Comment on "Improved Experimental Limit on the Electric Dipole Moment of the Neutron"

A recent measurement of the neutron electric dipole moment (EDM) [1] was influenced by a systematic "geometric phase" (GP) effect [2,3]. To analyze and account for this effect the authors use the deviation of the ratio of neutron and Hg comagnetometer frequencies, $|\omega_n/\omega_{\mathrm{Hg}}|$ from its expected value, $|\gamma_n/\gamma_{\mathrm{Hg}}|$, as a measure of the volume averaged magnetic field gradient, $\langle \partial B_z/\partial z\rangle_V \equiv G$, in the apparatus, due to the small offset in the centers of mass of the two gases caused by gravity. The gradient determined in this way is then used to calculate the systematic shift due to the GP effect. In order to establish a zero for this effect the authors then make use of the fact that the slope of the relation between the gradient and the frequency ratio deviation changes sign when the direction of magnetic field is reversed. However, the resonance frequency of the two species is shifted in opposite directions due to the Earth's rotation. This alters the gradient vs frequency ratio relationship in such a way as to mimic a true EDM.

In the presence of the Earth's rotation the relation between the frequency ratio deviation and G is given by (noting that $\gamma_n < 0$, $\gamma_{\mathrm{Hg}} > 0$)

$$\frac{G|\Delta h|}{B_0} = \pm(R_a - 1) - \left(\frac{\omega_\oplus \sin\theta_L}{B_0}\right)\left(\frac{1}{\gamma'}\right), \qquad (1)$$

where Δh is the offset in centers of mass, the plus sign is for B_0 pointing down, $\omega_\oplus/2\pi = 11.6\ \mu$Hz, the sidereal rotation frequency of the Earth, $\theta_L \approx 45°$ is the latitude of the experiment's location (Grenoble. France), and $(\gamma')^{-1} = |\gamma_n|^{-1} + |\gamma_{\mathrm{Hg}}|^{-1}$.

The principal method of GP error removal in [1] is based on the determination of the crossing point of the linear relationships between R_a and d_{meas} for field up and down. The effect of the Earth's rotation satisfies the criteria for systematic errors given by the authors (p. 131081-2, last paragraphs). The authors also state that, "The crossing point (R_{a0}, d_n') [of the two lines defined by their Eq. (5)] provides an estimate of d_n' free of $d_{n,\mathrm{Hg},f}$." The crossing point occurs at $R^* = (R_{a0\downarrow} + R_{a0\uparrow})/2$, with implication

$$d_{\mathrm{meas}} = d_n' + k\left[\frac{(R_{a0\uparrow} - R_{a0\downarrow})}{2}\right] \qquad (2)$$

$$= d_n' - k\left[\left(\frac{\omega_\oplus \sin\theta_L}{B_0}\right)\left(\frac{1}{\gamma'}\right)\right] + \ldots, \qquad (3)$$

where the up and down arrows refer to magnetic field up and down, respectively. With the experimentally determined value $k = 1.90 \pm 0.25 \times 10^{-26} e$ cm/ppm, Eq. (3) indicates an Earth rotation EDM value of $d_{n\oplus} = -(2.57 \pm 0.34) \times 10^{-26} e$ cm. Many of the systematic effects in Table I of [1] that contribute d_n' result from shifts in R_{a0}; the Earth rotation effect, $d_{n\oplus}$, is about 5 times larger than the largest entry in that table. Including $d_{n\oplus}$ in Table I and following the correction procedure of [1] results in $d_n = (2.7 \pm 1.5(\mathrm{stat}) \pm 0.5(\mathrm{syst})) \times 10^{-26} e$ cm. Therefore the systematic uncertainty and 90% confidence limit appear as underestimated in [1].

A second method used in [1] to extract d_n takes advantage of the fact that the $R_a - 1$ values for the up and down field seem to average to zero for the entire data set. However, as can be seen from Eq. (1) above, when this average is zero, a nonzero magnetic field gradient persists that compensates the Earth's rotation, implying the existence of a GP EDM, with value that is similar to $d_{n\oplus}$ from the crossing method.

In the Reply, two additional analysis methods are described; they were mentioned in [1] as "additional diagnostics." These methods rely on determining the zero gradient point by the T_2 relaxation time, or by use of a variable height bottle. These *ex post facto* methods, which are subject to the Earth rotation via Eq. (1), assume that the quadrupole magnetic gradient is a fixed property of the apparatus. It is reasonable to assume that there are gradient components that change when the magnetic shields are disassembled and reassembled, casting some doubt on the reliability of these methods, particularly given the apparent average mutual cancellation, to better than 6σ accuracy, between the background quadrupole field and the Earth rotation effect.

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