Can we observe “stimulated” proton beta decay?

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Abstract

The possibility of observing proton beta decay in a scattering system proton- (high Z) nucleus is examined from a simplified perspective. The proton is supposed to move on a Rutherford trajectory and the extra proton energy necessary to compensate the mass difference with respect to decay products can be provided on the account of potential energy of the proton in the electrostatic field of the nucleus.

Introduction

The two archetypes of beta decay are illustrated in fig.1. The weak (point) interaction is mediated by the (charged) W boson with a mass of about 80.4 GeV/c². At the energies implied in the beta decay this value makes a huge denominator in the Feynman propagator, where from the attribute “weak”. Of the two archetypes, only the free neutron decay is observed in nature and it is the longest lifetime of an elementary particle. While the free proton decay is forbidden energetically (the proton is lighter than the decay products by about 1.8 MeV), its decay is rather common in nuclei (especially proton rich nuclei) where the needed mass difference is provided on the account of its binding energy.

Figure 1: The two archetypes of nucleon beta decay

It is also worth noting that the start reaction of the solar nucleosynthesis is the fusion of two protons giving rice to deuterium, positron and electron neutrino via a weak interaction in which the necessary mass difference is provided by the relative kinetic energies of the colliding protons. The cross section of this reaction is very small (S factor $S(E)=4\times 10^{-22}$ keV bn) [1] giving rice to a reaction rate of $10^{-18}/s/proton$ at temperatures of $10^7$ K. Only the huge number of protons in the sun makes this reaction important. To my best knowledge, this reaction was not yet observed in the laboratory, even at energies in the range of few MeV. This reaction can be considered as the inverse of neutron beta decay, the second proton being needed for providing via collision energy the necessary mass deficit. This observation can drive the idea that other ways of providing this deficit may lead also to “induced” proton decay.
On the other hand, the transition probability for the weak process in the case of proton and neutron is expected to be almost the same (if the influence of the inactive quarks is neglected or small), as the masses of $W^+$ and $W^-$ bosons are practically identical.

In the following we will examine the possibility that the potential energy of a proton moving in the electrostatic field of an atomic nucleus compensates the necessary mass deficit and renders in this way the beta decay of that proton possible.

**The neutron decay**

Before referring to the proton moving in an electrostatic field it is may be useful to recall few facts about the neutron decay. The neutron lifetime, according to PDG [2] has a value of $T_{1/2} = 885.7$ s, that represents an average of the results obtained by beam techniques (counting the initial number of neutrons and the decay protons). Some relatively recent experiments [3] using ultra cold neutrons and a storage technique propose a value of 878.5 s. Though the difference is at the level of 1%, it is considered important by the implied cosmological (Big Bang Nucleosynthesis (BBN)), astrophysical (p-p fusion) and Standard Model (SM) consequences [4-7]. Also the precise calculation of the neutron lifetime is not a simple task, various corrections being necessary [8]. In its decay, the n-p mass difference of 1.293 MeV is used for the production of the electron and antineutrino and provides kinetic energy for all emerging three particles. Neglecting the mass of antineutrino and subtracting the electron mass of 0.511 MeV, 0.782 MeV remain available for the kinetic energy of decay products – the so called Q value. This energy is shared among the three products in a continuous way, giving rise to a phase space volume. The following formula [ref. 5 and citations therein] is proposed for the lifetime:

$$f_{\text{neutron}} = K \cdot \left[ 1 + 3|\lambda|^2 \right]^{-1} \cdot |G_V|^2 \cdot |G_s|^2 \cdot \lambda$$  \hspace{1cm} (1)

in which $K$ and $\lambda$ and $G_V$ are constants and $f$ is the contribution of the phase space volume. Without entering into details, this contribution depends on the Q value of the decay that fixes the integration limits for the phase space volume. In its Q dependence, the leading term is $Q^5$ [4].

**Coulomb scattering of the proton**

Let us briefly consider the Rutherford scattering of a proton on a high Z nucleus, e.g. $^{208}$Pb at energies below the Coulomb barrier ($V_c = 12.2$ MeV). The condition of a Coulomb field higher than the mass deficit of 1.8 MeV is fulfilled for a sphere of 70 fm radius or, in other terms, a geometrical cross section of 150 bn. If the proton enters this region, its beta decay is no longer energetically forbidden. One should remark that this condition is reached in a scattering system and that the nuclear structure of $^{208}$Pb does not play any role, view the sub barrier energies. Also, this condition is fulfilled only for the short time interval when the proton is inside the R=70 fm sphere. This time interval is many orders of magnitude less than the lifetime of the free neutron. While the transition probabilities for proton and neutron are expected to be the same (as stated already above), their phase space factors can be very different. Indeed for the decay of a scattered proton with a potential energy of 9.6 MeV, 1.8 MeV will be necessary to compensate the mass difference between proton and its decay products and the remaining Q value of 7.8 MeV will create a much larger phase space volume. If for the neutron this Q value is only 0.78 MeV, for proton the value is 10 times larger. As the phase space factor $f$ [formula 1] varies with Q as $Q^5$, the lifetime of proton will decrease correspondingly by a factor 10$^5$.

In the following, a rough estimate will be given for the average time spent by a proton inside the region delimited by the sphere with a radius of 70 fm. The velocity of the proton along its hyperbolic trajectory varies also, being maximal at the entrance and exit and minimal for the distance of closest approach. The corresponding times will be longer for the region around the closest approach where the
potential energy of the proton is also maximal. To take full benefit of decay time decrease due to the $Q$ value increase, we will limit ourselves to trajectories in a restricted range of impact parameters such as to allow the proton to spend a longer time close to the nucleus, where the potential energy is high. Taking a maximal value for the potential energy of 10 MeV, leads to impact parameters below 12 fm (which corresponds to a geometrical cross section of 4.5 bn). For these protons, the trajectory will have a length slightly smaller than 140 fm, say 130 fm. The average velocity (between incident velocity and the velocity at the turning point) will be around $\beta=0.05$, leading to a time $\Delta t$ on trajectory inside the $R=70$ fm sphere of about $9\times10^{-21}$ s. Taking also an average value for the potential energy (between 1.8 MeV and 10 MeV) along the trajectory as 6 MeV implies an average $Q$ value of 4.2 MeV, i.e. 5.4 times higher than the neutron value. This increased $Q$ value gives a decrease of the decay time for the scattered proton by a factor of about 4600, i.e. $T_{1/2}=0.19$ s. Using this figures one can evaluate the probability that a proton decay occurs during the time when it is inside the $R=70$ fm sphere. For the exponential decay law, the number of decays in an interval $dt$ is $\Delta N = N_0 \cdot 0.67 \cdot T_{1/2}^{-1} \cdot dt$. In our case, $\Delta N = N_0 \cdot 0.67 \cdot 9 \cdot 10^{-21}/0.19 = N_0 \cdot 3.1 \cdot 10^{-20}$, with $N_0$ being the number of scattered protons in the above mentioned conditions. To give an estimate for $N_0$, one can consider a $^{208}$Pb target with a thickness of 160 mg/cm$^2$ and a proton beam with energy of 11 MeV to be safe under barrier and an intensity of 1 $\mu$A or 6.25 $10^{15}$ protons/s. The beam energy will be decreased by the target from 11 MeV to 8.8 MeV centered on the above 10 MeV value. Considering the mentioned cross section of 4.5 bn, the number of scattered protons results as $N_0 = 1.3 \cdot 10^{13}$ per second. The resulting $\Delta N = 4 \cdot 10^7$ per second or $1.4 \cdot 10^{-1}$ events per day (one event in 7 days). This value is discouragingly small especially considering the rather high current used in the evaluation but it had to be expected for a weak decay. A more precise evaluation will result from a simulation program which is in preparation and the results may differ substantially from this crude estimate. Such a long experiment will need special precautions for the background conditions and for an unambiguous identification of a proton decay event. Hopefully, from the decay results a positron which, after being stopped, annihilates with an electron, giving rise to two coincident gamma rays of 511 keV emitted back to back, a strong signature for such an event. Among the precautions one can mention a beam dump placed far downstream, to avoid an unnecessary load of Ge detectors placed in a close geometry around the target. Also under barrier reactions like $(p,n)$ or Coulomb excitation of the target. The first one has an unfavorable $Q$ value (therefore small cross section, especially under barrier) and leads to $^{208}$Bi that decays back to $^{208}$Pb by internal conversion while the second, due to the small charge of the proton and the large excitation energy of the first level in $^{208}$Pb (2614.5 keV) has also a very small probability.

An interesting alternative is to use a $^{232}$Th target that will have a higher Coulomb barrier, affording to use a thicker target with the corresponding gain in cross section. One should remark that the nascent positron from this point interaction/decay has a potential energy in the Coulomb field equal to that of the decaying proton, therefore it is off shell. However, at these energies it is relativistic and the time to come back on shell is very short. The relation $\Delta E = \hbar \cdot \Delta t$ is fulfilled for $\Delta E = 6$ MeV (the average energy) and $\Delta t \geq 10^{-22}$ s which correspond to distances of more than 30 fm for relativistic positrons. This observation will not affect the phase space factor but it may have an influence on the spectral shape of the decay products.

The experiment can be done during repeated beam times periods of e.g. 7 days and it is possible to be performed at a Tandem electrostatic accelerator.

**Conclusions**

Irrespective to the obtained result (non-observation or observation after a certain integrated proton current) information will be obtained on a fundamental decay. In particular, such information may be of importance for the mechanism of energy transmission from the electrostatic field to the scattered proton, possible implications for a weak-electromagnetic interaction and also possible consequences for
the BBN and SM. On the other hand, such a mechanism may accelerate the decay rate for some far from stability isotopes that undergo frequent collisions during the nucleosynthesis process.

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