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NEUTRON-ANTINEUTRON OSCILLATIONS IN NUCLEI*

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(presented by J.M. Richard)

Abstract. We briefly review the state of the art for extracting the period of neutron-antineutron oscillations from the lifetime of nuclei. The most recent data on nuclear stability provide a limit of 10^8 s for the oscillation period.

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1. Introduction

As explained in the talk by Mohapatra /1/, there are interesting scenarios of unification of all interactions where the unique or major source of baryon number violation is the $\Delta B = 2$, $\Delta L = 0$ transition from neutron to antineutron, and vice-versa.

In these "Grand Unified Theories" with or without supersymmetry, a crucial experimental quantity is the oscillation period τ of neutrons, on the same footing as the branching ratios for some "forbidden" kaon decays.

One source of information on the oscillation period τ is obtained by the study of the stability of nuclei in experiments located in deep mines or tunnels. The fact that ^{16}O survives more than 10^{31} or 10^{32} years /2/ ensures that the constituent protons do not decay too fast and also that the bound neutrons are not too easily transformed into antineutrons which would annihilate immediately.

This is why nuclear stability provides a useful lower limit on τ . The relationship between the nucleus lifetime T and the oscillation period τ has been elaborated by several authors /3-9/ and will be explained in Section 3.

Of course, a positive signal in an underground experiment would hardly lead to a unambiguous signature for neutron - antineutron oscillation, even if the energy release is measured to be of the order of 2 GeV. The ultimate evidence for neutron oscillations should come a direct observation of some antineutrons in a neutron beam. This is the purpose of the ILL experiment, which is described elsewhere in these Proceedings /10/.

2. Free versus bound neutrons

At first, the free neutron experiment and a ^{16}O or ^{56}Fe experiment could be thought as measuring different periods, say the bare or genuine period τ and the renormalized period τ' relevant for nuclei. The possible magnitude of the ratio τ'/τ was the subject of several discussions and controversies, which involved for instance the chairman of this session /8/ and the present authors /9/.

Whatever mechanism induces neutron-antineutron oscillations, Higgs, Super-Higgs or generalized intermediate boson exchange, the process involves the probability of finding the three quarks of the neutron essentially at the same place and the antiquarks are produced very

close together. The EMC effect /11/ tells us that the quark distributions are modified when nucleons experience nuclear binding, though the effect remains small in magnitude. Antineutrons could also be deformed in nuclei.

In fact, if one insists on being pessimistic, one can find many other reasons for τ' being different from τ deep inside the nucleus. Some counterarguments have been given in ref./9/. One could argue, for instance, that entire chapters of nuclear physics, including β -decay which involves the quark level, are consistent with the picture of the nucleus as a collection of weakly bound and modestly deformed nucleons.

In our opinion, the most convincing argument for calculating τ from the nucleus lifetime comes "a posteriori" from the computation : in a nucleus, the neutrons oscillate only when they are in the tail of the nuclear density, i.e. in a region where medium corrections are negligible. Thus the discussion of the ratio τ'/τ at central nuclear densities is somewhat academic.

Why so ? The nuclear instability induced by neutron-antineutron oscillations is governed by two conflicting requirements. On the one hand, if a neutron gets the chance of becoming a antineutron, it must encounter other nucleons in order to annihilate. This favours the centre of the nucleus. On the other hand, the average potential V_2 felt by an antineutron in the nuclear medium is considerably different from the potential V_1 felt by a neutron. This suppresses strongly the oscillation inside the nucleus. The computation shows that the latter effect is much more important than the the former one.

In ref./6/, we gave the example of a square-well potential with a realistic radius R and reasonable strengths V_1 and V_2 . The calculation can be done in a simple analytic form. At first, one is tempted to neglect the small part of the neutron density located beyond R . In fact, this external tail turns out to contribute to almost all the nuclear instability. This effect was not seen in some early calculations, where incorrect approximate formulas were given for the nuclear lifetime by neglecting the tail of the wave-function.

It is in fact amusing that in the ILL experiment/10/, the neutrons have to get rid of the magnetic potential energy to avoid a dramatic suppression of the oscillation effect and that in the Frejus or IBM experiments/2/, the neutrons have to escape the nuclear potential.

3. The formalism

Let us start with the Deuteron. Neglecting its unessential quadrupole deformation, it is described by

$$u''(r) + m (E - V_1) u(r) = 0 \quad (1)$$

where $u(r)$ is the reduced wave-function and V_1 the n-p potential, both well-known and constrained by the data. The Deuteron has a very tiny antineutron-proton component with radial wave-function $v(r)$ given to first order by the Sternheimer equation /12/

$$v''(r) + m (E - V_2) v(r) = m \frac{u(r)}{\tau} \quad (2)$$

The essential assumption in eq.(2) is that the transition potential is independent of the n-p separation r and equal to its free space value $1/\tau$. Here V_2 is a complex (optical) potential describing the antineutron-proton interaction realistically. Once eq.(2) is solved, one gets the second order energy shift and, in particular, the imaginary part corresponding to a width

$$\Gamma = -2 \int_0^\infty |v(r)|^2 \text{Im } V_2(r) dr \quad (3)$$

The lifetime $T = \Gamma^{-1}$ of the nucleus is obviously of the form

$$T = T_R \tau^2 \quad (4)$$

a formula which summarizes the three crucial quantities

- i) T is the experimentally measured lifetime of the nucleus
- ii) τ is the oscillation period to be compared with free neutron experiments and theoretical models of grand unification such as SO(10)
- iii) T_R is the "nuclear factor" (in s^{-1}) which is obtained from low energy hadron physics as input

Some surprises emerged from the calculation /6,9/. We already mentioned that neutrons prefer to oscillate outside the nuclear radius. We also discovered that the value of T_R depends very little on the choice of the antinucleon-nucleon potential V_2 .

For more complicated nuclei, we repeated the calculation in a simple shell-model picture. Each neutron is described by an equation of type (1) with a specific effective potential for each orbit (including sometimes a centrifugal barrier) and a specific binding energy E . To each shell is associated a small antineutron component of type (2).

The diagonal potential V_2 in eq.(2) is now an antineutron-nucleus potential. At the time of our first calculation /6/, V_2 was not well known, since it was constrained only by early data on antiprotonic atoms. Even so, the eqs.(2-3) exhibit a remarkable stability, since the value of T_R is almost unchanged when one changes changing dramatically the potential V_2 . Nowadays, the LEAR data on antiprotonic atoms and antinucleon-nucleus scattering have further restricted the allowed range of V_2 /14/, and the uncertainty in T_R is even smaller /7/. To be honest, experimental data from LEAR constrain the optical potential V_2 only near the nuclear surface, since the antiprotons do not experience the interior of the nucleus. But this is precisely the domain which is relevant for nuclear instability.

4.Results

The comparison of the results for the Deuteron with those for Beryllium, Oxygen and Iron is instructive as well as the comparison, for a given nucleus, of the relative contribution of each neutron shell. This confirms the point we have been making all along : the more externally localized the neutron is, the more likely that it contributes to nuclear instability. There is an order of magnitude difference in oscillation rate between the loosely bound last neutron of ^9Be and the most interior neutron of ^{56}Fe .

Since not even the IBM collaboration can afford to fill a swimming pool with liquid deuterium, we have to work with ordinary material, say concrete or steel, or ^{16}O and ^{56}Fe , typically. This gives an average T_R of around 10^{23} s^{-1} . This means that, with the latest results of the Frejus collaboration and other experiments /2/, one obtains a lower limit :

$$\tau > 10^8 \text{ s} \quad (5)$$

A serious challenge for our ILL friends !

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5. References

- /1/ R.N. Mohapatra, Contribution to these Proceedings
- /2/ See, e.g., various contributions to "9th Workshop on Grand Unification", Aix-les-Bains, April 1988, ed. R. Barloutaud (World Scientific, 1988)
R. Barloutaud and J. Rich, private communication
- /3/ P.G. Sandars, J.Phys. G6, L161 (1980)
- /4/ W.M. Alberico, J. Bernabeu, A. Bottino and A. Molinari, Nucl.Phys. A429, 445 (1984)
- /5/ M.V. Kazarnoskii et al, JETP Lett. 32, 82 (1980)
K.G. Chetyrkin et al, Phys. Lett 99B, 358 (1981)
Riazzudin, Phys.Rev. D25, 885 (1982)
- /6/ C.B. Dover, A. Gal and J.M. Richard, Phys.Rev.D27,1090 (1983)
- /7/ C.J. Batty, M. Fidecaro and H.B. Prosper, Nucl.Phys. A446, 473 (1987)
- /8/ P.K. Kabir, Phys.Rev.Lett 51, 231 (1983)
P.K. Kabir and J.V. Noble, "Nuclear Instability and limits on neutron-antineutron oscillations", submitted to Phys.Rev C (Comments)
P.K. Kabir, private communication
- /9/ C.B. Dover, A. Gal and J.M. Richard, Phys.Rev.C31,1423 (1985);
Response to Kabir and Noble, submitted to Phys.Rev C (Comments)
- /10/ G.Puglierin, Contribution to this Workshop
- /11/ See, e.g., C. Llewellyn Smith, in Proc. 10th Int. Conf. on Particles and Nuclei, Heidelberg, 1984, ed. B. Povh and G. zu Putnitz, Nucl. Phys. A434, 35c (1985)
K. Rith, in "The Elementary Structure of Matter", Proc. Les Houches Workshop, 1987, ed. J.M. Richard et al, Springer-Verlag (1988)
- /12/ R.M. Sternheimer, Phys. Rev. 84, 244 (1951)
J.P. Killingbeck, "Techniques of Applied Quantum Mechanics", Butterworths, London (1975)
- /13/ See, e.g., several contributions in "Physics at LEAR in the ACOL Era", ed. U. Gastaldi et al, Ed. Frontieres, Gif-sur-Yvette, France (1985)