Limit on the Strength of Intermediate-Range Forces Coupling to Isospin

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A laboratory experiment searching for intermediate-range forces coupling to $N-Z$ of nuclei has been performed. This yields the bound on the strength of any such force to be less than 3.0×10^{-3} of gravity per baryon, for all ranges $\lambda > 3$ m.

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The observation that the residuals in the famous experiments of Eötvös *et al.* correlate with the differences in the baryon number per atomic mass unit of the two substances placed on either side of the torsion balance led Fischbach *et al.* to suggest[1] the possible existence of a new composition-dependent force. Its range and strength were estimated to be $\lambda\sim100$ m and $\alpha\sim10^{-2}$ of gravity per atomic mass unit, on the basis of the variation of Earth's gravity measured as a function of depth in mines by Holding, Stacey, and Tuck.[2] This stimulated a considerable amount of theoretical speculations and experimental activity directed at determining more precisely the parameters describing this new force.[3-10] Naturally, most of these experiments were performed with modern versions of Eötvös-type balances operated at geological sites specially chosen to have large horizontal components of gravity. It has become customary to describe the new force by adding a Yukawa term to the Newtonian gravitational potential between two bodies, and to write

$$V(r)=-G\frac{m_1m_2}{r}(1+\alpha_{12}e^{-r/\lambda}), \tag{1}$$

where α_{12} is the new composition-dependent coupling. Despite a considerable amount of experimental work, it has not been possible to determine the value of the range λ and the nature of the dependence of the coupling α_{12} on composition uniquely. For example, Boynton *et al.* suggested[5] that $\alpha_{12}=q_1q_2\xi$ with

$$q_i=\beta(N+Z)_i/\mu_i+(1-\beta)(N-Z)_i/\mu_i, \tag{2}$$

so that the new effective charge q_i is a linear combination of the baryon number $B=N+Z$ and the nuclear isospin $I_z=N-Z$ of nuclei; μ_i is the mass of the atom in atomic mass units. With this parametrization and an assumed value of $\lambda\simeq100$ m, they could bring the results of all the new experiments to mutual consistency if the force were to couple essentially to isospin ($\beta\approx0$) with ξ in the range 1.4×10^{-2}-4×10^{-3}. We adapted our apparatus, primarily designed for a study of the equivalence principle, to observe this force with laboratory source masses, and find $\xi<3.0\times10^{-3}$ for all $\lambda>3$ m. A much more stringent limit $\xi<4\times10^{-4}$ has been obtained by Adelberger *et al.*[11] for similar values of λ.

Our apparatus consists of a torsion pendulum which operates inside a vacuum chamber at $\sim10^{-8}$ Torr and is shielded from the Earth's magnetic field to levels below 5×10^{-3} Oe and from thermal waves to negligible levels ($<10^{-3}$ °C). The mass element of the torsion balance is in the form of a ring formed by the sandwiching of two semicircular rings, one of copper and the other of lead, between thin rings of aluminum. The ring has an internal diameter of 14 cm, an outside diameter of 20 cm, and a thickness of 1 cm. Azimuthal grooves were cut in the lead part of the ring to equalize its mass, and its first two mass moments about the suspension axis, with that of the copper part. The ring, weighing 1500 g, was suspended with its plane horizontal by a tungsten wire of diameter 105 μm. The natural period of the balance, τ_0, is 790 s. A sketch of the apparatus is shown in Fig. 1. The whole apparatus was operated in an underground laboratory $\sim$23-m deep that was specially designed for such experiments, where it was isolated effectively from thermal variations and microseisms which are larger near the surface. Because of the azimuthal symmetry of the mass distribution of the ring, its coupling to gradients in gravity is expected to be very small, about a factor of 10^3 smaller than that of a dumbbell of similar mass and size.

The source mass consisted of two columns of lead, each of 260 kg, separated azimuthally by 90° with respect to the suspension axis of the ring, designated as the z axis, and at a distance 150 cm from it. This arrangement ensures cancellation of residual torques due to gravitational gradients coupling to small differences in the quadrupole moments $(Q_{xx}-Q_{yy})$ of the ring that might be present at the $\sim10^{-3}Q_{zz}$ level because of imperfections of fabrication. Couplings to Q_{xz} and Q_{yz} are reduced by splitting each of the 260-kg masses into two equal units separated vertically by a distance approximately equal to their distance from the suspension axis and placed symmetrically with respect to the plane of the ring as shown in Fig. 1. This ensures that the gravitational field generated by the masses is highly uniform, with negligible gradients in the vertical direction. Counterweights with a similar structure but having smaller masses suspended at a larger distance of 175 cm reduce the effectiveness of the source masses by a factor

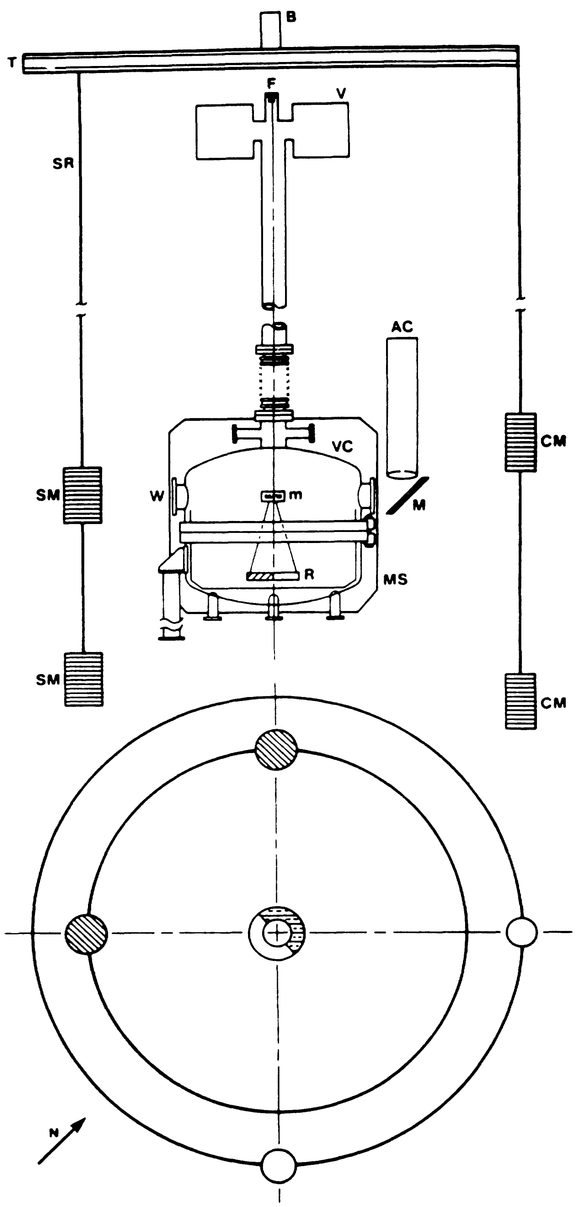

FIG. 1. Sketch of the apparatus, along with the plan view; B = bearing, T = truss, F = fiber holder, SR = suspension rods, V = ion pumps, SM = source masses, CM = counterweights, VC = vacuum chamber, W = optically flat windows, m = $\lambda/20$ mirror, M = 45° mirror, AC = autocollinator, R = ring, and MS = magnetic shield.

of ~ 3. During the experiment the masses are driven in a circular path about the suspension axis at the natural frequency ω_0 of the balance. Whereas this procedure causes the coupling to $Q_{xx} - Q_{yy}$ merely to be modulated at $2\omega_0$, more importantly, it leads to a resonant buildup of the amplitude of the torsional oscillations, should there exist any composition-dependent coupling to the ring. The rate of growth of the amplitude for a pure isospin coupling of $\xi = 10^{-3}$ is 1.7×10^{-8} rad per period of the balance. The smallness of the expected growth rate

TABLE I. The growth rate of the amplitude of the balance for various modes and the implied strength of the coupling to $N - Z$. The statistical error on an individual run is negligible. (Quadrature drive leads to an increase in the amplitude of the component $\pi/2$ out of phase with the balance, and π-phase drive leads to an increase and 0-phase drive to a decrease of the amplitude of the balance for a repulsive force.)

Run	Mode	Growth rate $\times \tau_0$ (rad)	ξ
1	Quadrature	1.4×10^{-8}	8.2×10^{-4}
2	π phase	0.5×10^{-8}	-2.9×10^{-4}
3	0 phase	-0.9×10^{-8}	-5.3×10^{-4}
4	0 phase	3.2×10^{-8}	1.9×10^{-3}
5	0 phase	-3.4×10^{-8}	-2.0×10^{-3}
6	0 phase	6.3×10^{-8}	3.7×10^{-3}

is simply due to the minuteness of the horizontal component of the gravitational field that is generated by our source masses. This is only about 3×10^{-7} cm s^{-2}, and is a factor of $\sim 10^5$ smaller than that available at suitabie geological sites.

Suppose the angular position θ of the balance can be expressed as

$$\theta = A \sin(\omega_0 t + \Psi) , \quad (3)$$

and the driving torque due to the masses as

$$\zeta = C \sin(\omega_0 t + \Phi) , \quad (4)$$

then by choosing Φ suitably one could either increase or decrease the amplitude A or merely change the phase Ψ. These modes are designated, respectively, as 0, π, and quadrature in Table I. The angle θ of the balance was measured with an accurate autocollimator operated at a resolution of $\sim 2 \times 10^{-8}$ rad Hz$^{-1/2}$ and data were acquired in each particular mode for typically 30–70 cycles. The growth rates obtained in the various modes are given in Table I. Notice that even though several sequences of data yield growth rates of $(\sim 10^{-8}\text{ rad})\tau_0^{-1}$ there is one extremely noisy pattern which gives a growth rate of $(6 \times 10^{-8}\text{ rad})\tau_0^{-1}$.

The data presented in Table I are subjected to a statistical analysis relevant to small groups. First the noisiest data set (run 6) is omitted and the rest are averaged to yield

$$\xi = (-0.03 \pm 1.5) \times 10^{-3} , \quad (5)$$

so that the omitted point lies just below 3 standard deviations from the average. The 2σ upper limit (95% confidence) implied by Eq. (5) is

$$|\xi| < 3.0 \times 10^{-3} . \quad (6)$$

To check whether systematic noise in our apparatus could have masked a much larger value of ξ, we note two possible effects which operate precisely at the driving frequency and phase: (i) coupling of Q_{xz} and Q_{yz} of the ring to gravity gradients generated by a misalignment of the masses—this is estimated to contribute less than 1% of the observed growth rate even for a misalignment as large as 1 cm—and (ii) the magnetic coupling of the source masses to the ring, which causes even smaller effects. Thus we conclude that the upper bound on $|\xi|$ given in Eq. (6) is valid. It is applicable to all values of $\lambda \gg 1.5$ m and increases rapidly at shorter distances as $\sim \exp[-(1.5\text{ m})/\lambda]$.

This result is complementary to the bounds[5] obtained from experiments near cliffs whose sensitivities increase approximately linearly with λ up to a few kilometers. For small values of λ, below about 10 m, these experiments do not yield useful bounds. In closing, we note that with marginal improvement of the source-mass configurations our apparatus would become sensitive to isospin-dependent couplings which are smaller by more than an order of magnitude with respect to the bounds presented in this Letter.

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