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TEST OF TIME REVERSAL SYMMETRY WITH RESONANCE NEUTRON SCATTERING

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It may be possible to search for a time-reversal-odd, parity-odd interaction between nucleons in a nucleus with a sensitivity of 10^{-5} of the weak interaction between nucleons. It has been shown experimentally that large parity violating effects are present in the scattering of cold and epithermal neutrons from nuclei. The possibility of using this phenomenon to carry out sensitive tests for time reversal symmetry violation has been discussed theoretically by several authors.[1,2,3,4,5] In this contribution I will discuss the possibility of searching for time-reversal symmetry violation in the scattering of epithermal neutrons from the Los Alamos spallation neutron source from nuclei. I will discuss both statistical and systematic errors.

How large might one expect time reversal violation to be? There are two indications, CP violation in K decays and searches for an electric dipole moment of the neutron. In K mixings[6] CP-odd mixing amplitudes are measured to be 2×10^{-3} of CP-conserving decay amplitudes. Since the product TCP is believed to be conserved this amplitude ratio may be taken as the size of time reversal symmetry violation. Two types of theories are used to describe CP violation in the kaon system; milliweak theories in which CP-violating mixing between the K^0 and $\bar{K}^0$ takes place via a $\Delta S = 1$ interaction acting in second order, or super weak theories in which the mixing takes place via a $\Delta S = 2$ interaction acting in first order. For milliweak theories, CP-odd effects may be as large in other systems as they are in kaon decays. For super weak theories CP violation will be unobservably small outside of the kaon system. The present limit on the electric dipole moment of the neutron, d, is $d < 6 \times 10^{-25}$ e cm.[7] The neutron electric dipole moment is zero if either time reversal symmetry or parity symmetry holds. Following Wolfenstein[8] we take the nuclear magneton divided by the speed of light as an estimate of the size of d to be expected in the absence of any inhibiting symmetries. As an estimate of the reduction due to parity symmetry we take

$$\frac{G_F m_q^2}{4\pi} = 10^{-7} \quad ;$$

then

$$d = \frac{\mu_n}{c} \frac{G_F m_q^2}{4\pi} R < 6 \times 10^{-25}$$

where R is the fraction of the weak force which is time-reversal odd, G_F is the Fermi constant, m_q is a quark mass, and μ_n is the nuclear magneton. Then $R < 6 \times 10^{-4}$. These qualitative estimates make a search for R with a sensitivity of 10^{-5} attractive.

The energy dependence of the cross section for the scattering of epithermal neutrons from nuclei exhibits a rich structure of resonances. The density of states having a given set of quantum numbers is 0.1 eV and typical widths are 0.1 eV. Resonances are characterized by the orbital angular momentum of the neutron relative to the target. S-wave resonances have have cross sections as large as 10^{-20} cm^2, possible angular momenta of J + 1/2 and J - 1/2 (where J is the angular momentum of the target ground state) and the same parity as the ground state. For S-wave resonances, gamma decay and neutron decay compete. P-wave resonances have smaller cross sections, 10^{-24} cm^2. Angular momenta range from J - 3/2 to J + 3/2, their parity is opposite to the ground state, and gamma decay dominates.

Large parity-violating admixtures of S-wave resonances into P-wave resonances have been observed in the scattering of polarized neutrons from unpolarized targets.[9] In pulsed reactor experiments the neutron energy is measured by time of flight. The 0.9 eV resonance in ^{139}La shows a helicity dependence of 0.07. Because the density of states is high and the S-wave scattering amplitudes are much larger than P-wave amplitudes, mixing matrix elements of 10^{-3} eV can result in such large effects. Mixing matrix elements extracted from observed helicity dependences range from 0.38 to 3.0 MeV.[7]

The characteristics of the spallation neutron source at the LAMPF proton storage ring represent a thousand-fold improvement over the Dubna pulsed reactor where the above measurements were done. The neutron spectrum has an approximately 1/E shape above thermal energies with a flux of 5×10^7 neutrons per second into 0.1 msr. The 1 microsecond pulse width allows the resolution of resonances up to 100 eV with a 10-meter flight path.

The studies of parity violation used the observable $\sigma \cdot k$ where σ is the neutron polarization and k is the neutron momentum. The quantity $\sigma \cdot k$ is parity-odd, time-reversal-even. The study of time reversal requires a polarized target with polarization vector I. The observable is $\sigma \cdot I \times k$ which is both parity-odd and time-reversal-odd. There are three effects which may be studied: a dependence of the total cross section of a P-wave resonance on $\sigma \cdot I \times k$, the development of a neutron polarization perpendicular to both I and k when an unpolarized neutron beam passes through a polarized target, and the precession of the neutron polarization about I×k. Adelberger[5] has discussed the third of these in the context of cold neutrons. For epithermal any of these effects may be used as probes of time-reversal symmetry violation. I will concentrate on the the first, although the choice of the effect depends on factors such as resonance parameters, as well as considerations of systematic and statistical errors.

The statistical sensitivity is excellent. For a one interaction length ^{139}La target, with the same type of polarimeter as used in the Dubna experiments, a statistical error of 3×10^{-7} eV in the time-reversal odd-mixing matrix element can be obtained in a 10^5 second run at the proton storage ring. For ^{139}La the measured mixing matrix element is 1.28 × 10 MeV.[7] The ratio R of time-reversal-odd, parity-odd matrix element to time-reversal-even parity-odd matrix element is measured with a statistical sensitivity of 2.3×10^{-4}. A 10^7 run, which appears feasible, would obtain a 10 times smaller statistical sensitivity.

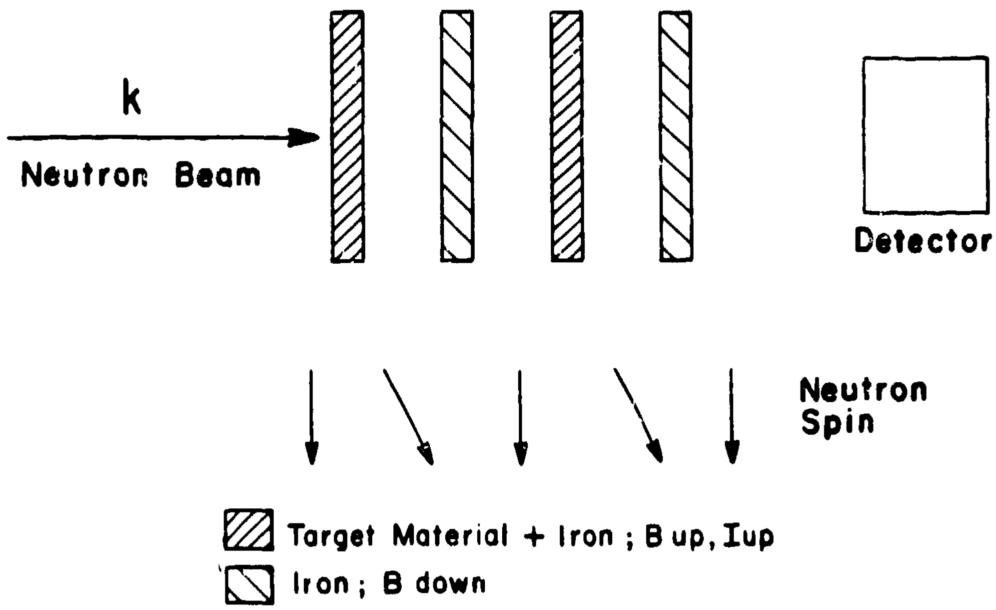
An attractive feature of the type of time-reversal searches under consideration is the absence of final-state interaction effects. Kabir[1] has shown that final-state interactions do not falsify a time-reversal-odd mixing.

There are a number of interactions that change the direction of the neutron. In designing an experiment to search for a change in the neutron spin resulting from time-reversal symmetry violation it is important that these other interactions are not confused with time-reversal symmetry violation. The interactions that change the neutron spin are:

1. Magnetic fields. Magnetic fields result from at least three sources: external fields used to polarize the target, magnetization fields in ferromagnetic target materials, and the magnetic fields resulting from the polarization of the target nuclei.
2. Abragam rotation.[10] This source of spin rotation is associated with the polarization of the target nuclei, but is not a magnetic field. Due to the spin-orbit force the real part of the neutron scattering amplitude is different for the neutron spin parallel or antiparallel to the target polarization. This coherent effect causes the neutron spin to precess around the target polarization direction.
3. Parity-violating $\sigma \cdot k$ interaction. As discussed above the existence of a parity-violating $\sigma \cdot k$ interaction causes the total neutron scattering cross section to depend on the neutron helicity. In addition the neutron polarization will precess about k.

It is important to use thick targets in order to achieve good statistical accuracy. For a strong P-wave resonance a target thickness of 10^{22} nuclei/cm^2 would be appropriate. The use of thick targets means that the three sources cited above act over long distances and that spin rotation angles may be large. One must therefore deal with the problem of keeping the neutron spin direction perpendicular to both I and k on the average. An attractive approach to the above problems is the use of internal fields in ferromagnetic alloys to polarize the target nuclei. When a rare-earth atom is alloyed with iron the magnetic field at the point of the rare-earth nucleus may be much larger than the bulk magnetization of the iron. Fields for dilute substitutional alloys are typically hundreds of kilogauss. The magnetic field that acts on the neutron spin would be the bulk field, while the magnetic field that polarizes the target nucleus would be the much larger internal field.

The figure shows an approach to the use of these ideas. Magnetized plates of sample alloy are alternated with plates of iron. The iron plates are magnetized in the opposite direction to the target plates. The flux return path is within each plate, so that the fields outside of the plates are small. The function of the dummy iron plates is to undo the neutron spin rotation that takes place in the target plates.



The first task in a search for time-reversal-odd effects is to make a survey of parity violation in nuclear levels. A good candidate level for time reversal would show large parity violation, a cross section larger than the potential scattering background, have an energy of a few electron volts, and be polarizable. The survey of parity violation would itself produce interesting results. A knowledge of the size, distribution, and signs of parity-violating weak matrix elements between states would lead to a better understanding of the questions of nuclear structure relevant to the interpretation of both parity violation and time-reversal violation.

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