IS THE GRAVITON A GOLDSTONE BOSON?

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SUMMARY

The Nambu theory of elementary particles is examined. We encounter grave difficulties if we insist upon Lorentz invariance. But the model provides an ether, which can violate Lorentz invariance. By taking this idea completely seriously, we can show how the photon and the graviton arise as collective oscillations, and can estimate their coupling constants. These fields travel with velocity c in spite of being collective oscillations, so that classical experiments seem to have no bearing on the existence of an ether. A new experiment to look for the ether is described in the final section.

1. Introduction

It is very difficult to investigate gravitation directly. The theory still rests on the three classical tests, although new experiments[1,2] are under way. Some physicists[3,4] have tried a different approach, and have looked for effects of Mach's principle. These experiments so far have given null results, and we seem as far as ever from making progress. This essay outlines another indirect method. The basic idea did not come from the study of gravitation, but from a theory of elementary particles. Only after I had developed it quite extensively did it become clear that gravitation must play a fundamental role. The theory is based on well-known work of Nambu[5], which we will review briefly. We will describe the difficulties inherent in this theory, and the one radical suggestion we make to eliminate them. This move apparently brings us into conflict with classical optical experiments, but it turns out that the theory is constructed in just such a way as to keep us out of trouble. The extension from electromagnetism to gravitation was made last summer[7], and shows fairly clearly its function in the theory. A new set of experiments to check the underlying idea presents itself, and is described in the concluding section.

2. The Nambu Model

The BCS theory[8] of superconductivity raised a serious question of principle, because it seemed at first sight not to be gauge-invariant. One of the deepest studies of this problem was made by Nambu[9], who showed that the collective oscillations which were needed to save the situation were in fact a direct consequence of the gauge invariance of the original Lagrangian, and the violation of the symmetry by the new vacuum state. The electrons in a superconductor are in a highly-correlated state, and the lowest excitations above the ground state do not behave either as electrons or holes, but as a coherent mixture of both. These excitations are called quasiparticles.

Nambu noticed that the equations of motion he obtained for the quasi-particles were strikingly similar to the Dirac equation, with the energy gap in the superconductor taking the place of the rest mass. He was led to suggest[5] that the elementary particles might be quasiparticles against a background of correlated pair states. In order to preserve Lorentz invariance, he was obliged to let this background contain states of arbitrarily high momentum, but it was clear that one could reformulate the theory without ever mentioning the underlying pairs, just as the Dirac electron sea can be transformed away.

Nambu was trying to interpret the pion as the analog of the collective oscillations in a superconductor. But he discovered, to his chagrin, that these oscillations had zero rest mass in his theory. This has since been shown to be no accident[10], and the situation is summarized in the Goldstone theorem: "In a theory which is Lorentz invariant, and contains a continuous symmetry which is broken by the vacuum state, we will discover collective oscillations of zero mass."

This theorem has thwarted all attempts to make real sense of the Nambu theory. However, a superconductor is not restricted by the theorem, because it is not Lorentz invariant. I therefore wondered whether the Nambu theory could be saved in the same way, and was led to investigate the evidence for Lorentz invariance. This essay is the result of my inquiry.

3. The ether, the photon and the graviton.

The Nambu model provides us with an obvious way of breaking Lorentz invariance. We have simply to restrict the background pair states to energies less than a certain cutoff A. Since the background is unobservable when Λ is infinite, we may hope that observable effects will be small when Λ is finite but large, and that all experiments so far carried out may be consistent with Lorentz invariance. So we introduce into our theory small terms designed to violate Lorentz invariance in the simplest way. These terms have the general form $g\lambda^{\mu} j_{\mu}$, where g is a coupling constant, j_{μ} a current, and λ^{μ} a fixed four-vector. It is important to remember that λ^{μ} is not a field generated by surrounding matter; it represents the averaged effect of the background of pairs. This background is not Lorentz invariant, but defines a preferred set of reference frames, in which the momenta of the pairs are isotropic. In such frames, we take λ^{μ} to have the form (1,0,0,0), i.e., its space components are zero. What we have done is to reinstate the ether, and with it an ether drift velocity, given by the spatial part of λ^{μ} as measured by an observer on the earth.

The theory has to meet an immediate crisis, because we are brought up to believe that the Michelson-Morley experiment disposed of the ether once and for all. We could, it is true, postulate that light is an autonomous field unaffected by the ether, but this is obviously unpleasant. Much better would be the emergence of the photon as a mode of vibration of the ether, in keeping with the classical idea. Yet this collective oscillation must travel with velocity c :

The essential step was taken by Bjorken[6], who established that such oscillations do exist in a Nambu theory containing a vector λ^{μ}, that they are a direct result of the presence of this vector, as the Goldstone theorem indicates, and that they travel with velocity c because of the conservation of charge (gauge invariance). It was not too difficult to extend this method, though imperfectly, to gravitation[7], with the result that we can estimate the cutoff energy Λ to be related to the gravitational coupling constant G by

$$G \approx \frac{1}{\Lambda^2}$$

implying that $\Lambda \approx 10^{29}$ ev.

The function of these collective oscillations is to disguise, as far as possible, the fact that a symmetry has been broken. This is neatly illustrated here. It has often been suggested that no energies greater than about 10^{29} ev are physically meaningful, because of distortions of the measuring device by gravitational fields. In our theory, which has a built-in cutoff at this level, a gravitational field is automatically generated to make it impossible for us to measure higher energies.

4. Testing the theory.

In a recent paper[11], the effect of a term $g\lambda^{\mu} j_{\mu}$ was critically examined. We found that the decay rate[12] of $K_2^0 \rightarrow 2\pi$, and some magnetic-resonance experiments[13], set the present limit, but that it can be extended by several orders of magnitude if a special experiment is designed for the purpose. It turns out that this will be sensitive enough to cover the expected range, as estimated in references 7 and 11.

In our experiment, we take j_{μ} to be the axial-vector current, which for a stationary electron has the form $(0, \vec{\sigma})$. Any velocity $\vec{v}$ of the earth through the ether gives rise to a coupling of the form $g\vec{v}\cdot\vec{\sigma}$, which will have effects similar to those of the magnetic coupling $\vec{H}\cdot\vec{\sigma}$. If the ambient magnetic field can be reduced sufficiently, a magnetometer can be constructed to respond to $\vec{v}$. We will not discuss here the technical problem of eliminating magnetic effects; there are two tricks one can play which promise to make this a less serious nuisance than several other sources of interference. But it is interesting to get a picture of the probable behavior of $\vec{v}$.

Apart from a general recession, the galaxies are nearly stationary with respect to each other. It is natural to guess that they are also at rest in the ether. The earth is near the rim of our galaxy, and has a velocity of about 10^{-3} c due to galactic rotation. Superimposed on this is a velocity ten times smaller due to our motion around the sun. To an observer on the earth, the vector $\vec{v}$ will appear to rotate once a day, and the magnetometer will give a corresponding response. The period will actually be a sidereal day, and the phase should be consistent with a velocity directed along our galactic arm. However, it requires some ingenuity to obtain $\vec{v}$; the coupling term contains a constant g which is unknown, so that at first it seems that we can only find the line of $\vec{v}$, not its nagnitude or sense. But we can hope to observe the modulation of the main effect by our motion around the sun, and this suffices in principle to determine $\vec{v}$ completely.

Our magnetometer is a torsion pendulum carrying a bar magnet. Its deflection is measured by an optical-lever system modelled after that of Dicke[4]. The torque to be detected is estimated to be equivalent to that of a magnetic field of 10^{-6} gauss. It is not hard to obtain adequate sensitivity, but background noise will be our principal problem. We have been building this instrument for about eighteen months, with the support of the National Science Foundation and of the National Aeronautics and Space Administration. We hope to obtain preliminary data within the coming year.

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