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ULTRACOLD NEUTRONS AND THEIR POTENTIAL VALUE IN GRAVITATIONAL RESEARCH

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SUMMARY

This essay studies the properties of cold neutrons and the problems involved in the generation of an ultradense neutron gas suitable for experiments in gravitation. New methods for obtaining large numbers of ultracold neutrons are proposed. It is shown that the Fermi exclusion principle presents an obstacle to the condensation of the cold neutrons into a dense form of matter, but two possible mechanisms for bypassing this limitation through the formation of bosons are pointed out. Even assuming that a stable, ultradense neutron gas can be formed, it is shown that in order to generate a strong artificial gravitational field, even over a very small region, it will be necessary to wait for the development of fusion power sources, which produce large numbers of neutrons during their operation.

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INTRODUCTION

It has been emphasized in previous work that one of the research areas that will lead to the control of gravitation is the study of the generation, containment, and control of ultradense matter.[1] Of all the particles that could be considered by the experimenter looking for methods of obtaining dense matter, the neutron is of most interest because of its availability and lack of charge.

PROPERTIES OF NEUTRONS

This section outlines the known characteristics of the neutron and its interaction with various environments. The fundamental properties of the neutron are fairly well known and are summarized in the following table.[2]

Spin		$\frac{1}{2}$ (Fermi-Dirac statistics)
Decay		
	Half-life	12.8 minutes
	Decay time	1110 sec
	Energy	782 keV
Magnetic Moment μ		-1.913 nuclear magnetons
Mass m		1.00898 amu

The kinetic energy of a neutron can be expressed directly in energy units, or in terms of the velocity, wavelength, or equivalent temperature. Each of these various equivalent properties is valuable in demonstrating the behavior of the neutron.

$$E = 1/2\, mv^2 = 1/2\, \frac{h^2}{m\lambda^2} = kT \quad .$$

Since a neutron has wave properties, with wavelengths in the angstrom region, it is valuable to consider periodic structures for the control of neutrons. They have already been used to some extent with room temperature neutrons from a fission reactor.[3] Here the wavelength of the neutron

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is comparable to atomic dimensions (1 to 2 Å), and reflection from crystalline structures is used to form and direct beams of monochromatic neutrons. It is proposed to use multilayer thin film structures of beryllium, lead, nickel, and lithium for the construction of filters and reflectors for use with ultracold neutrons with very long wavelengths (> 100 Å).

The potential energy of a neutron can arise in various ways depending upon the interaction of the various intrinsic properties of the neutron with the environment. These considerations are important in the problem of developing potential energy walls to control or contain neutrons whose kinetic energy is comparable to the potential energy of the barriers. The following forms of potential energy have been identified:

Magnetic — Since the neutron has a magnetic moment, when it is in a magnetic field it has a potential energy given by

$$E_m = \pm \mu B$$

where the sign depends upon the orientation of the magnetic moment with respect to the field direction.

Gravitational — Since the neutron has a mass, it has a potential energy due to the gravitational field of the earth of

$$E_g = mgh \; .$$

Although usually very small, this energy is sufficiently large that it must be considered in problems of neutron containment.[4]

Meissner Effect — Since the neutron has a magnetic field, it can experience repulsion by a superconductor. The problem is equivalent to the repulsion of a magnetic dipole by its image in the superconductor:

$$E_s \approx E_\mu = \frac{\mu\mu}{4\pi r^2} \; .$$

This is always negligibly small.

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Self Gravitational — A sphere of neutrons has a gravitational field. If it is sufficiently dense, the force next to the surface can be many g's. (This is shown later.) Although the forces are large, the gravitational potential energy of the sphere

$$E_G = \frac{GmM}{R}$$

is very small even for large masses and high densities.

Nuclear — The nuclear forces between a neutron and an atom are varied and complex. The most useful part of this interaction for the study of cold neutrons is the coherent scattering cross section of the atom for the neutron. This can be described by saying that the neutron has a potential energy inside a material which differs from that outside and which is given by

$$E_n = \frac{h^2}{2\pi m} Na$$

where

$a \equiv$ the nuclear coherent scattering amplitude for a single atom of a given nuclear species

$N \equiv$ the number density of the atoms.

The total potential is seen to be the coherent sum of the individual potentials.

NEUTRON OPTICS

Hughes[5] has pointed out that potential energy interactions can be compared with the early work in corpuscular optics, and he has given an expression for the "index of refraction" of a material for neutrons of the form

$$n^2 = 1 - E_n/E - E_m/E$$

$$= 1 - \frac{Na}{\pi}\lambda^2 \pm \frac{\mu B}{E}$$

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where E is the kinetic energy of the neutron. In this expression, the other sources of potential energy are neglected as small compared with the nuclear and magnetic potential energy. Since both the magnetic and the nuclear potential energies can be positive or negative depending upon the nuclear scattering amplitude of the atoms and the orientation of the magnetic moment of the neutron with respect to the magnetic field in the material, we see that the index of refraction can be greater or less than one. If the index is less than one, then we can have total reflection at the surface for angles less than the critical angle. If the energy of the neutrons is sufficiently low, then the index of refraction becomes less than zero, and the neutrons cannot enter the material even at perpendicular incidence. This leads to methods for perfect containment of cold neutrons.

CONTAINMENT OF COLD NEUTRONS

The basic method of containment of cold neutrons is the construction of a potential energy well which will capture any neutron which has a kinetic energy smaller than the potential energy of the barriers. Various possible methods of constructing this well have been discussed in the Russian literature.[4,6,7] The most promising in terms of ease of construction and height of the potential barrier are the configurations that use hollow spheres made of beryllium or carbon,[6,7] which have a large coherent scattering amplitude. Since the neutron waves penetrate a little way into the material of the walls, there is some loss by capture, which leads to requirements for containers 1 m across. It is proposed that walls made of superfluid helium films may be of more value. Helium also has a positive coherent scattering amplitude; although the condition of total reflection occurs only for neutrons with velocity less than 2 m/sec, the very small capture cross section for helium (so far too small to be measured) will prevent wall losses and allow construction of smaller containers.

Other methods of control and containment using walls made of magnetic fields have been proposed, as well as combinations which use attractive magnetic potentials and repulsive centrifugal forces.[4]

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The collective interactions of a large number of neutrons are not well enough known to enable one to be sure of their effect on the formation and containment of a cold neutron gas, although a number of papers have discussed the problem.[8-13]

GENERATION OF COLD NEUTRONS

The best source of neutrons today is the large thermal neutron flux available from fission reactors. These neutrons have a Maxwellian distribution of velocities with a maximum at 2200 m/sec. If one wishes to contain the neutrons by trapping in a potential energy well, only those in the low energy tail will be available and these correspond to 10^{-8} of the total thermal flux. If we cool the neutrons by inelastic scattering in cryogenically cooled substances such as solid methane cooled with liquid helium,[14,15] the Maxwellian distribution can be shifted to lower energies. Even with this precooling, only 10^{-5} of the neutrons are moving slowly enough to be trapped. This thermal cooling process using inelastic scattering has been found to become very inefficient at these low temperatures due to the lack of energy absorbing mechanisms, and it is doubtful that colder moderators would give higher fluxes even if they were available.

A new method of cooling neutrons below cryogenic temperatures is proposed which would involve the use of moving, decelerating, potential barriers that "catch" the neutrons in a beam and decelerate them to zero velocity. Either sequentially operated magnetic field coils or moving walls of a neutron repelling material, such as beryllium,can be used. A complete study of these various mechanisms is in progress. As an example of this type of operation, consider a neutron with kinetic energy E entering a solenoid with its spin in the high energy orientation. As it enters the coil through the high magnetic gradients, its energy is decreased by an amount μB, so that inside the solenoid it has the energy $E - \mu B$. While the neutron is inside the solenoid, the magnetic field is reversed. Because there are no gradients inside the coil, no energy transfer takes place; when the

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neutron leaves the other end of the solenoid, it again must climb up a potential well, losing more energy. After traversing n solenoids the energy of the neutron is

$$E_n = E_o - 2\, n\mu B \ .$$

Application of these and similar techniques will lead to the development of long decelerators which when used with the thermal fluxes of fission or fusion reactors will result in the production of large quantities of ultracold neutrons, which can then be captured and investigated to determine the behavior of a cold neutron gas.

DENSE NEUTRON GAS

We have shown that it is possible to cool, collect, and store an appreciable number of neutrons to obtain a rarefied, cold neutron gas. Although there are no electrostatic forces between the neutrons and there is an attractive nuclear force, it is not necessarily true that the gas will condense into a cold supernucleus of high density. Neutrons with spin 1/2 are fermions, and when fermi particles are collected in one place they cannot have the same energy. Although the first neutrons are cold, the later neutrons must be inserted into the region with a finite energy which depends upon the density. These "warm" neutrons will be difficult to contain. Since the various methods for containment cannot hold neutrons with energies much greater than 10^{-7} eV, we find that the Fermi exclusion principle will limit our neutron densities to 10^{-8} gm/cm^3 (10^{22} neutrons/m^3).

However, there is a strong possibility that this limitation may be overcome by nature itself. If an even number of neutrons are coupled together by some mechanism, the resulting "particles" are bosons, which do not have this Fermi energy limitation. In fact, bosons are known to have a tendency to seek a condition of high density in momentum space, usually in the ground state. This phenomenon is well illustrated by the unusual behavior of superconductors and superfluid helium. There are two ways in

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which bosons can form in a neutron gas. One is for the neutrons to join up directly to form dineutrons (n^2) or tetraneutrons (n^4). It is generally believed that a dineutron is unstable[16,17]; however, this may not be true in an environment of a dense neutron gas. In any case, it is expected that the tetraneutron will be stable against nucleon emission,[18] and the conditions expected in a cold neutron gas will give it an ideal opportunity to form.

Another mechanism will allow a phase space condensation. The electrons in superconductors are fermions, but when they are cold they are found to collect in the ground state. This is because pairs of electrons interact through various secondary mechanisms to form "quasi"-particles with Bose statistics. It is also possible that a cold neutron gas could set up collective interactions that would result in superfluid behavior with a condensation in phase space and, hopefully, a similar condensation in real space.

Although it is possible that a superheavy nucleus could condense out of a neutron gas by the formation of bosons and be stable against nucleon emission, it is very doubtful that it will also be stable against beta decay.[18] However, in our present state of knowledge there is no way to predict the decay rate.

GRAVITATIONAL PROPERTIES OF A DENSE NEUTRON GAS

We have pointed out the difficulties that prevent us from obtaining an ultradense neutron gas. Let us suppose that all these difficulties have been overcome and we are able to obtain a reasonable amount of ultracold neutrons in the form of a stable superheavy nucleus. Let us now consider its gravitational properties.

It was pointed out in a previous essay[1] that in order to obtain measurable non-Newtonian forces it was necessary to have not only dense matter but also relativistic velocities. It is possible that the conditions for the formation of superheavy nuclei may require that the particles in the nucleus orbit at high speeds. If so, then the superheavy nuclei will have

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non-Newtonian gravitational properties; however, it is not necessary to postulate such a behavior, since the ordinary Newtonian potential of a very dense mass is of sufficient interest in itself. The Newtonian gravitational field depends not only upon the mass of the gravitating body, but also on its density. Even a very small mass can have a large gravitational field if it is sufficiently dense.

$$a = \frac{F}{m} = \frac{GM}{r^2} = \frac{4\pi}{3} G \rho r$$

If we assume that nuclear densities can be reached in a collection of cold neutrons, or $\rho \approx 10^{15}$ gm/cm^3, then the gravitational field at the surface of a small sphere of a micron radius of this density will be

$$a = 2.8 \times 10^{-10} \rho r \approx 300 \frac{m}{sec^2}$$

which is about 30 g's. The total mass of this object will be

$$M = \frac{4\pi}{3} \rho r^3 \approx 4 \text{ kg.}$$

Although this object has very small dimensions, for a first step in the field of gravitational control it would be very valuable since the gravitational field obtained is quite high. This particular configuration of the dense matter also has a very high gravitational field gradient of

$$\frac{da}{dr} = \frac{4\pi}{3} G\rho = 2.8 \times 10^{-10} \rho \approx 3 \times 10^{7} \frac{g's}{m} .$$

These high field gradients will have interesting properties in themselves since the differential forces on an object passing near the gravitating body will be quite high.

A configuration without a field gradient is a dense matter disc. It is well known that this configuration has a field given by

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$$a = - 2\pi G\rho h \left[1 - \frac{r}{(R^2 + r^2)^{1/2}} \right] \approx - 2\pi G\rho h \ ,$$

which for $R > r$ has no gradient. Thus if the disc is large enough or the test object is close enough to the center of the disc, the acceleration or gravitational force is essentially constant. If we assume that we want a one g field in the upward direction underneath the disc, so that we can create a gravity free region on the earth, then the product of the density and the radius must satisfy the condition that

$$\rho h \approx \frac{g}{2\pi G} = 2.34 \times 10^{10} \ .$$

For nuclear densities, where $\rho \approx 10^{15}$ gm/cm^3 the necessary height is about 200 Å. For an area about 10 μ in diameter, this corresponds to a total mass of about 2 kg.

It is no easy matter to collect a kilogram of neutrons. Besides the inevitable losses involved in cooling and capturing them, there is the problem of making them. If we plan to use a uranium pile as the source, to collect 1 kg of neutrons will require at the very minimum the fissioning of 235 kg of uranium. A D-D fusion reaction is much more promising since half of the reactions produce neutrons in the $D(d,n)He^3$ reaction, and only 8 kg of deuterium are required to produce 1 kg of neutrons. Thus the number of available neutrons per second per megawatt of reactor power is orders of magnitude larger for a fusion power plant. Again we see that future research in the field of gravitation will involve vast amounts of money, energy, and effort.

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REFERENCES

1. R. L. Forward, "Guidelines to antigravity," Gravity Research Foundation Essay — 1962; Am. J. Phys. 31, 166 (March 1963).
2. American Institute of Physics Handbook (McGraw-Hill Book Co., New York, 1957), pp. 8-129.
3. D. J. Hughes, Pile Neutron Research (Addison-Wesley Publishing Co., Cambridge, Mass., 1953).
4. V. V. Vladimirskii, "Magnetic mirrors, channels and bottles for cold neutrons," Soviet Phys. — JETP 12, 740 (April 1961).
5. D. J. Hughes, Neutron Optics (Interscience Publishers, Inc., New York, 1954).
6. Ya. B. Zel'dovich, "Storage of cold neutrons," Soviet Phys. — JETP 9, 1389 (L) (1959).
7. A. G. Doroshkevich, "Storage of cold neutrons," Soviet Phys. — JETP 16, 56 (January 1963).
8. F. G. Werner and J. A. Wheeler, "Superheavy nuclei," Phys. Rev. 109, 126 (January 1958).
9. E. E. Salpeter, "Matter at high densities," Ann. Phys. 11, 393 (December 1960).
10. Ya. B. Zel'dovich, "The existence of new isotopes of light nuclei and the equation of state of neutrons," Soviet Phys. — JETP 11, 812 (October 1960).
11. J. S. Levinger and L. M. Simmons, "Neutron gas," Phys. Rev. 124, 916 (November 1961).
12. K. A. Brueckner, J. L. Gammel, and J. T. Kubis, "Binding energy of a neutron gas," Phys. Rev. 118, 1095 (May 1960).
13. P. E. Nemirovskii, "On the stability of nuclei," Soviet Phys. — JETP 9, 627 (September 1959).

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14. I. Butterworth, P. A. Egelstaff, H. London, and F. J. Webb, "The production of intense cold neutron beams," Phil. Mag. 2, 917 (July 1957).

15. S. Hautecler and W. van Dingenen, "Etude Systematique de Sources de Neutrons Froids," Int. Conf. Inelastic Scattering in Solids and Liquids, Vienna, October 11-14, 1960, p. 453.

16. F. W. Fenning and F. R. Holt, "Possible emission of the di-neutron in fission," Nature 165, 722 (May 1950).

17. Masakatsu Sakisaka and Michio Tomita, "Experiments on the possible existence of a bound di-neutron," J. Phys. Soc. Japan 16, 2597 (1961).

18. A. I. Baz', V. I. Gol'danskii, and Ya. B. Zel'dovich, "Undiscovered isotopes of light nuclei," Soviet Phys. — Uspekhi 3, 729 (March-April 1961).

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