Constraint on the Higgs-Boson Mass from Nuclear Scattering Data

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We exploit the experimental energy dependence of the neutron-lead scattering cross section to find a bound on the mass of the Higgs boson, m_H. We use the recently determined coupling constant of the Higgs particle to nucleons, $g=2.1\times10^{-3}$, and find $m_H \gtrsim 18$ MeV.

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The search for the Higgs boson is one of the most pressing issues in particle physics. A variety of physical processes have been used to constrain the mass of the Higgs particle.[1] Some of them have theoretical uncertainties that make them not completely reliable at present.[2] In the light of this fact it is important to study phenomena that may lead to safe constraints on the Higgs-boson mass.

Nuclear scattering data have proven to be useful for placing constraints on the Higgs boson. Barbieri and Ericson[3] were the first to notice that the angular dependence of the scattering cross section of neutrons on a nucleus was sensitive to the potential originated by a light-boson exchange. Here we shall show that the consideration of the energy dependence of the total cross section also leads to a limit on the Higgs-boson mass, which turns out to be more stringent.

In the low-energy region the energy dependence of the neutron-Pb scattering cross section

$$\sigma(k)=\sigma(0)+a_1k+a_2k^2, \qquad (1)$$

with k the wave vector of the incoming neutron, has been accurately determined by a recent experiment.[4] The result is

$$\sigma(0)=11.253(5)\ \text{b}, \qquad (2a)$$

$$a_1=0.60(51)\ \text{b fm}, \qquad (2b)$$

$$a_2=-371(27)\ \text{b fm}^2, \qquad (2c)$$

where the fit is obtained with data in the range $1.5\times10^{-3}\le k\le 3.1\times10^{-2}\ \text{fm}^{-1}$.

The aim of the experiment in Ref. 4 was the determination of the electric polarizability of the neutron, which is a parameter related to the linear term in k in the cross section (1). This very small effect is largely due to the nuclear charge distribution and its electric field[4] and we will neglect it. On the contrary the values of $\sigma(0)$ and a_2 in Eq. (2c) can be understood in terms of a simple hard-core potential and its effective range.[5]

Indeed, the scattering amplitude for this nuclear potential reads

$$f_N=-R[1-ikR-\tfrac{2}{3}k^2R^2+O(k^3R^3)], \qquad (3)$$

where R is the radius of the potential and we have only displayed the relevant terms in the low-energy regime ($kR\ll1$). Defining the effective range r_{eff} through

$$\sigma=4\pi R^2[1-R(R-r_{\text{eff}})k^2], \qquad (4)$$

then in our hard-core potential r_{eff} is predicted to be

$$r_{\text{eff}}=\tfrac{2}{3}R. \qquad (5)$$

The consistency of this theoretical prediction with data can be seen as follows. In the presence of the nuclear potential only, the value of R is obtained by using

$$R=[\sigma(0)/4\pi]^{1/2}=9.46\ \text{fm}. \qquad (6)$$

Introducing this value in Eq. (5) we obtain

$$r_{\text{eff}}^N=6.3\ \text{fm}. \qquad (7)$$

This has to be compared to the effective range extracted from the experimental data in Eq. (2c),

$$r_{\text{eff}}(\text{expt})=6.0\pm0.3\ \text{fm}, \qquad (8)$$

which is in agreement with the prediction in Eq. (7).

A light Higgs boson would change the potential felt by a neutron when scattered off a nucleus. Indeed, a Higgs-boson exchange generates an attractive potential

$$V_H=-\frac{Ag^2}{4\pi}\frac{e^{-m_Hr}}{r}, \qquad (9)$$

where A is the atomic mass, m_H the Higgs-boson mass, and g the coupling constant of the Higgs boson to nucleons.

Now we need the scattering amplitude for the combined effect of the nuclear and the Higgs-induced potential, regarding the latter contribution as a perturbation. As we will see the Higgs-boson exchange only affects the value of the parameters $\sigma(0)$ and a_2 in Eq. (1). Therefore we will restrict our discussion to them. The proper treatment of our problem is the "distorted-wave Born approximation."[6] This approximation takes into account the distortion produced by the nuclear potential on the first-order scattering caused by V_H, which is the weak potential. The total scattering amplitude can be written as[6]

$$f = f_N + f_H + \delta f\,, \tag{10}$$

where f_N is the amplitude for the nuclear potential and is given by Eq. (3), and f_H is the standard Born-approximation amplitude for V_H only,

$$f_H(\theta) = 2\mu \frac{Ag^2}{4\pi} \frac{1}{2k^2(1-\cos\theta) + m_H^2}$$
$$\approx 2\mu \frac{Ag^2}{4\pi m_H^2} \left[1 - \frac{2k^2}{m_H^2}(1-\cos\theta) + O\left(\frac{k^4}{m_H^4}\right)\right]. \tag{11}$$

Here μ is the reduced mass and θ the scattering angle. The term δf represents the distorting effect of the nuclear potential and is given by

$$\delta f = -2\mu \int_0^\infty V_H(r)[R_0^2(r) - j_0^2(kr)]r^2 dr\,. \tag{12}$$

In the integrand, we have the S-wave-function solution in the presence of the nuclear potential alone,

$$R_0(r) = \theta(r-a)\frac{\sin k(r-a)}{kr}\,, \tag{13}$$

as well as the free solution $j_0(\rho) = (1/\rho)\sin\rho$. Explicit calculations show that δf is given by

$$\delta f \approx \frac{\mu A g^2}{2\pi}(I_0 + k^2 I_1)\,, \tag{14}$$

where

$$I_0 \equiv \int_0^\infty dr\, e^{-m_H r} r^2 \left(\frac{e^{-m_H R}}{r+R} - \frac{1}{r}\right), \tag{15}$$

and

$$I_1 \equiv -\tfrac{1}{3} \int_0^\infty dr\, e^{-m_H r} r^4 \left(\frac{e^{-m_H R}}{r+R} - \frac{1}{r}\right). \tag{16}$$

In the range $5 \lesssim m_H \lesssim 30$ MeV, the above integrals can be very well approximated by

$$m_H^2 I_0 \approx \frac{0.06}{(m_H R)^{1/2}} - 0.68(m_H R)^{1/2}\,, \tag{17}$$

$$m_H^4 I_1 \approx \frac{-0.1}{(m_H R)^{1/2}} + 1.35(m_H R)^{1/2}\,. \tag{18}$$

The final amplitude in Eq. (10) can now be calculated by adding f_H and δf given respectively by (11) and (14) to the nuclear amplitude f_N given by (3).

Our idea is simple. It can be seen that the effect of the Higgs-boson potential is to *increase* the prediction for the effective range in Eq. (7), destroying the agreement we had in the limit $m_H \to \infty$, i.e., without Higgs-boson exchange. To be conservative, we shall require that the nuclear and the Higgs-boson-induced potentials keep the agreement between theory and experiment within two standard deviations.

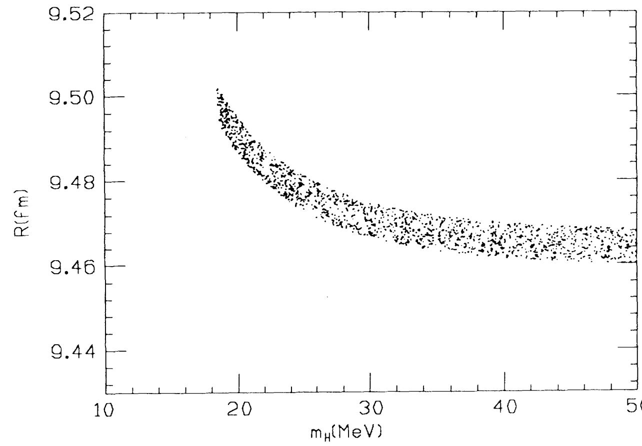

FIG. 1. Allowed values (shaded area) for R and m_H.

The limit on m_H obviously depends on the coupling g of the Higgs boson on nucleons. Since the nucleon is a composite particle, some care is needed. The analysis of Ref. 7 leads to

$$g = 8.5 \times 10^{-4} \frac{n_h}{3}\,, \tag{19}$$

where n_h is the number of heavy quark flavors. However, recent experimental evidence for a large strange-quark sea in the nucleon increases the value in Eq. (19) for $n_h = 3$ up to[8]

$$g = 2.1 \times 10^{-3}\,. \tag{20}$$

We can now find our bound as follows. We evaluate the total contribution to $\sigma(0)$ and a_2 keeping R and m_H as free parameters. We require that the predicted values for $\sigma(0)$ and a_2 agree with the experimental data shown in Eqs. (2a) and (2c) at the two-standard-deviation level. The allowed values of R and m_H are shown in Fig. 1, for the g given by Eq. (20). We see that for high masses of the Higgs boson, R tends to the value in Eq. (6), as it should. Also, from Fig. 1 we can extract a lower limit on the mass of the Higgs boson,

$$m_H \gtrsim 18 \text{ MeV}\,. \tag{21}$$

This is our main result.

We have also calculated our limit for the coupling in Eq. (19). For $n_h = 3$, we find

$$m_H \gtrsim 12 \text{ MeV}\,, \tag{22}$$

whereas for $n_h = 4$ we get

$$m_H \gtrsim 14 \text{ MeV}\,. \tag{23}$$

Finally, it is interesting to compare our results with previous work. The method of Barbieri and Ericson[3] leads to the limit $m_H \gtrsim 10$ MeV for $g = 2.1 \times 10^{-3}$.[9] However, as the authors pointed out, their result holds if there are no fortuitous cancellations. Notice that our limits do not require this assumption.

Limits on m_H coming from K decays are subject to uncertainties[2] that make them unreliable at present. A strong bound can be obtained from $0^+ \rightarrow 0^+$ decays:[10] $m_H \gtrsim 14$ MeV for the g given by Eq. (20), and $m_H \gtrsim 9$ MeV when g is the value of Eq. (19) with $n_h = 3$. The other limits are weaker and we refer the reader to Refs. 1 and 11 for recent reports on them.

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