Is There a Light Scalar Boson?

L. Resnick, M. K. Sundaresan, and P. J. S. Watson
Department of Physics, Carleton University, Ottawa, Canada
(Received 28 July 1972; revised manuscript received 2 January 1973)

In view of recent theoretical interest in the possibility of a light scalar boson ϕ we discuss some of its properties and possible methods for detecting it. Cross sections for its production are typically 10^{-8} of competing processes, with the possible exception of $0^+ \to 0^+$ transitions in nuclei. We also give a general method of determining the mass of a particle from the energy of its decay products alone, which does not seem to be well known.

I. INTRODUCTION

Interest in the unified model of weak and electromagnetic interactions of Weinberg[1] has been recently aroused by a number of theoretical developments.[2-6] Among the requirements of the model is the existence of a scalar boson, coupling to muons and electrons, whose mass is not predicted by the theory. Two of the present authors[7] have recently shown that the discrepancy between the theoretical predictions and the experimental values of certain muonic x-ray transitions can be explained if a light scalar meson exists, with an effective coupling of about that of the weak interactions.[8]

In this paper we amplify the comments made about the ϕ in Ref. 7, and discuss possibilities for observing it. In Sec. II we discuss the mass, couplings, and decay modes of the ϕ; in Sec. III we discuss potential effects on known processes, and in the final Sec. IV various possible experiments are analyzed.

II. PROPERTIES OF THE ϕ

In Ref. 7 an upper limit of 8 MeV was given for the mass of the ϕ, based on the relative shifts in the Ba $4f \to 3d$ and Pb $5g \to 4f$ muonic x-ray transitions. We have now performed a χ^2 analysis on all the data[9,10] and this shows that the previous upper limit was too low. The χ^2 plot shows a broad minimum centered on 8.5 MeV, but any value between 0 and 22 MeV is acceptable. Although it is not possible to put a lower limit on the mass from the muonic data, we can put a very rough limit from other arguments. The mass must clearly be finite, as a massless particle with an effective coupling some 10^{30} times larger than the gravitational coupling would give rise to enormous nonsaturating forces. Macroscopic experiments to measure G find essentially the same result (to within much better than 10%), using experimental designs with widely varying interaction lengths between a centimeter and a kilometer. The potential due to ϕ exchange and gravitation has the form

$$\frac{1}{r}(g_{\phi N\bar{N}}{}^2 e^{-m_\phi r} + G m_p{}^2),$$

and so we require

$$g_{\phi N\bar{N}}{}^2 e^{-m_\phi r}/G m_p{}^2 \lesssim \tfrac{1}{10}$$

when $r \sim 1$ cm. This leads to a very approximate lower limit of 10^{-4} eV.

The value of $g_{\phi\mu\bar{\mu}}\, g_{\phi N\bar{N}}$ required to fit the data[9,10] varies between 4×10^{-6} for $m_\phi = 22$ MeV and 2×10^{-7} for $m_\phi = 0$. If this is accepted at face value and we take

$$g_{\phi\mu\bar{\mu}}{}^2/4\pi = (1/2\pi)(m_\mu{}^2/m_p{}^2)(G_F m_p{}^2/\sqrt{2}) \tag{1}$$

as provided by Weinberg's model, where G_F is the Fermi coupling constant and m_p is the mass of the proton, we find $g_{\phi\mu\bar{\mu}}{}^2/4\pi = 1.3\times10^{-8}$. The value of $g_{\phi N\bar{N}}{}^2/4\pi$ is then dependent on the mass of the ϕ, and we find

$$g_{\phi N\bar{N}}{}^2/4\pi = 1.8\times10^{-8} e^{0.26 m_\phi} \quad (m_\phi \text{ in MeV}) \tag{2}$$

to an accuracy of a few percent in the range $0 < m_\phi < 30$ MeV. We note as a curiosity that if we assume (quite unjustifiably) that the ϕ couples to *all* fermions proportional to their mass, then

$$\frac{g_{\phi N\bar{N}}{}^2}{4\pi} = \frac{G_F m_p{}^2}{2\sqrt{2}\,\pi} = 1.1\times10^{-6},$$

which implies $m_\phi = 16$ MeV, well within the allowed range.

Since the ϕ couples to nucleons it is also necessary that it couple to pions via hadronic loops, but the triangle diagram corresponding to a single nucleon loop is divergent. Thus the coupling constant of ϕ to pions cannot be calculated reliably, and we will assume below that it is negligible. However, it would be very interesting to measure the *pionic* x rays corresponding to the muonic x rays measured by Dixit *et al.* to see if there was any similar anomaly.

The two decay modes available to the ϕ meson are to e^+e^- and to two photons. The former [Fig. 1(a)] is calculated straightforwardly in Weinberg's model and has a probability

$$\Gamma(\phi \to e^+e^-)=\frac{g_{\phi e\bar{e}}{}^2}{4\pi}\frac{m_\phi}{2}[1-(4m_e{}^2/m_\phi{}^2)]^{3/2}. \quad (3)$$

The two-photon decay mode involves the well-known triangle diagram [Figs. 1(b) and 1(c)] that has already been evaluated by Steinberger,[11] Schwinger,[12] and others.[13] We have only included the contributions due to e^+e^- and $\mu^+\mu^-$ intermediate pairs and not included contributions from hadrons [Fig. 1(c)] in the intermediate loop. Using $g_{\phi l\bar{l}} \propto m_l$ $(l = e, \mu)$ in Weinberg's model, we find

$$\Gamma(\phi \to 2\gamma)=\frac{g_{\phi e\bar{e}}{}^2}{4\pi}\left(\frac{e^2}{4\pi}\right)^2\frac{m_\phi}{4\pi^2}\left(\frac{m_\phi}{m_e}\right)^2|I_e+I_\mu|^2,$$
$$I_l=\int_0^1 dx\int_0^{1-x} dy\,(1-4xy)[1-(xy\,m_\phi{}^2/m_l{}^2)]^{-1}. \quad (4)$$

For $m_\phi = 8$ MeV, it turns out that $I_\mu = 0.333+0i$, $I_e = -0.033+0.069i$, and we obtain a branching ratio $\Gamma(\phi\to 2\gamma)/\Gamma(\phi\to e^+e^-)=6.46\times 10^{-5}$. Hadronic contributions may very well give larger effects than the μ,e loops but are difficult to calculate quantitatively. However, it is most unlikely they would make the two-photon mode as large as the e^+e^- mode. For example the effect of the hadronic loop in Fig. 1(c) may be represented as a factor $1+g_{\phi N\bar{N}}m_\mu/g_{\phi\mu\bar{\mu}}m_N \simeq 1.5$ multiplying I_μ, because $I_N/I_\mu \simeq 1$; even then the branching ratio is increased by a factor less than 2. We find for m_ϕ in the range, $1.022 < m_\phi < 30$ MeV, a lifetime of the order of 10^{-9} sec; the path length before decay is several to tens of centimeters. If the mass of the scalar meson m_ϕ is less than $2m_e$, it cannot decay into e^+e^- pair and the only decay mode available is into two photons. Its lifetime is then of the order of 10^{-4} sec and its detection by the usual methods of high-energy experiments would be very difficult.

III. EFFECTS OF A LIGHT ϕ

Clearly the existence of the ϕ will alter the electromagnetic and weak properties of elementary particles, and it might be thought that already existing measurements would be sufficient to rule it out. Perhaps surprisingly, this is not so. For example, Jackiw and Weinberg[4] have calculated its effect on the μ anomalous magnetic moment and found it below the observable level.

There are a number of models in the literature[5] which discuss Weinberg-type models incorporating hadrons. At least one of these requires that m_ϕ be greater than 10 GeV (Refs. 14, 6), and all require the existence of further particles of various kinds. At the present we are therefore inclined to regard the ϕ in a mainly phenomenological manner, with the minimum of additional theoretical ideas which we have taken from Weinberg's original model. It is therefore necessary to ask what restrictions on the interactions of the ϕ can be deduced from known results, in addition to those mentioned above. It would appear necessary that the ϕ couplings conserve strangeness, otherwise we would expect $K^\pm \to \pi^\pm\mu^+\mu^-$ to be roughly competitive with $K\to\pi\mu\nu$ (Fig. 2), but this may be effected by other means. Paschos and Wolfenstein[15] have indicated that Weinberg's original model may already be incompatible with experiments measuring inclusive neutrino cross sections. However, this is due to the presence of a massive neutral vector boson, which induces neutral currents, rather than the ϕ. The coupling of the ϕ to leptons is proportional to the mass of the lepton, and thus it does not couple to neutrinos; hence neutrino interactions are unaffected by it.

An intriguing possibility, however, arises in certain nuclear transitions. As is well known $0^+\to 0^+$ transitions such as those in ^{16}O and ^{214}Po proceed by pair emission (as in ^{16}O) or internal conversion (as in ^{214}Po), and these are of order α^2. However, the ϕ can be emitted by a first-order process, and it appears that the two processes might be competitive. The matrix element

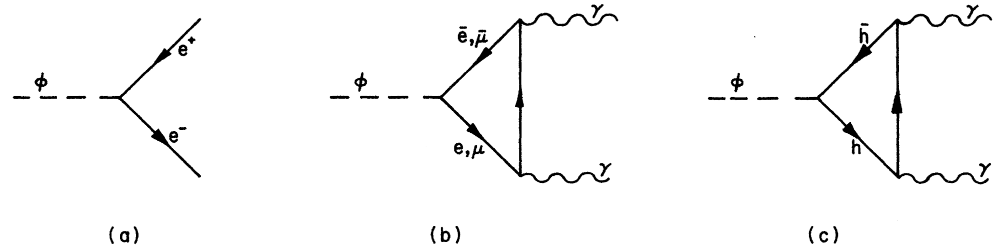

FIG. 1. (a) Decay of ϕ into e^+e^-. (b) Decay of ϕ into 2γ through a lepton triangle. (c) Decay of ϕ into 2γ through a hadron triangle.

for ^{16}O decay by pair emission is (Fig. 3)

$$M=\sum_n e_n \langle \psi_{fn} | e^{i\vec{q}\cdot\vec{r}_n} | \psi_{in}\rangle \frac{1}{|q|^2}\, \bar{u}(p_1)\gamma_0 u(p_2), \quad (5)$$

where e_n and r_n are the charge and position of the nth nucleon, ψ_{in} and ψ_{fn} are the initial and final nuclear wave functions and we have made a nonrelativistic approximation for the nuclear motion, so the photon has become a static field. Defining the electric mean square radius as

$$R^2=\frac{1}{e}\sum_n e_n \langle \psi_{fn} | r_n^2 | \psi_{in}\rangle \quad (6)$$

one obtains a rate for e^+e^- emission as

$$\Gamma_{e^+e^-}=\frac{\alpha^2}{135\pi} R^4 E^5, \quad (7)$$

where we have ignored the electron mass, and E is the energy difference between the initial and final nuclear excitations.[16]

The amplitude for ϕ emission is straightforward to evaluate from the matrix element

$$M=g_{\phi N\bar{N}}\sum_n \langle \psi_{fn} | e^{i\vec{q}\cdot\vec{r}_n} | \psi_{in}\rangle , \quad (8)$$

and we obtain

$$\Gamma_\phi=\frac{g_{\phi N\bar{N}}^2}{16\pi}\left(\frac{A}{Z}\right)^2 \frac{R^4}{18}\, \frac{M_N q^5}{(q^2+m_\phi^2)^{1/2}+(q^2+m_N^2)^{1/2}}, \quad (9)$$

$$q^2\simeq E^2-m_\phi^2,$$

where A and Z are the nuclear mass number and charge. Thus we find for ^{16}O ($A=2Z$)

$$\frac{\Gamma_\phi}{\Gamma_{e^+e^-}}\simeq\frac{15\pi}{2\alpha^2}\left(\frac{g_{\phi N\bar{N}}^2}{4\pi}\right)\left(1-\frac{m_\phi^2}{E^2}\right)^{5/2}, \quad (10)$$

and using (2) this gives values for this transition ranging from 3% for $m_\phi\simeq 0$ to 2% for $m_\phi=4$. Obviously this requires $m_\phi<E$ which is 6.06 MeV for this transition. In Sec. IV we discuss the possibilities of basing an experiment on this effect.

A possible further effect arises in $m_\phi<2m_e$. Assuming the correctness of Weinberg's model, the ϕ couples to e^+e^-, and hence if $m_\phi<2m_e$, it will appear as a peculiar bound state in the positronium spectrum, since its quantum numbers are that of the $^3P_0$ state (essentially it would be a Castillejo-Dalitz-Dyson pole). We would, therefore, expect to see the decay

$$(e^+e^-)_{^3S_1}\to\phi+\gamma.$$

It is important to note that the competing mode is $^3S_1\to 3\gamma$, *not* $e^+e^-\to\gamma\gamma$, which is a factor of 10^3 faster. A straightforward calculation[17] gives

$$\frac{\Gamma_{^3S_1\to\phi\gamma}}{\Gamma_{^3S_1\to 3\gamma}}=\frac{2g_{\phi e\bar{e}}^2}{\alpha^3 4(\pi^2-9)}\left(1-\frac{m_\phi^2}{4m_e^2}\right)^{1/2}, \quad (11)$$

which is approximately 10^{-7} if the phase-space factor is not too small, i.e., m_ϕ is not close to $2m_e$. This must be multiplied by a statistical factor of $\frac{3}{4}$ to give the branching ratio per positronium atom.

IV. EXPERIMENTS

A relevant experiment which is likely to be performed in the near future is high-precision low-energy μ-p scattering.[18] However, the effects of the ϕ will be of the order $g_{\phi N\bar{N}}g_{\phi\mu\bar{\mu}}/\alpha$, which would require experiments to be done to the unobtainable accuracy of about 0.001%.

The light mass of the ϕ meson permits its production by a quasiradiative process, and since $g_{\phi l\bar{l}}\propto m_l$, it seems best to look for it in radiative corrections to weak decay involving muons and the emission of ϕ in place of the photon. Of the various possibilities, the most attractive seems to be the process $\pi\to\mu\nu\phi$, shown in Fig. 4. The specific experiment we envisage is the decay of stopped π^+, with the observation of e^+e^- pair in coincidence, which would enable the invariant mass to be determined. The decay rate can be calculated from Fig. 4 by standard techniques.

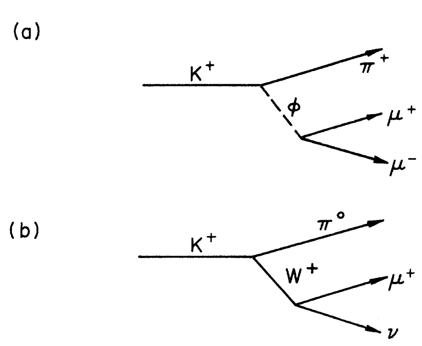

FIG. 2. (a) $K\to\pi\mu^+\mu^-$. (b) $K\to\pi^0\mu^+\nu$.

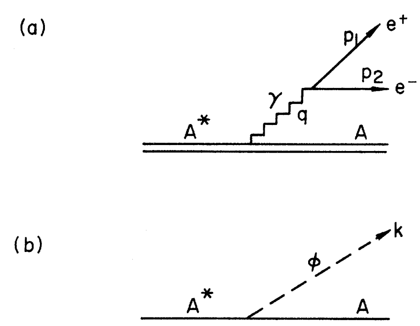

FIG. 3. (a) $A^*\to Ae^+e^-$. (b) $A^*\to A\phi$.

Writing $(E_p, \vec{p})$ and $(E_k, \vec{k})$, respectively, as the μ and ϕ four-momenta, G_F as the Fermi coupling, and $p = |\vec{p}|$, $k = |\vec{k}|$,

$$z = \frac{1}{2pk}\left[m_\pi^2 + m_\phi^2 + m_\mu^2 - 2m_\pi(E_k + E_p) + 2E_kE_p\right],$$

$$A = (4m_\mu^2 - m_\phi^2)(m - E_k - E_p)(E_p - p^2 - pkz),$$

$$B = [4\mu\, m_\mu^2 + 2(E_kE_p - pkz)]$$
$$\times[(m_\pi - E_k - E_p)E_k - k^2 - pkz],$$

we obtain

$$\Gamma_{\pi\to\mu\nu\phi} = \frac{(G_F^2/2)(g_{\phi\mu\bar{\mu}}^2/4\pi)m_\pi}{(2\pi)^2}$$
$$\times\int dE_p \int dE_k \frac{AB}{(m_\phi^2 + 2E_kE_p - pkz)^2}$$
$$\times\theta(1-z)\theta(1+z). \qquad (12)$$

The upper curve in Fig. 5 shows the ratio

$$\frac{\Gamma_{\pi\to\mu\nu\phi}}{\Gamma_{\pi\to\mu\nu}}\left(\frac{4\pi}{g_{\phi\mu\bar{\mu}}^2}\right).$$

Using the value 1.3×10^{-8} for this coupling constant from Eq. (1), one obtains a branching ratio of around 10^{-9}. This value is similar to the branching ratio $\pi^+ \to \pi^0 e^+ \nu$, which has, of course, been observed. As might be expected, the Dalitz plot is heavily weighted towards low-momentum ϕ's, which renders the experiment a little easier.

As the ϕ has no interactions other than weak, it will, from the experimental point of view, appear rather like a neutrino with a finite rest mass. Hence, it will have an interaction length many orders of magnitude larger than π, μ, e, or γ. In carrying out this proposal, one would need to worry about the enormous background of e^+ and μ^+, so a shielding sufficiently thick to stop all muons and shower particles would be needed.

The remaining background from stray γ's would be harder to eliminate. However, while the ϕ can decay *in vacuo,* the γ cannot, thus allowing a simple discrimination. Moreover, the γ can be converted to e^+e^- by an absorber (such as gas) while the conversion probability for a ϕ would be very small. Since the π^+ decays at rest, and the ν and μ^+ are not observed, the target will be a relatively clean isotropic source of ϕ mesons, with approximately 1 for every 10^9 stopped π^+. There should be no difficulty with counting rates at intense meson facilities like TRIUMF and LAMPF.

To detect the ϕ meson unambiguously, it would be sufficient to measure in coincidence the angles of e^+ and e^- and their energies E_+ and E_-, and reconstruct the invariant mass. This would be suitable for a refined later experiment; we would like to suggest here a relatively easy and inexpensive way to measure m_ϕ that would be suitable for a first experiment. This requires knowledge only of E_+ and E_-. We note that $E_\pm = \gamma(E^* \pm \beta p^* \cos\theta^*)$. Here $E^* = \frac{1}{2}m_\phi$, $p^* = (E^{*2} - m_e^2)^{1/2}$. γ is the boost parameter from the π decay (lab) frame to the ϕ decay (*) frame, $\beta = (1-\gamma^{-2})^{1/2}$, θ^* is the polar angle of the positron in the * frame, referred

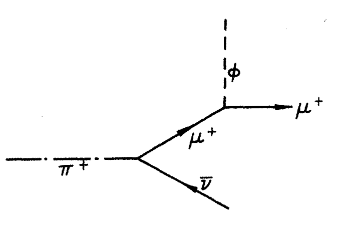

FIG. 4. Emission of ϕ in π^+ decay.

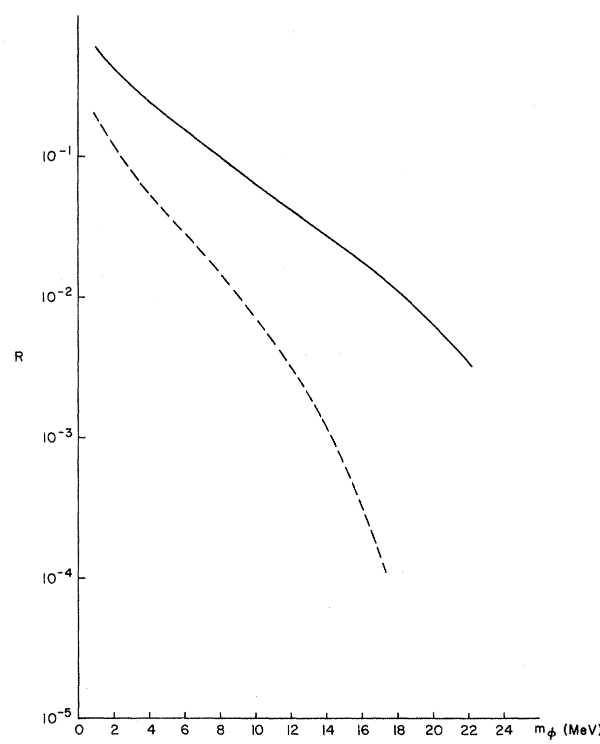

FIG. 5. Solid curve: plot of

$$\frac{\Gamma(\pi^+\to\mu^+\nu\phi)}{\Gamma(\pi^+\to\mu^+\nu)}\left(\frac{4\pi}{g_{\phi\mu\bar{\mu}}^2}\right)$$

as function of m_ϕ. Dashed curve: plot of

$$\frac{\sigma(PA\to PA\,\phi)}{\sigma(PA\to PA)}\left(\frac{4\pi}{g_{\phi N\bar{N}}^2}\right)$$

as a function of m_ϕ.

to the boost direction as the polar axis. Using the isotropy of the decay in the * frame, and lack of dependence of the production probability on the angle θ^*, it follows that $\langle \cos^2\theta^* \rangle = \frac{1}{3}$, $\langle \gamma^2 - \gamma^2\beta^2 \rangle = 1$, where $\langle\ \rangle$ denotes an average and is experimentally observable. If we define $F_\pm = E_+ \pm E_-$, then m_ϕ^2 is the solution of the quadratic equation

$$\tfrac{1}{4}(m_\phi^2)^2 + (\tfrac{3}{4}\langle F_-^2\rangle - \tfrac{1}{4}\langle F_+^2\rangle - m_e^2)\, m_\phi^2 + m_e^2 \langle F_+^2\rangle = 0. \tag{13}$$

Thus, m_ϕ^2 is determined from experimental second moments, and can be used in consistency checks for higher moments. For example, m_ϕ must then satisfy the fourth moment equation

$$5[1 - (4m_e^2/m_\phi^2)]^{-2}\langle F_-^4\rangle = \langle (F_+^2 - m_\phi^2)^2\rangle . \tag{14}$$

This would distinguish between real events and background accidentals that could give a spurious solution to (13). Such moments are not equivalent to detailed knowledge of the production cross section; this latter would also require averages like $\langle E_\pm\rangle \propto \langle\gamma\rangle$ which may be calculated numerically from theory if desired. It is important to note that these moment rules are completely independent of the production mechanism, or, for that matter, the spin of the particle. All that is required is that it decay to e^+e^-.

One might also envisage an experiment similar to that performed by M. Schwartz at SLAC. As the ϕ couples to the proton, it will be produced by a bremsstrahlunglike process, and thus a proton beam stopped in a target would act as a source of ϕ's, whose direction would now have some correlation to the beam direction. The experiment would be essentially similar in principle to the previous one, and the various remarks made above still apply.

However, the cross section will clearly be different, and theoretically the process is much less "clean." By a similar analogy with bremsstrahlung processes, the ϕ can be produced by proton collisions, preferably off heavy nuclei. The following very crude calculation may be made to estimate the order of magnitude of the effect. The diagrams in Figs. 6(a) and 6(b) give rise to a matrix element of the form

$$T' = g\bar{u}(p_f)\left(\frac{1}{\not p_i - \not k - m_N}\, T + T\,\frac{1}{\not p_f + \not k - m_N}\right) u(p_i), \tag{15}$$

where T is the elastic proton-nucleus scattering amplitude which we approximate by

$$T = A \exp(\tfrac{1}{2}\beta\cos\theta),$$

where A is a scalar quantity. The cross section involves some angular integrations which may be greatly simplified by assuming $|\vec{k}|, |\vec{p}_i|, |\vec{p}_f|, m_\phi \ll m_N$, the nucleon mass (the error induced by this is less than 5%). We arrive at the result

$$\frac{d\sigma}{dk}\Big/\sigma_{\text{tot}} = \frac{16 m_N^2 g^2 k^2 p_f}{(2\pi)^2 p_i E_i^2 E_k^5 (E_i - E_k)^2} \times \left\{ (m_\phi^2 + E_k^2)^2 + \frac{k^2}{3}\left[(|\vec{p}_i| + |\vec{p}_f|)^2 + \frac{2|\vec{p}_i||\vec{p}_f|}{\beta^2}\right]\right\}. \tag{16}$$

Note that the form we have chosen for T only enters into the ratio via the parameter β: Provided this is large, its specific value is unimportant and we have chosen it to be 10, which is a reasonable value for proton-nucleus scattering.[19] This function has been plotted in Fig. 7 for various m_ϕ, again with $g_{\phi N\bar{N}}^2 = 1$ and the incident energy $E_i = m_N + 20$ MeV. Note that the cross section

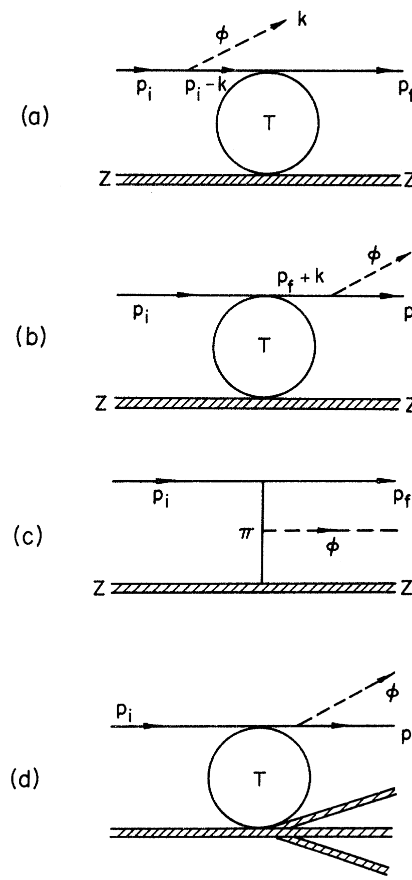

FIG. 6. Diagrams contributing to ϕ production off nuclei.

depends on the proton mass approximately as $1/m_N^2$, which would be expected by analogy with photon bremsstrahlung. The ratio $R = (\sigma_\phi/\sigma_{\text{tot}}) \times (4\pi/g_{\phi N\bar{N}}^2)$ is plotted in Fig. 5 (lower curve) where

$$\sigma_\phi = \int_0^{k_{\max}} dk \frac{d\sigma}{dk} .$$

We have ignored diagrams where the ϕ is emitted from an exchanged particle [Fig. 6(c)] or from an inelastic collision [Fig. 6(d)] because we have no way to calculate them, but presumably they would be of roughly similar magnitude.

To convert this cross section into an experimental rate, it is necessary to make some further assumptions. We assume that the experiment is done with 20-MeV protons incident on Pb, and, fairly arbitrarily, that no ϕ's are produced once the energy falls below 15 MeV. If the energy loss is dE/dx, then the nuclear collision must take place in the first $5/|dE/dx|$ cm of target. The probability for this to occur it $1/L$, where L is the collision length, so the number of ϕ's produced is

$$n = \frac{5N}{L|dE/dx|} R \frac{g_{\phi N\bar{N}}^2}{4\pi} , \qquad (17)$$

where N is the number of protons incident per second. For Pb, L has a value of about 90 g cm^{-2}, while $|dE/dx|$ is about 2.7 MeV g^{-1}cm^2, so that the dimensionless number $5/L|dE/dx|$ is about $\frac{1}{50}$. Thus, we would expect a rate lying between 10^{-11} and 10^{-13} ϕ's per proton. The enormous theoretical uncertainty in this number is more than made up for by the ease with which 20-MeV protons can be produced: Low-energy accelerators can produce more than 10^{15} protons per second, so the actual number of ϕ's produced could be much higher than in the $\pi \to \mu\nu\phi$ process.

These experiments depend crucially on m_ϕ being greater than m_e (~1.02 MeV), as its detection would be essentially impossible if its lifetime were around 10^{-4} seconds. It is, therefore, desirable to have an experiment to search in the region $m_\phi < 2m_e$.

Above it was pointed out that it is possible the ϕ would appear as a bound state in the positronium spectrum, and we now suggest an experiment based on this. One might expect one positronium in 10^7 to decay into a single γ ray and an unseen ϕ, in contrast to the usual decay into two (with $E_\gamma = m_e$) or three γ rays; kinematics of course requires the γ's to be emitted in opposite directions. Hence, one can envisage a positron source being used to create positronium inside a large counter with as close to 4π geometry as possible, divided into halves in anticoincidence.

The experiment, unfortunately, seems to be possible only in principle, as it appears that present-day photon counters are unable to detect photons with the required efficiency of essentially 100%. Apart from the low branching ratio, other problems would arise from random background in one counter, and from the tendency of the $^3S_1$ level to de-excite to $^1S_0$ by collision, which would lower the rate of 10^{-7} per atom still further.

Finally, we discuss the possibility of an experiment based on the nuclear transitions mentioned above. As noted above, a 2% branching ratio for ϕ production would be possible, and this would alter the lifetime by a corresponding amount. The measured lifetime for ^{16}O is $(5.5 \pm 0.5)\times 10^{-11}$ sec,[16,20] and it might be just possible to remeasure this to the required accuracy of about 0.1%. However,

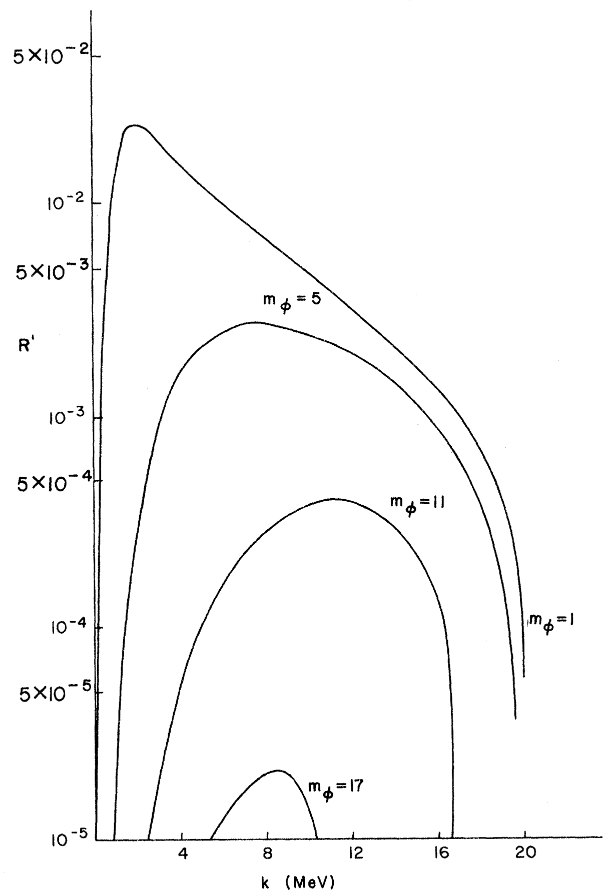

FIG. 7. Plot of

$$\frac{d\sigma_\phi/dk}{\sigma_{\text{tot}}} \frac{4\pi}{g_{\phi N\bar{N}}^2} \equiv R'$$

as a function of k.

the theoretical calculation depends sensitively upon the value of R, for which an accurate value cannot be given.

It seems hard to exploit this comparatively large branching ratio in an experiment. An ^{16}O nucleus would make an apparently energy-non-conserving transition to the ground state. However, it is necessary to show that the excited state existed in the first place, and this is normally done by observing the radiation emitted on its decay. In other words, we require the creation of the excited state to be tagged by some observable effect (such as α emission). Unfortunately, there seems to be no suitable processes, and thus the effect appears to be unobservable.

Obviously, observation of the ϕ would be of enormous theoretical interest, as the existence of such a particle would give a strong clue to the puzzle of electron-muon universality. If Weinberg's model is not correct, some of the above calculations are invalid, in particular the branching ratios. However, it is encouraging that the value (1) for $g_{\phi\mu\bar{\mu}}$ requires a coupling of similar magnitude for $g_{\phi N\bar{N}}$. If either of the couplings were exceptionally small, the other would be large and thus the ϕ should have been seen long since.

ACKNOWLEDGMENTS

We are very grateful to Professor E. P. Hincks for a number of conversations which gave rise to this paper, and to Professor D. Kessler and to Dr. C. K. Hargrove for their comments.

[1]S. Weinberg, Phys. Rev. Lett. 27, 1688 (1971).
[2]G. van 't Hooft, Nucl. Phys. B35, 167 (1971).
[3]G. Altarelli *et al.*, Phys. Lett. 40B, 415 (1972).
[4]R. Jackiw and S. Weinberg, Phys. Rev. D 5, 2396 (1972).
[5]J. D. Bjorken and C. H. Llewellyn Smith, Phys. Rev. D 7, 887 (1973), and references therein.
[6]J. Primack and H. Quinn, Phys. Rev. D 6, 3171 (1972).
[7]M. K. Sundaresan and P. J. S. Watson, Phys. Rev. Lett. 29, 15 (1972).
[8]We follow the notation ϕ for this meson introduced by Weinberg.
[9]M. Dixit *et al.*, Phys. Rev. Lett. 27, 878 (1971).
[10]A recent paper by H. K. Walter *et al.* [Phys. Lett. 40B, 197 (1972)] finds similar discrepancy in two x-ray transitions in Hg and Tl which are also removed by this interaction.
[11]J. Steinberger, Phys. Rev. 76, 1180 (1949).
[12]J. Schwinger, Phys. Rev. 82, 664 (1951).
[13]B. Lautrup and P. Olesen, Phys. Lett. 22, 342 (1966).
[14]H. Georgi and S. L. Glashow, Phys. Rev. Lett. 28, 1494 (1972).
[15]E. A. Paschos and L. Wolfenstein, Phys. Rev. D 7, 91 (1973).
[16]S. de Benedetti, *Nuclear Interactions* (Wiley, New York, 1964), Sec. 3.15.
[17]J. Sakurai, *Advanced Quantum Mechanics* (Addison-Wesley, Reading, Mass., 1967), p. 227.
[18]H. W. Fearing, Phys. Rev. D 6, 203 (1972).
[19]This is found by a rough fit to the data of I. E. Dayton and G. Schrank, Phys. Rev. 101, 1358 (1956).
[20]Equation (7) is an approximate one. A more accurate form is to be found in R. H. Dalitz, Proc. R. Soc. Lond. A206, 521 (1951). The experimental value [S. Devons *et al.*, Proc. Phys. Soc. Lond. A67, 134 (1954)] implies $R = 1.95$ F.