EFFECT OF NUCLEAR ELECTRIC DIPOLE MOMENTS ON NUCLEAR SPIN RELAXATION IN GASES *

P. A. Franken and H. S. Boyne
Physics Department, The University of Michigan, Ann Arbor, Michigan
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There has been much recent effort applied to the problem of particle and nuclear electric dipole moments (EDM). It is now known[1] that the electron EDM is less than $2\times10^{-4}\mu_b$, where μ_b is the Bohr magneton $e\hbar/2mc = e(1.8\times10^{-11}$ cm). The neutron[2] is known to have an EDM of less than $5\times10^{-6}\mu_N$, where μ_N is the nuclear magneton $e\hbar/2Mc = (1/1836)\mu_b = e\times10^{-14}$ cm. The situation for other particles is much less satisfying. The proton is know to have an EDM less than $\sim10\mu_N$, as evaluated from the Lamb shift.[3] Very little is known about nuclear electric dipole moments.

It is the purpose of this Letter to demonstrate that the nuclear spin relaxation times of pure gases at high pressures can be very sensitive to nuclear electric dipole moments.[4] We shall describe the analysis for noble gases and apply it to the experimental data available for He^3 and Xe^{129}.

Consider a gas of pure He^3 at Kelvin temperature T. Let us assume that the He^3 nucleus has an EDM equal to $K\mu_N$, where K is dimensionless for Gaussian units. The electric dipole-dipole interaction is responsible for a negligible contribution to the nuclear spin relaxation time providing the electric dipole moment is of order one μ_N or less.[5] The predominant EDM relaxation effect arises from the strong electric field the nucleus experiences during a collision. This electric field must be felt by the nucleus, despite electronic shielding factors, because the nuclear velocity is changed in the collision.

Consider a collision between two He^3 atoms. Rectangular coordinates are situated such that the z axis is collinear with an applied homogeneous magnetic field. Let us assume that the helium nucleus we wish to study has its spin along the magnetic field. During the collision this nucleus will suffer an acceleration $(\dot{V}_x, \dot{V}_y, \dot{V}_z)$. It must therefore experience an electric field $(M/Ze)\times(\dot{V}_x, \dot{V}_y, \dot{V}_z)$, where M is the nuclear mass and Ze the nuclear charge. The x and y components of this field can produce a spin flip, assuming the nucleus possesses an EDM. The collision time is very small compared with the period of nuclear precession in the magnetic field and the transition probability p is much less than unity. We find

$$p = 4M^2\mu_N^2K^2\left[(\Delta V_x)^2 + (\Delta V_y)^2\right](\hbar Ze)^{-2}, \qquad (1)$$

where ΔV_x and ΔV_y are the changes in the x and y components of velocity. The EDM has been taken to be $K\mu_N$, and the units are Gaussian.

An important feature of Eq. (1) is that the transition probability depends only upon the difference between the initial and final velocities. In order to calculate the spin relaxation time T_1, we shall require the average value of the transition probability per collision, $\bar{p}$, in terms of which the spin relaxation time T_1 is given by

$$T_1 = 1/(2N\bar{p})$$

where T_1 is in seconds and N is the number of collisions per second per atom. We shall assume that the scattering is isotropic and elastic, which assumption permits a ready computation of $\bar{p}$. We then obtain for T_1:

$$T_1 = [Ze\hbar]^2\,[6M]^{-1/2}\,[8\pi K^2\mu_N^2D^2n]^{-1}\,[kT]^{-3/2}, \qquad (2)$$

where n = density in number of atoms/cm^3 and D is the hard-sphere helium diameter. If we take $D = 2.5\times10^{-8}$ cm and assume that the ideal gas law is obeyed, we can rewrite Eq. (2) in convenient form for He^3:

$$K^2(\mathrm{He}^3) = 35\,T^{-1/2}\,[T_1P]^{-1}, \qquad (3)$$

where P is the gas pressure in atmospheres, T is in °K, T_1 is in seconds, and K is the EDM in units of the nuclear magneton.

Romer and Fairbank[6] have found T_1 to be $\sim10^3$ seconds for He^3 at ~ one atmosphere and 4°K. From Eq. (3), we conclude that EDM(He^3) $\leq 0.13\mu_N$.

Garwin and Reich[7] report a measurement for T_1 of 80 seconds at 70 atmospheres and 4°K. From Eq. (3) we conclude that EDM(He^3) $\leq 0.06\mu_N$. [The ideal gas law assumed in Eq. (3) does not obtain for this case, but it should be noted that the departure from ideality is in such a direction as to provide an even smaller upper limit for the EDM].

It is quite possible that the reported relaxation times are artificially short, in the sense that they could be due primarily to paramagnetic impurities in the sample and on the walls of the systems. If this is so, smaller limits might ultimately be placed on the He^3 EDM.

It should be noted that the relaxation time at constant pressure produced by magnetic dipole-dipole effects should go roughly as $T^{+3/2}$ as compared with $T^{-1/2}$ for the electric dipole effects. Thus, measurements at 300°C should provide an order or two of magnitude more sensitivity to the EDM.

The analysis discussed in this Letter can be applied to Xe^{129}, although the data here are not very precise. Brun, Oeser, Staub, and Telschow[8] report a T_1 measurement of 10^3 seconds for room temperature xenon gas at 50 atmospheres and a density 1.6 that predicted by the ideal gas law. Equation (2) yields

$$\mathrm{EDM}(Xe^{129}) \leq 0.04\mu_N.$$

The analysis might also be applied with fair approximation to polyatomic gases such as H_2 but the relaxation time is greatly reduced by interactions other than magnetic dipole-dipole. Thus the upper limits one can obtain for nuclear EDM with these gases are rather large, in the range of a few nuclear magnetons.

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[1]Nelson, Schupp, Pidd, and Crane, Bull. Am. Phys. Soc. 4, 250 (1959).

[2]J. Smith, Purcell, and Ramsey, Phys. Rev. 108, 120 (1957).

[3]G. Feinberg, Phys. Rev. 112, 1637 (1958); E. E. Salpeter, Phys. Rev. 112, 1642 (1958).

[4]During the preparation of this manuscript for publication we learned that Myer Bloom [Bull. Am. Phys. Soc. Ser. II, 4, 250 (1959)] has performed an apparently related calculation on relaxation times in the solid state.

[5]The dipole-dipole contribution to the relaxation time is proportional to the inverse fourth power of the moment, whereas the effect we shall consider is proportional to the inverse second power.

[6]R. H. Romer and W. M. Fairbank (private communication). We wish to thank Dr. Romer for discussions concerning these data.

[7]R. L. Garwin and H. A. Reich, Phys. Rev. (to be published). We wish to thank Dr. Reich for discussions concerning these data.

[8]Brun, Oeser, Staub, and Telschow, Phys. Rev. 88, 904 (1954).

ASTRONOMICAL TESTS OF THE EXISTENCE OF Li^4†

Hubert Reeves
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York
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Five years ago, the possible existence of the nuclear species[1] Li^4 was announced; an unstable isotope, decaying with a half-life of 0.4 sec, was detected, and there was reason to believe that this isotope could be Li^4. Because it seems that such an unlikely aggregate of nucleons (3 protons, 1 neutron) could not stay together long enough to decay by beta emission, the conclusion was drawn with judicious reserve.

This Letter has nothing to add for or against this unlikely nuclear species. But if the conclusion that Li^4 exists were correct, it would have important astrophysical implications; the whole theory of energy generation in stars might have to be modified.

Indeed, instead of the familiar proton-proton (p-p) cycle, one would have the following set of reactions:

$$H^1(H^1,e^+\nu)H^2(H^1,\gamma)He^3(H^1,\gamma)Li^4(e^+\nu)He^4.$$

The usual (p-p) cycle begins with the same two first steps, but involves $He^3(He^3,pp)He^4$ or $He^3(He^4,\gamma)Be^7$ instead of $He^3(H^1,\gamma)Li^4$. Because of the lower Coulomb barrier, the new third step is expected to be very much faster than either of the two former ones.

The Q value of the $Li^4(e^+\nu)He^4$ is estimated to be about 20 Mev. On the average, the electron and the neutrino each take half of this energy. In consequence, more than 40% of the energy released in the over-all nuclear process ($4p \to He^4$) would be lost as far as stellar core heating is concerned. Existing solar models would have to be revised, and higher temperatures assigned