Pis'ma v ZhETF, vol. 96, iss. 12, pp. 841 – 843

Constraints on strongly coupled chameleon fields from the experimental test of the weak equivalence principle for the neutron

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Submitted 31 October 2012

The chameleon scalar field is considered as a possible cause of accelerated expansion of the Universe. The chameleon field induces an interaction potential between particle and massive body. Previous experiments with falling cold neutrons intended to measure the neutron coherent scattering lengths and verification of the weak equivalence principle for the neutron are used to constrain the parameters characterizing the strength of the scalar chameleon fields.

One of the most pressing mysteries in physics and cosmology is discovery of the accelerated expansion of the Universe. The nature of this effect is not understood. Amongst several theoretical schemes proposed to explain this astronomical observation one is a new cosmological scalar field of the quintessence type [1] dominating the present day density of the Universe (recent reviews are for example [2, 3]).

Acting on cosmological distances the mass of this field should be very small – of order of the Hubble constant: $\hbar H_0/c^2 = 10^{-33}\,\mathrm{eV/c^2}$.

The scalar fields appearing in modern string and supergravity theories should couple to matter with gravitational strength. Direct coupling of light scalar fields to matter with a strength of gravitation leads to large violation of the equivalence principle. But the experimental data yield very strict constraints on such a field demanding their coupling to matter to be unnaturally small.

The particular variant of the scalar field coupling to matter proposed in [4–9] has a form that in result of self-interaction and interaction of the scalar field with matter the mass of the scalar field depends on the local matter environment.

In the proposed theory coupling of scalar field to matter is of order as demanded by string theory, but is very small on cosmological scales. In high matter density surrounding, according to the proposed field equations, the mass of the field is increased, the interaction range is strongly decreased, and the equivalence principle is not violated in laboratory experiments for the search for the long range fifth force. The scalar field is confined inside the matter screening its existence to the external world.

The chameleon fields constructed in this way do not contradict to laboratory tests of the equivalence principle and the fifth force experimental searches even if these fields are strongly coupled to matter. In result of the screening effect the laboratory gravitational experiments of Galileo-, Eötvös- or Cavendish-type [10] performed with macro-bodies at macroscopic distances are unable to set an upper limit on the strength of the chameleon-matter coupling. At smaller distances 10^{-7}–10^{-2} cm the new forces can be observed in measurements of the Casimir force between closely placed macro-bodies [11] or in the atomic force microscopy experiments. Casimir force measurements may evade to some degree the screening and probe the interactions of the chameleon field at the micrometer range despite the presence of the screening effect [9, 12, 13].

It was shown in [14] that the chameleon interaction of elementary particles with bulk matter should not be screened – the chameleon induced interaction potential of bulk matter with neutron can be in principle observed. It was proposed also in [14] to search for chameleon field through the energy shift of ultracold neutrons in vicinity of reflecting horizontal mirror. From already performed experiments on observation of gravitational levels of neutrons the constraints were obtained in [14] on parameters characterizing the force of chameleon-matter interaction.

Chameleons can also couple to photons. In [15, 16] it was shown that the chameleon-photon coupling leads to the afterglow effect in a closed vacuum cavity in magnetic field. The continuing GammeV-CHASE [17, 18] and ADMX [19] experiments based on the proposal of [15, 16] are intended to measure (constrain) the coupling of chameleon scalar field to matter and photons.

In the approach proposed here only chameleon-matter interaction is taken into account not relying on existence of the chameleon-photon interaction.

According to the chameleon scalar field theory [4–9] the chameleon effective potential is

$$V_{\mathrm{eff}}(\phi) = V(\phi) + e^{\beta\phi/M_{\mathrm{Pl}}}\rho, \tag{1}$$

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where $V(\phi)$ is the scalar field potential:

$$V(\phi) = \Lambda^4 + \frac{\Lambda^{4+n}}{\phi^n}, \tag{2}$$

and ρ is the local energy density of the environment. In these expressions $\Lambda = (\hbar^3 c^3 \rho_{d.e})^{1/4} = 2.4\,\text{meV}$ is the dark energy scale, $\rho_{d.e} \approx 0.7 \cdot 10^{-8}\,\text{erg/cm}^3$ is the dark energy density.

The chameleon interaction potential of a neutron with bulk matter (in our consideration Earth's surface) was calculated in [14]:

$$V(z) = \beta \frac{m}{M_{\text{Pl}}\lambda} \left(\frac{2+n}{\sqrt{2}}\right)^{2/(2+n)} \left(\frac{z}{\lambda}\right)^{2/(2+n)} = \\ = \beta \cdot 0.9 \cdot 10^{-21}\,\text{eV} \left(\frac{2+n}{\sqrt{2}}\right)^{2/(2+n)} \left(\frac{z}{\lambda}\right)^{2/(2+n)}, \tag{3}$$

where $\lambda = \hbar c/\Lambda = 82\,\mu\text{m}$.

In obtaining constraints on strength of the chameleon field expressed by the parameter β we use the results of experiments of Koester [20] on measurement of critical height of reflection of free neutrons falling in the Earth's gravitational field from horizontal liquid lead and bismuth mirrors.

The acceleration of the free atom g_{micro} in the Earth's gravitational field has been measured by the Stanford group in 1999 with an accuracy $3 \cdot 10^{-9}$ [21]. They also compared their result with the value of g_{macro} obtained at the same laboratory site using a Mickelson interferometric gravimeter. It was found that the macroscopic object used in this measurement falls with the same acceleration to within $7 \cdot 10^{-9}$. From thus experimentally confirmed universality of free fall it follows that the gravitational accelerations of free micro-particles (including neutron) and of bulk matter are equal, and the weak principle of equivalence for micro-objects established experimentally with precision better than 10^{-8}.

By the free fall in the Earth's gravitational field neutrons gain an energy mgh, and if this energy is equal to the Fermi potential of the reflecting horizontal mirror

$$mgh = \frac{\hbar^2}{2m} \cdot 4\pi N b, \tag{4}$$

where m is the neutron mass, h is the fall's height, N is the number of nuclei in a unit volume of a mirror material, b is the coherent scattering length on a bound nucleus of the mirror, h may be considered as a critical height for the reflection. With measured with high precision N, g, and h one obtains the neutron scattering lengths.

Koester compared neutron scattering lengths measured in the gravitational diffractometer and those obtained by the neutron diffraction and scattering methods independent of gravity. The result of this comparison may be expressed by the factor γ expressing the ratio of the neutron scattering lengths obtained by two methods: $\gamma = 1 \pm 2.5 \cdot 10^{-4}$.

Schmiedmayer [22] used all available data on scattering lengths and took into account all systematic errors improving precision almost two times: $\gamma = 1 \pm 1.7 \cdot 10^{-4}$.

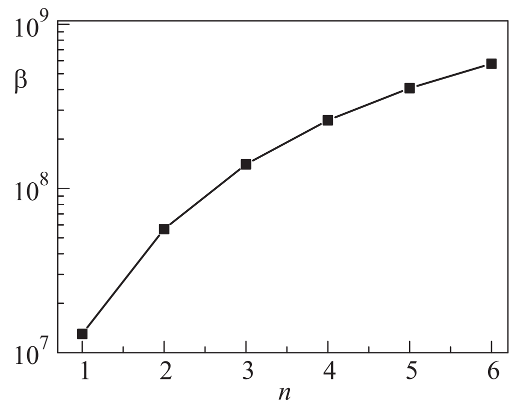
The experiments of Koester [20] may be interpreted as precision measurement of the neutron potential energy above the Earth's surface, based on an assumption that the neutron coherent scattering lengths do not depend on the method of measurement and, therefore, independent knowledge of the Fermi potential of the mirror and of the Earth's gravitational acceleration for microscopic (and macroscopic) bodies.

As was mentioned for macroscopic bodies the chameleon shielding effect should eliminate the effect of the scalar chameleon field on the acceleration of free fall. But presence of additional chameleon-induced interaction should change the potential energy of a neutron in vicinity of the Earth's surface.

We can use the uncertainty of the Koester's measurements [20] and the Schmiedmayer's additional consideration [22] to obtain the upper limit of the effect of the chameleon field on a neutron's free fall acceleration in vicinity of the Earth's surface:

$$\Delta V(h) = \beta \cdot 0.9 \cdot 10^{-21}\,\text{eV} \times \\ \times \left(\frac{2+n}{\sqrt{2}}\right)^{2/(2+n)} \left(\frac{h}{\lambda}\right)^{2/(2+n)} \le \Delta(gmh). \tag{5}$$

The constraints on parameter β for different n obtained from Eq. (5) are shown in Figure. The value of h was taken 62 cm – the critical height for bismuth.



Constraints on the parameter β of the chameleon potential in dependence on n. Allowed region is below the curve

Existing constraints on the parameters β and n of the chameleon field potential of Eq. (1) are not strong. From the atomic physics it follows [23], that $\beta \le 10^{14}$. More serious limits obtained from the experiments, demonstrating quantum levels of neutrons reflecting from horizontal mirror in the Earth's gravitational field, may be found in Fig. 1 of Ref. [14]. For example the allowed range of parameters for the strong coupling regime $\beta \gg 1$ are: $50 < \beta < 5\cdot 10^{10}$ for $n = 1$, $10 < \beta < 2\cdot 10^{10}$ for $n = 2$, and $\beta < 10^{10}$ for $n > 2$.

It is seen that the result following from our work constraints the strength of the chameleon field in the large coupling area of the theory parameters: $\beta \leq 1.3\cdot 10^7$ for $n = 1$, $\beta \leq 6\cdot 10^7$ for $n = 2$ with weaker constraints for $n > 2$ but still better than existing constraints [14].

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