UPPER LIMIT OF THE ELECTRON'S ELECTRIC DIPOLE MOMENT *

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Various experiments have been carried out to measure a possible electric dipole moment of the electron. The literature has been summarized by J. Goldemberg and Y. Torizuka [1] who made one of the most recent measurements using the 180° electron scattering method. The theory underlying this method was suggested independently by B. Margolis et al. [2], and G. V. Avakov and K. A. Ter-Martirosyan [3].

The experiment of Goldemberg and Torizuka was carried out on He^4 gas at 41.5 MeV and at a value of the momentum transfer of $q = 0.44$ fermi^{-1}. This experiment has now been repeated at the higher energy of 100 MeV, using C^{12} as a target material with $q = 1{,}000$ fermi^{-1}. The results indicate an upper limit to the dipole moment of $\leqslant 0.9 \times 10^{-5}\ e\hbar/m_0c$. If expressed in terms of a length the dipole moment is less than 3.5×10^{-16} *e*-cm.

I. INTRODUCTION

Many experiments have been performed to detect a possible electric dipole moment of the electron, the existence of which would indicate a breakdown of quantum electrodynamics. The literature has been summarized by Goldemberg and Torizuka [1], who have attempted a recent measurement of this quantity. The most accurate determinations of the upper limit of the dipole moment have been made by scattering electrons from spin zero nuclei, the method suggested independently by Margolis et al. [2] and by Avakov and Ter-Martirosyan [3]. The results obtained by this method are shown in Table 1.

The cross section for the scattering of electrons from a spin zero nucleus is given by

$$\frac{d\sigma}{d\Omega} = \sigma_M F^2(q^2)\left[1 + \alpha^2(q^2)\left(\frac{\hbar q}{m_0 c}\right)^2 \times \frac{1}{1-\beta^2\sin^2\frac{\theta}{2}}\right], \quad (1)$$

Table 1

Upper limits of the electron's electric dipole moment, λ in units ($e\hbar/m_0c$) obtained by electron scattering

Momentum transfer, fermi-1	Scattering nucleus and angle	λ	Author
1.5—2.5	He^4 60°, 135°	$<2\times10^{-4}$	Burleson and Kendall [4]
0.44	He^4 180°	$<5\times10^{-5}$	Goldemberg [a] and Torizuka
1.00	C^{12} 180°	$<0.9\times10^{-5}$	Present experiment

[a] Uncertainties in the solid angle in this experiment have increased the dipole limit from the published [1] value J. Goldemberg, private communication.

where σ_M is the Mott cross section, $F(q)^2$ is the nuclear charge form factor at momentum transfer q, Θ is the scattering angle, and α represents the intrinsic electron dipole moment in units ($e\hbar/m_0c$). α^2 may in principle consist of two parts: $\alpha^2(q^2) = \lambda^2(q^2) + \mu^2\beta^2\left(1 + \frac{4}{\mu}\sin^2\frac{\theta}{2}\right)$, where λ, μ are possible intrinsic electric and magnetic dipole moments respectively. It is impossible to determine λ and μ separately. (μ is quite distinct from the electron's well established anomalous magnetic moment.) The possible dependance of α on the momentum transfer was suggested by Margolis et al. [2].

The expression (1) indicates that in attempting to measure α^2, it is advantageous to observe electron scattering at 180° where the Mott cross section is a minimum. At scattering angles near 180°, the cross section may be simplified by substituting in (1) : $\xi = \pi - \theta$ which gives

$$\left(\frac{d\sigma}{d\Omega}\right)_{180°} = \left(\frac{Ze^2}{2E_0}\right)^2 \frac{F^2(q^2)}{(1+2E_0/Mc^2)} \times \left[\frac{\xi^2}{4} + \frac{1}{\gamma^2}\right] + \left(\frac{Zr_0}{1+2E_0/Mc^2}\right)^2 F^2(q^2)\,\alpha^2(q^2) \quad (2)$$

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where $\gamma = E_0/m_0$ and M is the mass of the nucleus.

It is apparent that measurement of the angular variation and magnitude of the cross section around 180° enables the nuclear form factor and α^2 to be obtained independently. It should be noted that the residue of the Mott cross section at 180°, due to the finite electron mass, is significant in this type of experiment. In previous experiments, the target nucleus has been He^4, which provides the maximum amount of charge scattering at incident energies of order 100 MeV and has the simplest structure of the spin zero nuclei. However, the experiment may be performed in principle with any spin zero nucleus and C^{12} was chosen, mainly for convenience, in the present case.

The 2nd Born approximation to elastic electron-charge scattering was originally calculated by McKinley and Feshbach [5] whose results show that this correction to the Mott formula varies directly as ξ^2 around 180°. Thus if the cross section is measured as a function of ξ, no contribution to the 180° value is made by this correction. Goldberg [6] has examined 2-photon exchange scattering in which the nucleus is in an excited virtual state and concludes that any correction applicable to this type of experiment is of the same form as, but much smaller than the Coulomb correction, provided $q'M \ll 1$, so that this also has no effect on the result.

In principle it would be desirable to obtain limits on α^2 as a function of q. For the preliminary experiment, however, the momentum transfer was chosen to optimise the statistical accuracy in order to set as low a limit as possible. If the ratio (final statistical error/possible dipole scattering) is minimised for C^{12}, it is found advantageous to use $q \sim 1.0$ fermi^{-1} which corresponds to an incident electron energy of 100 MeV.

II. EXPERIMENTAL CONSIDERATIONS

In practice, at exactly 180°, charge scattering from the C^{12} nucleus is non-zero for the following reasons:

(a) Finite electron rest mass
(b) Finite solid angle
(c) Multiple scattering in the target
(d) Finite angular and spatial spread of the incident beam

If these effects are taken into account and (2) is integrated over a solid angle determined by horizontal and vertical spectrometer slits subtending angles at the target of $2\Delta\psi$ and $2\Delta\eta$ respectively, the total cross section obtained is:

$$\sigma_{180^\circ} = \Big\{ \Big(\frac{Ze^2}{2E_0} \Big)^2 \frac{F^2(q^2)}{(1+2F_0/Mc^2)} \Big[\frac{\xi^2}{4} + \frac{\Delta\psi^2+\Delta\eta^2}{12} + \frac{1}{\gamma^2} + \frac{\langle\theta^2\rangle_T + \langle\theta^2\rangle_B}{4} \Big] + \Big(\frac{Zr_0}{1+2E_0/Mc^2} \Big)^2 F^2(q^2)\, \alpha^2(q^2) \Big\}\, 4\Delta\psi\Delta\eta \qquad (3)$$

where $\langle\theta^2\rangle_B$ is the mean square angular spread of the incident beam and includes effects of the finite beam size, and $\langle\theta^2\rangle_T$ is the mean square multiple scattering angle for the total electron path within the target.

As electrons leave the target from the same face as they enter, $\langle\theta^2\rangle_T$ is not constant but may be calculated with sufficient accuracy from the measured energy loss of the electrons in the target.

In order to measure α^2 it is necessary to observe the cross section as a function of ξ around 180°. This determines $F^2(q^2)$ and enables one to subtract the charge scattering contribution at exactly 180°. However, double scattering of the electrons is significant in targets of thickness > 0.1 g/cm^2, so that this must also be subtracted in practice. A small correction was also necessary for the magnetic scattering from the 1.1% C^{12} in natural carbon.

III. APPARATUS

180° electron scattering was achieved with an apparatus similar in principle to that used by Goldemberg and Torizuka. This principle is illustrated in Figure, where scattered electron trajectories for an infinitely heavy nucleus are shown. For finite nuclei, $\varphi_f > \varphi_i$, but the cylindrical symmetry of the magnetic field enables the effective solid angle and scattering angles to be easily determined for any nucleus. With the magnet in its «central» position, electrons from the Stanford Mk III linear accelerator enter the uniform magnetic field radially and after being deflected about 35°, pass out of the field region and through the target. Those electrons scattered at ~801° pass through the field a second time and are analysed by a vertical 180°, $n = \frac{1}{2}$ magnetic spectrometer of mean orbit radius 72″.

It has already been indicated that in order to subtract the finite charge scattering at 180°, it is necessary to vary the scattering angle a few degrees either side of the backward direction. The most obvious way to do this is to vary the angular position of the spectrometer.

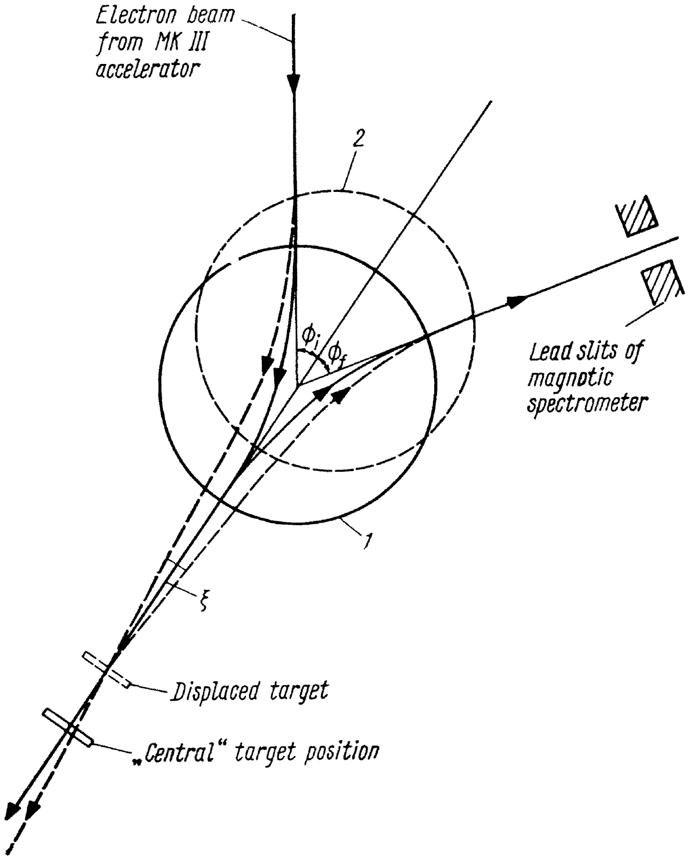

Diagram of the experimental arrangement of incident beam, deflecting magnet, target and spectrometer. 1 —«central» magnet pole position for 180° scattering; 2 — displaced magnet position for scattering at (180°— ξ).

However, if this instrument is to be used at its maximum solid angle, the mean electron trajectory entering the slits must be along the optic axis. Any small deviation from this condition severely restricts the available solid angle and as the effective target position is well away from the spectrometer's centre of rotation, only scattering angles very close to 180° can be obtained. Goldemberg and Torizuka varied the scattering angle by varying the magnetic field. This method also suffers from the above disadvantage however and scattering is not always from the same part of the target.

Figure indicates how the scattering angle was varied in this experiment. A displacement of the magnet, vacuum chamber and target along the line of the beam at the target, together with a slight change in the magnetic field enabled the scattering angle to be varied to 176° on either side with only a small (easily calculated) variation of the solid angle.

Elastically scattered electrons were detected by a 10 channel scintillation ladder mounted at the top of the spectrometer. For each scattering angle and target, 2 or 3 spectrometer settings were used.

IV. ANALYSIS OF THE DATA

The contributions to $F^2(q^2)$ and $\alpha^2(q^2)$ were obtained for each channel separately by fitting a parabola of the form (3) to the counts observed as a function of ξ. After allowing for the overlapping of the channels, a radiation correction was applied and the charge form factor and the apparent cross section at 180° were obtained for each run.

Three target thicknesses were used and the results indicated that double scattering of the electrons was significant. The statistics obtained however were not of sufficient accuracy to permit a useful extrapolation to zero target thickness. The effect of the double scattering for each target thickness was therefore calculated and the 180° cross sections were appropriately corrected. (The effective α^2 due to double scattering in the 0.607 g/cm² target was estimated to be $\alpha^2_{eff} = (0.38 \pm 0.08) \times 10^{-9}$, This is consistent with the value obtained by a phenomenological least squares fit to the 3 target data which gives $\alpha^2_{eff} = (0.59 \pm \pm 0.43) \times 10^{-9}$.)

Table 2

Results

Target g/cm²	No. of run	α^2, $\times 10^{-9}$ (double scat. subtracted)	fermi²
0.607 C^{12}	3	0.03 ± 0.20	0.139 ± 0.010
0.303 C^{12}	2	-0.05 ± 0.17	0.130 ± 0.007
0.159 $C^{12}H_2$	1	-0.21 ± 0.32	0.113 ± 0.014
Wted mean	6	-0.04 ± 0.12	0.130 ± 0.005

Upper limit (68% confidence level) : $\alpha^2 \leqslant 0.8 \times 10^{-10}$
equiv. length : $\leqslant 3.5 \times 10^{-16}$ cm

In table 2, the results are shown with the double scattering and C^{12} contributions subtracted. In order to qualify for inclusion in these results, each run had to exhibit a reasonable χ^2 fit of the data to expression (3) and the values for F^2 had to be consistent with the accepted value ~ 0.13 [7]. A check on the absolute efficiency of the apparatus was made by scattering from H^1.

(The possibility of experimental negative values for α^2 is of course entirely due to statistics and has no physical significance).

V. CONCLUSIONS

The upper limit of the electron's electric dipole moment obtained in this experiment is 3.5×10^{-16} e—cm.

Greater accuracy would be difficult to obtain using C^{12}, but further work it planned with a liquid He^4 target with which it should also be possible to investigate the dipole moment as a function of momentum transfer.

Establishment of a suitably low limit on the dipole moment will enable the apparatus to be used to investigate magnetic scattering from various nuclei.

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