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CONF-8805142--8

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LA-UR--88-2062

DE88 014421

TITLE TESTS OF TIME REVERSAL IN NEUTRON-NUCLEUS SCATTERING

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SUBMITTED TO The 3rd Conference on The Intersections Between Particle
and Nuclear Physics, Rockport, Maine, May 14-19, 1988.
(June 1988)

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TESTS OF TIME REVERSAL IN NEUTRON-NUCLEUS SCATTERING

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ABSTRACT

Experiments to test time-reversal invariance are discussed. The experiments are based on observables constructed from the momentum and spin vectors of epithermal neutrons and from the spin of an aligned or polarized target. It is shown that the proposed tests are detailed balance tests of time-reversal invariance. The status of the experiments is briefly reviewed.

I will report on tests of time-reversal invariance (TRI), which are in the beginning stages of experimental work at the Proton Storage Ring (PSR) at Los Alamos. I discussed plans for this work two years ago at the Lake Louise conference.¹ A workshop on Tests of Time-Reversal Invariance in Neutron Physics was held in Chapel Hill, North Carolina in April 1987, and the reader is referred to the proceedings² for a more complete discussion of many points than will be presented here. The initial work that will be discussed has been carried out by a collaboration between Los Alamos, Harvard, and Princeton. During 1988 colleagues from TUNL, TRIUMF, Delft, and University of Virginia joined in the work.

Figure 1 illustrates the classical meaning of TRI. A system evolves from an initial state i to a final state f . The system is described by momenta p and

Fig. 1. Illustrates classical trajectories that obey $f \rightarrow i$, and violate $f \rightarrow i^*$ time-reversal invariance (see text).

coordinates q . A new initial state $\bar{f}$, is formed by time-reversing the state f . The signs of the p 's are changed and the q 's are kept. The system evolves from the state $\bar{f}$ to some state i^* . TRI holds if the state i^* is the same as the time-reversed initial state $\bar{i}$. For a quantum system TRI holds if the amplitude for the system to make a transition from i to f has the property

$$S(i \rightarrow f) = S^*(\bar{f} \rightarrow \bar{i}) . \quad (1)$$

Since only the squares of amplitudes are measurable, Eq. (1) implies that tests of TRI must be based on measurements that test whether or not

$$\sigma(i \rightarrow f) = \sigma(\bar{f} \rightarrow \bar{i}) . \quad (2)$$

In order to see a TRI-violating phase change, the amplitude S must be a sum of two or more amplitudes whose phases change differently under time reversal (TR).

Interest in the use of neutron-spin observables as probes of symmetry violations in nuclear states was sparked by the observation by V. P. Alifimov, et al.,³ of a large helicity ($\sigma \cdot K$) dependence of the total scattering cross section at the energy of a p-wave resonance in ^{139}La . Table I summarizes the properties of the neutron spin (σ), the neutron momentum (K), and the target spin (J) under parity (P) and TR transformations. The idea of the present work is to use the spin of epithermal, 0.1 to 10 keV, neutrons to construct observables with which to test TRI. Using the fluxes available at the PSR, 10^{14} neutron-scattering events from a p-wave resonance can be detected in 10^7 seconds. Thus, transmission asymmetries as small as 10^{-7} can be studied. Two types of measurements have been suggested. P. K. Kabir,⁴ L. Stodolsky,⁵ and V. E. Bunakov and V. P. Gudkov⁶ suggested the parity-odd observable $\sigma \cdot J \times K$. P. K. Kabir⁷ proposed the parity-even observable $(J \cdot K)(\sigma \cdot J \times K)$.

TABLE I

Table I shows the parity- and time-reversal-transformation properties of various quantities discussed in the text.

Observable	Symbol	Parity	Time Reversal
Neutron Spin	σ	+	-
Neutron Momentum	P	-	-
Target Spin	J	+	-
Neutron Helicity	$\sigma \cdot K$	-	+
Triple Product	$\sigma \cdot J \times K$	-	-
Five-Fold Product	$(J \cdot K)(\sigma \cdot J \times K)$	+	-

V. E. Bunakov and V. P. Gudkov⁸ showed that the large helicity dependence of the total cross section could be understood as resulting from the mixing of nearby s-wave resonance into the p-wave resonance by the parity-violating weak nucleon-nucleon force. Two enhancement factors increase the size of the observed effect: 1) the small energy spacing, 10 eV, in the compound nucleus and 2) the large ratio of s-wave to unambiguous neutron decay amplitudes. They argued that the enhancement of the dependence of the cross section on the TR-odd P-odd scalar triple product $\sigma \cdot J \times K$ should be the same as that of the helicity. Since the helicity dependence of the cross section has been measured to be as large as 10%, a 10^{-7} measurement of the dependence of the cross section on the scalar triple product would test for a TR-odd P-odd interaction at the level of 10^{-5} of the weak force between nucleons, a sensitivity competitive with searches for a non-zero electric dipole moment of the neutron.

V. E. Bunakov⁹ has recently estimated the nuclear enhancement of the cross-section dependence of the TR-odd P-even five-fold product, which arises from the mixing of p-wave resonances, to be between 10^3 and 10^5 . Thus, a 10^{-7} measurement of the dependence of the cross section on the five-fold product would test for a TR-odd P-even force with a sensitivity of 10^{-10} of the strong force between nucleons. P. Herczeg¹⁰ has studied the relationships between theories of CP violation in the kaon system and TRI violation in $\Delta S = 0$ nuclear systems.

Figure 2 shows an experiment designed to look for a dependence of the total cross section on the scalar triple product. This approach is flawed. The

Fig. 2. A neutron beam with momentum K passes through a polarizer and energies with a spin σ . The target spin J is perpendicular to K . The neutron spin is switched so that the triple product $\sigma \cdot J \times K$ changes sign. A change in the neutron transmission upon switching σ is not an ambiguous test of TRI (see text.)

real part of the spin-orbit force ($\sigma \cdot J$) will cause the neutron spin, which is initially perpendicular to both J and K , to precess around J . The vector σ will then develop a component along K and the $\sigma \cdot K$ interaction will produce an asymmetry even in the absence of TRI violation. The appearance of a fake TRI-violating asymmetry in the above gedanken experiment is closely related to the falsification of TRI violation by final-state interactions in scattering experiments. L. Stodolsky¹¹ proposed that by adding an analyzer after the target, as shown in Fig. 3, the apparatus could be made TR invariant and that detailed-balance TRI experiments in the sense of Eq. 2 above would result. In order to test for

Fig. 3. Adding an analyzer, which is switched simultaneously with the polarizer leads to an unambiguous test of TRI (see text).

TRI in the scalar triple product the polarizer-target-analyzer configuration is necessary. In the Chapel Hill workshop I¹² showed that since the five-fold-product experiment could be carried out with an aligned target, where the average value of J is zero, the analyzer is not necessary.

We began work on parity and time-reversal experiments at Los Alamos in 1986. In our first experiment we measured the degree of helicity dependence in the total cross section of the 0.734 eV resonance in ¹³⁹La. The Alfenkov, et al.,⁹ experiment, which measured an asymmetry of $7.2 \pm 0.4\%$, and the A. Masaike, et al.,¹³ experiment, which measured an asymmetry of $10.4 \pm 0.3\%$, both used polarized proton filters to prepare a polarized neutron beam. In 1986 no polarized neutron beam was available at Los Alamos. We carried out an asymmetry measurement as shown in Fig. 4. The helicity dependence in the total cross section was used both to polarize and to analyze the neutron beam. We obtained an asymmetry of $8.2 \pm 1.7\%$. To my knowledge, this is the first time the weak interaction has been used both to polarize and analyze a beam.

Fig. 4. Los Alamos experiment to measure the helicity dependence of the total scattering cross section. Target 1 prepares a polarized neutron beam, which is analyzed by target 2.

Fig. 5. The system which detects neutrons at rates up to 10^{12} Hz in a current mode.

The 1986 work was done by counting individual neutrons using a ^6Li loaded glass scintillator. Pulse-counting techniques limited us to instantaneous rates of less than 10^6 Hz. The PSR delivers neutron beams into a few micro steradians of 10^{12} Hz. In order to utilize fully the available neutron fluxes we developed and

tested neutron-current measuring techniques in 1987. Our detection apparatus is shown in Fig. 5. Using these techniques, we will be able to take advantage of the full intensity available from the PSIt without loss of neutron-energy resolution or degradation on the statistical accuracy of the number of neutrons detected. Using this detector we began a survey of p-wave resonances in atoms that allow nuclear polarization or alignment.

In 1987, our colleagues from Princeton and Harvard set up a polarized ^3He filter, which prepared a polarized neutron beam. About 10-atmosphere-cm³ of ^3He were polarized using optical pumping techniques. This apparatus has been described by K. Coulter¹⁴ in the Chapel Hill workshop. Using this polarized neutron beam we repeated the ^{139}La experiment, and searched for new examples of p-wave resonances with helicity-dependent cross sections. One such resonance was identified in ^{151}Gd . This technique has the attractive feature that it is modest in scale and is noncryogenic. Furthermore, the ^3He spin, and, hence, the neutron spin, can be reversed relative to a weak holding field using an adiabatic fast passage. Reversing the neutron spin in this way is attractive for symmetry-test experiments because the neutron spin is reversed without changing the magnetic fields used for spin transport. The weakness of this technique is that since the $n-^3\text{He}$ cross section decreases as the inverse of the neutron velocity, neutrons can only be polarized up to a few eV, and over a fraction of a square centimeter using a 10-atmosphere-cm³ cell. The ^3He technique is attractive as a polarization-sensitive detector or as a polarizer/analyzer if thicker cells can be developed.

For 1988, we are developing a dynamically polarized proton filter with which to polarize the neutron beam up to 10 keV. This project is well under way, with our collaborators from TRIUMF and Delft playing a leading role. We expect to have an area of 10 cm² with a polarization of 70%. We have developed a seven-detector array, which is suitable for measurements over a 60-m flight path. We will have adequate energy resolution up to energies of 100 keV. We have designed and built a spin flipper that can reverse the neutron's spin between energies of 0.01 and 10 keV. A new data acquisition and analysis code has been written by the TUNL team. With this apparatus we plan to continue our search for p-wave resonances suitable for TRI tests to higher energies and additional targets. The data obtained in this survey will determine the distribution and strength of parity violation as a function of atomic mass. It will be interesting to see whether or not meson-exchange models of the weak nucleon-nucleon force with experimentally determined couplings combined with theories of the compound nucleus can correctly explain the observed distribution of parity-violating mixing amplitudes.

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