Restrictions imposed on light scalar particles by measurements of van der Waals forces

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(Submitted 5 May 1982)
Pis'ma Zh. Eksp. Teor. Fiz. **36**, No. 2, 49–52 (20 July 1982)

Analysis of direct measurements of van der Waals forces yields restrictions on the mass of light scalar particles and the coupling constant for the coupling of these particles with fermions. For the scalar particles of the supersymmetry theory (the scalar axion) the scale of a supersymmetry violation would be restricted to $M^2 > 10^6$ GeV^2.

PACS numbers: 11.30.Pb, 12.70. + q

Supersymmetry principles (Fermi-Bose symmetries) are finding progressively more use in the construction of unified theories of the strong, weak, and electromagnetic interactions.[1] To a large extent, these supersymmetries reduced the degree of arbitrariness in the choice of the coupling constants, the set of elementary particles, and their mass spectra. One of the most important characteristics of the supersymmetry theory is that their quantum divergences are far weaker than usual, so that, in particular, the problem of gauge hierarchies can be solved[2] in a natural way. The combination[3] of the supersymmetry with the $U(1)_{PQ}$ symmetry introduced by Peccei and Quinn[4] to solve the *CP* problem in strong interactions leads to the prediction of (in addition to the axion) superpartners of the axion: a light scalar boson (a scalar axion) and a fermion (an axino). An experimental observation of these predicted particles is becoming an extremely important problem.

In the present letter we will show that the experimental observation of scalar axions would be feasible even today; we are already on the verge of the discovery of the scalar axion in experiments involving the measurements of van der Waals forces (the Casimir effect) between macroscopic objects.

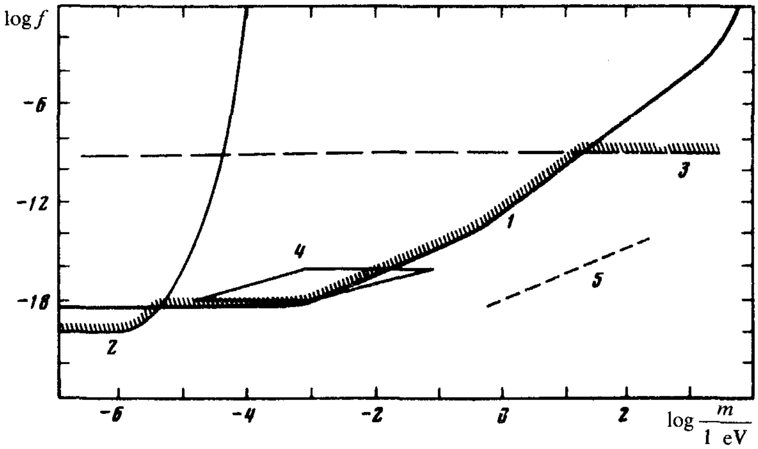

FIG. 1. Restrictions imposed on the magnitude of the scalar (Yukawa) coupling f and on the mass of light particles. 1—By measurements of van der Waals forces; 2—by gravitational experiments; 3—by astrophysical considerations. 4—Boundary of the region of predictions of the supersymmetry theories; 5—line corresponding to a magnitude of 10^{-10} dyn for the scalar forces between two objects.

By virtue of the supersymmetry, the coupling of a scalar axion with nucleon is directly related to the Yukawa interaction constant of the axion and given by

$$f \sim \frac{m_N}{M_{PQ}} \sim 10^{-9}-10^{-18}, \tag{1}$$

where m_N is the scale mass of the nucleon, and $M_{\text{PQ}} \sim 10^9$–10^8 GeV is the scale of the violation of the violation of the $\text{U}(1)_{\text{PQ}}$ symmetry. The mass of the scalar axion is[5]

$$m \sim M^2/M_{PQ}, \tag{2}$$

where M is the scale of the violation of the supersymmetry. To resolve the problem of gauge hierarchies, we need[2] $M \sim 10^2$–10^3 GeV, so that we find $m \sim 10^{-5}$–10^6 eV. The most natural value for M_{PQ} in the grand unification models is the unification scale M_X, equal to[6] $M_X \sim 10^{16}$–10^{18} GeV in the supersymmetry series. The most probable values for the properties of the scalar axion are thus as follows (Fig. 1): $f \sim 10^{-16}$–10^{-18} $m \sim 10^{-5}$–10^{-1} eV. What restrictions do existing experimental data impose on the properties of light scalar particles?

Particles with $m < 1$ keV, whose coupling with electrons is described by a constant $f_e > 10^{-11}$, would carry off a significant fraction of the energy of a star.[7] We thus find the restriction[8] $M_{\text{PQ}} > 10^9$ GeV, i.e., $f < 10^{-9}$ (Fig. 1). Down to distances less than m^{-1}, gravitational interactions are equivalent to a Yukawa interaction with nucleons, with a coupling constant $f = 10^{-19}$. Gravitational forces have been measured to distances ~ 10 cm within $\sim 1\%$. We must therefore rule out particles with $f > 10^{-20}$ and $m < 10^{-16}$ eV.

Nevertheless, a scalar particle, whose properties satisfy these restrictions, would be seen in many other interesting macroscopic experiments. Any macroscopic object that contains N_0 particles (a source) creates around itself a classical scalar field

$\phi \sim f N_0 e^{-mr}/r$. When a test object is brought near the source, the mass of any particle (and, proportionally, of any object) would change by an amount $\Delta M \sim f\phi$. In particular, this change would shift the atomic and nuclear energy levels and the frequencies of emitted photons. With $f \sim 10^{-13}$ and $m \sim 10^{-4}$ eV ($\lambda \sim 10^{-1}$ cm), for example, the energy of the hyperfine splitting of hydrogen levels would change by $\Delta\nu/\nu \sim 10^{-14}$, while the nuclear spectral lines in the Mössbauer effect would change by $\Delta\nu/\nu \sim 10^{-17}$.

We will show below that measurement of the van der Waals forces between macroscopic objects would be the most pertinent to a search for light scalar particles with the properties in (1) and (2), predicted by the supersymmetry theories. The customary approach is to measure[9] the van der Waals force between a plane and a spherical lens with a large radius of curvature:

$$F = \frac{2\pi R}{3} \frac{B}{d^3}, \tag{3}$$

where d is the distance between the surfaces, and R is the radius of curvature. Derjaguin *et al.*[9] carried out measurements for the separation interval 5×10^{-7} cm $< d < 10^{-4}$ cm and found a value for B and a change in the force with the distance, in good agreement with the theory. The exchange of scalar particles between these objects would give rise to an additional force

$$F_{\text{scalar}} = \frac{(2\pi)^2 f^2 n^2 e^{-md}}{m^3} R, \tag{4}$$

where n is the number of particles (of charge f) per unit volume (in the derivation of this expression we used $m^{-1} \ll R \sim 7$m). Working from a 10% experimental accuracy, we find the region shown in Fig. 1 to be the region of unusual values of f and m.[1)] In the interval of distances d for which measurements were carried out, and which corresponds to 1 eV $\lesssim m \lesssim 10^3$ eV, this region is specified by

$$f^2/m^6 < \frac{e^3}{27} \frac{B}{60\pi n^2},$$

so that with $n = 2 \times 10^{24}$ and $B = 0.6 \times 10^{-19}$ erg cm we would have $f/m^3 < 10^{-13}$ (eV)$^{-3}$. From Fig. 1 and Eqs. (1) and (2) we find a restriction on the scale of the supersymmetry violation. Specifically, for $M_{\text{PQ}} \sim M_X \sim 10^{17}$ GeV we should have $M^2 > 10^6$ GeV^2. Before now, the most stringent restriction on M^2 has been $M^2 > 2.6 \times 10^3$ GeV^2, which Fukugita and Sakai[10] derived from astrophysical considerations, by analyzing the effect of light particles on the evolution of stars in their later stages.

As can be seen from Fig. 1, measurements of van der Waals forces (the Casimir effect) are extremely effective for searching for scalar interactions and for testing the supersymmetry theories over a broad range of the Yukawa scalar coupling constants, $10^{-18} < f < 10^{-9}$, and over a broad range of the mass of the scalar particles, 10^{-6} eV $< m < 10$ eV. At lower masses, $m < 10^{-6}$ eV, the most effective way to search for new particles would be to carry out gravitational experiments, while at 10 eV $< m < 1$ keV the most stringent restrictions follow from astrophyics.

Scalar particles with the properties in (1) and (2) arise, we might note, upon the violation of any global symmetry in the supersymmetry theory. In this case, M_{PQ} should be replaced by the scale of the violation of the corresponding symmetry.

The results obtained from measurements of the Casimir effect already place a substantial restriction on the region of allowed values of f and m, as can be seen from Fig. 1. We do not rule out the possibility that as experiments of this type become more accurate (if, perhaps, experiments involving a cancellation of van der Waals forces are carried out) the particles predicted by the supersymmetry theories will be discovered. Curve 5 in Fig. 1 corresponds to the case in which the force of the scalar interaction between two objects is 10^{-10} dyn. Forces with absolute values at this level have already been measured.[11]

We wish to express our deep gratitude to L. N. Gurvich, G. V. Domogatskiĭ, G. T. Zatsepin, A. Yu. Ignat'ev, M. V. Kazarnovskiĭ, V. M. Lobashev, V. A. Matveev, V. G. Nedorezov, V. A. Rubakov, Yu. Ya. Stavisskiĭ, A. N. Tavhelidze, and A. E. Chudakov for interest in this study and for useful discussions.

[1)] This restriction is, of course, valid for the coupling of scalar particles with electrons.

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Translated by Dave Parsons
Edited by S. J. Amoretty