The Electric Dipole Moment of the Neutron

In 1952 Purcell and Ramsey raised a remarkably anticipatory issue[1] when they questioned the deduction that particles must have a zero electric dipole moment because the deduction rested on the assumption of parity conservation, an assumption which ultimately had to stand on experimental fact rather than theoretical fancy. Along with Smith they proceeded to test the assumption by searching for an electric dipole moment of the neutron in a magnetic resonance apparatus modified so that possible line shifts due to applied electric fields could be observed. They concluded[2] that the electric dipole moment (EDM) must be less than 5×10^{-20} e cm compared with the magnetic dipole moment which is about 2×10^{-14} e cm.

When, in 1957, it was discovered that the weak interactions were not parity-invariant the question of the neutron EDM was again closely inspected. It was found[3, 4] that for the EDM to exist *both* parity and time-reversal invariance must fail. In its simplest form the argument proceeds as follows.[5] We recall that a nonzero value for the pseudoscalar quantity $\langle \boldsymbol{\sigma} \cdot \mathbf{p} \rangle$, where $\boldsymbol{\sigma}$ and $\mathbf{p}$ are the spin and momentum of a particle, is a signature of parity violation as in $\pi \rightarrow \mu + \nu$ decay. Under the parity operation $\boldsymbol{\sigma} \cdot \mathbf{p}$ is odd since $\sigma \xrightarrow{P} \sigma$ and $p \xrightarrow{P} -p$. One detects the EDM magnitude μ_E by its interaction with an electric field E. We can write the interaction as $\mu_E \hat{\sigma} \cdot \mathbf{E}$ since the spin direction $\hat{\sigma}$ is the only vector that can be associated with the particle. This quantity is odd under parity since $E \xrightarrow{P} -E$. But we note too that $\mu_E \hat{\sigma} \cdot \mathbf{E}$ is simultaneously odd under time reversal since $\sigma \xrightarrow{T} -\sigma$ and $E \xrightarrow{T} E$. This is in contradistinction to the case of $\boldsymbol{\sigma} \cdot \mathbf{p}$ since this quantity is odd under parity but even under the time-reversal operation.

It was therefore concluded in 1957 that even with parity violation particles will not have an EDM because of time-reversal invariance. The small CP violation now observed in K^0 decay and the implied non-invariance under time reversal opens the Purcell–Ramsey question for the third time. A number of theoretical estimates of the neutron EDM have been made based on the magnitude of the CP violation in K^0 decay.

Depending on the model these range from $\sim 10^{-19}$ to $\sim 10^{-28}\ e$ cm. We refer the reader to a paper by Boulware[6] for a sample of these estimates. To the extent that these estimates can be considered hard numbers a new experimental limit on the neutron EDM, based on two new and quite different experiments, rules out some of the proposed models for *CP* violation.

One of the two new experiments[7] follows the method used by Smith, Purcell, and Ramsey. A very considerable refinement in the technique, however, has enabled the authors to decrease the limit by a factor of about 100 over the older value.

The basic idea is to observe the neutron magnetic resonance in a situation where, in addition to the usual magnetic field, an electric field, parallel to the magnetic, can be applied. A $\mu_E \hat{\sigma} \cdot \mathbf{E}$ interaction will shift the resonant frequency. Such a shift is most sensitively detected by adjusting the B field or radio frequency so that one is detecting neutrons about half way up the resonance curve and looking for variations in the magnitude of the signal as the polarity of the applied electric field is reversed. Certain systematic effects can be eliminated by observing on both the ascending and descending sides of the resonance curve. Of course, the greatest sensitivity is effected if the resonance line-width is made extremely narrow. This is done by using very slow neutrons selected by bent collimators (60 m/sec) and the split rf field technique originated by Ramsey. These authors average the results from the two sides of the resonance curve and obtain

$$\mu_E = (-2 \pm 3) \times 10^{-22}\ e \text{ cm}.$$

They make the observation that the result from one side of the resonance departs from the average by 3 standard deviations. This lack of consistency in the data is still to be understood. It is not clear from the paper whether the error quoted is the so-called external or internal error.

The results of the other experiment give about the same limit. Shull and Nathans, working at Brookhaven, have used nuclear electric fields to search for an EDM in the neutron.[8] They observe that an electric dipole will scatter *in the plane* of the (transverse) polarization with an imaginary amplitude of

$$f_{\mathrm{ED}}(\theta) = iZe(1-f)\mu_E / [\hbar v \sin(\theta/2)],$$

where Ze is the nuclear charge, $1-f$ is the electronic screening factor, v is the speed of the neutron, and θ is the scattering angle. For a cadmium nucleus and thermal neutrons this gives a scattering amplitude $|f_{\mathrm{ED}}(\theta)| \cong 0.2 \times 10^{-13}$ cm$/\sin(\theta/2)$ for $\mu_E = 5 \times 10^{-20}\ e$ cm.

The authors say that this is about 0.3% of the imaginary part of the nuclear scattering amplitude. As one reverses the direction of the spin the relative sign of the nuclear and EDM amplitude reverses. Therefore, one can expect a 0.6% effect in the scattering for $\mu_E = 5 \times 10^{-20}\, e$ cm. To enhance the signal-to-noise and discriminate heavily in favor of elastic scattering they observe the coherent first-order Bragg scattering from the 004 plane in CdS.

In experiments where null results are found there is always the question whether the effect in fact would have been seen if it were present. In this case there is a control. In the scattering plane at right angles to the one used in this experiment one has present the scattering of the well-known *magnetic* dipole from the Coulomb field of the nucleus. While this effect is relatively large compared to the effect sought in this experiment this so-called Schwinger scattering has been studied in detail and is well understood. It gives one confidence that if an EDM is present its effects are predictable.

A crucial part of the experiment is that the scattering plane be perpendicular to the plane in which the Schwinger scattering occurs. Indeed the Earth's magnetic field did introduce some Schwinger scattering and this was corrected for. It was finally determined that the difference in the scattering on reversal of the neutron polarization was 6.2 ± 9.9 parts in 10^5. Using the arguments above this translates into an EDM of $\mu_E = (+2.4 \pm 3.9) \times 10^{-22}\, e$ cm.

With these two results we are faced with a new limit for the EDM of the neutron of a few times $10^{-22}\, e$ cm. If the electromagnetic interaction is responsible in a maximal way for the *CP* violation observed in *K* decay[9] then a rough estimate of the EDM is 10^{-19}–$10^{-20}\, e$ cm. Saltzman and Saltzman[10] have proposed that the *CP* violation be explained through the existence of a *W* particle with an intrinsic EDM. This model leads to an EDM for the neutron of $\sim 10^{-20}\, e$ cm. Both of these proposals would appear to be ruled out by the new results. In view of the difficulties in making reliable estimates of the EDM these new results probably do not rule out the various theories so much as they make their proponents uncomfortable. But it's clear that, from these experiments, we still have not found the key to the ultimate origin of the *CP* violation.

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