On the Magnetic Moments of the Proton and Neutron

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ONE of the principal difficulties encountered by the theory of elementary particles is the explanation of the "anomalous" magnetic moments of the proton and neutron, for the moments are markedly different from the values of one nuclear magneton ($\mu_N=e\hbar/2Mc$) and zero, respectively, which would be expected from the Dirac equation. Current theories ascribe this difference to the effect of the circulation of mesons in the vicinity of a bare nucleon. All attempts at obtaining quantitative agreement between values calculated from this model and experiment seem to have been uniformly unsuccessful.[1] As a result, it may be of value to approach the problem from a somewhat different level of sophistication. In fact, as we shall see below, the most rudimentary semiclassical and dimensional considerations lead directly to extremely accurate formulas for the moments; in particular, the proton moment obtained in this way agrees *exactly* with the best available experimental value.

We begin by remembering that a characteristic length a which can be associated with the proton is the corresponding classical radius of a charged particle,[2] *viz.*, $a=2e^2/3Mc^2$. In addition, we recall that the existence of an isolated magnetic pole has been shown by Dirac to be compatible with the requirements of quantum mechanics.[3] The magnitude of this pole is $g=\hbar c/2e$. Since the dimensions of magnetization are those of field, i.e., pole/(length)^2, it is natural to take $I_0=g/a^2$ as the simplest formula for any magnetization which may be characteristic for this case. A sphere of radius a which is uniformly magnetized with magnetization I_0 has a magnetic moment

$$\mu_p=4\pi a^3I_0/3=4\pi ag/3=(8\pi/9)\mu_N.$$

Identifying this moment with that of a proton, we see that its value in units of μ_N is $8\pi/9=2.79253$. Within the experimental uncertainty, this agrees exactly with the value 2.79255 ± 0.00010 given by Mack.[4]

Magnetization can also be expressed as pole/area, so one may wonder what the consequences may be of considering a circle of radius a to be the fundamental area; this leads to a characteristic magnetization $I_1=g/\pi a^2$. Of more interest for us, however, is the difference, $\delta I=I_0-I_1=(\pi-1)I_0/\pi$. For a sphere of radius a, the similar use of δI leads to a moment

$$|\mu_N|=4(\pi-1)a^3I_0/3=(8/9)(\pi-1)\mu_N.$$

In this case $(8/9)(\pi-1)=1.90364$, while the neutron moment is 1.91280.[4] The discrepancy in the two values is less than $\frac{1}{2}$ percent of the experimental value; this discrepancy may result from the necessity of using a radius for the neutron slightly different from that which is useful for the proton. From above, we immediately obtain the convenient formula: $|\mu_N|/\mu_p=(\pi-1)/\pi$. This has the value 0.6817 as compared to the experimental value of 0.6850.

Although these models are suggestive and lead to the correct values for the moments, they are probably more of heuristic value than as a picture which can be taken literally. For example, the radius used is much smaller than that usually associated with nucleons, the latter being more of the order of the Compton wavelength, $h/Mc\approx e^2/mc^2\approx$range of nuclear forces. One would naturally prefer to obtain these numerical values directly from some general equation involving only e, $\hbar$, c, and m, say, rather than by invoking models of such specificity, but, in any case, the results obtained above are accurate and covenient formulas.

[1] For example: K. M. Case, Phys. Rev. **74**, 1884 (1948); J. M. Luttinger, Phys. Rev. **75**, 309, 1277 (1949); S. D. Drell, Phys. Rev. **76**, 427 (1949); S. Borowitz and W. Kohn, Phys. Rev. **76**, 818 (1949).
[2] M. Abraham and R. Becker, *Theorie der Elektrizität*, II, (Teubner, Leipzig, 1933), p. 43.
[3] P. A. M. Dirac, Phys. Rev. **74**, 817 (1948).
[4] J. E. Mack, Rev. Mod. Phys. **22**, 64 (1950).

Excited State of C^{14} from the $C^{13}(d,p)C^{14*}$ Reaction*

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AT present there is very little information concerning the excited states of C^{14}, and that which does exist has been confined to the $C^{13}(d,p)C^{14*}$ reaction. Bennett *et al.*,[1] using 1.0-Mev deuterons, found only the ground-state group with a Q-value of 6.09 ± 0.2 Mev. They concluded that there were probably no levels in C^{14} below 2.8 Mev. Humphreys and Watson,[2] using 3.8-Mev deuterons, reported two proton groups with Q-values of 5.82 ± 0.2 and 0.59 ± 0.3 Mev, which they assigned to the ground state of C^{14} and an excited level at 5.2 Mev. The increase in yield of the latter group with increased amount of C^{13} is not obvious from their published results. Recently, Curling and Newton,[3] using 0.93-Mev deuterons, measured a Q-value of 5.91 ± 0.03 Mev for the ground-state $C^{13}(d,p)C^{14}$ group. In addition, they observed a proton group, which, if assigned to the $C^{13}(d,p)C^{14*}$ reaction, would have a Q-value of 0.32 ± 0.03 Mev, corresponding to an excited state of C^{14} at 5.59 ± 0.04 Mev. This group occurred at the same range as a $N^{14}(d,p)N^{15*}$ group; however, they considered the group to be five times more intense than expected for the $N^{14}(d,p)N^{15*}$ group.

The gamma-radiations from $C^{13}+d$ have been measured by Thomas and Lauritsen.[4] They found a gamma-ray of 6.115 ± 0.030 Mev at 0.6-Mev bombarding energy which could only be assigned to the $C^{13}(d,p)C^{14*}$ reaction on the basis of energy considerations. In addition, they assigned a gamma-ray of 5.69 ± 0.05 Mev to the $C^{13}(d,p)C^{14*}$ reaction on the basis of the results of Curling and Newton.[3]

In view of the paucity of reported levels in C^{14} and also because C^{13} occurs as a contaminant on all targets (1.1 percent of natural carbon), it was decided to investigate the $C^{13}(d,p)$ reaction using the M.I.T. magnetic spectrometer. The targets used for this investigaton were prepared by allowing a few drops of a suspension of $BaCO_3$ in water to evaporate onto a thin film of Formvar stiffened by a thin layer of evaporated gold. By this method, targets were prepared of both normal $BaCO_3$ and $BaCO_3$ in which the C^{13} was enriched to 52 percent of the carbon content.[5] Direct evaporation of the $BaCO_3$ was not possible, inasmuch as it decomposes at high temperatures. The target thickness was estimated to be about 90 kev for the $C^{13}(d,p)C^{14}$ ground-state proton group. It was found that these targets survived long exposures to the bombarding deuterons, and their considerable thickness was not a disadvantage in the present work.

The lower curve in Fig. 1 indicates the results of a partial survey made at 1.507-Mev bombarding energy using an enriched $BaC^{13}O_3$

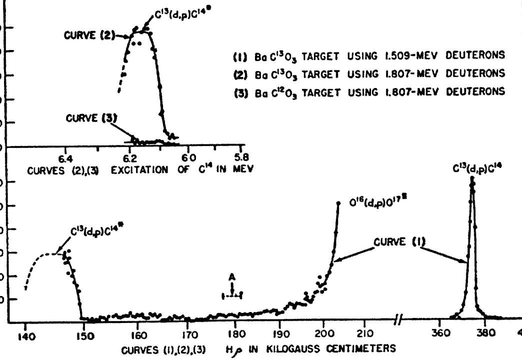

FIG. 1. Proton groups observed from targets of normal $BaCO_3$ and enriched $BaC^{13}O_3$ at bombarding energies of 1.509 and 1.807 Mev.