Ref.TH.2011-CERN

EVIDENCE AGAINST THE EXISTENCE OF A LOW MASS SCALAR BOSON
FROM NEUTRON-NUCLEUS SCATTERING

R. Barbieri and T.E.O. Ericson
CERN - Geneva

A B S T R A C T

The existence of a weakly-coupled scalar boson, recently proposed to explain the apparent discrepancy in X rays from muonic atoms is shown to be inconsistent with the angular distribution measurements in low energy neutron-nucleus scattering. Other negative evidence from various different physical situations is also briefly reviewed.

Ref.TH.2011-CERN
23 April 1975

It has been pointed out by several authors¹⁾ that the persistent discrepancies between theory and experiment in the studies of the transition energies between large orbits in high Z muonic atoms can be removed by assuming an interaction between the muon and the nucleons mediated by a scalar (isoscalar) boson ϕ of very low mass (at most a few MeV). Such a particle, of undetermined mass μ , is indeed called for in unified gauge theories of the weak and electromagnetic interactions (the Higgs particle). More than that, for example in the prototype Weinberg-Salam theory²⁾, the predicted coupling for this ϕ boson is consistent with the one required to remove the muonic X-ray discrepancies if $\mu \lesssim 20$ MeV³⁾.

For this reason it is of great importance to investigate what limitations can be put on the couplings and on the mass of such a boson by other experiments and to enquire what other phenomena would follow from its existence.

Based on these considerations, Resnik, Sundaresan and Watson³⁾ have suggested looking, via the $\phi \rightarrow e^+e^-$ decay mode, for ϕ mesons emitted in $0^+ \rightarrow 0^+$ nuclear transitions. Results of such an experiment have been recently reported by Kohler, Watson and Becker⁴⁾, who have used the transitions between the excited ^{16}O (6.05 MeV) and ^4He (20.2 MeV) 0^+ levels and the corresponding 0^+ ground states. Since no signal has been found, compared to what would be expected from estimates³⁾ of the ϕ -production branching ratio and the ϕ lifetime, this seems to rule out the existence of a light scalar boson. In principle, from this experiment the upper limit on the ϕ mass $\mu < 1.022$ MeV can be put, where the e^+e^- decay mode starts being energetically allowed.

The purpose of the present paper is to demonstrate that low-energy neutron-nucleus scattering provides completely independent evidence against a meson of mass $\mu \lesssim 13$ MeV and that this evidence is overwhelming for $\mu < 5$ MeV^{*)}.

The idea is simply to look into the angular dependence effects caused on the neutron-nucleus differential cross-section by a ϕ -exchange interaction described by a neutron-nucleus potential of the form

$$\delta V_{nN} = - \frac{g_n^2}{4\pi} A \frac{e^{-\mu r}}{r}, \quad (1)$$

where g_n is the ϕ -nucleon coupling constant and A the atomic number of the nucleus. Very prominent effects are indeed expected for $\mu \rightarrow 0$, since this potential simulates a Coulomb interaction, which, on the other hand, is not present between the neutron and the nucleus.

High-precision neutron-scattering experiments on heavy nuclei have been performed in the keV region mainly to determine the neutron electric polarizability. The following result⁵⁾ has been obtained in a n-Pb scattering experiment with a

---

*) By comparison with the gravitational coupling, a very approximate lower limit $\mu > 10^{-4}$ eV can be put on the ϕ mass³⁾.

neutron of kinetic energy E between 1 and 26 keV: parametrizing the differential cross-section in the form

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_0}{4\pi} [1 + \omega E \cos \theta]$$

it is found that $\omega = (1.91 \pm 0.42) \times 10^{-3} \text{ keV}^{-1}$.

On the other hand the potential of Eq. (1), treated in the Born approximation, would produce the following modification of the scattering amplitude

$$\Delta f = 2m_n \frac{g_n^2}{4\pi} A \frac{1}{4m_n E(1 - \cos \theta) + \mu^2}.$$

Such an amplitude, interfering with the strong interaction amplitude, will show up in the following contribution to ω for $E \rightarrow 0$:

$$\Delta\omega = -16 \frac{m_n^2}{\sqrt{\frac{\sigma_0}{4\pi}}} \frac{g_n^2}{4\pi} \frac{A}{\mu^4}.$$

The minus sign in this expression means that the real part of the nuclear scattering amplitude in the case considered is negative. Of course ω receives a contribution ω_s also from the strong interaction amplitude, and eventual cancellations can occur between ω_s and $\Delta\omega$. It seems nevertheless reasonable to assume that $\Delta\omega$, if at all present, cannot be bigger than the measured value of ω $|\Delta\omega| < 2 \times 10^{-3} \text{ keV}^{-1}$, otherwise accurate cancellations must be invoked, since $\Delta\omega$ has opposite sign with respect to the one measured for ω . Having $\sqrt{\sigma_0/4\pi} \approx 10 \text{ fm}$ and $A = 208$, we therefore end up with the following limit:

$$\frac{g_n^2}{4\pi} \frac{1}{(\mu \text{ MeV})^4} \lesssim 3.4 \times 10^{-11}. \quad (2)$$

Note the dependence of the left-hand side on the inverse fourth power of μ , which makes the bound very sensitive to the low-mass region^{*}). In order to put a limit on the mass μ , we now need an estimate for the ϕ -nucleon coupling constant. For this purpose we can use the information coming from the muonic X-ray experiments.

In this situation a very light ϕ boson ($\mu \lesssim 5 \text{ MeV}$) affects essentially only the coupling of the Coulomb interaction between the muon and the nucleus:

$$-\frac{Z\alpha}{r} \rightarrow -\left(Z\alpha + \frac{g_\mu g_n}{4\pi} A\right) \frac{1}{r} \quad (3)$$

where g_μ denotes the ϕ -muon coupling constant and Z the charge of the nucleus.

Fitting Eq. (3) to the μ -mesic X-ray data gives therefore a value for the coupling⁶⁾

^{*}) Since in the actual experiment $E \gtrsim 1 \text{ keV}$, this bound, as well as the expression for $\Delta\omega$, applies only for $\mu > \sqrt{m_n E} \sim 1 \text{ MeV}$. However, for $\mu \lesssim 1 \text{ MeV}$ and for the considered values of $g_n^2/4\pi$ [see below Eq. (6)], the full angular dependence of Δf violently disagrees with the measured one in $d\sigma/d\Omega$. To reconcile them, taking as reference point $E \approx 1 \text{ keV}$, one should have $g_n^2/4\pi \ll 3.4 \times 10^{-11}$.

$$\frac{g_\mu g_n}{4\pi} \approx -10^{-7} \approx -10^{-5} \alpha, \quad (4)$$

roughly independent from the value of $\mu \lesssim 5$ MeV. When μ increases, the Yukawa nature of the interaction mediated by the ϕ boson becomes important and Eq. (4) becomes an upper limit:

$$\frac{g_\mu g_n}{4\pi} \lesssim -10^{-7}. \quad (5)$$

On the other hand, the value for $g_\mu^2/4\pi$ is predicted by the Weinberg-Salam theory to be

$$\frac{g_\mu^2}{4\pi} = \frac{1}{2\pi} \frac{G_F m_\mu^2}{\sqrt{2}} = 1.3 \times 10^{-8}.$$

Using this equation and the empirical strength given in Eqs. (4) and (5), one then gets a limit value for $g_n^2/4\pi$:

$$\frac{g_n^2}{4\pi} \gtrsim 0.7 \times 10^{-6},$$

which has to be consistent with the bound given in Eq. (2). For this to be true, we must have $\mu > 13$ MeV. Furthermore, even more significant than this bound is the fact that for $\mu \approx 1$ MeV, the limit in Eq. (2) disagrees by five orders of magnitude with the value for $g_n^2/4\pi$ required to explain the muonic X-ray discrepancy. This, in our opinion, constitutes the most clear evidence against the existence of a very light ϕ boson.

To even strengthen this conclusion, it is also important to know that other arguments, based on different experiments, can be given against the existence of a low-mass scalar boson. Let us summarize them, before concluding. One of these arguments⁷⁾ is based on the effects eventually produced by the ϕ -exchange potential

$$\delta V_{\mu n} = - \frac{g_\mu g_n}{4\pi} A \frac{e^{-\mu r}}{r}$$

on the recently measured⁸⁾ separation $\Delta E_{\text{He}} (2P_{3/2} - 2S_{1/2})$ between the $2P_{3/2}$ and the $2S_{1/2}$ levels of the helium muonic ion $(\mu^4\text{He})^+$. Such a potential would give a contribution to this splitting,

$$\delta E = \frac{g_\mu g_n}{4\pi} \frac{\mu^2}{\alpha m_\mu} \left[1 + \frac{\mu}{2\alpha m_\mu} \right]^{-4},$$

which should be less than 10^{-2} eV in order not to introduce more than one standard deviation discrepancy between theory and experiment, which are at present in agreement. One therefore gets the following limit (μ in MeV):

$$\left| \frac{g_\mu g_n}{4\pi} \right| \mu^2 (1 + 0.6 \mu)^{-4} < 0.7 \times 10^{-8},$$

which, combined with Eq. (4), gives $\mu < 0.5$ MeV or $\mu < 5.5$ MeV.*)

Another argument, suggested by Adler, Dashen and Treiman⁹⁾, is based on the effects of the interaction between the electron and the neutron mediated by the ϕ boson:

$$\delta V_{en} = - \frac{g_e g_n}{4\pi} \frac{e^{-\mu r}}{r},$$

on the scattering of thermal neutrons from atomic electrons. The contribution of this potential to the neutron-electron spin averaged scattering length a is given by (m_n = neutron mass):

$$\delta a = 2 \frac{m_n}{\mu^2} \frac{g_e g_n}{4\pi}.$$

On the other hand, the best determinations of a are $(-1.34 \pm 0.03) \times 10^{-3}$ fm¹⁰⁾ and $(-1.56 \pm 0.04) \times 10^{-3}$ fm¹¹⁾, which are correctly accounted for by the main part of the theoretical scattering length, namely the neutron magnetic moment contribution

$$a_{MM} = \frac{\alpha \mu_n}{2M} \approx -1.47 \times 10^{-3} \text{ fm}.$$

We can then put a limit on δa , $|\delta a| \leq 0.3 \times 10^{-3}$ fm, which in turn gives the following limit on the quantities of interest

$$\left| \frac{g_e g_n}{4\pi} \right| \frac{1}{(\mu \text{ MeV})^2} \leq 0.8 \times 10^{-9}.$$

Making the additional assumption $g_e = (m_e/m_\mu) g_\mu$ as suggested by the structure of the ϕ -boson couplings in the mentioned theories of weak and electromagnetic interaction, and using the empirical strength of Eq. (4), one then gets a lower limit on the ϕ mass, $\mu > 0.7$ MeV.

In conclusion, even though the actual limits on the mass μ coming both from the $(\mu^4\text{He})^+$ fine structure separation and from the low-energy electron-neutron scattering are not so stringent as the bound from the neutron-nucleus scattering since they rely on the estimates of the uncertainties of the various measured quantities, it is nevertheless significant that any effect from the existence of the

*) Actually a more detailed analysis⁷⁾ shows that even for $\mu > 5.5$ MeV the ϕ -boson effects needed to explain the μ -mesic X-ray discrepancy are not consistent with the present knowledge of the fine structure separation in the $(\mu^4\text{He})^+$ system.

low-mass ϕ boson does not show up in various very different physical situations.
Of course, all this means that the muonic X-ray discrepancy remains to be explained
as a different effect.

Acknowledgement

We thank E.J. Blomqvist for useful conversations.

REFERENCES

- 1) M.K. Sundareshan and P.J.S. Watson, Phys. Rev. Letters 29, 15 (1972);
R. Jackiw and S. Weinberg, Phys. Rev. D 5, 2396 (1972).
- 2) S. Weinberg, Phys. Rev. Letters 19, 1264 (1967); A. Salam, in Elementary
Particle Physics (ed. V. Svartholm) (Almqvist and Wiksell, Stockholm,
1968), p. 367.
- 3) L. Resnick, M.K. Sundareshan and P.J.S. Watson, Phys. Rev. D 8, 172 (1973).
- 4) D. Kohler, B.A. Watson and J.A. Becker, Phys. Rev. Letters 33, 1628 (1974).
- 5) Y.A. Aleksandrov, G.S. Samosvat, J. Sereeter and Tsoy Gen Sor, JEPT Pisma 4,
196 (1966) [English translation: JETP Letters 4, 134 (1966)].
- 6) S.L. Adler, Phys. Rev. D 10, 3714 (1974).
- 7) R. Barbieri, CERN preprint Ref. TH.1963, to appear in Phys. Letters.
- 8) A. Bertin et al., CERN preprint February 1975, to appear in Phys. Letters.
- 9) S.L. Adler, R.F. Dashen and S.B. Treiman, Phys. Rev. D 10, 3728 (1974).
- 10) V.E. Krohn and G.R. Ringo, Phys. Letters 18, 297 (1965); Phys. Rev. 148,
1303 (1966).
- 11) E. Melkonian, B.M. Rustad and W.W. Havens Jr., Phys. Rev. 114, 1571 (1959).