ing towards the beam. Therefore, the angular distribution of the spectator proton becomes slightly forward peaked. A more detailed discussion is given in Ref. 2.

[4] N. W. Dean, Phys. Rev. D 5, 1661 (1972).

[5] C. Richard-Serre *et al.*, Nucl. Phys. B20, 413 (1970).

[6] N. W. Dean, Phys. Rev. D 7, 3349 (1973).

[7] H. P. Durr and H. Pilkuhn, Nuovo Cimento 40A, 899 (1965).

[8] T. G. Trippe *et al.*, Phys. Lett. 28B, 203 (1968); P. E. Schlein, in Meson Spectroscopy, edited by C. Baltay and A. H. Rosenfeld (Benjamin, New York, 1968), p. 161.

Experimental Search for a Low-Mass Scalar Boson*

D. Kohler, B. A. Watson, and J. A. Becker
Lockheed Palo Alto Research Laboratory, Palo Alto, California 94304

(Received 15 October 1974)

Two experiments are reported in which a search was made for the scalar boson predicted to be produced in the ^{16}O(6.05 MeV) to ground state and ^{4}He(20.2 MeV) to ground state 0^+ to 0^+ transitions with subsequent in-flight decay into electron-positron pairs. Taken together, our results show that the light scalar boson proposed by Sundaresan and Watson to account for certain muonic x-ray energy discrepancies cannot have a mass in the range $1.030 \leq m \leq 18.2$ MeV.

One of the characteristic features of the currently developing unified gauge theories of electromagnetic and weak interactions is the prediction of the existence of, as yet, undiscovered particles. The new particles predicted by these gauge theories are typically very massive (many GeV/c^2) and, hence, are expected to be very difficult to observe. Almost all of these theories, in particular the prototype Weinberg-Salam theory,[1] require the existence of a scalar particle, φ (the Higgs scalar), with well-defined coupling constants for the lepton-scalar interaction but unfortunately with a completely unspecified mass. For the φ, however, it has been pointed out[1-4] that even a very low mass cannot be excluded by observations to date. In fact, experimental evidence suggestive of a low-mass scalar particle has been accumulated in muonic x-ray studies. Dixit *et al.*,[5] and also Walter *et al.*,[6] have found certain discrepancies between measured and theoretically calculated muonic x-ray energies in several transitions among high-Z elements. Sundaresan and Watson[4] and Resnick, Sundaresan, and Watson[3] have shown that these discrepancies can be removed by assuming the φ particle with coupling constants consistent with the Weinberg-Salam theory and with $m_\varphi \leq 22$ MeV. Resnick, Sundaresan, and Watson[3] suggest several experimental possibilities for production and study of these hypothetical particles. Among these, one promising approach follows from the relatively large branching ratios expected for the production of the scalar particle in 0^+ to 0^+ nuclear decays; for example the decay of the ^{16}O(6.05 MeV) 0^+ excited state would have a φ branching ratio up to a few percent if m_φ was not too close to the 6.05-MeV production threshold.

Based on these considerations a search for the φ branching mode in the decay of the ^{16}O 6.05-MeV level was carried out with negative results. Since the upper bound for m_φ was limited by $E_x(^{16}\mathrm{O})$, the investigation was extended to a search for φ production in the decay of the ^{4}He 20.2-MeV level, again with negative results. Thus, almost the entire mass region for m_φ suggested from the muonic x-ray anomalies[3,4] is now excluded. Details of the experiment are given below.

The experiment on the ^{16}O(6.05 MeV) state will be described first. The φ should, according to the Weinberg theory, decay via the weak interaction into an electron-positron pair provided that $m_\varphi \geq 1.022$ MeV. The lifetime[3] for the decay ranges from approximately 0.7 nsec near $m_\varphi = 6.05$ MeV to many microseconds near $m_\varphi = 1.022$ MeV (below 1.022 MeV only the two-photon decay mode is available with a lifetime expected[3] to be $\gtrsim 10^{-4}$ sec). Since the particle possesses only the weak interactions, it would readily penetrate[3] matter much as does the neutrino. A heavily shielded scintillation detector placed near a target in which the ^{16}O(6.05 MeV) state is produced should suffice to detect φ's which decayed within the volume of the detector; the signal from such a decay would approximate that of a 6.05-MeV γ ray.

The ^{16}O 6.05-MeV state was produced in the reaction $^{19}F(p,\alpha)^{16}O(6.05\ MeV)$ at $E_p = 1.90$ MeV, thus taking advantage of a resonance in the production cross section[7] for the 6.05-MeV state. The target was a layer of CaF_2 0.45 mg/cm^2 thick evaporated onto a thick Ta backing. The detector, an 8.3-cm-diam by 21.0-cm-long cylinder of NE 102, was placed at 90° to the proton beam direction with its front face located 28.3 cm from the reaction site. An absorber composed of 20.3 cm of lead and 5.1 cm of Mallory metal was interposed between target and detector to remove γ rays produced in other reactions, particularly the decay of the ^{16}O 6.13-MeV level. Long runs with a proton beam current of typically 0.5 μA were taken to accumulate spectra from both the CaF_2 target and the reverse side of the target. The principal signal in either case was due to cosmic-ray muons. Spectra corresponding to a total charge of 4.17×10^4 μC on the CaF_2 target were collected with a total running time of 19 h; the background spectrum was accumulated over 10 h. The background spectrum was subtracted from the $^{19}F+p$ spectrum after normalization at the broad high-energy muon peak ($E\sim15$ MeV). Integrated over the region of the spectrum covering the expected peak due to a scalar particle the resulting difference was -61 ± 130 counts (statistical error only). The response function was assumed to be approximately that observed for 6-MeV γ rays, which approximation should be quite adequate for the purpose of the present effort. An upper limit (1σ) of 3.1×10^{-3} count/μC was obtained within a window covering the peak of the response function which included an estimated 40% of the total response-function area. A nominal correction of 1×10^{-4} count/μC due to residual γ-ray leakage, estimated from the runs at reduced absorber thickness and assuming the measured attenuation coefficient of the absorber, was not applied to the above yield since the nominal difference is already a negative quantity and must be bounded below by zero. The final result for the total φ yield, corrected for the peak-to-total ratio, is a 1σ upper limit of 7.8×10^{-3} count/μC.

This last result is compared in Fig. 1 with the theoretical estimate of the yield as a function of m_φ normalized to the present experimental conditions, i.e., the curve represents the total number of φ decays within the detector volume per microcoulomb of protons. The mass dependence of the decay rate and the time dilation of the decay constant were both taken into account. For the calculation it was assumed that the 6.05-MeV state is produced with an average 30-mb cross section[7] throughout a 50-keV-thick target centered on the peak of a resonance at 1.88 MeV. The φ-production branching ratio and the particle lifetime were taken from Resnick, Sundaresan, and Watson.[3] The observed upper limit of 7.8×10^{-3} count/μC (1σ) is displayed as a horizontal line with hatching. The intersection of the upper-limit line and the theoretical yield curve establishes that the proposed particle cannot have a mass within the range $1.030 \leq m_\varphi \leq 5.84$ MeV.

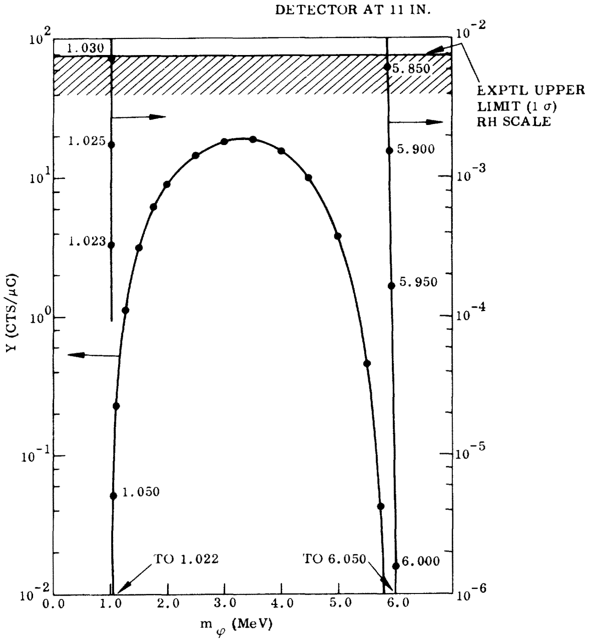

FIG. 1. Theoretical yield (counts/μC of proton beam) of detected φ's from the reaction $^{19}F(p,\alpha)^{16}O(6.05\ MeV) \rightarrow {}^{16}O(g.s.) + \varphi$ versus assumed m_φ. (Note the separate parts of the yield curve and corresponding scales.) Also shown is the measured upper limit to the yield of detected φ's as a horizontal line with hatching crossing the lower wings of the yield curve (right-hand scale only).

A second experiment of the same nature was performed making use of the ^3H+p reaction at the $E_p = 515$-keV resonance to populate the first 0^+ excited state at 20.2 MeV in the ^{4}He nucleus.[8] For increased detector efficiency and to absorb the full range of decay electrons, a 12.7-cm $\times$15.2-cm NaI(Tl) scintillation detector was used rather than the NE 102 scintillator described above. The detector was placed at 0° with respect to the proton beam so as to minimize the flux of γ rays from the reaction $^3H(p,\gamma)$ (these

γ rays have a nearly pure $\sin^2\theta$ angular distribution at low proton energies[8]). The γ-ray absorber thickness used for the final data runs was 5.08 cm of Mallory metal plus 5.08 cm of lead which allowed a target-to-detector front-face separation of 11.4 cm. A proton beam energy of 600 keV was used together with a tritiated titanium target with a tritium thickness of $0.031^{+0.03}_{-0.015}$ mg/cm^2. A target wobbler was employed to permit beam currents up to ~6–7 μA without significant target degradation. After several hours running time a total beam charge of 0.287 C was accumulated. A comparable run to accmulate a cosmic-ray background spectrum (the only apparent contribution to the spectrum in the 20-MeV range) was carried out. The resultant spectrum was subtracted from that of the scalar-particle run after normalization of the two spectra at the cosmic-ray muon peak. The difference in the two spectra was ~0 with a standard deviation of about 122 counts over 75 channels covering the peak of the expected response function which, for these purposes, is assumed to be the same as that observed for a 20-MeV γ ray. The 75 channels represent about 29% of the total response-function area so that the standard deviation over the full response function is 421 counts. This result then corresponds to a 1σ upper limit of 1.5×10^{-3} count/μC.

The theoretical yield function with which this result should be compared is shown in Fig. 2. The function was constructed by using the decay width Γ_φ and coupling constants given by Resnick, Sundaresan, and Watson.[3] A total width Γ_p of 0.340 MeV[8] at resonance was assumed for the 20.2-MeV state in ^{4}He. The reaction kinematics was approximated by that appropriate to the reaction at resonance only for computing the velocity of the φ and the resultant decay length. The yield was calculated by assuming the nominal target thickness given previously and a Lorentzian resonance shape. Effects of the finite resonance width on the kinematics of the φ production, significant only near the upper mass limit of our experiment, were not taken into account but are of such a nature that the theoretical curve is underestimated so that upper limits on m_φ are simply more conservative than they would otherwise be. Full integration of the φ decay probability over the detector volume was carried out as before. The experimental upper limit previously presented,[9] but raised by a factor of 2 to account for the target-thickness uncertainty, is shown by the hatched horizontal line in Fig. 2.

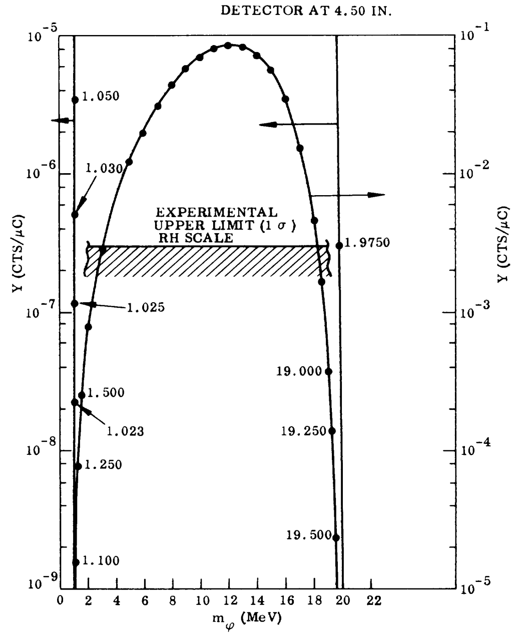

FIG. 2. Theoretical yield (counts/μC of proton beam) of detected φ's from the reaction $^3\mathrm{H}(p)^4\mathrm{He}(20.2\text{ MeV}) \rightarrow {}^4\mathrm{He}(\text{g.s.}) + \varphi$ versus assumed m_φ. (Note the separate parts of the yield curve and corresponding scales.) Also shown is the measured upper limit to the yield of detected φ's as a horizontal line with hatching crossing the central portion of the yield curve (right-hand scale only).

The result is that m_φ within the range $3.10 \leq m_\varphi \leq 18.2$ MeV can be excluded.

These two experiments taken together then show that the scalar particle of Sundaresan and Watson,[4] if it exists at all, cannot have a mass in the range $1.030\text{ MeV} \leq m_\varphi \leq 18.2$ MeV. The total range of masses judged acceptable by Resnick, Sundaresan, and Watson[3] was $0 \leq m_\varphi \leq 22$ MeV (masses $\leq 10^{-4}$ eV could already be excluded by an argument[3] relating to measurements of the gravitional constant, G). Thus the major portion of the total proposed mass range can now be excluded, suggesting a relatively low probability for the correctness of the Sundaresan and Watson proposal. This observation should perhaps be tempered by the realization that there are ~10 orders of magnitude between the 1-MeV upper limit from this work and the 10^{-4}-eV limit from the gravitational-constant measurements.

The experiments here could be improved in several respects. However, the mass limits that might be achieved would at best be only ≈1.022 MeV and ≈19.5–19.75 MeV, i.e., little better than those already found. Other reaction possibilities, however, might enable the lower mass limit to be pushed past the 22-MeV figure. There is a probable (0^+, $T=0$) structure[10] at approximately 24.0 MeV in ^{8}Be which could be reached, e.g., by ^{6}Li$+d$, $Q=22.28$ MeV.[10] Whether or not the resonance parameters are such as to permit a feasible scalar-particle search is not clear. There may well be suitable 0^+ structures in the energy-level scheme of ^{12}C though the relevant information is not yet available. For instance structures[11] at 26.9 MeV and 28.46 MeV in the ^{12}C nucleus are suggestive of 0^+ though certainly not established. Use of the reaction ^{9}Be$+^3$He, $Q=26.28$ MeV,[11] would seem to provide a reasonable approach provided a suitable state in ^{12}C can be found. (It should be noted that any J^π to J^π transition might be a suitable candidate since particle decay widths will dominate for the decay of such high-lying states anyway.) Finally it should be noted that ^{16}O might have suitable high-lying 0^+ states which could be reached, for instance, with the ^{13}C$+^3$He reaction, $Q=22.79$ MeV,[12] though the first two possibilities mentioned above would seem more likely to be useful.

The authors wish to acknowledge the helpful suggestions and encouragement given by Dr. L. F. Chase and Dr. R. E. McDonald.

---

*Research supported by the Lockheed Independent Research Fund.

[1] S. Weinberg, Phys. Rev. Lett. 27, 1688 (1971).

[2] R. Jakiw and S. Weinberg, Phys. Rev. D 5, 2396 (1972).

[3] L. Resnick, M. K. Sundaresan, and P. J. S. Watson, Phys. Rev. D 8, 172 (1973).

[4] M. K. Sundaresan and P. J. S. Watson, Phys. Rev. Lett. 29, 15 (1972).

[5] M. Dixit *et al.*, Phys. Rev. Lett. 27, 878 (1971).

[6] H. K. Walter *et al.*, Phys. Lett. 40B, 197 (1972).

[7] F. Ajzenberg-Selove, Nucl. Phys. A190, 1 (1972).

[8] W. E. Meyerhof and T. A. Tombrello, Nucl. Phys. A109, 1 (1968).

[9] D. Kohler, J. A. Becker, and B. A. Watson, Bull. Amer. Phys. Soc. 19, 514 (1974).

[10] T. Lauritsen and F. Ajzenberg-Selove, Nucl. Phys. 78, 1 (1966).

[11] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. A114, 1 (1968).

[12] F. Ajzenberg-Selove, Nucl. Phys. A166, 1 (1971).

Observation of Charge-Independence-Violating Effects in $\bar{p}d$ Annihilations at Rest*

T. E. Kalogeropoulos
Department of Physics, Syracuse University, Syracuse, New York 13210, and Nuclear Research Center Demokritos, Aghia Paraskevi, Attikis, Athens, Greece

and

T. A. Fillipas, G. Grammatikakis, Th. Papadopoulou, E. Simopoulou, and A. Vayaki
Nuclear Research Center Demokritos, Aghia Paraskevi, Attikis, Athens, Greece

and

L. Gray, J. Roy, and G. Tzanakos
Department of Physics, Syracuse University, Syracuse, New York 13210

(Received 26 September 1974)

For $\bar{p}d$ annihilations at rest, charge independence and energy conservation imply that the average energy going to charged pions is $\langle E_\pm \rangle = 1241 \pm 2$ MeV per annihilation. Experimentally this number is found to be 1169 ± 10 MeV after corrections for events with invisible $K^0\bar{K}^0$. This discrepancy of 72 ± 10 MeV cannot be accounted for by the known η and ω production which is estimated to contribute $\sim 14 \pm 3$ MeV.

Studies of antiproton annihilations in hydrogen and deuterium at rest and low energies have revealed many unusual phenomena suggestive of narrow $\bar{N}N$ bound and resonant states.[1] If such states do exist electromagnetic effects might be unusually large, leading to a measurable violation of charge independence in these reactions. A test of charge independence in $\bar{N}N$ reactions, apart from testing the general principle, would also throw some light on the nature of these nar-