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The puzzle of neutron lifetime

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ABSTRACT

In this paper we review the role of the neutron lifetime and discuss the present status of measurements. In view of the large discrepancy observed by the two most precise individual measurements so far we describe the different techniques and point out the principle strengths and weaknesses. In particular we discuss the estimation of systematic uncertainties and its correlation to the statistical ones. In order to solve the present puzzle, many new experiments are either ongoing or being proposed. An overview on their possible contribution to this field will be given.

1. Introduction

The lifetime of the free neutron is a basic physical quantity, which is relevant in a variety of different fields of particle and astrophysics. Being directly related to the weak interaction characteristics it plays a vital role in the determination of the basic parameters like coupling constants or quark mixing angles as well as for all cross-sections related to weak p–n interaction. We shall briefly give an overview on such processes:

1.1. Astrophysics

One of the key processes with relevance to neutron decay is primordial nucleosynthesis [1]. A few minutes after the big bang weak interaction causes an almost equilibrium of neutrons and protons owing to the reactions $\mathrm{n}\rightarrow \mathrm{p}e^-\overline{\nu}_\mathrm{e}$ and the electron capture reactions $\mathrm{p}e^-\leftrightarrow \mathrm{n}\nu_\mathrm{e}$ and $\mathrm{n}e^+\leftrightarrow \mathrm{p}\overline{\nu}_\mathrm{e}$. The equilibrium of these reactions is broken once the expansion rate of the universe wins over the mean free path of the neutrinos (governed by the strength of the weak interaction $\Gamma_{\mathrm{n}\leftrightarrow\mathrm{p}}\sim G_\mathrm{F}^2\cdot T^5$). At this temperature T neutrinos decouple from the system and T determines the n/p ratio $\mathrm{n/p}=e^{-Q/T}$, where $Q=1.293\,\mathrm{MeV}$ is the neutron–proton mass difference. This ratio changes subsequently owing to free neutron decay. As the universe expands the temperature drops below the photo-dissociation threshold for deuterons and efficient nucleosynthesis starts, leading to the production of light elements like deuterium, helium and lithium. The abundance predictions of the standard model of cosmology using the neutron lifetime as input parameter is shown in Fig. 1 as function of the baryon-to-photon ratio η_{10}, where Y_P denotes the helium mass fraction in the early universe [1]. Fig. 2 demonstrates, as an example, the effect of changing the neutron lifetime in the model [2]. Although having big influence, the value of Y_P determined from low metalicity regions is not yet measured with good enough precision and systematic uncertainties in the extrapolation of the helium abundance to regions with zero metalicity dominate the experimental error band. Thus, the consistency of the standard model is not in question.

1.2. Particle physics

In the standard model, neutron decay is governed by weak interaction with the underlying *V–A* structure. The Lagrangian contains two parts, a leptonic and a hadronic one. The latter one is written as [5]

$$V_\mu - A_\mu = i\overline{\Psi}_\mathrm{p}\left\{f_1(q^2)\gamma_\mu + f_2(q^2)\frac{\sigma_{\mu\nu}q^\nu}{m_\mathrm{p}} + if_3(q^2)\frac{q_\mu}{m_\mathrm{e}}\right\}\Psi_\mathrm{n} - i\overline{\Psi}_\mathrm{p}\{f_i\rightarrow g_i\gamma_5\}\Psi_\mathrm{n}. \tag{1}$$

Using the conserved vector current (CVC) hypothesis most form factors f_i and g_i can be set to zero but

$$G_V = f_1(q^2\rightarrow 0)\cdot V_\mathrm{ud}\cdot G_\mathrm{F} = g_V\cdot V_\mathrm{ud}\cdot G_\mathrm{F}$$

$$G_A = g_1(q^2\rightarrow 0)\cdot V_\mathrm{ud}\cdot G_\mathrm{F} = g_A\cdot V_\mathrm{ud}\cdot G_\mathrm{F}$$

and we obtain an expression for the first element of the Cabibbo–Kobayashi–Maskawa quark mixing matrix V_ud

$$\text{with}\quad \lambda = \frac{G_A}{G_V} = \frac{g_A}{g_V};\quad |V_\mathrm{ud}|^2 = \frac{1}{\tau_\mathrm{n}}\frac{(4908.7\pm 1.9)\mathrm{s}}{(1+3\lambda^2)}. \tag{2}$$

Largest theoretical uncertainties come from radiative corrections which are common to both free neutron decay and pure Fermi-transitions in nuclei [6].

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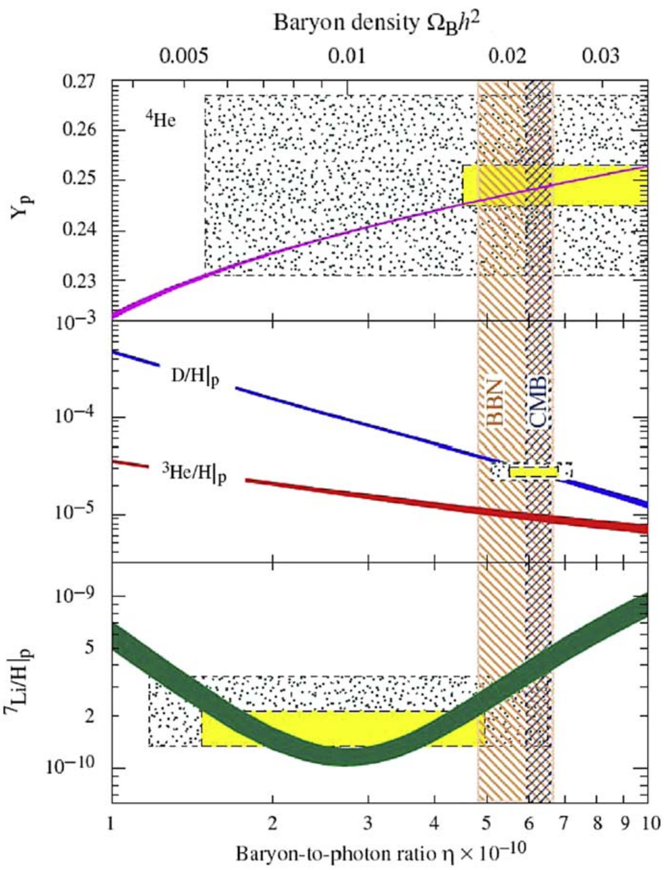

Fig. 1. Isotope mass fraction versus the baryon fraction in the universe using the standard model of cosmology (lines). The solid areas depict the statistical errors for astronomical observations, the dotted ones the systematic uncertainties [1].

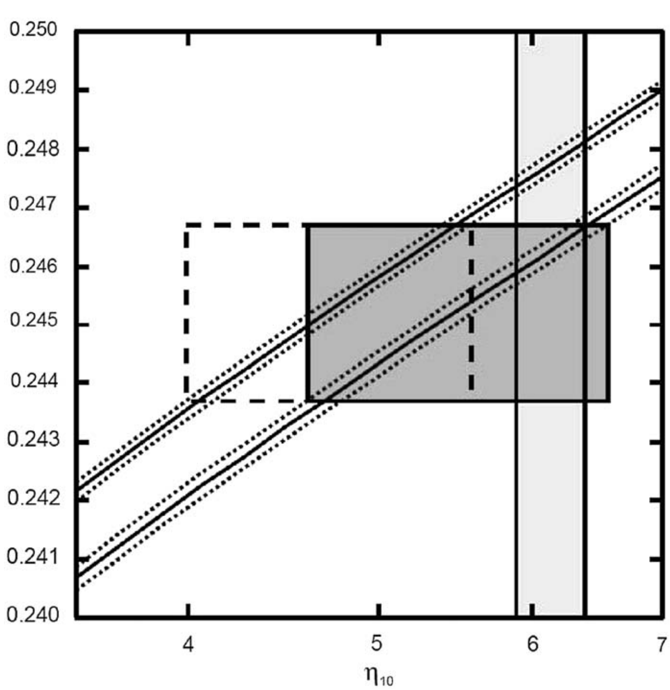

Fig. 2. Helium mass fraction versus the baryon fraction in the early universe for two different values of the neutron lifetime [2]. Upper: PDG value [3], lower: Ref. [4]. The boxes show the allowed values for the baryon mass fraction with the box size indicating statistical uncertainties for Y_P only. The vertical band shows the baryon fraction deduced from WMAP data.

1.3. Exotic implications

The energy production in our sun proceeds predominantly via two processes, *pp* fusion and the CNO cycle [7]. The relative strength of the two processes depends among others on the coupling strength determining the *pp* fusion which in turn involves G_A. Thus, the neutrino spectrum from the sun depends indirectly on the neutron lifetime and its uncertainty. However, the temperature (T) dependence of other processes is enormous and masking this effect (e.g. the ^{8}B neutrino rate is proportional to T^{16}).

On the other hand neutrino cross-sections relevant in all neutrino experiments [8] also involve G_A. In turn the measured neutrino cross-section directly yields the neutrino helicity H_ν and thus G_A is linked to a fundamental neutrino property in weak interaction [9]:

$$R = \frac{\sigma(\overline{\nu} + \mathrm{p} \rightarrow \mathrm{n} + e^+)}{\sigma_{\mathrm{expected}}} = \frac{1}{2}(1 + H_{\overline{\nu}}).$$

Here $H_{\overline{\nu}}$ is the anti-neutrino helicity. A lower value for the neutron lifetime (as inferred from more the recent measurement—see next section) would result in higher coupling constants and thus higher cross-section and in turn raises the lower limit for $H_{\overline{\nu}}$ to $H_{\overline{\nu}} > 0.97$ (assuming $\tau_n = 878\,\mathrm{s}$).

2. Measuring methods for the neutron lifetime

Two general methods exist to determine τ_n: *in beam* and *storage* experiments. In the first method a neutron beam passes a fiducial decay volume and the number of decay products is recorded. Absolute count rates are needed for the neutron flux and the number of decay particles as well as a precise and stable knowledge of the decay volume. Uncertainties due to spectral effects in the neutron velocity distribution cancel to first order as the neutron detection efficiency and the effective exposure time have the same velocity dependence $\varepsilon \sim 1/v_n$ (for the common case of small neutron detection efficiencies). For the latter group of experiments only relative count rates are important (measurement of the exponential shape of the decay-time distribution) but the measured lifetime always is a combination of two effects, the β-decay rate and a loss rate which can have various origins but typically exhibits strong spectral dependence

$$\frac{1}{\tau_n} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{\mathrm{loss}}}. \qquad (3)$$

Thus, both methods are complementary in their systematic uncertainties.

2.1. In-beam measurements

In-beam measurements have the longest tradition and were the base for the first determination of the neutron lifetime. Robson [10] in his experiment extracted protons from a fiducial decay volume and estimated the neutron lifetime to be between 9 and 25 min. The latest of such experiments obtained a more than 100 times higher precision. Key ingredients to this experiment are a well controlled fiducial decay volume, which is made from a set of ring shaped electrical cathodes which define a trapping volume (Penning trap) for decay protons (see Fig. 3) and very well calibrated particle detectors. Accumulated over a preset time decay protons are extracted onto a proton counter. The decay volume can be extended by equal portions $k \cdot L$ (L being the length of a trap subsection) and the lifetime extracted according to the