Search for a Light Scalar Boson Emitted in Nuclear Decay

S. J. Freedman and J. Napolitano
Argonne National Laboratory, Argonne, Illinois 60439

and

J. Camp and M. Kroupa
University of Chicago, Chicago, Illinois 60637, and Argonne National Laboratory, Argonne, Illinois 60439
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The possibility that a scalar boson is sometimes emitted in the decay of ^{4}He(20.1 MeV, 0^+) is examined experimentally. Finding no positive evidence the authors exclude scalars with Higgs-like couplings for $3 \lesssim m_\varphi \lesssim 14$ MeV/c^2, where the precise range depends upon the model.

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One exciting aspect of gauge theories is the notion that new scalar bosons may await experimental discovery.[1,2] For example, the standard model of electroweak interactions requires a new neutral scalar, the Higgs boson. Simple assumptions imply a heavy scalar, $m_\varphi \geq 6-7$ GeV/c^2,[3] but complications could spoil the bound. Moreover, scalars seem ubiquitous in gauge theories and it is prudent to search for them regardless of mass.[2]

An early suggestion of a light scalar was based on anomalous muonic x-ray shifts.[3,4] Resnick *et al.*[5] argued that the relative shifts of Ba $4f$-$3d$ and Pb $5g$-$4f$ could be accounted for by a force mediated by a scalar with mass in the range $0 \lesssim m_\varphi \lesssim 22$ MeV/c^2 and Higgs-like couplings. This possibility motivated Kohler *et al.*[6] to search directly in the decays ^{16}O(6.05 MeV, 0^+) $\rightarrow$ ^{16}O(g.s., 0^+) + φ and ^{4}He(20.1 MeV, 0^+) $\rightarrow$ ^{4}He(g.s., 0^+) + φ. The evidence for x-ray anomalies has not held up[7] but Kohler *et al.* are generally credited with excluding Higgs-like scalars with $1.030 \leq m_\varphi \leq 18.2$ MeV/c^2.[2] Recently, however, Barroso *et al.*[8] noted that while the ^{16}O experiment provides stringent limits in the range $1.03 \lesssim m_\varphi \lesssim 5.84$ MeV/c^2, the ^{4}He experiment was incorrectly interpreted and actually too insensitive to be useful. In fact, we find that the experiment was two orders of magnitude too insensitive to give limits on particles like the Higgs boson. To clarify this issue we conducted a much more sensitive search in ^{4}He(20.1 MeV, 0^+) decay.

Helium-4 in the first excited 0^+ level $E_x = 20.1 \pm 0.05$ MeV [9] is produced by proton capture on tritium. Any produced Higgs-like scalars with mass above 1.022 MeV should decay primarily to e^+e^- with a lifetime on the order of nanoseconds. We attempt to detect $\varphi \rightarrow e^+e^-$ with a well shielded NaI detector in which the signal approximates that of a 20-MeV γ ray. Higgs-like scalars should be semiweakly interacting and, unlike direct-capture photons, able to penetrate thick shielding material. In this Letter we describe the experiment and we compare the results to available theory.

Figure 1 shows the experimental arrangement. A 600-keV proton beam from the Argonne National Laboratory Dynamitron bombards a tritium target. The target is ≈ 30 μg/cm^2 tritium implanted in ≈ 1 mg/cm^2 erbium deposited over a 5-cm circle inside a tantalum "wobbler-target cup." The wobbler spreads the irradiation on the perimeter of a 4-cm circle mitigating tritium loss from excessive heating. With the wobbler an average power dissipation of $\lesssim 70$ W can be tolerated. The maximum obtainable beam current is 100–120 μA and the beam is pulsed on and off during alternate 100-msec periods. The prin-

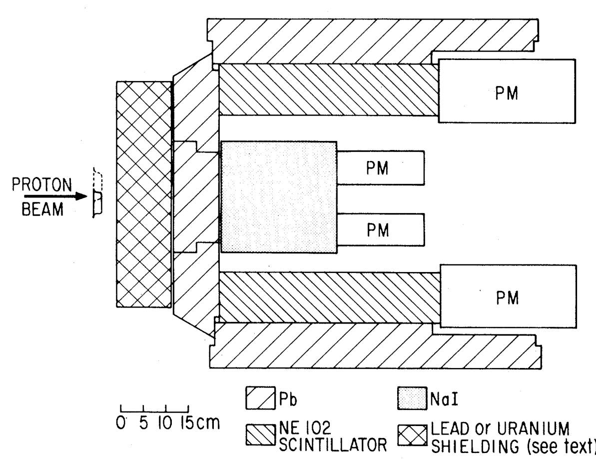

FIG. 1. Schematic diagram of the apparatus.

cipal background is cosmic rays so that pulsing provides the best duty cycle consistent with available beam and target stability. The cosmic-ray background is monitored during beam-off periods.

The detector is a 25×25-cm NaI(Tl) crystal enclosed in a cylindrical 12-cm-thick plastic scintillator anticoincidence counter and 11 cm of lead shielding. A collimated hole in the lead shielding is usually plugged with lead. Data are obtained in two slightly different configurations. In run 1 the target is 30 cm from the NaI and the target shielding is 11 cm of lead and 7.5 cm of depleted uranium, giving an attenuation of $\sim 4\times10^{-8}$ for a 20-MeV photopeak.[10] 12.8 C of protons are accumulated. In run 2 the target to detector distance is 25 cm and there is 22 cm of lead, giving an attenuation of $\sim 1\times10^{-7}$.[10] In run 2, 11.5 C are accumulated. The direct-capture γ-ray angular distribution is nearly $\sin^2\theta$,[11] and thus the detector is at $0°$ to minimize the incident photon flux.

Figure 2(a) is the capture γ-ray spectrum obtained by removing the target shielding. Spectra like Fig. 2(a) are used to monitor the NaI detector and the target. The γ-ray yield, typically 0.9 count/μC, determines the product of the target thickness and γ-ray detection efficiency when combined with the known direct-capture differential cross section.[11] Since 20-MeV γ rays in NaI interact mostly by pair production, Fig. 2(a) is similar to that expected for scalar $\varphi \to e^+e^-$.

Figures 2(b) and 2(c) are the spectra from the two runs. The cosmic-ray background spectra are shown as histograms. The unvetoed cosmic-ray rate is ≈ 20 (MeV h)$^{-1}$ at 20 MeV. There is no evidence for a "photopeak" at 20 MeV—the signal for scalar decay—in either run with shielding. The excess of counts above background at energies below 20 MeV is from degraded showers caused by capture γ rays. The enhancement in this background in run 2 relative to run 1 is expected; the solid angle is larger and there is less shielding. To obtain a limit we fitted with a smooth function plus a peak which is simply the observed capture γ-ray spectrum times a constant.[12] The largest acceptable peaks at the 2σ level are shown in Figs. 2(b) and 2(c).

The number of scalars detected per microcoulomb of accumulated charge is given by the expression $N_\varphi = n_b\langle\sigma\rangle n_T \epsilon_\gamma BP$, where $n_b = 6.25\times10^{12}$ is the number of protons per microcoulomb, $\langle\sigma\rangle$ is the known excitation cross section[13] averaged over the proton energy loss in the implanted target (we find $\langle\sigma\rangle \approx 2.8$ b), n_T is the number of tritium nuclei per unit area, and ϵ_γ is the photopeak

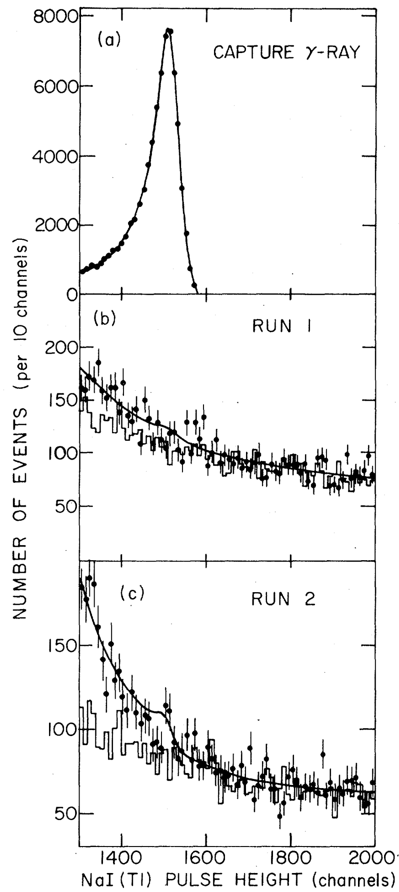

FIG. 2. γ-ray spectra in the region above ≈ 17 MeV. (a) A spectrum of ≈ 20-MeV capture γ rays with the collimator plug and target shielding removed. (b) The spectrum from run 1. The histogram is the cosmic-ray background counted for equal time. The curve is a fit with a smooth background plus the largest peak with the same shape as spectrum (a) that is acceptable at the 2σ level. (c) The spectra from run 2.

efficiency for a 20-MeV photon. We determine the product $n_T\epsilon_\gamma$ directly as noted above; we obtain $n_T\epsilon_\gamma \approx 1.0\times10^{18}$. The branching ratio for scalar decay, $B=\Gamma_\varphi/\Gamma$, and P, the probability that an emitted scalar decays inside the NaI, are discussed in more detail below.

The 2σ upper limits for N_φ are $N_\varphi \leq 4.7\times10^{-6}/\mu$C from run 1, and $N_\varphi \leq 1.1\times10^{-5}/\mu$C from run 2. The experimental limit on N_φ can be directly interpreted as a bound on the product BP. Instead, we chose to determine P for a given φ lifetime and mass and express our results as a limit on combinations of B and η. P depends on the effective solid angle and the experimental geometry as well as η. For $\eta \approx 5\times10^{-10}$ sec corresponding to $m_\varphi \approx 12$ MeV/c^2, we get $P \approx 5\times10^{-3}$

for the run with 25 cm between target and detector. Figure 3 shows the region in the B-η plane excluded at 2σ by the combined results of runs 1 and 2. The limits from Kohler *et al.*[6] in Fig. 3 are recalculated with use of Ref. 6 and the above procedure. The relevant input values are $N_\varphi \leq 3 \times 10^{-3}/\mu\text{C}$ (2σ), $\langle\sigma\rangle \approx 3.6$ b, $n_T = 3\times 10^{18}$, and $\epsilon_\gamma = 29\%$. For $m_\varphi = 12\ \text{MeV}/c^2$ we obtain $P \approx 0.01$ for the geometry in Ref. 6. The improvement in this work is due primarily to significantly better background rejection and much more accumulated charge.

The quantities B and τ depend on the scalar-nucleon and scalar-electron coupling constants $g_{\varphi N\bar{N}}$ and $g_{\varphi e\bar{e}}$, respectively. The expression for τ is straightforward to obtain,[5]

$$\frac{1}{\tau} = \frac{g_{\varphi e\bar{e}}^{\ 2}}{4\pi}\frac{m_\varphi}{2}\left(1 - \frac{4m_e^{\ 2}}{m_\varphi^{\ 2}}\right)^{3/2},$$

and for the simplest model of the Higgs boson (the Weinberg model)

$$g_{\varphi e\bar{e}}^{\ 2}/4\pi = (1/2\pi)m_e^{\ 2}G_{\text{F}}/\sqrt{2} \approx 3\times 10^{-13},$$

where G_{F} is the Fermi constant.

The expression for φ emission in $0^+ \to 0^+$ transitions in a nucleus with mass number A and charge Z was obtained by Resnick *et al.*,[5]

$$\Gamma_\varphi = \frac{g_{\varphi N\bar{N}}^{\ 2}}{16\pi}\left(\frac{A}{Z}\right)^2\frac{R^4}{18}\frac{m_N q^5}{(q^2+m_\varphi^{\ 2})^{1/2} + (q^2+m_N^{\ 2})^{1/2}},$$

where we use $q^2 \approx E^2 - m_\varphi^{\ 2}$. R is the electromagnetic "transition radius" which also determines the probability of pair decay, $\Gamma_{e^+e^-} = (\alpha^2/135\pi)R^4 \times E^5$.

The experimental value of $\Gamma_{e^+e^-} = (1.1 \pm 0.03)\times 10^{-3}$ eV[15] and the total width $\Gamma = 0.270 \pm 0.050$ MeV[16] allow us to determine $B = \Gamma_\varphi/\Gamma$ up to a factor of $g_{\varphi N\bar{N}}^{\ 2}$.

Resnick *et al.*[5] obtain an estimate for $g_{\varphi N\bar{N}}$ assuming that scalars explain the muonic x-ray anomaly; they obtain $g_{\varphi N\bar{N}} = 2.3\times 10^{-7}e^{0.26 m_\varphi}$.

Shifman *et al.*[14] calculated $g_{\varphi N\bar{N}}$ more directly. They find that the main contributions to $g_{\varphi N\bar{N}}$ are from heavy quarks, obtaining $g_{\varphi N\bar{N}} = n_h 2^{1/4}G_{\text{F}}^{\ 1/2}$ (70 MeV), where n_h is the number of "heavy" quarks. Taking the s quark as heavy and anticipating the discovery of the t quark, we use $n_h = 4$.

The predictions for B and η are shown in Fig. 3. The uncertainty in the theoretical predictions from the experimental input is about $\pm 40\%$. Thus we contradict expectations based on Resnick *et al.* in the range $4.5 \lesssim m_\varphi \lesssim 14.1\ \text{MeV}/c^2$ and Shifman *et al.* (with $n_h = 4$) in the range $2.8 \lesssim m_\varphi \lesssim 11.5\ \text{MeV}/c^2$. As previously noted, the mass region

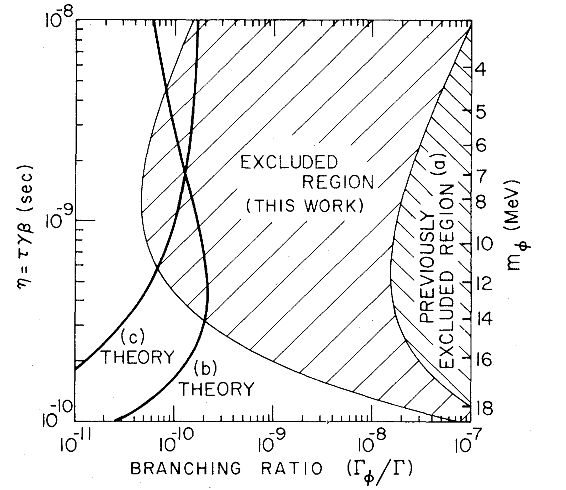

FIG. 3. The experimentally excluded region (at the 2σ level) in the lifetime–branching-ratio plane. The previously excluded region (*a*) (at the 2σ level) from Kohler *et al.* is calculated by our procedure (see text) with information in Ref. 6. The theoretical prediction (*b*) is from Ref. 5 and (*c*) is from Ref. 14 (if we assume four heavy quarks). The right-hand scale for m_φ refers to theories in which the φ coupling to e^+e^- is mass dependent in the standard fashion.

$1.03 \lesssim m_\varphi \lesssim 5.8\ \text{MeV}/c^2$ is already excluded by Kohler *et al.*[6]

Other limits on light Higgs-like scalars have been obtained from neutron-nucleus[17] scattering and exotic decays of the K[18] and the η.[19] From the decay $K^\pm \to \pi^\pm e^+e^-$, Willey and Yu[18] claim a limit $m_\varphi \gtrsim 325\ \text{MeV}/c^2$ subject, however, to controversial theoretical interpretation. Without a good way to access the reliability of estimates of scalar couplings to different hadrons it is difficult to compare limits from searches with different systems. However, $0^+ \to 0^+$ nuclear decay is possibly the most direct way to find very light Higgs-like scalars.

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