On the Possibility of Electric Dipole Moments for Elementary Particles and Nuclei

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April 27, 1950

IT is generally assumed on the basis of some suggestive theoretical symmetry arguments[1] that nuclei and elementary particles can have no electric dipole moments. It is the purpose of this note to point out that although these theoretical arguments are valid when applied to molecular and atomic moments whose electromagnetic origin is well understood, their extension to nuclei and elementary particles rests on assumptions not yet tested.

One form of the argument against the possibility of an electric dipole moment of a nucleon or similar particle is that the dipole's orientation must be completely specified by the orientation of the angular momentum which, however, is an axial vector specifying a direction of circulation, not a direction of displacement as would be required to obtain an electric dipole moment from electrical charges. On the other hand, if the nucleon should spend part of its time asymmetrically dissociated into opposite magnetic poles of the type that Dirac[2] has shown to be theoretically possible, a circulation of these magnetic poles could give rise to an electric dipole moment. To forestall a possible objection we may remark that this electric dipole would be a polar vector, being the product of the angular momentum (an axial vector) and the magnetic pole strength, which is a pseudoscalar in conformity with the usual convention that electric charge is a simple scalar.

The argument against electric dipoles, in another form, raises directly the question of parity. A nucleon with an electric dipole moment would show an asymmetry between left- and right-handed coordinate systems; in one system the dipole moment would be parallel to the angular momentum and in the other, antiparallel. But there is no compelling reason for excluding this possibility. It would not be the only asymmetry of particles of ordinary experimence, which already exhibit conspicuous asymmetry in respect to electric charge. Although magnetic poles were used above as an illustration of a particular mechanism by which a nuclear electric dipole could arise, this is, of course, not the only possibility.

The question of the possible existence of an electric dipole moment of a nucleus or of an elementary particle in view of the above becomes a purely experimental matter. The evidence from most past experiments on molecules, atoms, nucleons, and elementary particles is not as conclusive as one might suppose. Most past experiments are in fact very insensitive to the effects of a nuclear electric dipole, because of the smallness of the electric field at the position of a charged nucleus or the antisymmetric nature of the electric dipole potential. We have analyzed a number of experiments including conversion of ortho- to parahydrogen, depolarization of neutron beams, ionization by neutrons, relaxation times of nuclei in liquids, nuclear scattering of neutrons, hyperfine structure studies, the Lamb-Retherford experiment, and the experiments on the interaction of electrons and neutrons. Non-scattering experiments on charged nuclei are particularly insensitive to the existence of an electric dipole moment and even the most favorable would not have revealed an electric dipole moment smaller than the charge of the electron multiplied by a distance D less than 10^{-13} cm. The scattering experiments[3,4] to detect an electron-neutron interaction are by far the most sensitive; the results of Havens, Rabi, and Rainwater[3] would correspond to a D of 3×10^{-18} cm if they were due to an electric dipole moment.

We are now undertaking, in collaboration with Mr. James H. Smith, an experiment which should directly measure the electric dipole moment of the neutron if it has a value of D of approximately the above magnitude. The experiment will utilize a neutron beam magnetic resonance[5] apparatus of high resolution[6] to detect a possible shift of the neutron precession frequency upon the application of a strong electric field.

The authors wish to thank Mr. Smith for suggesting an important correction to our original calculation on the neutron-electron interaction experiment.

[1] A typical argument is given by H. A. Bethe, *Elementary Nuclear Theory* (John Wiley and Sons, Inc., New York).
[2] P. A. M. Dirac, Phys. Rev. **74**, 817 (1948).
[3] Havens, Rabi, and Rainwater, Phys. Rev. **72**, 634 (1947).
[4] E. Fermi and L. Marshall, Phys. Rev. **72**, 1139 (1947).
[5] L. W. Alvarez and F. Bloch, Phys. Rev. **57**, 111 (1940).
[6] N. F. Ramsey, Phys. Rev. **76**, 996 (1949).

Supernovae*

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April 27, 1950

SUPERNOVAE of type I are characterized by: (a) a high intensity maximum of 20 to 30 days duration; (b) an exponential tail to the light curve of half-life 55 days ($\Delta m=0.0137\pm0.0012$ magnitudes per day;[1] (c) an integrated visual light emission of nearly 10^{49} ergs;[1] (d) a residual gaseous shell of low hydrogen content expanding at a velocity[2] of 1300 km/sec. and radiating 10^{36} ergs/sec. visible light about 900 years later.[3]

These characteristics may be accounted for by the following proposed mechanism. The original star, of mass many times the sun, e.g., $15M_\odot$, undergoes gravitational contraction after burning its hydrogen. As the contraction progresses the central temperature will rise until a new reaction occurs. At a temperature of 2 to 3×10^9 °C a second-order endothermic reaction will occur between alpha-particles

$$2\alpha\rightarrow Be^7+n,\quad Q=-18.6\text{ Mev}.$$

This reaction absorbs energy at the center of the star, permitting rapid gravitational collapse. The reaction rate can be calculated by methods of simple chemical kinetics since barrier penetration is a negligible correction at an energy of 19 Mev.

$$Z=N^2r^2(4\pi kT/m)^{\frac{1}{2}}e^{-(Q/2kT)},$$

where Z is the number of processes per second cm^3; N is the number of particles per cm^3; r and m are the radius and mass of the alpha-particle (1.6×10^{-13} cm and 6.6×10^{-24} g); Q is the reaction threshold; k is the Boltzman constant and T is the temperature. It may be noted that the reaction velocity per unit volume increases as the square of the helium concentration and exponentially with the temperature. The reaction will therefore accelerate under conditions of gravitational collapse, so that the star may collapse in a time approaching free fall.

The reaction will proceed until there are sufficient concentrations of the reaction products to produce the reverse reaction. The expression at equilibrium may be given

$$K=[Be^7][n]/[He]^2,$$

where the entries denote atomic concentrations per unit volume. Since neutrons will be absorbed rapidly in a system containing

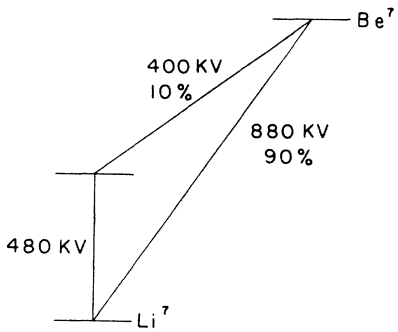

FIG. 1. Decay scheme of Be^7.

heavy elements and heat is removed in the formation of Be^7, the equilibrium will favor the production of Be^7. Even if the system achieves equilibrium, the equilibrium will be displaced toward Be^7 by increased pressure, or temperature.

The reaction may always be rate controlled, however, and may never reach equilibrium during the collapse process.

Neutrons generated will be absorbed by the heavy elements present in the star. Nitrogen in particular has a (n,p) resonance of 0.1×10^{-24} cm^2 cross section at 550 kev. Since the most probable energy at 3×10^9 °C is 260 kev, and nitrogen may be expected to be present to an extent of 0.1 to 1 percent, nitrogen will be an important absorber.

After collapse the star becomes unstable and explodes, driving off a considerable fraction of its mass as an expanding gas cloud, probably leaving a core in a highly degenerate state. The exact mechanism of this explosion is not understood. Several possible mechanisms are: (a) the formation of a highly degenerate core, driving the outer layers away by radiation pressure;[4] (b) accelerated decay of Be^7 at increased electron density and the regeneration of helium from Li^7 and hydrogen; (c) rotational instability of the star.

The expanding gas envelope carries with it the Be^7 and C^{14} produced by the reaction. As the density drops, the thermal energy is radiated away as the initial maximum of the light curve. Thereafter the energy source is Be^7 ($T=52.9$ days), decaying according to the decay scheme of Fig. 1. The energy source will follow an exponential curve unless, (a) the diffusion of light to the surface of the gas envelope takes a long time compared to the radioactive life or, (b) the gas envelope becomes so tenuous as to permit appreciable loss of the 480-kev gamma-rays. In the case of two well-known supernovae, observed in 1054 A.D. and in 1937 in extragalactic nebula IC 4182, these restrictions were not found to be limiting from 40 days to 600 days past maximum. The quantity of Be^7 required for these stars was 3×10^{32} g.

After the decay of Be^7, the energy source may progress through intermediate periods, representing fortuitous neutron induced activities, but will rapidly approach the period of C^{14} ($T_{\frac{1}{2}}=4700$ years). In the case of the supernova of 1054 A.D. the gaseous envelope, the Crab nebula, is readily observed.[3] Its energy source corresponds to 10^{32} g C^{14}. Assuming an initial mass of 4×10^{34} g, the nebula should contain about 0.2 percent C^{14} and about 0.7 percent Li^7. Spectroscopic data show an unusually low abundance of hydrogen (<5 percent) but show helium, nitrogen and oxygen.[5] The abundances of these elements have not been derived from the spectrum.

Experiments will be initiated to measure the Be^7 yield from the (α,α) reaction. A more extensive discussion will be presented for publication in this Journal.

* This work was done at Brookhaven National Laboratory under the auspices of the AEC.

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The Chromium Isotope of Mass 55

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April 21, 1950

THE isotope of chromium of mass number 55 has been reported by several investigators to be radioactive, with half-lives of 1.3, 1.6, and 2.3 hr.[1] These observations resulted from the bombardment of chromium with deuterons and slow neutrons, and the activity of about two-hour half-life was attributed to Cr^{55} resulting from a (d,p) or (n,γ) reaction. Most of these reports stated that the activity in question was weak. The absence of a chromium activity of about two-hour half-life among the spallation products of copper[2] and arsenic[3] with high energy deuterons has emphasized the need for further investigation of this assignment.

In order to clarify the situation, 6.0 g of manganese dioxide was irradiated for 2.7 hr. with neutrons of maximum energy 16 Mev, produced by bombarding lithium with 56 microampere-hours of 1.4 Mev deuterons. The irradiated MnO_2 was dissolved in a nitric acid-hydrogen peroxide mixture, inactive Cr^{+3} added as carrier, and the chromium fraction chemically separated and purified. The chemical procedure included $Cr(OH)_3$ precipitation, removal of manganese as MnO_2 from concentrated nitric acid, and several extractions of peroxychromic acid from dilute nitric acid into diethyl ether. One-tenth of the purified chromium fraction was mounted and counted with an end-window (*ca.* 3 mg mica/cm^2). Geiger-Müller tube at about 10 percent geometric efficiency. The activity observed 2.5 hr. after the end of the bombardment was not appreciably different from the background rate; a maximum of five counts per minute might have been due to radioactivity in the chromium sample. It should be pointed out that the counting system used would not have detected electrons of energy less than about 0.07 Mev. One would certainly expect, however, that a β^--emitter of several hour half-life would emit electrons having an energy appreciably greater than 0.07 Mev. Seren, Friedlander, and Turkel[1] report a mass absorption coefficient of 8.3 cm^2 per g of aluminum for the electrons of their 1.3-hr. activity, corresponding to an electron energy of one to two Mev.

The only unstable chromium isotope which could have resulted from this irradiation is Cr^{55}, produced by a (n,p) reaction on Mn^{55} (the only stable manganese isotope). The results of this investigation (assuming 100 percent counting efficiency) indicate that, if Cr^{55} has a half-life in the previously reported range (1.3 to 2.3 hr.), the cross section for its formation by $Mn^{55}(n,p)$ is less than 5×10^{-5} barn. Alternatively, if a cross section of greater than 10^{-2} barn is assumed, Cr^{55} would have to possess a half-life of less than 15 min. or greater than 100 days in order to have escaped detection.

Nelson and Pool[4] have recently reported results in agreement with these findings. They found no indication of a two-hour chromium isotope by a (d,p) reaction on Cr^{54}—enriched Cr_2O_3, nor by a (n,α) reaction on Fe^{58}-enriched Fe_2O_3. Present evidence therefore seems to offer no substantiation to the assignment of a one- or two-hour activity to Cr^{55}.

The author wishes to thank Mr. W. B. Dayton for his cooperation in performing the cyclotron bombardment.

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Temperature Dependence of the Energy Gap in Monatomic Semiconductors*

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April 20, 1950

EXPERIMENTAL evidence indicates that the energy gap in a semiconductor depends upon the temperature. The long wave-length edge of the optical absorption band for both silicon[1] and germanium[2] shifts toward shorter wave-length as the temperature is decreased. The threshold of photoelectric effects in these materials shows corresponding shifts.[3] Furthermore, the variation of intrinsic concentrations of free electrons and holes in silicon, calculated from resistivity and Hall effect data, was found to lead to a temperature dependence of the energy gap.[4]

The volume of the crystal and the excitation of the lattice vibrations change with temperature. Both these effects can produce shifts in the energy levels, thereby changing the energy