Limits on the Axial Coupling Constant of New Light Bosons

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We report on a neutron particle physics experiment, which provides for the first time an upper limit on the strength of an axial coupling constant for a new light spin 1 boson in the millimeter range. Such a new boson would mediate a new force between ordinary fermions, like neutrons and protons. The experiment was set up at the cold neutron reflectometer Narziss at the Paul Scherrer Institute and uses Ramsey's technique of separated oscillating fields to search for a pseudomagnetic neutron spin precession induced by this new interaction. For the axial coupling constant g_A^2, an upper limit of 6×10^{-13} (95% C.L.) was determined for an interaction range of 1 mm.

The standard model (SM) of particle physics explains the interaction between matter particles in terms of the exchange of bosons. It is believed that the SM corresponds to the low energy limit of a more fundamental theory, that should ultimately also describe gravity in the same framework. Various extensions of the SM based on new ideas, such as superstring theory, are being developed in this direction; they all generically predict new particles and thus new interactions beyond the SM. A new boson with mass M would induce an interaction between ordinary particles with an interaction range $\lambda_c = \hbar/Mc$. The Large Hadron Collider can probe new bosons with a mass up to 1 TeV/c^2, provided they are strongly coupled with matter. Lighter bosons could have escaped detection up to now if they are weakly coupled. In the latter case, one does not search for the boson itself but for the additional interaction the boson mediates between ordinary particles. All possible interactions have recently been classified [1]. This Letter reports the first result from a tabletop experiment designed to probe spin-dependent interactions in the millimeter range, induced by a vector boson with a mass of about 10^{-4} eV. In the framework of relativistic quantum field theory, the interaction between a nucleon ψ and a new vector (spin 1) boson X^μ is generically characterized by the Lagrange function $\mathcal{L} = \bar{\psi}(g_V \gamma^\mu + g_A \gamma^\mu \gamma^5)\psi X_\mu$, which is parametrized by a vector coupling constant g_V and an axial-vector coupling constant g_A. For the sake of simplicity, we assume identical coupling to protons and neutrons and no coupling to electrons. The vector term induces a spin-independent repulsive force with a strength proportional to g_V^2. Numerous experiments are searching for such a fifth force with different techniques to probe ranges from subatomic to astronomical distances [2–7]. At the millimeter range, the best limit is extracted from the Seattle torsion pendulum experiment [5], looking at tiny deviations from Newton's law of gravity acting on macro-

scopic bodies, with the present best upper limit of $g_V^2 < 5 \times 10^{-40}$. The axial-vector term induces a new spin-dependent interaction and can only be probed by using spin polarized particles. One way to access this term is to look at a dipole-dipole type of interaction, as done in a recent experiment performed at Princeton [8]. It uses a ^{3}He spin source and a K-^{3}He comagnetometer probe and reports the limit

$$g_A^2 e^{-r/\lambda_c} < 1.5 \times 10^{-40} \tag{1}$$

with $r = 0.5$ m being the distance between the ^{3}He spin source and the K-^{3}He comagnetometer. Another way to probe the axial-vector term is to look at the induced spin-velocity interaction between a particle considered as a source and another polarized probe particle. The corresponding interaction potential, in the nonrelativistic limit, can be written as

$$V_{\text{Axial}}^{\text{point}}(r) = \frac{g_A^2}{16\pi} \frac{(\hbar c)^2}{mc^2} \vec{\sigma} \cdot \left(\frac{\vec{v}}{c} \times \frac{\vec{r}}{r}\right)\left(\frac{1}{\lambda_c} + \frac{1}{r}\right)\frac{e^{-r/\lambda_c}}{r}, \tag{2}$$

where $\vec{\sigma}$ is the spin and m is the mass of the probe particle, r is the distance, and $\vec{v}$ is the relative velocity between the source and the probe, respectively. This potential corresponds to $f_\perp$ in the notation of Ref. [1]. The fact that the interaction does not depend on the source particle's spin allows us to use an unpolarized macroscopic object as a source.

Here, we describe how this exotic interaction is probed for the first time by employing a beam of polarized slow neutrons as a probe and a macroscopic plate as a source, as proposed in Ref. [9]. Near the surface of the plate, the potentials (2) induced by the individual nucleons in the bulk add up coherently. This therefore creates an effective pseudomagnetic field, directed orthogonal to both the neutron direction of flight and the surface normal of the sample. In the configuration presented in Fig. 1, the
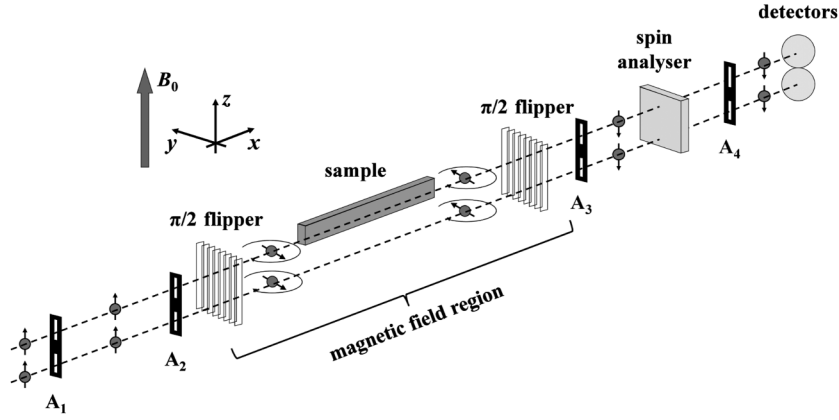
FIG. 1. Schematic of the experimental setup to probe the axial interaction between polarized neutrons and a macroscopic sample plate as a function of the distance Δy. The polarized neutron beam is separated into two beams by several apertures A_{1-4}. The sample is located between the two $\pi/2$ spin flippers where the neutron spins precess in the x-y plane perpendicular to the static magnetic field B_0.

neutron velocity is directed along x, and the pseudomagnetic field would be directed along z. If the neutron beam is initially polarized in the x-y plane, the pseudomagnetic field will induce a spin precession around the z axis of

$$\varphi = l \frac{g_A^2}{4} N \frac{\hbar c}{m_n c^2} \lambda_c e^{-\Delta y/\lambda_c}, \qquad (3)$$

where $\Delta y > 0$ is the distance between the neutron beam and the sample surface, l is the length of the sample in the x direction, N is the nucleon number density of the sample, and m_n is the neutron mass. A very accurate method to measure such a neutron spin precession is Ramsey's technique of separated oscillating fields [10]. In Fig. 1, a schematic drawing of the utilized Ramsey setup is depicted, which was installed at the polarized neutron reflectometer Narziss at the spallation source SINQ at the Paul Scherrer Institute. The neutron beam with a de Broglie wavelength of 0.5 nm and a velocity spread of 1.5% (FWHM) is polarized in the z direction. It is shaped and separated by means of the apertures A_1 and A_2 into two beams each with a height of 10 mm. The distance in the z direction between the beams is 20 mm from center to center. The width of the upper beam was measured to be (0.46 ± 0.02) mm (FWHM). It passes by the sample in a distance Δy, and the lower beam, passing at a distance much larger than Δy, serves as a reference (*two-beam method*). Along the beam path, two phase-locked radio frequency (rf) $\pi/2$ spin-flip coils, with a thickness of 10 mm and a distance to each other of 570 mm, are placed in a magnet which provides a static field B_0 of approximately 3 mT in the z direction. The field is continuously monitored by using a 3D Hall probe, which is installed outside of the homogeneous field region in the vicinity of the magnet in a field of 2.3 mT. The investigated sample is placed between the two $\pi/2$ spin-flip coils, which produce linear oscillating fields in the y direction. The spins of the neutrons are analyzed by using a polarizing supermirror

and are finally detected by using two ^{3}He gas detectors. The number of detected neutrons is normalized by means of a fission chamber monitor detector placed in the incident neutron beam. The additional apertures behind the sample (A_3 and A_4) avoid detecting neutrons which are accidentally scattered in the air or on the sample surface. A so-called Ramsey pattern is obtained by measuring the detector count rate as a function of the spin-flipper frequency close to the neutron Larmor resonance, as presented in Fig. 2(a) [11–13]. Any additional precession of the neutron spins due to the sample will cause a corresponding phase shift of the Ramsey pattern of the sample beam, while the phase of the Ramsey pattern of the reference beam will stay unchanged. Instead of measuring a complete Ramsey pattern, only a set of 21 data points is taken to reduce measuring time, as shown in Fig. 2(b). The sinusoidal fit to the data points provides a fit accuracy of the phase of about $\pm 1.4°$. The same fit yields a Ramsey oscillation frequency $\Delta f = (1353 \pm 12)$ Hz, which is in good agreement with the expected theoretical value of 1358 Hz determined by using Eq. (4) in Ref. [11]. The stability of the apparatus was tested by repeatedly performing Ramsey scans for almost 10 hours without a sample. The result is presented in Fig. 3 and demonstrates that, although the phases of the individual beams might drift slightly (probably due to magnetic field and thermal drifts), the phase difference remains constant and scatters purely statistically. This important advantage of the two beam method, i.e., allowing us to compensate for inadvertent drifts, is mandatory to perform a high-accuracy measurement and was already demonstrated previously in Refs. [11,14].

As a sample, a 19 mm thick and 480 mm long copper plate was used (nucleon number density: $N \approx 5.3 \times 10^{24}$ cm^{-3}). The copper plate surfaces were machined to achieve a roughness and error in parallelism of less than 50 μm, and the sample was aligned parallel with respect to the neutron beam with an accuracy of better than 0.007°.
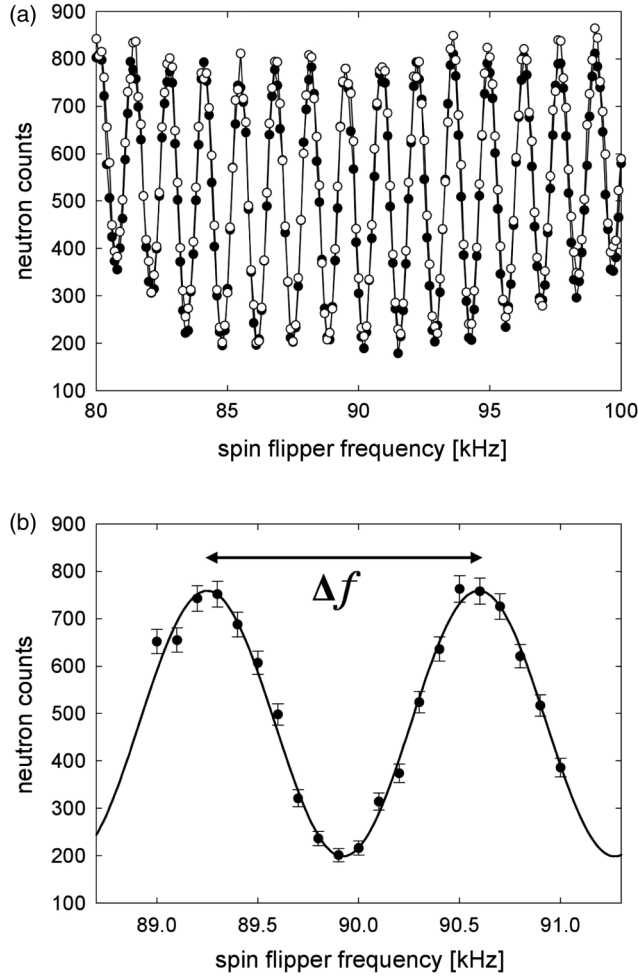
FIG. 2. (a) Ramsey oscillation pattern of the sample beam (●) and the reference beam (○) close to the neutron Larmor resonance of about 90 kHz. (b) A reduced Ramsey pattern consisting only of 21 data points, measured in a total time of approximately 5 minutes at a proton current of 1.35 mA on the SINQ spallation target.

The reproducibility of the sample positioning in the y direction was measured to be about $\pm 1~\mu m$, and the position of the sample surface was determined with an accuracy of $\pm 10~\mu m$. This yields an overall error for Δy of approximately $\pm 80~\mu m$, which is much smaller than the width of the neutron beam. One measurement cycle consists of five Ramsey scans taken at Δy equal to 0.57, 1.07, 2.07, 4.07, and 8.07 mm. Eight successive cycles with and 20 cycles without the sample were performed, in a total time of 12 hours. The combined results are summarized in Fig. 4(a), which shows the phase shift due to the sample as a function of the sample-to-beam distance. By fitting the exponential decay function $\varphi(\Delta y) = \varphi_0 e^{-\Delta y / \lambda_c}$ with fixed λ_c to the data points, one obtains the parameter φ_0 with its uncertainty $\delta \varphi_0$ [e.g., for $\lambda_c = 1$ mm: $\varphi_0 = (1.84 \pm 1.27)°$ and $\lambda_c = 10$ mm: $\varphi_0 = (0.75 \pm 0.48)°$]. From that, one can determine upper limits of the axial-axial coupling g_A^2 as a function of λ_c at 95% confidence level, by using
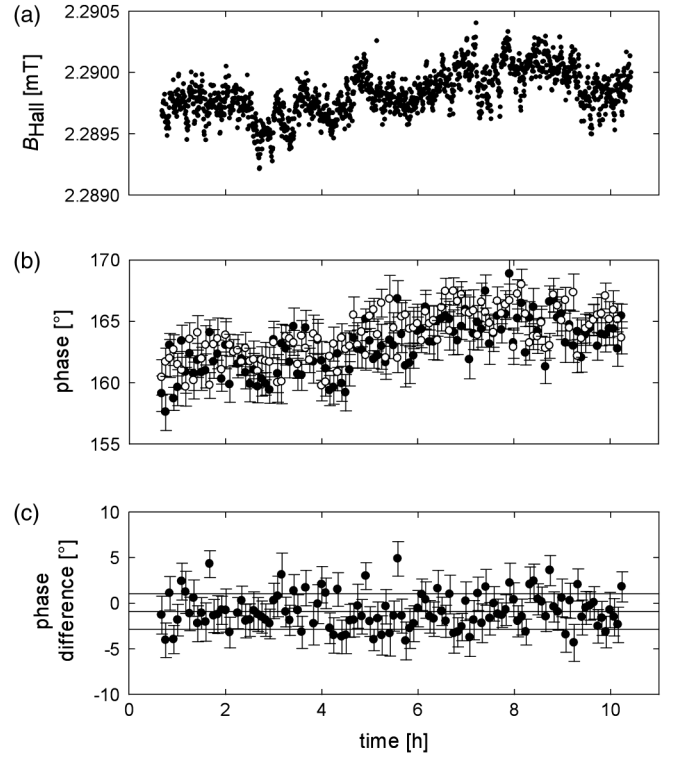

FIG. 3. Stability test of the Ramsey apparatus during approximately 10 hours. (a) Time histogram of the field magnitude seen by the 3D Hall probe in the vicinity of the B_0 magnet. (b) Individual phases of the Ramsey patterns of the sample (●) and reference beam (○). (c) Phase difference of the two beams. The horizontal lines indicate the mean constant offset $(-0.9 \pm 0.2)°$ and the standard deviation $\pm 1.9°$. The average individual error is also $\pm 1.9°$.

$$g_A^2 < \frac{4 m_n c^2}{l N \hbar c} \frac{1}{\lambda_c} (|\varphi_0| + 1.96 \delta \varphi). \qquad (4)$$

This leads to the exclusion plot presented in Fig. 4(b). It should be noted that for $\lambda_c < 0.5$ mm the size of the neutron beam was taken into account by performing a convolution over the beam distribution.

Finally, we consider possible systematic effects which could disguise a real or produce a false phase shift of the Ramsey signal. (i) One systematic effect might occur due to residual magnetic impurities at the surface of the sample. This was investigated by performing a fluxgate (Hall-probe) scan of the magnetic field in the z direction (y direction) close to the surface of the copper plate, at a distance of 4 mm (2.5 mm). The scans did not show any field inhomogeneity larger than 10 nT peak-to-peak for the fluxgate and 100 nT peak-to-peak for the Hall probe, respectively [15]. A numerical calculation shows that a single dipole at the surface, consistent with the field measurements, cannot induce a spin rotation larger than 0.02°. (ii) The diamagnetic property of copper ($\chi = -10^{-5}$) induces in the worst case—i.e., the neutron beam crosses the entire sample—a phase shift of $-0.2°$ in a field of 3 mT
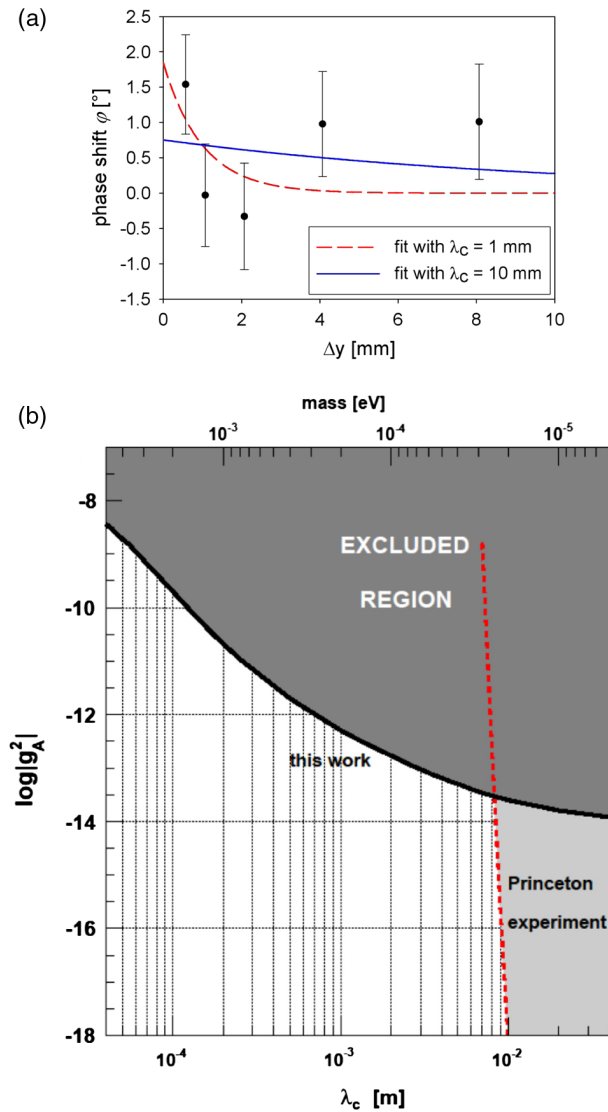
FIG. 4 (color online). (a) Phase shift due to the sample as a function of the distance Δy. The data have been corrected for possible drifts by using the reference beam. Two exponential fits to the data points with fixed λ_c are presented. (b) Exclusion plot for the axial-axial coupling g_A^2 (95% C.L.) as a function of the interaction range λ_c and the mass M of a new boson, respectively. The almost vertical dashed line represents the border of the exclusion region deduced from the experimental results by the Princeton group [8].

[16]. Since in the here presented experiment the neutrons do not penetrate the sample, the phase precession is much smaller and we can neglect this effect. (iii) The sample could influence the resonance condition of the $\pi/2$ spin-flip coils, which might produce a deviation of the relative phase of the locked rf signals. From off-line tests in which the rf signals of the spin flippers were recorded with and without a sample using two pickup coils, an upper limit of 0.1° can be stated. (iv) The largest field in the experimental area is produced by the sample magnet. All other sources of magnetic fields are further away and smaller. Hence, if

B_0 drifts, it could cause a change of the field gradient, which could yield a relative phase shift between the two beams. This effect is enormously suppressed due to the two-beam method and is smaller than 0.1° for a field drift of 4 μT, which is large considering the excellent stability of B_0 presented in Fig. 3(a). In summary, these possible sources for systematic errors are much smaller than the obtained statistical accuracy of about $\pm 0.75°$ [compare Fig. 4(a)] and, thus, can be neglected. However, if one increases the measuring time up to a week, chooses a broader neutron velocity spectrum of about 10%, and performs the experiment at a more intense neutron source (assuming a neutron flux increase by 10–100), the statistical precision could be improved with moderate effort by a factor of 10–30.

In conclusion, the search for a new spin-dependent fundamental interaction acting on nucleons has recently attracted increasing interest of a growing community of researchers. The case of a scalar (spin 0) boson mediating an *axionlike* interaction is actively investigated by using atoms [17], ultracold neutrons [18–20], and polarized ^{3}He [21]. We have presented a neutron Ramsey experiment to probe for the first time the case of a vector (spin 1) boson. This experiment yields an upper limit of $g_A^2 < 6 \times 10^{-13}$ for the axial-axial coupling at $\lambda_c = 1$ mm and represents, to our knowledge, so far the best method to probe spin-velocity interactions in the millimeter range.

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