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NEUTRON WEAK SPIN ROTATION: EXOTIC NUCLEAR PHYSICS OR A NEW WEAK FORCE?*

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ABSTRACT

First observations of neutron weak spin rotation have found an effect much greater than anticipated on conventional weak interaction theory. An explanation might be found in special circumstances involving a weak low energy resonance in $(n + Sn^{117})$. The possibility of a new weak force if conventional arguments fail is considered and tests of the various interpretations are proposed.

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When neutrons propagate coherently through ordinary matter the weak interaction should, at some level, induce an effect like the familiar optical activity for light. A transversely polarized neutron will find its spin direction rotated around an axis along its line of flight. When this occurs in the absence of any overt handedness such as magnetic fields, spiral structures or handed molecules, then it is evidence for the action of parity violating forces.

That such a "weak optical activity" should exist was first noted many years ago[1]. Sometime later its importance was emphasized by us[2], particularly in connection with the question of neutral weak currents.

The first observation of weak activity has now been reported by a group working at the ILL in Grenoble[3]. The size of the effect reported however is, in at least one case, thousands of times greater (in amplitude) than anticipated in the original calculations. We would like to examine some of the implications of this discovery, which promises to be of great interest.

Born Approximation

From the theoretical point of view, neutron weak activity should be the simplest of all phenomena involving parity violation in atoms and nuclei. There is no interference with unknown wave functions and there is a direct Born approximation calculation for the effect which involves no knowledge of nuclear structure. This provides us with a simple standard for comparison, and, one should think, a reasonable first estimate of the order of magnitude to be expected. We review the essentials of Ref. [2] briefly. The angle ϕ by which the neutron spin rotates in traveling a distance Z (calculated from the difference in the index of refraction for helicity plus and minus neutrons) is

$$\phi = \frac{4\pi}{p} (\mathrm{Ref})\rho Z \ . \tag{1}$$

p is the momentum of the neutron, ρ the number density of atoms in the material, and Ref the real part of the parity violating coherent forward scattering amplitude of the neutron on the atom; that is, f is given by a term $f\underline{\sigma}\cdot\underline{v}$ in the forward scattering amplitude. The amplitude f in turn can be estimated from an interaction of the four fermion type, e.g., $(G/\sqrt{2})\bar{\psi}\gamma_\mu(1+\gamma_5)\psi\bar{\psi}\gamma_u(1+\gamma_5)\psi$, between the neutron and the fermions of the material.

For this standard Fermi interaction plus neutral current interactions of the same general strength we obtain

$$f = \frac{pGW}{2\sqrt{2}\pi} \tag{2}$$

W is the "weak charge" of the atom, involving the contribution of electrons, protons and neutrons additively. For example[4] with a weak force of strength G between the neutron and protons only, we would have W = Z. Equation (2) results from assuming the neutron is a plane wave over the atom; in the nucleus this is clearly subject to modification. In Ref. [2] the modification was calculated for a simple square well model of the nucleus in terms of s and p wave scattering lengths a and b. The result found was that the nuclear part of W is to be multiplied by factor $\eta = (1 + 2a/R - 2b/R^3 - ab/R^4)$, where R is the nuclear radius.

The final result for ϕ is then

$$\phi = \sqrt{2}\, G \left(W_{electrons} + \eta W_{nucleons}\right) \rho Z \quad . \tag{3}$$

With $W = 10^2$ nominally for the middle of the periodic table and $\rho = 0.39 \times 10^{23}/cm^3$ as for tin, the formula yields for $\eta \sim 1$,

$$\phi = 1.3 \times 10^{-8} \text{ radians/cm} \quad . \tag{4}$$

The recently reported results are on tin [3].

$$Sn^{117}: \quad (-38 \pm 5) \times 10^{-6} \text{ radians/cm}$$

$$Sn^{124}: \quad (-0.63 \pm 0.95) \times 10^{-6} \text{ radians/cm}$$

$$\text{Sn (natural)}: \quad (-4.95 \pm 0.93) \times 10^{-6} \text{ radians/cm} \quad .$$

Due to the fortunate use of different isotopes of the same element, we can draw a useful conclusion: the large difference between the Sn^{117} sample and the other two shows that the effect cannot be principally attributed to the electrons (or the crystal structure) of the material. Henceforth we shall therefore concentrate on the nuclear contribution.

It is possible, within the errors, to attribute the effect on natural tin to its Sn^{117} content. It would be interesting to know if there is a general effect of order 10^{-6} or if it is peculiar to Sn^{117}. The Sn^{117} value in any case is quite striking, 3000 times greater than Eq. (4). While corrections of the type represented in η may certainly lead to variations around the simple estimate, it is difficult to imagine how they could account for a factor of hundreds or thousands. The s wave scattering length at least, is not unusual ($a = 6$ fm). The problem has also been investigated by the method of effective weak potentials [5]. Considerable variation has been found among the various models, but none vary from the simple estimate by more than an order of magnitude. Radiative capture is important for slow neutrons, but its effects on ϕ are not significant (see below).

The remaining place to look for a great increase in ϕ would appear to be in a resonant behavior of the $(n + Sn^{117})$ system. Enhancements in the framework of Eq. (3) due to a resonant behavior of η in a single particle potential picture have been considered [6]. If very great modifications are envisaged and if resonances are to play the major role, however, a Born approximation-like method is unsuitable; furthermore neutron resonances in heavy nuclei are complex many-particle states. It seems more plausible to use a phenomenological resonance dominated approach, to which we now turn.

Resonance Dominated Amplitude

In this approach we assume that the main contribution to f is from a level of the compound nucleus lying near (above or below) the neutron scattering threshold. Since in nuclei such as tin there are very many closely spaced neutron resonances, there will be some at least within 10's of eV of the threshold. In Sn^{117} the tables [7] show a very weak resonance at 1.3 eV and others at 34 and 38 eV. We shall take parity violation to be represented by an admixture of a state of the wrong parity in the resonance level, with amplitude $\mathscr{F}$. The neutron is to be absorbed by the resonance in an s wave and emitted in a p wave (and vice versa); one of which is parity forbidden. The forbidden width is written as $\mathscr{F}\Gamma_p$ or $\mathscr{F}\Gamma_s$, where Γ is the width the admixed resonance would have at that energy.

In order to assure correct threshold behavior and scattering theoretic properties of the amplitude we use a two-channel reaction matrix formalism[8], where $f = (1/p)K(1-iK)^{-1}$. K is a real symmetric matrix in the s and p channels which we write as $K = K° + K^{weak}$. The nuclear scattering is represented by K° which is a diagonal matrix, while K^{weak} connects s and p. K has a $p^{1/2}$ behavior for s channels and $p^{3/2}$ behavior for p channels, so the weak coupling through the resonance can be represented by

$$K^{weak} = \mathscr{F}\sqrt{\Gamma_p(p/p_o)^3}\sqrt{\Gamma_s(p/p_o)}\ (E-E_o)^{-1}$$

where one of the Γ's represents the forbidden amplitude and the other Γ the normal neutron width of the resonance, which is at energy E_o or momentum p_o. Now to first order in K^{weak}, $K(1-iK)^{-1}$ is approximately given by $K^{weak}(1-iK°)^{-1} + iK°(1-iK°)^{-1}K^{weak}(1-iK°)^{-1}$ so that

$$f = g\frac{1}{p}\ (1-iK°)^{-1}K^{weak}\ (1-iK°)^{-1}$$

$$f = g\frac{1}{p}\, e^{i\delta_s}\cos\delta_s\, e^{i\delta_p}\cos\delta_p\, \mathscr{F}\frac{\sqrt{\Gamma_p(p/p_0)^3\Gamma_s(p/p_0)}}{E-E_0} \qquad (5)$$

where the last step follows from $(1-iK)^{-1} = e^{i\delta}\cos\delta$ for a single channel, and g is a numerical factor depending on the angular momentum of the resonance $g = (2J+1)(2(2I+1))^{-1}$. With the level below threshold, the same formula applies with the $\sqrt{\Gamma}$'s interpreted as coupling constants. Equation (5) is essentially, except perhaps for the phases, what might have been guessed from a simple Breit-Wigner formula. It is more general, however, and can include the effects of potential scattering accompanying the resonance.

Another point that may be examined by this method is the role of radiative capture processes, which have large cross sections for thermal neutrons. Since our process is elastic scattering, real radiative reactions influence only the imaginary part of the amplitude and thus not ϕ. Furthermore radiative capture is big due to a kinematic 1/V factor which does not appear in the induced effect on the elastic amplitude. The imaginary parts of the phase shifts in (5), for example, are small, $\mathcal{O}(e^2)$. Similiarly, the radiative properties of resonance can only make themselves felt insofar as they influence the neutron widths.

To evaluate f at threshold we set δ and $E = 0$, so

$$f = p \frac{g}{p_0^2} \mathcal{F} \frac{\sqrt{\Gamma_p \Gamma_s}}{E_0} \quad . \tag{6}$$

For purposes of comparison, we take the ratio of this to the Born approximation estimate, and since widths in the Sn region are measured in millielectron volts, (meV), we express Γ in meV, and E_0 in eV, to have roughly ($W \approx 10^2$ and $2g \approx 1$).

$$\frac{\phi_{Res}}{\phi_{Born}} = \frac{f_{Res}}{f_{Born}} = \mathcal{F} \frac{\sqrt{\Gamma_p \Gamma_s / meV^2}}{E_0/eV^2} \quad 4.4 \times 10^9 \tag{7}$$

Using the known parameters of the low energy resonances in ($n + Sn^{117}$), let us see what value of $\mathcal{F}$ is needed to get a number like that measured, 3×10^3 for the ratio. Now the most favorable case is when the resonance is p wave so that the parity forbidden transition may be s wave. We thus ignore the 38 eV resonance, which is known to be s wave. The ℓ,J of the 1 eV and 34 eV levels are unknown, so we may assume them to be p states. The strongest resonance tabulated between 1 and 2 eV has a Γ_n of 3.3 meV so we set $\Gamma_s = 3.3$ meV for the 1.3 eV resonance.

Using the given width of 2×10^{-4} meV for this resonance we find that $\mathscr{F}$ must be $4\cdot 10^{-5}$. For the 34 eV level we use $\Gamma_s = 117$ MeV, as for Pd^{108}, the strongest resonance between 33 and 35 eV. Together with the known width of $3.4\cdot 10^{-2}$ meV this leads to $\mathscr{F}\approx 4\times 10^{-3}$.

The traditional value of $\mathscr{F}$ has been $10^{-6}-10^{-7}$, but in complex nuclei, as under consideration here, an enhancement of a factor 50 has been envisaged [9]. Thus while the value of $\mathscr{F}$ required for the 34 eV level seems absurdly large, it might be possible, with a favorable combination of circumstances, to use the 1.3 eV state to explain ϕ for Sn^{117} with the conventional theory.

Our general conclusion on the role of resonances is that p wave resonances (as first discussed by Forte [6]) might be important, but they must be very close (few eV) to threshold. A 60 eV resonance, as originally proposed [6], would have to have an implausibly large $\mathscr{F}$ to be effective at the necessary level.

Theoretical questions aside, ϕ will show certain features as already noted [6], when resonances are important. A characteristic shape for the energy dependence would be expected, which can be studied experimentally if the relevant level is above threshold. Replacing $e^{i\delta}\cos\delta$ by $(E-E_o)(E-E_o+i\Gamma/2)^{-1}$ gives

$$f = g\,\frac{1}{p}\,e^{i\delta}\cos\delta\,\frac{\mathscr{F}\sqrt{\Gamma_s\Gamma_p}}{E-E_o+i\Gamma/2}\quad, \tag{8}$$

with δ the phase in the nonresonant channel. Ref changes sign going through the resonance and in the wings of the resonance reaches very large values, on the order of Γ_{total}/E_o times the threshold value. This can lead to a substantial increase in ϕ near the resonance.

Other features of the resonance explanation concern the sign and magnitude of ϕ on different nuclei. Since ϕ depends on which nearby levels can mix with the resonance and these can be either above or below, we would expect the sign of ϕ to fluctuate more or less randomly from one nucleus to the next. Secondly, the magnitude of ϕ should decrease rapidly with lighter nuclei; the greater level spacing will both reduce $\mathscr{F}$ and increase the E_o factor in Eq. (6).

Apart from any explanation of the effect at threshold, the enhancement near resonances suggests that high resolution measurements, together with Eq. (8), may permit the systematic determination of the parity impurity $\mathscr{F}\Gamma$ of many states.

Finally we note that if the explanation is really to be found in terms of a very low energy $\ell = 1$ resonance, it might be interesting to investigate Pd^{108} where such a state has been identified.

A New Weak Force?

The discrepancy of $3 \cdot 10^3$ between the simple amplitude (2) and the Sn^{117} measurement is enough to raise suspicions on a fundamental level. It may be that the effect observed is due to some exceptional property of Sn^{117}, like the 1.3 eV resonance, and will appear in only a few isolated cases. But if this turns out not to be so and some conventional explanation we have overlooked is not found, we will be lead to inquire if it may not be due to a new weak force, a force between nucleons at about a hundred or a thousand times the Fermi interaction strength in amplitude. Such an interaction would, of course, be extremely interesting; all the more so since it is not foreseen in the present fundamental models of the weak interaction. This hypothesis would not be in blatant contradiction with any well-established facts; despite the great body of work that has been done [9], nuclear parity violating effects are very difficult to interpret precisely. It would provide a ready explanation for the famous large circular polarization in $n + p \rightarrow d + \gamma$ which is also $10^2 - 10^3$ too large for the conventional theory [10]. The only other source of information on the hadron-hadron weak interaction is nonleptonic strange (and recently charmed) particle decays. It has been a long-standing problem to explain why these are so greatly enhanced relative to the simple Fermi strength (Cabibbo theory) leptonic decays. Thus in the two areas where there is information on the weak force between strongly interacting particles, there is a suggestion of stronger than conventional forces.

How could the existence of such a force be established? The most obvious way with the neutron spin rotation effect would be to perform the experiment on Hydrogen (and Deuterium). It it is too small to be seen because of the low density, it would still be of the greatest interest to follow it down to the lightest nuclei. In light nuclei we would expect the amplitude to be given by the direct scattering mechanism, so that if the effect could be extrapolated from heavy nuclei by a factor like W, say $W \sim A$ then we would only expect to lose a factor four or so for ϕ in going from Sn to Be or B. An effect on the 10^{-6} rad/cm level here would be inexplicable with the resonance mechanixm, and would imply the greatest difficulties for the conventional theory. The new force would be naturally affected by the phenomenology of nuclear structure, both of the resonance and scattering length variety, which would have to explain the variation of ϕ among the tin isotopes, for example.

Assuming that the direct scattering mechanism would usually dominate at threshold, as the above discussion seems to indicate, ϕ would tend to have a definite sign superimposed on the fluctuations due to nuclear effects and as just mentioned, decrease relatively slowly, like W, with nuclear size. Further measurements of ϕ will be a the least quite interesting and may perhaps prove to be of great importance.

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