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EXPERIMENTAL LIMIT ON THE PROTON ELECTRIC DIPOLE MOMENT

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A high-precision molecular-beam-resonance experiment has been carried out to look for a violation of P and T invariances in a molecule. The null result can be interpreted in terms of the electric dipole moment of the proton to give $|d_p| = (7 \pm 9) \times 10^{-21} e$ cm.

The presence of an electric dipole moment (edm) on an elementary particle is strictly forbidden if either P or T invariance is valid. Interest in the experimental search for an edm has intensified since the discovery of the CP-nonconserving $K_L{}^0 \rightarrow 2\pi$ decay.[1] While the CP nonconservation implies through the CPT theorem that T invariance is violated, there is as yet no direct experimental evidence.

Ramsey and his co-workers[2] have carried out a series of very precise beam-resonance experiments to look for an edm on the free neutron; their current limit is $d_n \leq 4 \times 10^{-23} e$ cm. An independent limit on the edm of the proton is obviously of interest but is very much harder to obtain because the proton is charged. For this reason an experiment on the free proton similar to that of Ramsey is not possible. There is also a very general theorem (see, e.g., Schiff[3]) that a charged particle in equilibrium under electrostatic forces has no term in the energy linear in the electric dipole moment. This would at first sight appear to rule out experiments in which the proton is bound in a neutral molecule; however, Schiff points out that this theorem is inadequate to the extent that the nucleus of an atom has finite size and structure. Using Schiff's theory one of us[4] has shown that a useful test for an edm on the proton is possible in a suitable molecular beam resonance experiment. In this Letter we report the results of a preliminary experiment on TlF to demonstrate the feasibility of the suggested scheme. The limit we are able to place on the proton edm is more than 5 orders of magnitude lower than the best previously published value.

The important result found in Ref. 4 is that in polar molecules containing a heavy atom the Schiff effect referred to above is large enough to be useful. An edm on the unpaired $s_{1/2}$ proton in the Tl nucleus experiences an average electric field of order 2×10^4 V/cm along the internuclear axis of the TlF molecule. The molecular rotation normally averages this field to zero, but if the molecule is placed in an external electric field the internuclear axis, and hence the field experienced by the proton edm, has a nonzero component along the external field. Under the conditions of our experiment this field component is approximately 1.2×10^4 V/cm.

Thus if we apply a magnetic field parallel to the electric field and excite the normal magnetic resonance of the Tl nucleus, the resonant frequency will depend on the magnitude of the proton edm. The effect of the edm can be isolated by reversing the direction of the electric field with respect to the magnetic field. Any edm interaction will change sign with respect to the magnetic moment interaction. Indeed, one can see on very general grounds that any change in the resonant frequency with the relative direction of electric and magnetic fields must imply a violation of P and T invariances.

Our apparatus is basically a standard electric-deflection molecular-beam machine as described in Ramsey.[5] The deflecting fields are set so that the only observable resonance involves a change in the rotational state (J, M_J) from $(1, 0)$ to $(1, \pm1)$. The desired nuclear resonance of Tl in which the nuclear spin projection changes from $\pm\frac{1}{2}$ to $\mp\frac{1}{2}$ is not directly observable because the rotational state is unchanged. It is therefore detected by means of two additional subsidiary resonances in the so-called "triple resonance method."[6] The majority of our measurements were made on the Tl nuclear resonance in the $(1, 0)$ rotational state of the more abundant isotope Tl^{205}. The resonance was excited in a magnetic field of approximately 26 G and an electric field of 8×10^4 V/cm. A Ramsey double-loop setup[5] was used. The central peak of the double-loop pattern was approximately 500 Hz wide and the resonance magnitude was of order 10^4 molecules/sec with a background about 5 times bigger than this.

As mentioned above, the basis of the experiment is to excite the Tl nuclear resonance in parallel electric and magnetic fields and then to look for a shift of the resonance frequency as one of the fields is reversed with respect to the other. Any such shift $\Delta\nu_D$ is likely to be very small, and sensitive methods of detection are needed. We have used an extension of the method employed by Ramsey in his experiments on the neutron. The oscillator frequency was set on the point of maximum slope of the resonance so that any shift in the resonant frequency was accompanied by a maximum change in beam intensity. One can readily show that the ultimate sensitivity of this method is given by the half-width of the resonance divided by the overall signal-to-noise ratio with which it is observed. The best attainable signal-to-noise ratio is in turn determined by the counting statistics of the particles in the beam. Thus by observing for long periods one can in principle attain considerable precision.

In order to do this it is obviously essential to get rid of all nonstatistical fluctuations, drift, and other spurious effects. In the present experiment this was achieved by extensive use of an online PDP-8 computer, which controlled such apparatus parameters as the directions of the electric and magnetic fields, which side of the resonance the oscillator was set on, and the relative phase of the two separated rf loops. The computer was programmed to change these parameters in a complex manner designed to remove all the undesirable nonstatistical effects. The data, in the form of particle counts, were fed directly into the computer, which extracted that part which behaved in the way expected of an edm effect. In addition, the computer simultaneously generated and detected various calibration and check signals which were fed on to the resonance to ensure that at all times the experiment was functioning satisfactorily, and that an edm shift would be detected if it were present.

With these methods we have been able to attain a sensitivity limited by counting statistics in runs lasting several hours and involving approximately 10^9 particles. A series of runs have been carried out, and the results have been analyzed to give an experimental value for the frequency shift of the resonance which behaves in the way expected of an edm effect. The result is

$$\Delta\nu_D = +0.08 \pm 0.11 \text{ Hz}.$$

With the theory given in Ref. 4, this can be interpreted in terms of the edm on the proton to give

$$|d_p| = (+7 \pm 9) \times 10^{-21} e \text{ cm}.$$

This result is more than 5 orders of magnitude lower than the previously available limit[7] of $3 \times 10^{-15} e$ cm which was obtained from a precession experiment on free protons. An improved version of this experiment is now being designed, and we expect to be able to increase the sensitivity by a further factor of at least 100. A more detailed description of the molecular-beam and on-line computer techniques used in this experiment will be published elsewhere.

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ELASTIC SCATTERING OF NEGATIVE PIONS FROM DEUTERONS AT 2.01, 3.77, AND 5.53 GeV/c *

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The differential cross sections for the elastic scattering of negative pions by deuterons have been measured for 2.01-, 3.77-, and 5.53-GeV/c incident pion momenta, over an interval of the squared four-momentum transfer from -0.25 (GeV/c)^2 to ~ -1.0 (GeV/c)^2. The results are consistent with calculations based on a Glauber model of the scattering process.

We have measured the differential cross section for elastic scattering of negative pions from deuterons at 2.01, 3.77, and 5.53 GeV/c. Our preliminary data at 3.77 GeV/c have already been presented.[1] Other differential cross-section measurements of high-energy scattering from deuterium have been made in the past.[2]

Measurements of πd elastic scattering test various multiple-scattering theories such as the Glauber formalism[3] or Regge-pole models.[4] Our measurements were performed in the four-momentum transfer region which, in the context of the Glauber model, is sensitive to both single and double scattering in the deuteron. The data are consistent with calculations based on the Glauber model using a deuteron wave function with a 7% D state and no variation of the phase of the πN scattering amplitude with scattering angle.

The experiment was performed in the 17° beam of the zero-gradient synchrotron of the Argonne National Laboratory. The beam transport system determined the momentum of the pions to ±1% and brought the beam to a final focus on a 2.31-in.-long liquid-deuterium target. The beam intensity varied from $(3 \text{ to } 7)\times 10^5$ pions/pulse depending on the beam momentum, with a pulse repetition rate of 1000 pulses/h. The beam angular divergence was ±5 mrad horizontally and ±3 mrad vertically.[5] The experimental apparatus used to detect the elastic events is shown in Fig. 1. The pion beam was counted by a series of scintillation counters labeled S_1, S_2, S_3, and S_4. Counters S_1 and S_2 are not shown in the figure and are located near the first focus of the 17° beam. The beam size was defined by S_4, a $\frac{3}{4}$-in.$\times\frac{3}{4}$-in. counter.

Elastic events were detected in a double-arm spectrometer consisting of the two bending magnets $M1$ and $M2$ and scintillation counter arrays A, B, and D. Each of the A and B arrays consisted of 16 elements; the D array consisted of 30 elements. The dimensions for the A, B, and