AN UNAMBIGUOUS SEARCH FOR A LIGHT HIGGS BOSON

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A search for light Higgs bosons has been performed in an electron beam-dump experiment. No positive signal is observed which allows us to reject at 90% CL the existence of a standard Higgs in the range from 1.2 to 52 MeV. Non-standard Higgs bosons are also excluded in a large range of couplings. This search relies on the well controlled and calculable process of bremsstrahlung from electrons in the Coulomb field of large Z nuclei. Both production and decay are governed by the single coupling constant of Higgs to electrons.

1. Introduction

Among all the untested features of the electroweak standard model, it is annoying that the Higgs mechanism for the generation of mass is still not directly confirmed. Although indirect evidence for the existence of weak-isospin doublets of scalar fields has been obtained through the measurements of W and Z masses [1], the direct finding of the corresponding spin-0 particles would be the most welcome and definitive proof of this important phenomenon. On theoretical grounds the mass of the Higgs boson is little constrained. The only fact that it cannot be very heavy – less than a few TeV [2] – leaves open a wide field of experimental investigation which, but for a very small part, has not yet been attacked for lack of suitable processes. This state of affairs is expected to change shortly with the exploitation of LEP and SLC machines [3].

For light masses well below the electroweak energy scale, many experiments have been carried out and analysed. No evidence has been found and different mass ranges claimed to be excluded. On one hand, nuclear physics experiments eliminate very light Higgs bosons, with masses m_H below typically 10 MeV, in particular from neutron–nucleus scattering data [4], the measurements of X-ray transitions in muonic atoms [5] and 0^+–0^+ transitions in ^{4}He [6]. On the other hand, particle decays have been thoroughly explored for Higgs signals. After a long history of re-evaluations of the theoretical predictions, improved data on Υ [7] and B [8] decays now seem to rule out the presence of standard Higgs bosons in the range between 200 MeV and 5 GeV. Kaon decays can also be used to search in the lower mass region and recent null results have been obtained [9] in this way. Although these claims are probably correct, they are not completely safe if one takes into account the uncertainties in the theoretical predictions, essentially at the level of hadronic matrix elements. A possible exception was noted in considering the decay $\pi^+ \to e^+e^-e^+\nu_e$ [10] and in fact recent results have been published rejecting the existence of Higgs bosons between 10 and 110 MeV in this process [11]. However, even in this simpler case of a semi-leptonic decay, the tree level calculation has to be corrected for the gluonic content of the pion coupled to the Higgs via heavy quark loops, as calculated in chiral perturbation theory [12]. The result is to decrease the theoretical estimate by a factor of 2, still above the experimental limit: but this raises the question of the reliability of such large corrections in hadron decays.

In this letter, a new method to search for light Higgs boson is introduced. It relies on only one assumption, i.e. the existence of the He$\bar{e}$ coupling which is a necessary feature of any reasonable model with scalar fields. The process involved – electron bremsstrahlung of Higgs bosons – is completely and safely calculable, given a value for the Higgs mass. The data from a modest experiment are then used to perform an unambiguous search for a Higgs boson in the mass range from 1 to 50 MeV. In this domain, the $H\to\gamma\gamma$ decay branching fraction can be estimated to be at most 2% [13] and therefore only the $H\to e^+e^-$ channel has been considered. Both production and decay are then controlled by a unique coupling constant, totally specified in the minimal standard model and its simple extensions.

2. Electron bremsstrahlung of Higgs bosons

The process considered here is shown in fig. 1 and can be reliably calculated for any spin–parity of the radiated particle. For large masses, i.e. for $m_H \gg 2m$, where m is the electron mass, the cross sections for 0^+ and 0^- states become identical. They only differ slightly for masses m_H in the few MeV range. Consequently, expressions derived for axion bremsstrahlung are totally relevant to our purpose.

The Higgs angular distribution is peaked at very small angles to the incident electron direction, with a long tail at larger values. In our range of interest the median of the angular distribution is approximately given by $\sim\frac{1}{4}m_H/E_0$, where E_0 is the electron beam energy, i.e. a few milliradians in our experimental conditions.

When considering a large mass range, it is important to treat the atomic screening problem consistently. For small masses, atomic screening is complete since the typical momentum transfers are of the order of the inverse of the atomic radius. However, at larger masses, screening becomes unimportant. After integration over the scattered electron and Higgs directions, the cross section is expressed as a function of the normalised Higgs energy, $z=E_H/E_0$. For orientation, we give below the two limiting cases for a large Z target:

$$\frac{d\sigma}{dz} \simeq \frac{2\alpha^2\alpha_H Z^2}{m^2}\frac{z(1+\frac{2}{3}f)}{(1+f)^2}F$$

with

$$f=\frac{m_H^2(1-z)}{m^2z^2}, \quad \alpha_H=\frac{g_{He\bar{e}}^2}{4\pi}=\frac{m^2G_F\sqrt{2}}{4\pi},$$

$$F=\ln(184Z^{-1/3}) \qquad \text{complete screening [14]},$$

$$=\ln\frac{2E_0(1-z)}{mz\sqrt{1+f}}-\frac{1}{2} \qquad \text{no screening [15]}.$$

The fact that $d\sigma/dz$ peaks at $z=1$, contrary to ordinary (massless) photon bremsstrahlung, is a distinctive feature of the process which will be important in the experimental search.

The resulting cross section falls off slightly faster than m_H^{-2} and rate will eventually limit the search. However, another limitation will be imposed by the Higgs lifetime which also decreases as m_H^{-1},

$$\tau_H^{-1}=\frac{1}{2}\alpha_H m_H\left(1-\frac{4m^2}{m_H^2}\right)^{3/2}.$$

For $E_0=1.6$ GeV, a 5 MeV Higgs will travel $\sim$ 80 m on average before decaying, this value being only $\sim$ 75 cm for a 50 MeV boson. Any experimental set-up detecting possible decays in a given fiducial volume will therefore be sensitive for a certain mass range limited at low mass by the small decay rate despite the large cross section and a large mass by both the fast decay rate and the small production yield.

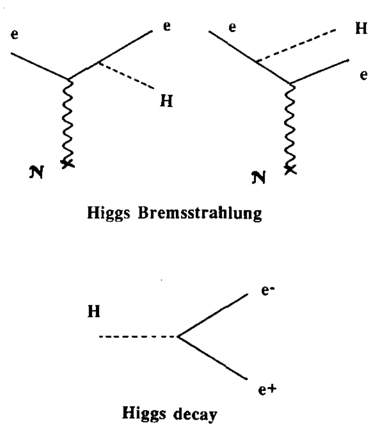

Fig. 1. The Feynman diagrams for the production of Higgs bosons by bremsstrahlung of electrons in the Coulomb field of a large Z nucleus. The Higgs boson decays into an e^+e^- pair. Both processes are controlled by the same $He\bar{e}$ coupling constant.

3. Description of experiment

The experiment used a beam-dump as shown in fig. 2. Incident electrons with an energy of 1.6 GeV were produced by the Orsay linac with 1.5 μs long pulses at 50 Hz. The intensity of the incident beam was

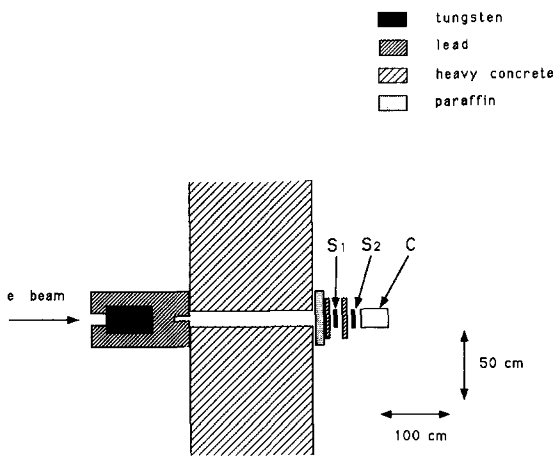

Fig. 2. The experimental lay-out with the beam-dump, the decay channel and the detection system comprising two scintillation counters (S_1, S_2) and a lead-glass Čerenkov calorimeter (C).

monitored with a toroidal pick-up transformer and the beam spot position was continuously checked. The average intensity was limited to 2×10^{12} electrons/s to avoid pile-up in the detectors. The beam dump was made of lead with a large 65 cm long core of tungsten in order to limit the penetration of electromagnetic showers and to range out any charged particles produced. The decay of penetrating particles, such as Higgs bosons, produced early in the dump (typically in the first radiation length) could be observed downstream in a 2 m long channel inside a thick heavy concrete wall which separated the beam switchyard from the experimental hall.

Detection of the decay products was accomplished by a coincidence between two scintillators S_1 and S_2, and a $14X_0$ lead-glass Čerenkov counter C placed behind to record the total electromagnetic energy. In order to reduce the neutron-induced background, a 15 cm thick paraffin shield was put upstream of the detectors, followed by $1.2X_0$ of lead mostly between S_1 and S_2. During the data-taking, most activity in the counters was generated by neutrons and soft electromagnetic products causing pile-up in the Čerenkov counter. With a trigger threshold of 250 MeV in the deposited energy, the typical counting rate was about one per minute for the coincidence.

A 1.2 GeV electron beam steered through the detection apparatus (with the dump removed) was used to calibrate the energy scale and measure the calorimeter response function. Although not a critical issue for this experiment, the energy resolution was measured to be $\sigma_E=10.7\%\sqrt{E}$, where E is the detected energy in GeV.

Most of the data were taken with a 1 m long dump, while some of the earlier running was done with a longer dump (1.2 m). However, in this latter run the electronics was less protected against pile-up and we had to set higher thresholds to eliminate backgrounds. A total of 2×10^{16} electrons was dumped during the data-taking part of the experiment which lasted only a few hours.

4. Results

Since they are expected to be produced near $z=1$ in electron bremsstrahlung, the signal for a Higgs boson in our experiment is a large amount of electromagnetic energy in the lead-glass calorimeter. The spectra taken in the two beam-dump configurations have been examined to this end: no count is observed above 0.75 GeV for data taken with the 1 m dump (see fig. 3) and above 1.1 GeV for the 1.2 m dump data set which is less sensitive anyway for larger mass Higgs with their correspondingly smaller lifetimes. We therefore see no signal and it only remains for us to establish the sensitivity of the experiment before we can quote any mass limits.

The cross section for Higgs bremsstrahlung has been folded with the electron shower distribution in the dump and the efficiency for detecting a Higgs boson of a given mass was determined in our set-up. The trigger requirements could be satisfied by one or both of the decay particles (e^+e^-). For masses considered in this experiment, the geometrical acceptance for the decay products was always very close to one; however, a large reduction occurred for small and large lifetime values due to the finite lengths of the dump and of the decay region. Together with the energy cut defined above in order to remove the background, the overall efficiency to detect a Higgs boson produced in our dump had a maximum value of 37% for a mass near 30 MeV and decreased on either side because of decays. At low mass, the limitation arises from the fixed length of the decay region and at high mass, most produced Higgs would decay in the dump and escape

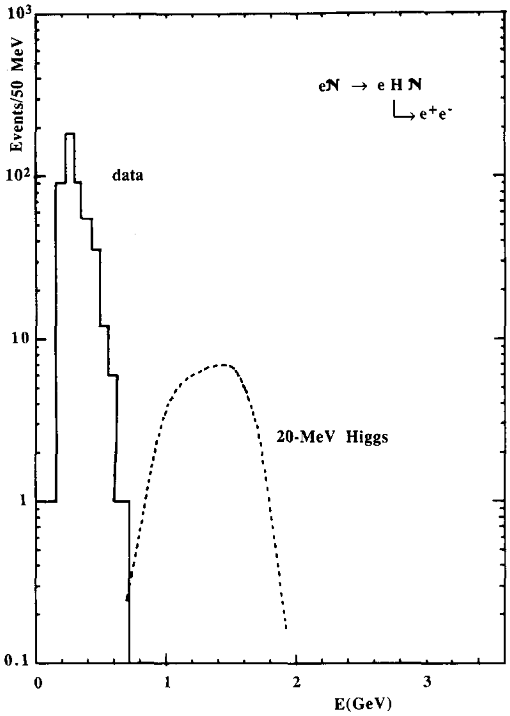

Fig. 3. The experimental energy spectrum in the lead-glass calorimeter obtained in the data-taking with the 1 m long dump configuration above a threshold of 250 MeV. The observed background rate falls off and no event is observed above 750 MeV. The dashed line indicates the expected yield from a 20 MeV Higgs boson in the same experimental conditions.

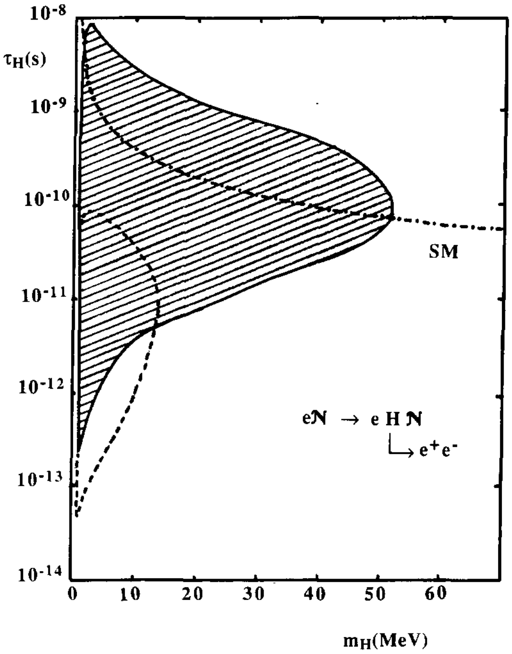

Fig. 4. The 90% CL excluded domain for the production of scalar (or pseudoscalar) particles of mass m_H and lifetime τ_H. Also shown with a dashed boundary is the region excluded by our previous experiment [15] with a short beam-dump. The expected lifetime for a standard Higgs boson of mass m_H is given (SM).

detection. As an example, at 50 MeV, the overall efficiency has fallen to 11%. At any rate, the efficiency remains rather high and it is well understood by a few simple geometrical factors. As an illustration of the expected signal, we show in fig. 3 the energy spectrum which would be associated with the production of a 20 MeV Higgs boson: if that were the case, about 80 events would have been observed in this experiment above our energy cuts where we in fact observe none.

The null signal from our search can be translated into an excluded mass region: a standard Higgs boson is ruled out by our experiment from 1.2 MeV to 52 MeV at 90% confidence level. More generally any scalar particles coupled to the electron can be excluded in a domain of their mass–lifetime space. The result is shown in fig. 4, demonstrating that the experiment was maximally efficient for detecting the standard Higgs boson. The same limits apply to pseudoscalar particles. Fig. 4 also recalls our earlier results from an experiment [16] designed to look for axions and using a short beam-dump with electrons. Although this latter experiment had a much smaller acceptance its sensitivity to smaller lifetimes permit us to extend the excluded region.

The minimal supersymmetric extension of the standard model [17] requires two doublets of Higgs fields with vacuum expectation values v_1 and v_2. After electroweak symmetry breaking, there remains two charged scalars $H^{\pm}$, two neutral scalars H_1^0 and H_2^0, and one neutral pseudoscalar h^0. Two parameters are needed to describe this system; α, a mixing angle from the diagonalisation of the $H_{1,2}^0$ mass matrix and

$$\tan\beta = \frac{v_2}{v_1} = x .$$

In this model, the $H^{\pm}$ and H_1^0 bosons are heavier than the W, Z bosons and H_2^0 and h^0 can be light. In the case where they are very light, one has $\alpha \sim -\beta$ and H_2^0 behaves as a standard Higgs with a coupling to electrons modified as

$$g_{H_2^0 e\bar{e}} = xm\sqrt{G_F\sqrt{2}}\ .$$

The same coupling in fact describes the he$\bar{\text{e}}$ interaction (times a γ^5 matrix).

We have analysed our results in this scenario. For $x<1$, Higgs bosons would be less produced but detected more efficiently as they would decay slowly. For larger x values which are generally by the seemingly large mass of the top quark, they are copiously produced but they tend to decay too fast. The experiment finally excludes a domain of masses for x values between 0.4 and 100 (fig. 5) with maximum sensitivity near $x=1$ as pointed out before. Again this diagram applies to both H_2^0 and h^0 when produced independently of each other as expected.

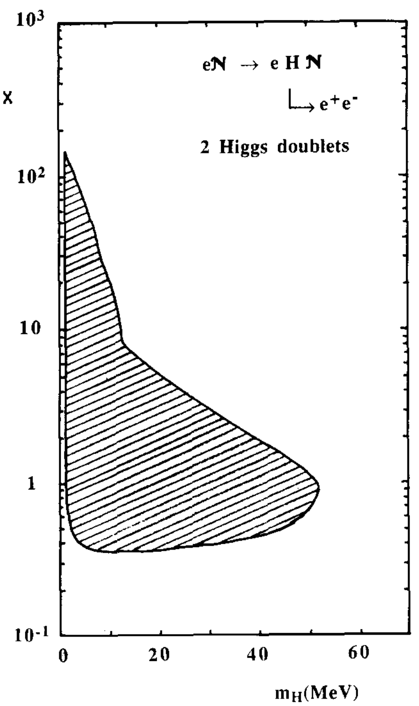

Fig. 5. The 90% CL excluded mass domain for scalar and pseudoscalar Higgs bosons in the supersymmetric minimal extension of the standard model. In this case, x is equal to the ratio of the vacuum expectation values of the two Higgs fields.

5. Conclusions

A very simple beam-dump experiment was designed to look for light Higgs bosons. The sensitivity of the method together with the fact that bremsstrahlung from electrons is a well controlled and calculable process only dependent on the existence of the coupling of Higgs to electrons, enabled us to exclude in a definitive way the mass range from 1.2 to 52 MeV for a standard Higgs.

We have also considered the supersymmetry-inspired minimal extension of the standard model and we have excluded a significant domain of masses and couplings for light scalar and pseudoscalar Higgs bosons. To our knowledge, these are the first results to constrain such models, for admittedly low, yet possible masses.

Acknowledgement

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References

[1] For a recent analysis of experimental data for testing the electroweak standard model, see U. Amaldi et al., Phys. Rev. D 36 (1987) 1385.

[2] M. Veltman, Acta Phys. Polon. B 8 (1977) 475;
B.W. Lee, C. Quigg and G.B. Thacker, Phys. Rev. Lett. 38 (1977) 883; Phys. Rev. D 16 (1977) 1519.

[3] H. Baer et al., in: Physics at LEP, CERN report CERN 86-02 (February 1986).

[4] R. Barbieri and T.E.O. Ericson, Phys. Lett. B 57 (1975) 270.

[5] I. Beltrami et al., Nucl. Phys. A 451 (1986) 679.

[6] D. Kohler, B. Watson and J. Becker, Phys. Rev. Lett. 33 (1974) 1628;
N.C. Mukhopadhyay, P.F.A. Goudsmit and A. Barroso, Phys. Rev. D 29 (1984) 565;
S.J. Freedman et al., Phys. Rev. Lett. 52 (1984) 240.

[7] P. Franzini et al., Phys. Rev. D 35 (1987) 2883;
J. Lee-Franzini, Les Rencontres de Physique de la Vallée d'Aoste (La Thuile, 1988).
[8] M.S. Alam et al., preprint CLNS 89/888 CLEO 89-4 (February 1989).
[9] N. Baker et al., Phys. Rev. Lett. 59 (1987) 2832;
T. Yamazaki et al., Phys. Rev. Lett. 52 (1984) 1089;
NA31 Collab., H. Burkhardt et al., presented at the Rencontres de Moriond (March 1989).
[10] S. Raby, G.B. West and C.M. Hoffman, Phys. Rev. D 39 (1989) 828.
[11] SINDRUM Collab., S. Egli et al., PSI preprint PR 89-02 (March 1989).
[12] S. Dawson, Phys. Lett. B 222 (1989) 143.
[13] L. Resnick, M.K. Sundaresan and P.J.S. Watson, Phys. Rev. D 8 (1973) 172.
[14] Y.S. Tsai, Phys. Rev. D 34 (1986) 1326.
[15] A.R. Zhitnitskii and Y.I. Skovpen, Sov. J. Nucl. Phys. 29 (1979) 513.
[16] M. Davier, J. Jeanjean and H. Nguyen Ngoc, Phys. Lett. B 180 (1986) 295.
[17] For a recent review see J.F. Gunion et al., preprint UCD 89-4 (June 1989).