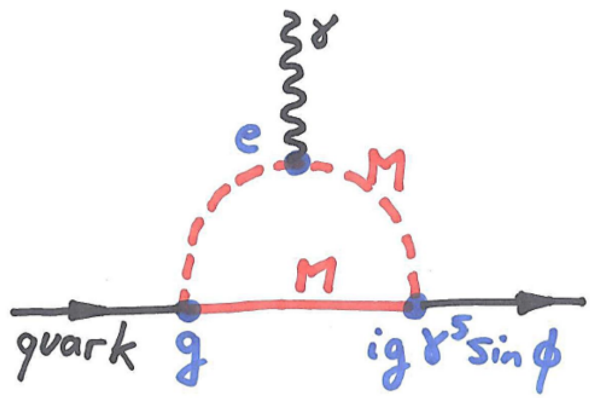

Figure 2: Virtual effects generating an EDM (electric dipole moment) for a quark, therefore generating a neutron EDM.

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.
- 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.
- 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.

2. Neutron factories

3. Neutron optics and ultracold neutrons

4. Neutron detection

5. The neutron lifetime

6. The neutron electric dipole moment

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]].