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# A NEW INTERMEDIATE RANGE SCALAR FORCE? *

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ABSTRACT

Characteristics of a force with range near 1 km and mediated by a scalar singlet are discussed. The predicted composition dependent and composition independent corrections to gravity are consistent with several recent experiments.

* Talk presented at Rencontres de Moriond 1988, Neutrinos and Exotic Phenomena



In this talk I discuss some consequences of a possible new intermediate range force mediated by a scalar which is a singlet with respect to the standard model gauge group SU(3)xSU(2)xU(1). Scalar singlets arise naturally in many attempts to unify electroweak, strong and gravitational interactions. They also may play an important role in early cosmology. A specific model where this scalar is the (pseudo-)dilaton of spontaneously broken dilatation symmetry has been proposed recently [1]. This talk is mainly a fruit of this collaboration, although I try to describe here a somewhat more general context.

STRENGTH OF THE INTERACTION

The electroweak gauge symmetry does not allow any renormalizable coupling of a scalar singlet S to quarks, leptons or gauge bosons. This is a consequence of the chiral nature of the standard model which forbids SU(2) x U(1) symmetric mass terms for quarks and leptons. (In contrast QED or QCD would allow couplings like $\bar{e}eS$ or $\bar{q}qS$.) The couplings of S to ordinary matter are therefore suppressed by a mass scale M

$$\mathcal{L}_{Sq} = c_1 \bar{q}_L q_R \varphi \frac{S}{M} + h.c. \qquad (1)$$

$$\mathcal{L}_{SG} = c_2 G^a_{\mu\nu} G_a^{\mu\nu} \frac{S}{M} \qquad (2)$$

(Here q stands for a quark, $\varphi$ is the standard Higgs doublet with expectation value $\varphi_0 \approx 174$ GeV, $G^a_{\mu\nu}$ the gluon field strength and $c_i$ are dimensionless coupling constants.) If the scalar originates from unification with gravity the most natural value for M is in the vicinity of the Planck mass $M_p$. The force mediated by S is then predicted to have gravitational strength.[1)]

1) There are possible renormalizable interactions between S and the weak doublet $\varphi$ of the standard model. In particular the linear coupling $\nu'|\varphi|^2 S$ could suggest an unsuppressed coupling to

In this respect a scalar singlet behaves very similar to the graviton which also has only nonrenormalizable interactions with ordinary matter. The extremely weak strength of both interactions has a common origin! (In contrast, an interaction mediated by gauge bosons could be much stronger. As a consequence the vector force coupling to baryon number proposed by Fischbach et al. [2] needs tiny dimensionless gauge couplings $g \approx 10^{-20}$.)

RANGE OF THE INTERACTION

A given unification scheme may lead to many scalar singlets (infinitely many for higher dimensional theories and string theories). Most of them have a natural mass of the order $M_p$ and are not directly observable. An important exception are the Goldstone bosons from spontaneously broken global symmetries. For an exact symmetry they are massless whereas they acquire a mass

$$\mu_s{}^2 = \Lambda^4/M^2 \qquad (3)$$

if the symmetry has anomalies. The scale $\Lambda$ is associated to the anomaly and may well be given by standard model physics. In the model of ref. 1 the scalar S arises from spontaneously broken dilatation symmetry and $\Lambda$ is the largest scale generated by the dilatation anomaly [3]. The effective potential can only depend on a dimensionless function of S/M

$$V = \Lambda^4 f\left(\frac{S}{M}\right) \qquad (4)$$

and (3) follows naturally if f has a minimum. As a rough guess one may consider $\Lambda = \Lambda_{QCD}$, $M = M_p$ which leads to a range of the scalar force

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the Higgs scalar. It is easy to show, however, that in all models where the mass $\mu_s$ of the scalar singlet arises naturally without extreme cancellations of different contributions the scale $\nu$ is bounded by $\mu_s$. For our models of interest one has $\mu_s{}^2 = \Lambda^4/M^2$ where $\Lambda$ is some typical mass scale of standard model particle physics. For these models the coupling of S to the weak doublet is also of gravitational strength. (Compare the model of ref. 1).



$$\lambda \approx M_p/\Lambda_{QCD}^2 \approx 10 \text{ km} \qquad (5)$$

Precise predictions of this range, however, are often quite difficult.

CHARGE

The scalar S interacts with quarks and gluons via singlet operators like $m_q\bar{q}q$ and $G^a_{\mu\nu}G_a^{\mu\nu}$ (compare (1), (2), $m_q = h_q\varphi_0$ ). In contrast to a force mediated by vector bosons it does not couple to a conserved charge like baryon number B or lepton number L. One expects that the coupling of S to a nucleus will reflect the complicated structure of quark and gluon expectation values in a nucleus. There is no good reason why the charge should be exactly linear in quantum numbers like B or N-Z. The mass operator $M_N$ for a nucleus also involves singlet operators like $G^a_{\mu\nu}G_a^{\mu\nu}$ or $m_q\bar{q}q$. However, the scalar charge $Q_N$ and the mass $M_N$ may involve the various singlet operators with <u>different</u> weights, resulting in a composition dependence of the scalar force. Let me neglect leptons, photons and heavy quarks and write in a simple model the mass and charge of a nucleus in terms of the gluon, up and down quark condensates

$$M_N = \langle \hat{G}^2\rangle_N + \langle \hat{m}_u\bar{u}u\rangle_N + \langle \hat{m}_d\bar{d}d\rangle_N \qquad (6)$$

$$Q_N = f_G\langle \hat{G}^2\rangle_N + f_u\langle \hat{m}_u\bar{u}u\rangle_N + f_d\langle \hat{m}_d\bar{d}d\rangle_N \qquad (7)$$

$$\langle \hat{G}^2\rangle_N = \left\langle \frac{\beta(g_s)}{2g_s} G^a_{\mu\nu}G_a^{\mu\nu}\right\rangle_N \qquad (8)$$

$$\hat{m}_q = (1+\gamma(g_s))m_q$$

Here $g_s$ is the strong gauge coupling with associated $\beta$-function

$\beta(g_s)$ and quark mass anomalous dimension $\gamma(g_s)$. The material dependence of the charge is related to the quark expectation values in nuclei

$$Q_N = f_G M_N + (f_u - f_G)\langle \hat{m}_u \bar{u}u \rangle_N + (f_d - f_G)\langle \hat{m}_d \bar{d}d \rangle_N \tag{9}$$

Evaluating the $\bar{q}q$ operators in a proton (and similarly in a neutron)

$$\hat{\sigma} = \frac{1}{2}(\hat{m}_u + \hat{m}_d)\langle \bar{u}u + \bar{d}d \rangle_p \simeq 40\text{-}60 \text{ MeV} \tag{10}$$

$$\hat{\delta} = (\hat{m}_d - \hat{m}_u)\langle \bar{u}u - \bar{d}d \rangle_p \simeq 2 \text{ MeV} \tag{11}$$

one finds

$$Q_N = \left\{ f_G \left[ 1 - (x_u + x_d)\frac{\hat{\sigma}}{\bar{m}} \right] + f_u x_u \frac{\hat{\sigma}}{\bar{m}} + f_d x_d \frac{\hat{\sigma}}{\bar{m}} \right\} M_N$$
$$+ \left\{ \frac{f_d m_d + f_u m_u}{m_d + m_u} - f_G - f_u x_u - f_d x_d + f_G (x_u + x_d) \right\} \hat{\sigma} B$$
$$+ \left\{ \frac{f_d m_d - f_u m_u}{m_d - m_u} - f_G \right\} \frac{\hat{\delta}}{2} (N - Z) \tag{12}$$

Here I have parametrized the contribution of quarks to the binding energy by

$$\langle \hat{m}_q \bar{q}q \rangle_N - Z\langle \hat{m}_q \bar{q}q \rangle_p - N\langle \hat{m}_q \bar{q}q \rangle_n = x_q (M_N - B\bar{m})\frac{\hat{\sigma}}{\bar{m}} \tag{13}$$

with $\bar{m}$ an average mass of a nucleon (1 amu). I also have neglected corrections $\sim\hat{\sigma}\hat{\delta}$ and $\sim\hat{\delta}^2$. Typically the charge is in leading order proportional to $M_N$ with a baryon number dependent piece suppressed by $\hat{\sigma}/\bar{m} \approx 1/20$ and a very small admixture of nuclear isospin N-Z which is proportional to the isospin breaking in a nucleon $\hat{\delta}/2\bar{m} \approx 10^{-3}$. The charge $Q_N$ depends linearly on B and N-Z only for $x_u, x_d$ constant. This is at best an approximation



since one expects that the relative quark contribution to the nuclear binding energy depends on the specific nucleus and therefore $x_u$, $x_d$ are (complicated) functions of N and Z.

POTENTIAL AND DIFFERENTIAL CHARGE

The potential between two atoms A,A' from the exchange of a boson with mass $\lambda^{-1}$ is

$$V = -\frac{G}{4\pi r}\,\varepsilon\, Q_A Q_{A'} \exp\left(-\frac{r}{\lambda}\right) \tag{14}$$

with $Q_A$ the charge of an atom with respect to the new force. Here $\varepsilon = +1$ for a scalar or tensor force and $\varepsilon = -1$ for a vector force. This induces a correction to Newtonian gravity of the form $(1 + \alpha \exp -\frac{r}{\lambda})$. Many experiments measure the difference in acceleration for two test bodies with charge $Q_1$ and $Q_2$ and equal mass m in the potential from a source (atoms with mass M) in the earth or the environment of the experiment. The potential difference relevant for these "differential experiments" is

$$\Delta V = \Delta q \,\frac{GMm}{r} \exp\left(-\frac{r}{\lambda}\right) \tag{15}$$

with

$$\Delta q = -\frac{\varepsilon}{4\pi}\,\frac{Q_s}{M}\,\frac{\Delta Q}{m}$$

$$\Delta Q = Q_1 - Q_2 \tag{16}$$

The charge of the source atoms $Q_s$ has to be appropriately weighted over the material surrounding the experiment. Under many circumstances $Q_s$ is in a good approximation proportional to M. I propose to quote experimental results always in terms of $\Delta q$ as defined by the potential difference (15). In the approximation where $Q_s/M$ is constant $\Delta q$ depends only on the charge of the test particles and a comparison between experiment and various different theories becomes easy. For a given model the deviations from $Q_S \sim M$ induce a theoretical correction factor in the relation between $\Delta q$ and the charge difference $\Delta Q$. This correction factor corresponds to a weighted mean value of $Q_S/M$ and will in general depend on the surroundings of the experiment and on $\lambda$.

The quantity $\Delta q$ depends on the materials used in differential experiments. Without further theoretical information nothing about the consistency or inconsistency of the experiments performed so far with different pairs of materials can be said. Using for the charge a linear approximation

$$Q_A = f_M M_A \left\{ 1 + \beta \left( \frac{B}{\mu} + \gamma \frac{N-Z}{\mu} \right) \right\} \tag{17}$$

$$\mu = M_A / \bar{m}$$

one obtains (for $|\beta\gamma| \ll 1$)

$$\Delta q = \alpha_B \left\{ \Delta\left(\frac{B}{\mu}\right) + \gamma \Delta\left(\frac{N-Z}{\mu}\right) \right\} \tag{18}$$

$$\alpha_B \approx - \frac{\varepsilon f_M^2 \beta (1+\beta)}{4\pi} \approx - \frac{\varepsilon \beta}{1+\beta} \alpha \tag{19}$$

Although $\varepsilon$ is positive for a scalar force, the sign of $\alpha_B$ can become positive for negative values of $\beta$[1]. A scalar exchange may imitate a repulsive force in differential experiments since these only measure if the force on a given substance is less attractive or more attractive than for another.

## THE COSMON MODEL

In the cosmon model[1] S is the Goldstone boson of spontaneously broken dilatation symmetry. As a consequence of the dilatation anomaly it couples to the anomalous trace of the energy momentum tensor $\vartheta^\mu_\mu$. If $\vartheta^\mu_\mu$ vanishes for some value $S = S_0$ and $m_S^2$ is positive for $S = S_0$ any static vacuum will have vanishing $\vartheta^\mu_\mu$. If the trace of the energy momentum tensor $T^\mu_\mu$ is



purely anomalous in the vacuum the cosmological constant is dynamically adjusted to zero. The cosmon charge of a nucleus is

$$Q_N = f \langle \vartheta^\mu_\mu \rangle_N \tag{20}$$

The coupling f is bounded $f^2/4\pi \lesssim 1/3$ and the interaction strength is predicted to be weaker than gravity. On the other hand f should not be too small ($f^2/4\pi \gtrsim$ a few times $10^{-3}$) since otherwise the scale of spontaneous breakdown of dilatation symmetry would be substantially larger than the Planck mass. The dominant contribution to $\langle \vartheta^\mu_\mu \rangle_N$ comes from the gluons ($f_G = f$, $f_u = f_d = \gamma(g_s) f/(1 + \gamma(g_s))$). With a linear approximation for the charge (17) ($x = x_u + x_d = $ const, $f_u = f_d = 0$) one obtains

$$f_M \approx f \left( 1 - x \frac{\hat{G}}{\bar{m}} \right) \tag{21}$$

$$\beta \approx -(1-x) \frac{\hat{G}}{\bar{m}} \tag{22}$$

$$\gamma \approx \frac{1}{(1-x)} \frac{\hat{S}}{2\hat{G}} \tag{23}$$

This model predicts an attractive force coupling dominantly to mass ($\alpha \approx f^2/4\pi$). For a linear comparison with differential experiments I will pick $x = 1/3$ so that

$$\alpha_B = \frac{1}{30} \alpha$$

$$\gamma = 0.03 \qquad (\gamma\beta = -10^{-3}) \tag{24}$$

The full differential charge $\Delta q$ should also account for the fact that x is material dependent. In our simple nuclear model the nonlinearity is only moderate:

$$\Delta q = \alpha \frac{\hat{G}}{\bar{m}} \left\{ \left(1 - \left(\overline{\frac{B}{\mu}}\right)\right) \Delta x + (1 - \bar{x}) \Delta \left(\frac{B}{\mu}\right) \right\} + \alpha \frac{\hat{S}}{2\bar{m}} \Delta \left(\frac{N-Z}{\mu}\right)$$

$$\left(\overline{\frac{B}{\mu}}\right) = \frac{1}{2}\left(\frac{B_1}{\mu_1} + \frac{B_2}{\mu_2}\right) \quad , \quad \bar{x} = \frac{1}{2}(x_1 + x_2) \qquad (25)$$

COMPARISON WITH EXPERIMENT

Indications for an attractive force ($\alpha\lambda \approx 5$m) were reported at this meeting by Eckhardt [4]. For $\alpha = 10^{-2}$ I have evaluated in the table the linearized $\Delta q$ (18) relevant for various experiments[2] with $\alpha_B = \alpha/30$, $\gamma = 0.03$

$$\Delta q = 3.3 \times 10^{-4} \left\{ \Delta\left(\frac{B}{\mu}\right) + 0.03\, \Delta\left(\frac{N-Z}{\mu}\right) \right\} \qquad (26)$$

In the last column I quote some of the experimental results and bounds reported so far, assuming $\lambda = 500$ m.

Table

| material | ref. | $\Delta q$ | $\Delta q$ (observed) |
|---|---|---|---|
| Cu - $H_2O$ | 5) | $2.6 \times 10^{-6}$ | $6.8 \times 10^{-6}$ |
| Cu - Be | 6) | $6.0 \times 10^{-7}$ | $< 4.9 \times 10^{-7}$ |
| Al - Be | 7) | $-6.2 \times 10^{-8}$ | $-1.7 \times 10^{-7}$ |
| Al - Be | 8) | $-6.2 \times 10^{-8}$ | $> -1.6 \times 10^{-7}$ |
| Cu - U | 9) | $-8.8 \times 10^{-7}$ | $> -6.2 \times 10^{-6}$ |
| Nylon - $H_2O$ | 10) | $-3.0 \times 10^{-7}$ | |

2) For probes not consisting purely of one material mean values of $B/\mu$ etc. are used.



Several comments are in order: For Cu - $H_2O$ and Cu - U the dominant contribution to $\Delta q$ becomes from the isospin difference $\Delta(N-Z)/\mu$. Although $\gamma$ is small this is compensated by the fact that $\Delta(N-Z)/\mu$ is more than hundred times larger than $\Delta B/\mu$. The $\Delta B/\mu$ and $\Delta(N-Z)/\mu$ components have the same sign for Cu - $H_2O$ (and Nylon - $H_2O$), but opposite signs for the other pairs of materials. One predicts that Thieberger should see a larger effect than other experiments. For Cu - Be and Al - Be the baryon and isospin components have the same order of magnitude. For $\gamma = 0.03$ there is actually a cancellation of these components for the pair Al - Be. For somewhat larger values of $\gamma$ the predicted $\Delta q$ for Al - Be can easily be around $-2 \times 10^{-7}$, whereas $\Delta q$ for Cu - Be decreases. It is surprising that all predictions fit so far quite well with the reported bounds and positive indications for a new force.[3] (The factor of two in Thieberger's observation compared to the linear expectation for $\Delta q$ is not very significant in view of the crude nuclear model I used.) For the time being I would not take this as an experimental indication for this particular model, especially since in view of eq. (12) alternative scalar singlet models may lead to a similar structure of the charge. If the reported observations of a new force persist, however, the above analysis strongly points towards a scalar force.

REFERENCES

1) R.D. Peccei, J. Solà and C. Wetterich, Phys. Lett. 195B (1987) 183

2) E. Fischbach, D. Sudarsky, A. Szafer, C. Talmadge and B.H. Aronson, Phys. Rev. Lett. 56 (1986) 3

3) C. Wetterich, DESY-87/123, to appear in Nucl. Phys. B

4) D. Eckhardt, report at this conference

5) P. Thieberger, Phys. Rev. Lett. 58 (1987) 1066

6) C.W. Stubbs et al., Phys. Rev. Lett. 58 (1987) 1070

3) The cosmon model predicts that the composition dependence of the charge is near the phenomenological "window" analyzed by Fischbach et al.[11].

7) P.E. Boynton et al., Phys. Rev. Lett. 59 (1987) 1385

8) E.G. Adelberger et al., Phys. Rev. Lett. 59 (1987) 849

9) T.M. Niebauer et al., Phys. Rev. Lett. 59 (1987) 609

10) P.G. Bizzeti, report at this conference

11) C. Talmadge and E. Fischbach, Proc. of International School of Cosmology and Gravitation: Gravitation Measurements, Fundamental Metrology and Constants, Erice 1987, ed. V. de Sabbata.