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

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

ABSTRACT

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 authors\(^1\) 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 \(\phi\) of very low mass (at most a few MeV). Such a particle, of undetermined mass \(\mu\), 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 theory\(^2\), the predicted coupling for this \(\phi\) boson is consistent with the one required to remove the muonic X-ray discrepancies if \(\mu \lesssim 20\) MeV\(^3\).

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 Watson\(^4\) have suggested looking, via the \(\phi \rightarrow e^+e^-\) decay mode, for \(\phi\) mesons emitted in \(0^+ \rightarrow 0^+\) nuclear transitions. Results of such an experiment have been recently reported by Kohler, Watson and Becker\(^5\), who have used the transitions between the excited \(^1^6\)O (6.05 MeV) and \(^4\)He (20.2 MeV) \(0^+\) levels and the corresponding \(0^+\) ground states. Since no signal has been found, compared to what would be expected from estimates\(^6\) of the \(\phi\)-production branching ratio and the \(\phi\) lifetime, this seems to rule out the existence of a light scalar boson. In principle, from this experiment the upper limit on the \(\phi\) 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 \(\mu < 13\) MeV and that this evidence is overwhelming for \(\mu < 5\) MeV\(^7\).

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

\[
\delta V_{\text{nN}} = -\frac{\mathbf{g}_\phi}{4\pi} A \frac{e^{-\mu r}}{r},
\]

where \(\mathbf{g}_\phi\) is the \(\phi\)-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 result\(^8\) has been obtained in a n-Pb scattering experiment with a

---

\(a\) By comparison with the gravitational coupling, a very approximate lower limit \(\mu > 10^{-8}\) eV can be put on the \(\phi\) mass\(^9\).
neutron of kinetic energy $E$ between 1 and 26 keV: parametrizing the differential cross-section in the form

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

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

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

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

$$\Delta \omega = -16 \frac{m_n^2}{v^2} \frac{e_n^2}{4\pi} \frac{A}{\mu^2} / \sqrt{4\pi}.$$ 

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

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

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

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

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

where $g_\mu$ denotes the $\phi$-muon coupling constant and $Z$ the charge of the nucleus. Fitting Eq. (3) to the $\mu$-mesic X-ray data gives therefore a value for the coupling $^6$)

(*) Since in the actual experiment $E \geq 1$ keV, this bound, as well as the expression for $\Delta \omega$, applies only for $\mu > \sqrt{m_n E} \sim 1$ MeV. However, for $\mu \lesssim 1$ MeV and for the considered values of $g_n^2/4\pi$ [see below Eq. (6)], the full angular dependence of $\Delta f$ violently disagrees with the measured one in $d\sigma/d\Omega$. To reconcile them, taking as reference point $E = 1$ keV, one should have $g_n^2/4\pi < 3.4 \times 10^{-11}$.}
\[
\frac{g_\mu g_n}{4\pi} \approx -10^{-7} \approx -10^{-5} \alpha,
\]
(4)
roughly independent from the value of \( \mu \lesssim 5 \text{ MeV} \). When \( \mu \) increases, the Yukawa nature of the interaction mediated by the \( \phi \) boson becomes important and Eq. (4) becomes an upper limit:

\[
\frac{g_\mu g_n}{4\pi} \leq -10^{-7}.
\]
(5)

On the other hand, the value for \( \frac{g_\mu^2}{4\pi} \) is predicted by the Weinberg-Salam theory to be

\[
\frac{g_\mu^2}{4\pi} = \frac{1}{2\pi} \frac{G_{\text{em}}^2}{\sqrt{2}} = 1.3 \times 10^{-8}.
\]

Using this equation and the empirical strength given in Eqs. (4) and (5), one then gets a limit value for \( \frac{g_\mu^2}{4\pi} \):

\[
\frac{g_\mu^2}{4\pi} \geq 0.7 \times 10^{-6},
\]
which has to be consistent with the bound given in Eq. (2). For this to be true, we must have \( \mu > 13 \text{ MeV} \). Furthermore, even more significant than this bound is the fact that for \( \mu \approx 1 \text{ MeV} \), 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 \( \phi \) 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 arguments\(^7\) is based on the effects eventually produced by the \( \phi \)-exchange potential

\[
\delta V_{\mu n} = -\frac{g_\mu g_n}{4\pi} A \frac{e^{-\mu r}}{r},
\]
on the recently measured\(^8\) 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 (\( \mu^+\text{He}\))\(^+\). Such a potential would give a contribution to this splitting,

\[
\delta E = \frac{g_\mu g_n}{4\pi} \frac{\mu^2}{2m_\mu} \left[ 1 + \frac{\mu}{2m_\mu} \right]^{-4},
\]
which should be less than \( 10^{-2} \text{ eV} \) 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 (\( \mu \) in MeV):

\[
\left| \frac{g_e g_n}{4\pi} \right| \mu^2 (1 + 0.6 \mu^{-1}) < 0.7 \times 10^{-8},
\]
which, combined with Eq. (4), gives \( \mu < 0.5 \text{ MeV} \) or \( \mu < 5.5 \text{ MeV} \).

Another argument, suggested by Adler, Dashen and Treiman, is based on the effects of the interaction between the electron and the neutron mediated by the \( \phi \) 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 (\( m_n = \text{neutron mass} \)):

\[
\delta a = 2 \frac{m_n g_e g_n}{\mu^2} \frac{e^{-\mu r}}{4\pi}.
\]
On the other hand, the best determinations of \( a \) are \((-1.34 \pm 0.03) \times 10^{-3} \text{ fm} \) \(^{10}\) and \((-1.56 \pm 0.04) \times 10^{-3} \text{ fm} \) \(^{11}\), which are correctly accounted for by the main part of the theoretical scattering length, namely the neutron magnetic moment contribution

\[
a_{\text{NM}} = \frac{\alpha n}{2M} = -1.47 \times 10^{-3} \text{ fm}.
\]
We can then put a limit on \( |\delta a| \leq 0.3 \times 10^{-3} \text{ fm} \), 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 \( \phi \)-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 \( \phi \) mass, \( \mu > 0.7 \text{ MeV} \).

In conclusion, even though the actual limits on the mass \( \mu \) coming both from the \((\mu^7\text{He})^+ \) 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

\[\text{---}
\]

\(^{\text{(*)}}\) Actually a more detailed analysis\(^7\) shows that even for \( \mu > 5.5 \text{ MeV} \) the \( \phi \)-boson effects needed to explain the \( \mu \)-mesic X-ray discrepancy are not consistent with the present knowledge of the fine structure separation in the \((\mu^7\text{He})^+ \) system.
low-mass $\phi$ 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


