Strength of Intermediate-Range Forces Coupling to Isospin

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An experimental search for new forces coupling to nuclear isospin with a range of ≥ 3 m was conducted using a torsion balance driven in resonance by a set of masses configured to generate a nearly pure isospin source field. The strength of any such coupling ξ in units of gravity per atomic mass unit is found to be bounded by $-2.3\times10^{-4}\leq\xi\leq+2.7\times10^{-5}$, where the positive sign represents an attractive force between like isospin charges.

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Experimental searches[1] for new intermediate-range forces weaker than gravity during the last three years have yielded much valuable information, even though, as yet, they have failed to provide any generally accepted positive evidence for the existence of such a force at the level first suggested by the reanalysis of the Eötvös experiment and by the mine-gravity data.[2]

The hypothetical force is usually represented by a Yukawa potential which, when added to the standard Newtonian gravitational potential, reads as

$$V(r)=-Gm_1m_2r^{-1}[1+\alpha\exp(-r/\lambda)]\,,$$

where α is the new coupling in units of gravity and λ is its range. The composition dependence can be made explicit by writing $\alpha=q_iq_j\xi$ with

$$q_i=\cos\theta(N+Z)_i/\mu_i+\sin\theta(N-Z)_i/\mu_i\,,$$

where the new effective charge has been written as a linear combination of the baryon number and nuclear isospin per atomic mass unit, in standard notation. In the present paper we assume a pure isospin coupling, i.e., $\theta=\pi/2$ and $q_i=(N-Z)_i/\mu_i$.

We have modified our[1(j)] earlier configuration of source masses so as to increase the expected signal for an isospin coupling and to suppress, further, the effects of gravity and its gradients on the pendulum. This has enabled us to extend the search for isopin-dependent forces to considerably higher levels of sensitivity than those reported earlier, the present measurement being characterized by the ability to measure differential accelerations of $\sim5\times10^{-13}$ cm s^{-2}.

A brief description of the apparatus can be found in Refs. 1(j) and 3. The torsion pendulum consists of two semicircular rings of copper and lead each of mean radius about 8.5 cm and mass about 700 g joined along their diameters; two pairs of grooves in the lead make its mass distribution match closely that of the copper half,[1(j),3] to reduce the coupling of the ring to gradients in the gravity field. This dual ring is suspended with its plane horizontal (x-y plane) by means of a tungsten fiber 250 cm long and 105 μm in diameter inside a vacuum chamber with pressure below 10^{-8} Torr. But for imperfections of fabrication and small tilts of the ring, the quadrupole moment tensor Q of the ring is diagonal and also has the property $Q_{xx}=Q_{yy}$. An optical-quality mirror, in an assembly weighing about 35 g, is attached to the ring at a height of 40 cm and within about 0.1 cm of the fiber axis. An autocollimating optical lever views this mirror and yields the angular orientation of the ring with an accuracy of 5×10^{-9} rad/Hz$^{1/2}$. The natural period of torsional oscillation of the pendulum was measured to be 795.6 s; this corresponds to a torsion constant of about 7 dyn cm/rad for the suspension. The instrument, which is operated inside a specially constructed well 25 m deep, and sees temperature variations around the frequency of measurement of less than 10^{-3}°C, is also magnetically shielded to below 10^{-3} Oe, while variations of the magnetic field around the frequency of observation are $<5\times10^{-6}$ Oe. Further, a wooden shroud separates the instrument from the source masses, thus shielding it from any convective air motions induced by the moving source masses.

The configuration of the source masses and their placement with respect to the balance are shown in Fig. 1. The source of the hypothetical isospin force field essentially consists of four lead masses about 160 kg each, suspended in two columns from the adjacent arms of a + shaped truss mounted on a bearing far above the vacuum chamber. The truss can be rotated so as to position the masses at any desired azimuth whose value is read off using a twelve bit shaft encoder. Notice that these columns are azimuthally separated by an angle of $\pi/2$ with respect to the axis of suspension of the pendulum; also the two masses constituting each column are placed symmetrically ~60 cm above and below the plane of the ring. These lead masses are counterbalanced by a similar set of brass masses suspended from diagonally opposite points of the truss. The axis of the bearing is kept within a few millimeters of the axis of suspension of the ring and the distances of all the mass columns are kept either at 105 or at 120 cm from the center during the experiment. Several features of this configuration of source masses may be noted: (i) The lead, with a large $(N-Z)/\mu$, generates the posited iso-

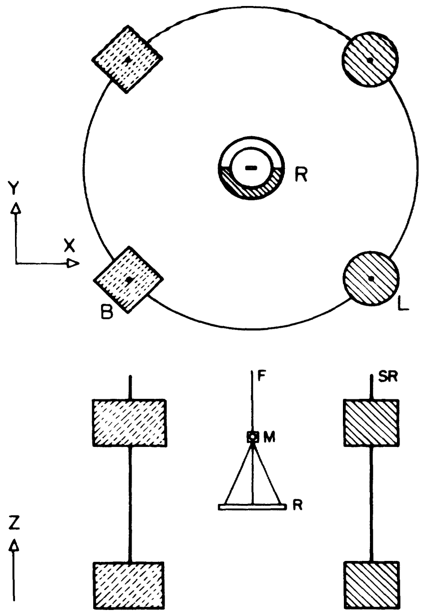

FIG. 1. Sketch showing the torsion balance and the placement of the source masses, in plan (top) and in elevation (middle); B = brass mass, L = lead mass, R = ring of dual composition, F = suspension fiber, M = mirror, and SR = suspension rod.

spin field in the horizontal direction normal to the plane containing the lead masses; (ii) each column generates only a small vertical gradient in the horizontal component of the gravitational field in the volume immediately surrounding the ring and also generates identical values of the horizontal gravity field at the ring and at the mirror assembly; (iii) the brass counter weights nullify the components of the gravitational fields due to the lead masses, but reduce the isospin field only slightly since $(N-Z)/\mu$ of brass is small; (iv) the mass distribution has a clear fourfold azimuthal symmetry so that only the higher-order multipole moments of the mass distribution in the ring couple effectively to the gravitational gradients generated by the masses.

Should an attractive force exist between like isospin charges, there would be a torque acting in the $+z$ direction on the dual ring for the configuration shown in Fig. 1; this torque will reverse its sign when the masses are moved to an azimuth 180° away, i.e., when the lead masses exchange their positions with those of the brass masses in the figure. This feature dictates our strategy of placing the lead masses for nearly half the natural period of the balance at each of these two locations, repeatedly, so as to drive it in resonance. Depending on the phase of these movements of the masses relative to that of the torsional oscillations, the amplitude of the balance in phase or in quadrature would be expected to increase or decrease. This mode of driving the masses has been designated as the "isospin mode." For a placement of the source at a distance of 105 cm from the suspension axis and for a $\lambda = 300$ cm we estimate a rate of growth of amplitude, $\dot{A}_E$, to be $+5.5\times10^{-5}\xi$ rad, per period of the balance.

Note that this method of modulating the possible effect of the source masses allows for a diagnostic mode where the lead masses occupy azimuthal positions shifted by 90° with respect to the position shown in Fig. 1. In this position the isospin force will be in the same direction as the composition axis of the dual ring so the torque should be zero; this mode is designated as the "90° mode." We could also have diagnostic runs with either the top or bottom pair of the lead masses exchanged in position with their brass counterparts. Now both the isospin field and the gravity field have a fourfold symmetry and the expected torque on the ring is again zero; we designate this mode as "null." Yet another handle on the behavior of the balance, as well as its response to variations in environmental parameters (temperature, magnetic field, etc.), is obtained by observing its "free-cycling" oscillations, during which the masses are kept stationary.

Besides the isospin couplings, the gradients in gravity of the source masses will couple with the imperfections in the fabrication of the ring and the mirror assembly to generate torques. The coupling to $Q_{xx}-Q_{yy}$ is strongly suppressed, as this occurs at twice the frequency of movement of the source masses and also because the torques due to the two pairs of lead masses cancel each other. More troublesome are the torques that act with the same periodicity as the torques generated by isospin couplings. In the present experiment such a torque may arise due to the coupling of the vertical gradients of the horizontal field to axial asymmetries in the torsion balance. For an economical description of the (near-field) effects involved here, it is convenient to split the torque into two parts. The first part arises due to the tilt of the ring out of the horizontal plane, and is of the form

$$\tau_z^Q = \frac{1}{3}\left[Q_{xz}\frac{\partial g_y}{\partial z} - Q_{yz}\frac{\partial g_x}{\partial z}\right]. \quad (1)$$

The second part is caused by the offsets of the centers of mass of the ring and the mirror with respect to the suspension fiber. An offset, $\mathbf{r}$, causes a moment $\mathbf{p} = m_{\text{mirror}}\mathbf{r}$; even though $\mathbf{p}_{\text{ring}} = -\mathbf{p}_{\text{mirror}}$, we would still have a torque

$$\tau_z^p = \mathbf{p}\times(\mathbf{g}_{\text{mirror}} - \mathbf{g}_{\text{ring}}). \quad (2)$$

In order to determine the values of the parameters Q_{xz}, Q_{yz}, and $\mathbf{p}$, diagnostic runs were carried out with masses of about 5 kg added on to the source configuration to generate large and well-defined asymmetries in the gravitational field.

The amplitude of free oscillations was damped by the application of magnetic fields to less than 10^{-6} rad before the acquisition of data in the various modes. The output of the autocollimator was low-pass filtered, and

TABLE I. Mean rates of amplitude growth in various modes.

Mode	Symbol	No. of runs	Total time clocked in hours	Growth rates (nrad/cycle)
Free cycling	$\dot{A}_F$	9	108	-0.5 ± 1.4
Control	$\dot{A}_C$	31	247	-2.7 ± 1.0
Isospin	$\dot{A}_I$	21	194	-5.7 ± 1.2
Estimated systematics[a]	$\dot{A}_S$	...	...	±4.8
Expected response	$\dot{A}_E$	...	...	$+5.5\times10^4\xi$

[a]Based on diagnostic runs with large gravity gradients.

then digitally recorded every 30 s and also displayed continuously on a chart recorder. Analaysis was carried out after correcting the observed voltages for a small nonlinearity with the angular deflection as measured during the calibration of the autocollimator. The data clearly show, besides the oscillations of the balance, a slow drift of its equilibrium position at the rate of $\leq 2\times10^{-5}$ rad/day. Each cycle of oscillation was fitted to a sinusoidal form and the resulting amplitudes were then fitted to obtain a mean rate of growth of amplitude $\dot{A}$ in each mode. The relevant growth rates are summarized in Table I. The data in the isospin mode that were taken with the source masses located at a distance of 120 cm were scaled assuming an r^{-2} dependence for $\dot{A}$ and were combined with the data taken at 105 cm to yield a mean $\dot{A}_I$. Also, all the data obtained with source configurations that did not generate an isospin-dependent torque, viz., the 90° mode and the null mode were combined to yield the growth rate $\dot{A}_C$ in the "control mode" (see Table I); $\dot{A}_C$ is a measure of the smallness of the various systematic effects, e.g., thermal coupling between the source masses and the balance. Similarly, observations of the balance in the presence of a deliberately introduced oscillatory magnetic field of amplitude 5×10^{-5} Oe show that under the normal conditions of the experiment, magnetic fields cannot cause a rate of growth of amplitude of more than 2×10^{-9} rad/cycle. Further, the free-cycling data show that the effects due to random variations in the environment (e.g., temperature, magnetic field) do not lead to growth rates much larger than $\sim1.4\times10^{-9}$ rad/cycle. The gravitational effects of misalignment of the masses may also be estimated. Each of the eight masses that constituted the source configuration was weighed to be the same within 100 g; this, coupled with the diagnostic data obtained with large field gradients, indicates that the contribution of this uncertainty is negligible (growth rate $<4.5\times10^{-10}$ rad/cycle). On the other hand, non-negligible torques are generated if the center of gravity of the upper source mass does not lie vertically above that of the lower mass in the same column; from the data on the diagnostic runs it is estimated that a 1-mm shift can generate a growth rate of $\sim1.6\times10^{-9}$ rad/cycle. Though the control data do not evidence a large contribution of this effect to the growth rates, solely on the basis of our metrology during alignment we are unable to rule out shifts of as much as 3 mm. Thus in Table I we list $\dot{A}_S=\pm4.8\times10^{-9}$ rad/cycle as a conservative limit on any systematic contribution of the mass shifts to the growth rates.

We now refer to Table I to note that the growth rate observed in the isospin mode, $\dot{A}_I=(-5.7\pm1.2)\times10^{-9}$ rad/cycle, could lie anywhere between the 2σ limits $\dot{A}_{I+}=-3.3\times10^{-9}$ rad/cycle and $\dot{A}_{I-}=-8.1\times10^{-9}$ rad/cycle. However, as mentioned above, the positioning of the masses in each individual run was not checked and systematic uncertainties in the growth rate as large as $\dot{A}_S=\pm4.8\times10^{-9}$ rad/cycle cannot be ruled out. Therefore, the growth rate $\dot{A}_L$ that could be caused by an isospin coupling has the 2σ bounds

$$-12.9\times10^{-9}\leq\dot{A}_L\leq1.5\times10^{-9}\ \text{rad/cycle}.$$

Since, for an isospin coupling of strength ξ, the expected growth rate is $\dot{A}_E=+5.5\times10^{-5}\xi$ rad/cycle under the conditions prevalent in the experiment, we obtain the fol-

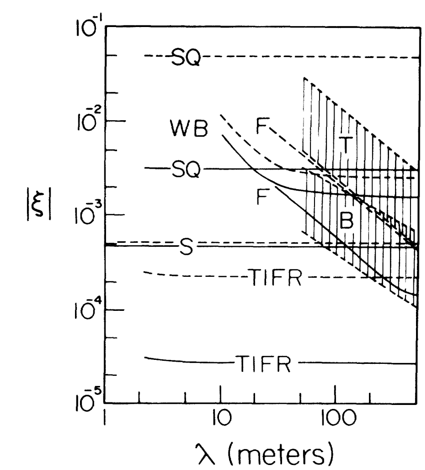

FIG. 2. 2σ upper bounds on the strengths of attractive (solid curves) and repulsive (dashed curves) isospin couplings as stated in SQ {Speake and Quinn [Ref. 1(i)]}, WB {Bennett [Ref. 1(k)]}, F {Fitch, Isaila, and Palmer [Ref. 1(g)]}, S {Stubbs *et al.* [Ref. 1(l)]}, and TIFR (this work). The hatched areas mark out, within 2σ limits, the strengths of the repulsive forces seen by T {Thieberger [Ref. 1(a)]} and B {Boynton [Ref. 1(e)]}.

lowing 2σ bounds on ξ:

$$-2.3\times 10^{-4} \leq \xi \leq +2.7\times 10^{-5}. \quad (3)$$

These bounds are valid for $\lambda \gtrsim 3$ m and their dependence on the assumed value of λ is shown in Fig. 2 along with the other published results. We also note that Nelson and Newman and Adelberger *et al.* have reported upper limits on ξ at a similar level of sensitivity.[4]

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[1](a) P. Thieberger, Phys. Rev. Lett. **58**, 1066 (1987); (b) C. W. Stubbs *et al.*, Phys. Rev. Lett. **58**, 1070 (1987); (c) T. M. Niebauer, M. P. McHugh, and J. E. Faller, Phys. Rev. Lett. **59**, 609 (1987); (d) E. G. Adelberger *et al.*, Phys. Rev. Lett. **59**, 849 (1987); (e) P. E. Boynton, D. Crosby, P. Ekstrom, and A. Szumilo, Phys. Rev. Lett. **59**, 1385 (1987); (f) G. I. Moore *et al.*, Phys. Rev. D **38**, 1023 (1988); (g) V. L. Fitch, M. V. Isaila, and M. A. Palmer, Phys. Rev. Lett. **60**, 1801 (1988); (h) D. H. Eckhardt *et al.*, Phys. Rev. Lett. **60**, 2567 (1988); (i) C. C. Speake and T. J. Quinn, Phys. Rev. Lett. **61**, 1340 (1988); (j) R. Cowsik, N. Krishnan, S. N. Tandon, and C. S. Unnikrishnan, Phys. Rev. Lett. **61**, 2179 (1988); (k) Wm. R. Bennett, Jr., Phys. Rev. Lett. **62**, 365 (1989); (l) C. W. Stubbs *et al.*, Phys. Rev. Lett. **62**, 609 (1989); (m) M. E. Ander *et al.*, Phys. Rev. Lett. **62**, 985 (1989); (n) K. Kuroda and N. Mio, Phys. Rev. Lett. **62**, 1941 (1989); (o) P. G. Bizzeti *et al.*, Phys. Rev. Lett. **62**, 2901 (1989).

[2]E. Fischbach *et al.*, Phys. Rev. Lett. **56**, 3 (1986); F. D. Stacey *et al.*, Rev. Mod. Phys. **59**, 157 (1987).

[3]R. Cowsik *et al.*, in *Gravitational Measurements, Fundamental Metrology and Constants,* edited by V. De Sabbata and V. N. Melnikov, NATO Advanced Study Institutes Ser. C, Vol. 230 (Kluwer, Boston, 1988); Adv. Space Res. (to be published).

[4]E. G. Adelberger, in Proceedings of the Moriond Meeting, Les Arcs, France, 1989 (to be published); (private communication); R. Newman, *ibid.*; (private communication).