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ACQUIRED POLARIZATION IN FUNDAMENTAL SYMMETRY EXPERIMENTS

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ACQUIRED POLARIZATION IN FUNDAMENTAL SYMMETRY EXPERIMENTS

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One interesting class of fundamental symmetry violation tests involves the measurement of low energy neutron transmission through a thick target as projectile/target spin orientations are changed. As the neutron beam propagates through a target, certain components are preferentially absorbed by nuclear resonances. This induces regenerative effects in thick targets, known as the acquired polarization effect, which complicate the interpretation of transmission measurements. We focus on the role that nuclear resonance spectroscopy plays in beam modification. We determine three basic results. First, with known resonance parameters for spin 1/2 targets 57Fe, 103Rh, 111Cd, 113Cd, 117Sn, and 203 Tl, and spin 7/2 target 139La, the relative sizes of the various terms are determined, including the values of the cross sections, transmission percentages, the size of the transmission effect, and the percentage of the transmission effect caused by acquired polarization. Second, the effect of imperfect target polarization reversal on the value of the transmission effect is determined in the case of 113Cd. It is found that target orientation inefficiencies as small as 3% will mimic a parity violation. Third, the effect of the depolarization term on the relative size of the acquired polarization is explored.

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Abstract

One interesting class of fundamental symmetry violation tests involves the measurement of low energy neutron transmission through a thick target as projectile/target spin orientations are changed. As the neutron beam propagates through a target, certain components are preferentially absorbed by nuclear resonances. This induces regenerative effects in thick targets, known as the acquired polarization effect, which complicate the interpretation of transmission measurements. We extend the work of Postma *et al.* [Po 62] to include parity mixing in the neutron resonances. We focus on the role that nuclear resonance spectroscopy plays in beam modification. From this, we determine three basic results. First, with known resonance parameters for spin 1/2 targets ^{57}Fe, ^{103}Rh, ^{111}Cd, ^{113}Cd, ^{117}Sn, and ^{203}Tl, and spin 7/2 target ^{139}La, the relative sizes of the various terms are determined, including the values of the cross sections, transmission percentages, the size of the transmission effect, and the percentage of the transmission effect caused by acquired polarization. For the case of ^{113}Cd, acquired polarization accounts for 40% of the transmission effect, and for ^{117}Sn it is nearly 100%. Therefore we see that the relative size of the acquired polarization term is very sensitive to the mixing ratio and, therefore, the detailed nuclear spectroscopic resonance parameters are extremely important for accurate analysis, a fact that had not been realized before this investigation. Second, the effect of imperfect target polarization reversal on the value of the transmission effect is determined in the case of ^{113}Cd. It is found that target orientation inefficiencies as small as 3% will mimic a parity violation. Third, the effect of the depolarization term on the relative size of the acquired polarization is explored, also for the case of ^{113}Cd. In this case it is determined that as the depolarization gets larger, the transmission effect gets larger, but the fraction of it caused by acquired polarization gets smaller.

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Lastly, I give my deepest thanks and love to my parents, Philip and Patricia Larson, and my brother, Chad. Without their support and caring through the last 22 years, I would never be where I am today.

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I. Introduction

A particle shot into a dense material will deflect from its original path. A beam of neutrons will lose intensity as it propagates through a target.

By studying this loss of intensity carefully, one can learn about the properties of the target material. Neutrons with speeds in the neighborhood of ≈ 44 kilometers/sec (≈ 10 eV kinetic energy) may be used to investigate the detailed properties of the atomic nucleus. One of the properties which is receiving considerable attention is parity symmetry.

We will be examining how the thickness of the target and the neutron-nucleus interaction affects the number of transmitted neutrons with reference to parity violation experiments. Gould may have been the first to realize that this complication might interfere with PNC (parity non-conservation) experiments [Go 90], although he felt that the effects would be negligible even with a maximum spin-spin interaction. His initial assumptions have been further explored with detailed calculations, and the effect has been found to be negligible in some cases, but significant in others. This research project is the first to examine how the thickness of the target affects the outcome of parity violation experiments.

1.0 Symmetries

In describing physical processes, there are three fundamental symmetries. The first concerns itself with an invariance of the process with respect to coordinate system inversion, and it is known as parity. The second, time reversal symmetry, deals with an invariance of the process with respect to the flow of time. The last involves an invariance with respect to the interchange of paricles with their antiparticles, and it is known as charge conjugation symmetry.

One way to imagine parity symmetry is to think of a right handed-rubber glove. The glove has certain properties; for example, it is water repellent and elastic. If it is turned inside out, a mirror image of the glove results - a left-handed glove. This glove has exactly the same properties, but the coordinates have been inverted. Parity symmetry says that a particle, or a system of particles, will interact in the same way regardless of the left-right handedness of space (Fig 1.0.1).

Time reversal symmetry is easier to understand. It says that a particle or a system will behave in the same manner regardless of the direction of time. In other words, a particle going backwards in time will behave the same as it did going forward in time, although with opposite results. If an object breaks up going forward in time, it should put itself back together going backwards in time (Fig 1.0.1).

The third symmetry is charge conjugation symmetry. This states that a system of particles will behave exactly the same way as an identical system of antiparticles. To illustrate, a baseball of antimatter on an antimatter earth will behave just as a baseball on our own earth (Fig 1.0.1).

1.1 Historical Background of Symmetry Violation

While these three symmetries seem to present themselves as irrefutable laws of physics, times do exist when they can be violated.

The first observation of parity non-conservation (PNC) occurred in 1957 in the beta decay measurements of Wu [Wu 57]. Wu measured the number of decay electrons emitted by Cobalt-60 nuclei parallel and antiparallel in direction to an applied external magnetic field, and she found that the parallel and antiparallel cases behaved differently, indicating a parity violation. For several years, most other examples of parity violation were found to occur in similar decay reactions of nuclei.

The first experiment not to rely on observations of decay was conducted by Abav *et al.* [Ab 64] in 1964. This experiment used a polarized neutron beam incident upon an unpolarized target nucleus, resulting in scattered gamma rays. The experiment looked for differences in the number of emitted gamma rays for positive and negative helicity neutron beam orientations. Helicity refers to the orientation of the neutron's spin with respect to its direction of motion. The experiment succeeded in observing a violation in ^{113}Cd, which was later confirmed independently [Wa 67]. As a result of this experiment, many researchers shifted to finding asymmetries using the beam on target method.

Time reversal violation (TRV) has never been directly observed, but it is implied in the case of two elementary particles known as neutral kaons (K_o) and neutral B mesons (B_o). It is hoped that some of the techniques currently being used to probe parity violations can be extended to look for time reversal violations as well. Before attempting the TRV experiments, it is prudent to understand all of the complications which can arise in the simpler PNC experiments.

1.2 Current Experiments

Experiments are currently being performed by the TRIPLE (Time Reversal Invariance and Parity at Low Energies) collaboration at LANL (Los Alamos National Laboratory), at the KEK laboratory in Japan, and at the Joint Institute for Nuclear Research in the USSR. All of these use the beam on target method. Instead of measuring scattered gamma rays, these experiments compare the actual transmitted intensities of polarized neutrons of opposite spin orientations, or helicity, as they travel through a thick target. Appendix A describes a typical experimental setup and the equipment being used by the TRIPLE group.

In these experiments, the kinetic energy of the neutron beam is varied. At certain beam energies, the neutrons have a much greater chance of being absorbed than at other energies. These special energies are called resonances, and fewer neutrons are transmitted where these occur. The parity violation is detected at the resonances because of a magnification of the effect there due to 1) the mixing of single particle states among the levels in the nucleus [Fl 84] and 2) the kinematic enhancement that occurs at a resonance-resonance interference [Bu 87].

In our proposed experiment, an unpolarized neutron beam is fired at a polarized target oriented either parallel or antiparallel to the beam, and the transmission difference is measured. This experiment has several advantages: more objects are polarized in the experiments, and it is much easier to polarize a target than it is a beam. The experimental group at KEK is considering this experimental geometry if they can develop a method for producing suitable targets, i.e. ones that maintain a high level of polarization.

These experiments are very tedius to perform, and two major systematic difficulties occur. First, the polarization of the beam, the temperature, and the magnetic field of the target must be rigidly controlled. It has been determined that the required level of accuracy can be maintained in order to perform the experiment [Ha 88, Go 87]. Second, the polarization of the incident neutron beam can change upon passing through the target. This second sytematic error had not been previously considered in detail. This paper will deal with the acquired polarization of the beam in similar parity violating experiments.

1.3 Acquired Polarization in PNC Experiments

The large spin-spin interaction (between neutrons and target nuclei) and the small PNC interaction in the experiment both cause the incident beam to change polarization as it travels through the thick target. Polarization is a term which describes the numbers of particles with positive and negative spins. If the polarization equals one, all the particles have a positive helicity, or all have a negative helicity. If it equals zero, the same number of positive and negative helicity particles are present. The acquired polarization occurs because of a difference in transmission for different components of the beam in the nuclear resonances, causing attrition of some spin components and an excess of others (preferential absorption). While the parity conserving aspects of acquired polarization have been considered in detail [Po 62], the PNC aspects have not. Exploring this aspect of acquired polarization is the main thrust of this paper.

Some of the specific questions that will be explored are as follows: How does the large parity conserving spin-spin term in the cross section cancel with a reversal of the target orientation? How large is the acquired polarization effect in comparison to the thin target terms in a PNC case? What effects do the beam polarization, as well as values of other variables, such as the target thickness, have upon the size of the acquired polarization effect in PNC experiments? Is the acquired polarization effect large enough to cause a distortion of the actual parity violation effect?

II. Theory

2.0 Attenuation of Neutron Beams

In these experiments, a beam of neutrons is fired into the material of interest. When an incident neutron strikes a nucleus and scatters, it is removed from the beam. The incident beam is therefore attenuated.

A differential equation is used to describe how the beam propogates through the target. This differential equation takes into account many different factors such as the number and size of the nuclei.

We first consider a simple case. Neither the neutrons or target nuclei have spin. The number of neutrons that disappear from the beam as one moves a distance dx into the target is proportional to the density of target nuclei n, the cross section σ, and the number of incident neutrons ω.

$$d\omega = -n\sigma\omega\, dx$$

The cross section σ has units of *length* ^{2} and can be thought of as representing the effective cross sectional area that a nucleus presents to the incoming neutron.

When the above differential equation is solved, one obtains an equation giving the number of neutrons transmitted through the target as a function of distance:

$$\omega(x) = \omega_0 e^{-n\sigma x}$$

with ω_0 being the initial number of neutrons incident upon the target and ω the number remaining after a distance x has been travelled. This equation shows that the neutrons are attenuated exponentially through the target, and the number transmitted through will approach zero as the target thickness approaches infinity. If the thickness were zero, the number transmitted will equal the number incident -- just as would be expected.

The exact value for the cross section σ depends upon the details of neutron-nucleus interaction. The cross section is not a fixed number but depends on the energy of the incident neutrons. Figure 2 illustrates this dependance for the target nucleus ^{113}Cd. At certain beam energies, the neutrons are preferentially absorbed -- that is, the nucleus presents a much larger "effective area". These special energies are the resonances. A resonance occurs due to the interaction of a specific neutron angular momentum ℓ with the target. If a parity violation has occurred in the experiment, a difference in the transmission of the oppositely polarized beams will be most easily detected at a p-wave ($\ell = 1$) resonance that is located near a strong s-wave ($\ell = 0$) resonance.

2.1 Attenuation of a Two Component Beam Through a Spin 1/2 Target

In the cases of interest both the neutron and the target nucleus will have an intrinsic spin. The cross section then carries an additional dependance on the orientation of these spins.

A neutron's spin can only have two orientations -- either parallel or anti-parallel to its direction of motion. These orientations are refered to as positive and negative helicities, respectively. To study the propagation of a beam of neutrons, one must track the attenuation of the neutrons in each helicity state separately. We follow an approach similar to Postma [Po 62]. The resulting differential equations describing the two beam components are:

$$d\omega_+ = [-\omega_+ n\sigma_+ - D\,(\,\omega_+ - \omega_-\,)]\,dx$$

$$d\omega_- = [-\omega_- n\sigma_- + D\,(\,\omega_+ - \omega_-\,)]\,dx$$

where ω_+, ω_- are the numbers of (+), (-) helicity neutrons; and σ_+, σ_- are the cross sections for each component. A new effect has been included in the differential equations which arises from the the fact that the targets are not ideal. As the neutron propagates through the sample it will encounter non-uniformities in the magnetic field direction relative to the external field applied to polarize the sample. These perturbations result from crystal anisotropy. The neutrons have some probability for flipping their spin. "D^{-1}" is the mean free path for this spin-flip due to atomic and bulk processes.

The beam has a polarization $P_z{}^n$, which changes as the beam propagates through the target. The polarization relates the numbers of neutrons in the positive and negative helicity states and is defined as follows:

$$P_z^n = \frac{\omega_+ - \omega_-}{\omega_+ + \omega_-}$$

the target also has a polarization that is similarily defined, except it deals with the spin states of the nuclei in the target, and not that of the incident neutrons.

The cross sections σ_+ (cross section for positive helicity neutrons) and σ_- (cross section for negative helicity neutrons) will be different. The cross section may contain dependence on the beam and target orientation and is written:

$$\sigma = a + bP_z^n + cP_z^T + dP_z^T P_z^n$$

The "a" term is parity conserving and is independent of neutron-nucleus orientation. The "b" term is parity non-conserving and is dependent only on incident neutron helicity. The "c" term is also parity non-conserving, but is dependent only on target nuclei orientation. Lastly, the "d" term is parity conserving, and it is dependent on both neutron and target orientation. This is the spin-spin term. The extended expressions for a, b, c, and d are given in Appendix B. Because parity violation is a Weak process, coefficients b and c are expected to be $\approx 10^7$ times smaller than coefficients a and d. For a single positive (negative) helicity neutron, $P_z{}^n = +1$ (-1). Parallel (anti-parallel) target orientation is given by $P_z{}^T = +1$ (-1).

These coupled differential equations can be solved by standard methods to obtain the intensities of the different beam components exiting the target :

$$\omega_+ = e^{-\alpha t} \; \{\omega_+{}^0 [\cosh \kappa t \; - \tau \sinh \kappa t \,] + \omega_- \nu \sinh \kappa t \,\}$$

$$\omega_- = e^{-\alpha t} \; \{\omega_-{}^0 [\cosh \kappa t \; + \tau \sinh \kappa t \,] + \omega_+ \nu \sinh \kappa t \,\}$$

where ω^0 is the original intensity of neutrons of that helicity incident on the target, ω is the intensity transmitted, t is the thickness of the target, and the other symbols are as follows:

$$\alpha = n(a+cP_z{}^T) + D \qquad\qquad \kappa = (n^2(b+dP_z{}^T\,)^2 + D^2)$$

$$\tau = n(b + dP_z{}^T) \;/\; \kappa \qquad\qquad \nu = D \,/\, \kappa$$

From these equations it is possible to derive expressions for the initial polarization of the beam of neutrons ($f_n{}^o$), final polarization of the beam (f_n), the percent transmission of the beam through a target polarized parallel or antiparallel to the incident beam (T_p, T_a), and the tranmission effect which relates the positive and negative transmission percentages (ε).

$$f_n^0 = \frac{\omega_+^0 - \omega_-^0}{\omega_+^0 + \omega_-^0}$$

$$f_n = \frac{\omega_+ - \omega_-}{\omega_+ + \omega_-} = \frac{f_n^0 - (\tau + v f_n^0)\tanh(\kappa t)}{1 - (\tau f_n^0 - v)\tanh(\kappa t)}$$

$$T_p\,(P_z^T = 1) = \frac{(\omega_+ - \omega_-)_p}{(\omega_+ + \omega_-)_p} = e^{-\alpha_p t}\,[\cosh(\kappa t) - (\tau f_n^0 - v)\sinh(\kappa t)]_p$$

$$T_a\,(P_z^T = -1) = \frac{(\omega_+ - \omega_-)_a}{(\omega_+ + \omega_-)_a} = e^{-\alpha_a t}\,[\cosh(\kappa t) - (\tau f_n^0 - v)\sinh(\kappa t)]_a$$

$$\varepsilon = \frac{T_p - T_a}{T_p + T_a}$$

The most general expression for the transmission effect can not be written in a compact form, and is therefore left as its definition.

2.2 Application of Attenuation to PNC Experiments

The experiment we consider measures the transmission of neutrons through a polarized target. If there is a difference in the transmission rates through targets oriented parallel and antiparallel to the incoming beam (i.e., the transmission effect is not zero), then parity violation is indicated. Our incident neutron beam contains equal numbers of positive and negative helicity neutrons ($\omega^0{}_+ = \omega^0{}_-$) and thus is initially unpolarized ($f_n{}^0 = 0$).

The expressions for the neutron transmission give percentages of beam transmission for both a beam incident to a parallel polarized target and an antiparallel polarized target. If the values of the parity violating terms in the cross section are zero, these two percentages will be the same, and the transmission effect is zero as well, indicating no parity violation, as would be expected. However, if the PNC terms are non-zero, these percentages will be slightly different over a range of neutron energies, and a transmission effect will be seen, indicating that a parity violation is taking place. To discover the exact source of this effect, the expression for the tranmission effect can be analyzed further. The expression for the transmission effect ε is extremely long and can not be simplified with its current variables, so the expression is given as its definition. However, if the incident beam polarization $f_n{}^0$ is assumed to be zero and we exclude spin-flip from bulk effects by setting D = 0, the expression can be simplified to:

$$\varepsilon = -nc\, P_z{}^T\, t + nbt \tanh(ndP_z{}^T t)$$

Both terms are parity violating, since b and c are parity violating terms. The first term is called the thin target term and is the expression encountered in the literature. However, the second term is new and comes from the existence of the acquired polarization effect caused by the spin-spin interaction between the neutrons and the target, which is what this paper concerns. Just how large this term is compared to the thin target term will be explored in the results section.

2.3 Extension of Attenuation Formulae to Targets of Higher Spin -- 7/2 Targets

For the spin 7/2 target, the differential equations for neutron attenuation and their solutions are similar, but the cross section term is much more complex (Appendix B). The cross section for this case is:

$$\sigma_+ = (a+c)+(d+f)P_z{}^n + bP_z{}^T + (e+g)P_z{}^T\, P_z{}^n$$

Note that this could be written as:

$$\sigma = a' + b'P_z^n + c'P_z^T + d'P_z^T P_z^n$$

Which is exactly the same form as the spin 1/2 case. Therefore, the same equations can be used for the spin 1/2 case, the only differences being the following:

$$\alpha = n[(a+c) + bP_z^T] + D \qquad \kappa = (n^2[(d+f) + (e+g)P_z^T]^2 + D^2)$$

$$\tau = n[(d+f) + (e+g)P_z^T] / \kappa \qquad \nu = D / \kappa$$

This time, the simplified expression for the transmission effect takes the following form:

$$\varepsilon = -nbP_z^T t + n(d+f)t \tanh[n(e+g)P_z^T t]$$

Once again, it is a two term solution, and one is the result of thin target effects, while the other is acquired polarization. The two are compared in the results section.

III. Discussion of Results

3.0 Programming

Programs to calculate results were coded in triple-precision FORTRAN on the Physics Department's VAX3500 computer. The ultra-high precision arithematic available using the VAX was important because of the size of the numbers involved, as well as the accuracy of the calculations needed in order to determine accurate results. On analysis of the power of the triple-precision, it was found to be accurate to 32 decimal places, as well as able to manipulate numbers ranging from 1×10^{-256} to 1×10^{256}. However, it was also learned that triple-precision subtraction was not as accurate as triple-precision addition, making it neccessary to adjust the programs to account for this fact.

3.1 Calculations

Calculations were performed for the spin 1/2 nuclei ^{57}Fe, ^{103}Rh, ^{111}Cd, ^{113}Cd, ^{117}Sn, and ^{203}Tl. These nuclei have been identified by J.E. Lynn [Ly 86, NNDC 91] as targets with suitable sets of s- and p-wave resonances for parity and time-reversal violation experiments. Resonance parameters necessary to describe the cross section have been compiled from the literature [Ly 86] and are presented in Table I. The "mixing angle" parameter is currently known for only two nuclei: ^{113}Cd and ^{117}Sn [Va 91]. The values used for the other nuclei have been artificially chosen to make the "b" and "c" terms in the cross section equal. We assume a parity violation matrix element V_{PNC} of 1 meV for most nuclei, with the exception of ^{113}Cd (.58 meV)and ^{117}Sn (.5 meV). The choice of V_{PNC} is guided by previous measurements in ^{81}Br and ^{232}Th [Fr 91]. Results of calculations are shown in Figures 3.1.1 through 3.1.7 and described below.

First consider the case of ^{113}Cd (Fig 3.1.1). The cross section is plotted from E_n(neutron energy) = 4 - 10 eV, and target thickness has been set to equal two mean free paths (about 134 cm for ^{113}Cd). The cross section for positive helicity neutrons is shown first (Fig 3.1.1.a). The generally decreasing trend of the cross section is because of the proximity of the tail of the large s-wave resonance at 0.178 eV of figure 2.0.1. The small p-wave resonance is visible. Neutrons of different helicity see different cross sections predominately because of the spin-spin term "d", and this is shown in the neighboring sub-figure (Fig 3.1.1.b). In our experiment, the incident neutron beam is unpolarized (both helicity states present in equal intensities). The fraction of neutrons emerging from a parallel oriented sample is shown next (Fig 3.1.1.c). Note the large amount of absorption due to the lower lying s-wave. The additional absorption from p-wave resonance is almost inconspicuous. In the actual PNC experiment one will measure the difference in transmission as the orientation of the target is flipped between parallel and anti-parallel (Fig 3.1.1.d). At the peak of the p-wave resonance, one will observe a difference of 3%. This is approximately 10^5 times larger than one would expect if the mechanism of resonance enhancement were not operating. The transmission effect ε plotted in these figures includes the acquired polarization effect generated by the thick target. To indicate the importance of the newly introduced thick target terms, the ratio of "nbt tanh(ndPt)" (the acquired polarization term) to "-ncPt" (the thin target term) is given. For the actual resonance parameters in ^{113}Cd, the acquired polarization term can be as large as 70% of the "normally" expected term. We see that thick target effects will generate about 40% of the measured yield in a ^{113}Cd experiment (Fig 3.1.1.e).

The only other nucleus where a complete set of resonance parameters is available is ^{117}Sn. Results for ^{117}Sn are shown in Figure 3.1.2. Many of the features are similar to the previous case and are not discussed. Note that the measureable transmission effect ε in

^{117}Sn will be around 1% (Fig 3.1.2.d). The importance of thick target effects is this case is rather striking --- the acquired polarization term is up to 200 times larger than the "normally" expected effect (Fig 3.1.2.e)! Acquired polarization completely dominates the experimental measurement! To understand why this is true, consider the ratio as the target thickness gets large (take $P_z{}^T = 1$).

$$\lim_{t \to \infty} \frac{N\, b\, t \tanh(N\, d\, P_z^A\, t)}{-N\, c\, P_z^A\, t} = -\frac{b}{c} = \frac{x - \sqrt{2}\, y}{x + \sqrt{2}\, y} = \frac{\tan\delta - \sqrt{2}}{\tan\delta + \sqrt{2}}$$

This asymptotic limit is completely determined by the ratio of "b/c", where the expressions for "b" and "c" have been taken from Appendix B, and thus the channel spin mixing ratios described by the mixing angle δ (Appendix B). For ^{117}Sn, the mixing ratio contribution to these terms in the cross section go as "c" ≈ 0.01 and "b" ≈ 1.99. Therefore we see that the relative size of the acquired polarization term is very sensitive to the mixing ratio and, therefore, the detailed nuclear spectroscopic resonance parameters are extremely important for accurate analysis. This had not been realized before this investigation.

In the remaining cases displayed in Figure 3.1.3 - 3.1.6, complete spectroscopic information is not available and the mixing angle has been chosen so that the "b" and "c" terms in the cross section have the same value. This will be obvious as the asymptotic limit of the "ratio" is unity (Fig 3.1.3.e, 3.1.4.e, 3.1.5.e, 3.1.6.e). The other graphs show some similarities to earlier results, but some interesting differences occur. The graphs for ^{103}Rh and ^{203}Tl are almost exactly alike in shape, although at different resonant energy values, and both have a negative transmission effect (i.e., the antiparallel transmission is greater then the parallel (Fig 3.1.3.d and 3.1.4.d). The results of ^{57}Fe and ^{111}Cd are also very close, showing that a transmission effect enhancement occurs at both the p-wave and the s-wave (Fig 3.1.5.d and 3.1.6.d), although the effect in cadmium is much larger.

For the case of a spin 7/2 target, the programs were modified to accomodate the different terms that are present in the cross section. The results of a run for ^{139}La (Fig 3.1.7) can be seen to be similar to any of the spin 1/2 cases, showing that the complexity of the terms in the cross section is irrelevant, as long as the terms can still be grouped into the four spin categories.

3.2 Improper Reversal of Target Orientation

The proper execution of the PNC experiment considered here requires the the orientation of the target be reversed from parallel to anti-parallel exactly. Any misalignment or polarization change in the two orientations will introduce systematic errors in the experiment which could mimic a true PNC effect. The programs written have the ability to investigate the size of such effects.

We consider the case of ^{113}Cd and set $V_{PNC} = 0$ -- i.e. no parity violation. We then ask the question: "How much of a improper reversal is required before one obtains a false PNC effect which really isn't there?" Results of this study are shown in Figure 3.2.1. Plotted is the apparent transmission difference ε versus $1\text{-}\phi$ -- the misalignment fraction. A misalignment of 3% will generate a false PNC signal of comparable size to that expected in an ideal experiment.

3.3 Depolarization Effects

In order to polarize a target, it must be maintained at extemely low temperatures (< 3 Kelvin) and a large magnetic field must be applied. This causes the nuclei in the target to align with the magnetic field lines. However, due to anisotropy of the crystals within the target, not all of the nuclei will align perfectly. This causes pockets of varying field strength (domains) [Po 62], within the target.

When a neutron encounters one of these new domains, the component of the local field present at right angles to the applied external field will cause a new precession of the neutron to occur (i.e. a spin flip). Because the samples used in this type of experiment are polycrystalline in nature, they are extremely sensitive to depolarization, but all samples in a different way. Therefore, the depolarization parameter D must be measured for each individual target sample.

The size of the depolarization, and, in turn, the precession, decreases as field strength increases. Postma [Po 62] has determined that the depolarization is negligible around 4 eV in Holmium-ethyl-sulfate when the applied field is greater than 10 kOe. Therefore, if a large enough field is applied, the effect can be ignored.

Sometimes, however, a large enough field can not be created, so the effects must be taken into account. In figure 3.3.1, a graph of the effects of D on the transmission effect is drawn. It can be seen that as the size of D increases, the size of the transmission effect increases as well. However, when the thin target and acquired polarization terms were looked at, it was discovered that the fraction of the effect caused by acquired polarization decreases: the thin target term becomes more dominant, although not completely so.

Summary

In conclusion, several important techniques were used in the completion of this project. The differential equations for neutron transmission were solved, and applied to equations for transmission percentage and the transmission effect. In order to do this, complex formulas for cross sections were derived, and several computer programs were written to explore the implications of the solutions. Three major results were determined as a result of these probings.

First, with known resonance parameters for spin 1/2 targets ^{57}Fe, ^{103}Rh, ^{111}Cd, ^{113}Cd, ^{117}Sn, and ^{203}Tl, and spin 7/2 target ^{139}La, the relative sizes of the various terms were determined, including the values of the cross sections, transmission percentages, the size of the transmission effect, and the percentage of the transmission effect caused by acquired polarization. For the case of ^{113}Cd, acquired polarization accounts for 40% of the transmission effect, and for ^{117}Sn it is nearly 100%. The results from all of the other targets contain similar characteristics, with some differences in sizes and resonance energies where the effects take place. Therefore we see that the relative size of the acquired polarization term is very sensitive to the mixing ratio and, therefore, the detailed nuclear spectroscopic resonance parameters are extremely important for accurate analysis. This had not been realized before this investigation. When the techniques were applied to the spin 7/2 target, it was found that the target behaves the same as a spin 1/2 target, but with a more complex expression for the cross section, although the expressions can still be reduced to just four basic terms. For this target, as well as the last four spin 1/2 targets, complete resonance parameters must be determined before the results will be completely accurate

Second, the effect of imperfect target polarization reversal on the value of the transmission effect was determined in the case of ^{113}Cd. It was found that target polarization reversal inefficiencies as small as 3% will mimic a parity violation.

Third, the effect of the depolarization term on the relative size of the acquired polarization was explored, also for the case of ^{113}Cd. It was determined that as the depolarization term becomes larger, the transmission effect becomes larger as well. However, the component of the transmission effect caused by acquired polarization becomes smaller, causing the thin target term to increase in dominance.

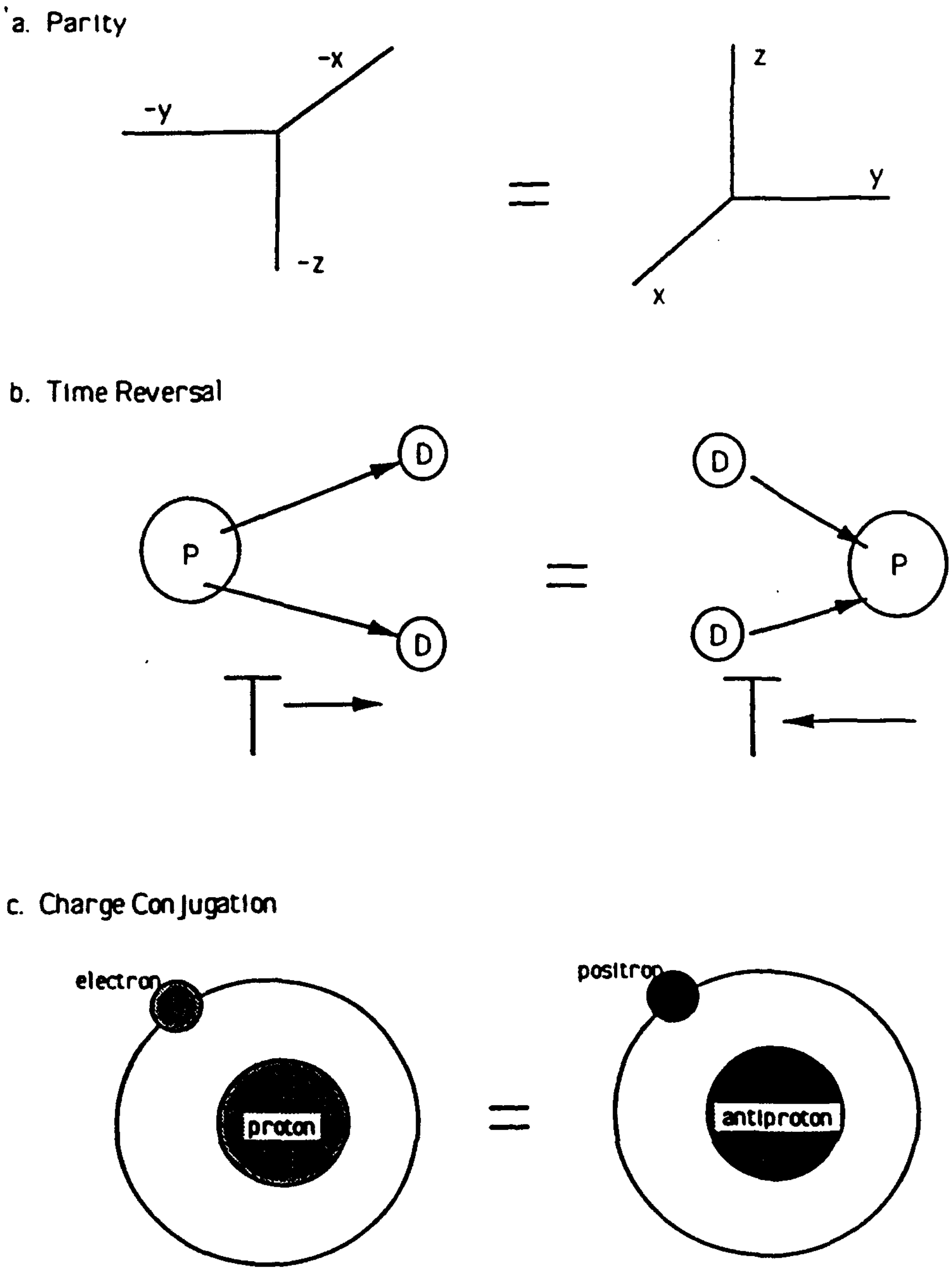

Figure 1.0.1 There are three fundamental symmetries in physical processes. Illustrated are parity (a), time-reversal (b), and charge-conjugation (c).

Neutron Cross Section for ^{113}Cd

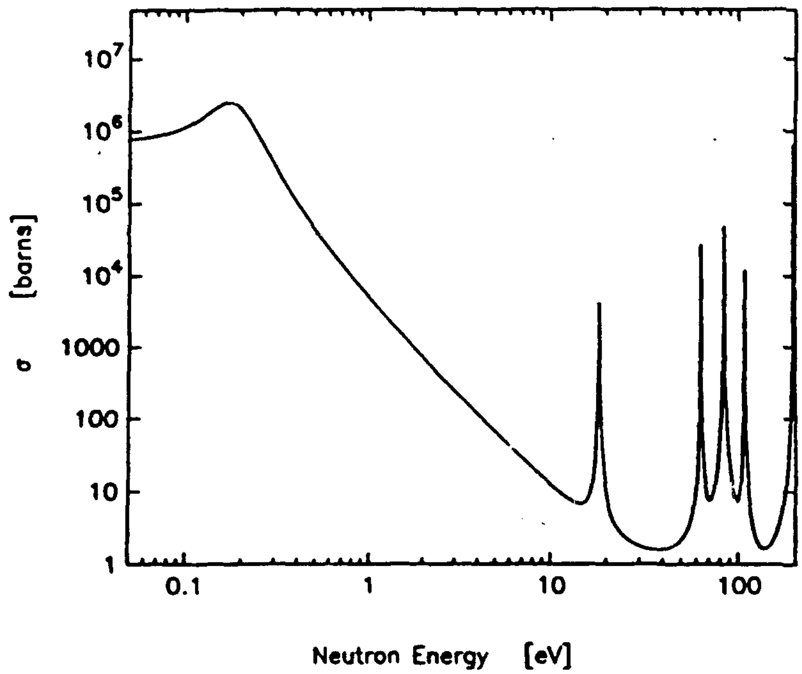

Figure 2.0.1 Total cross section for neutrons on ^{113}Cd. Barn is the conventional unit for cross sections. One barn corresponds to 10^{-24} cm^2. The cross section for this nucleus is not independent of neutron energy. Six resonances are evident. This cross section has been calculated using the resonance parameters of Shepkin in the NNDC data base [NNDC 91].

ACQUIRED POLARIZATION EFFECTS IN 113Cd

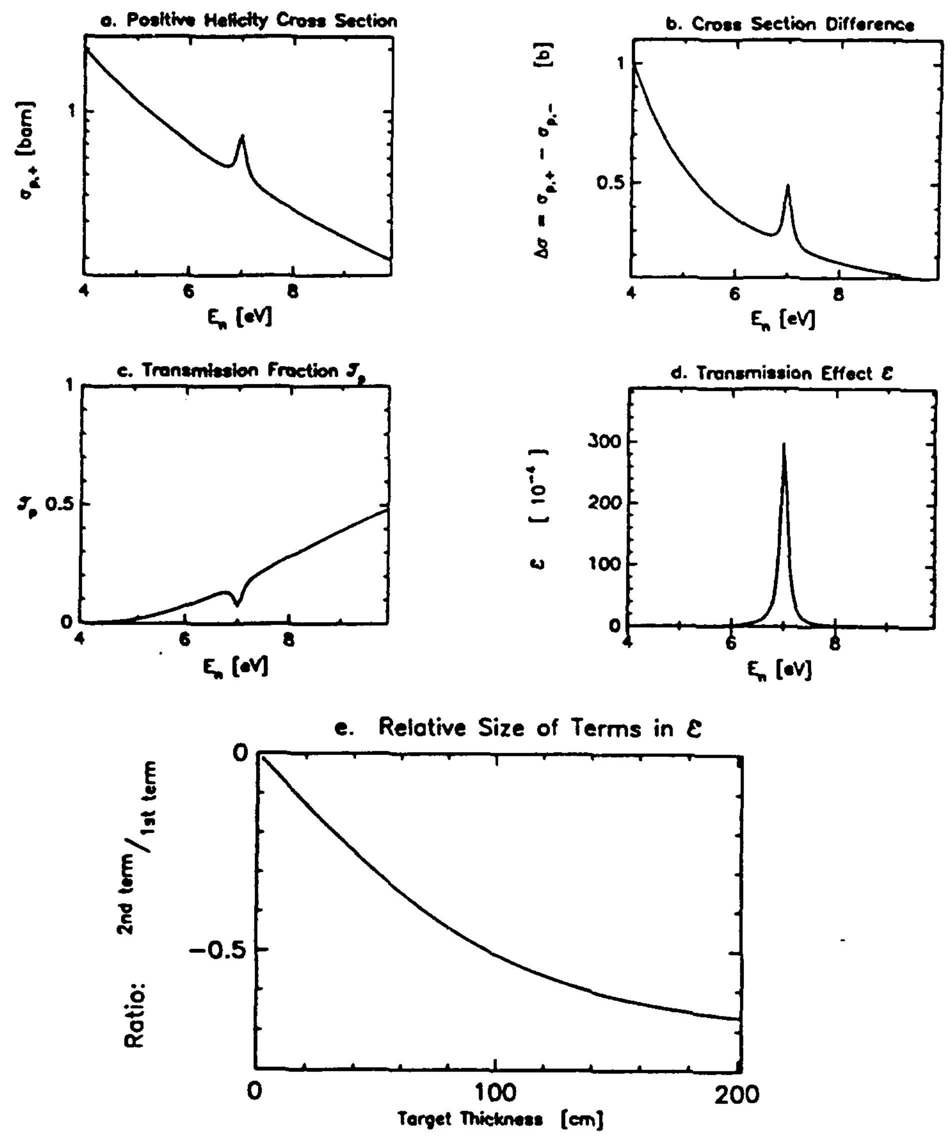

Figure 3.1.1 Acquired polarization effects in Cadmium-113. Subfigure a) shows the cross section for positive helicity neutrons on an parallel-oriented target. Subfigure b) indicates the difference in cross section for positive and negative helicity neutrons. Subfigure c) shows the fraction of neutrons transmitted through a target of two mean-free-paths thickness. The transmission effect to be observed is given in subfigure d). The relative importance of thick and thin target contributions to the transmission effect is given in subfigure e).

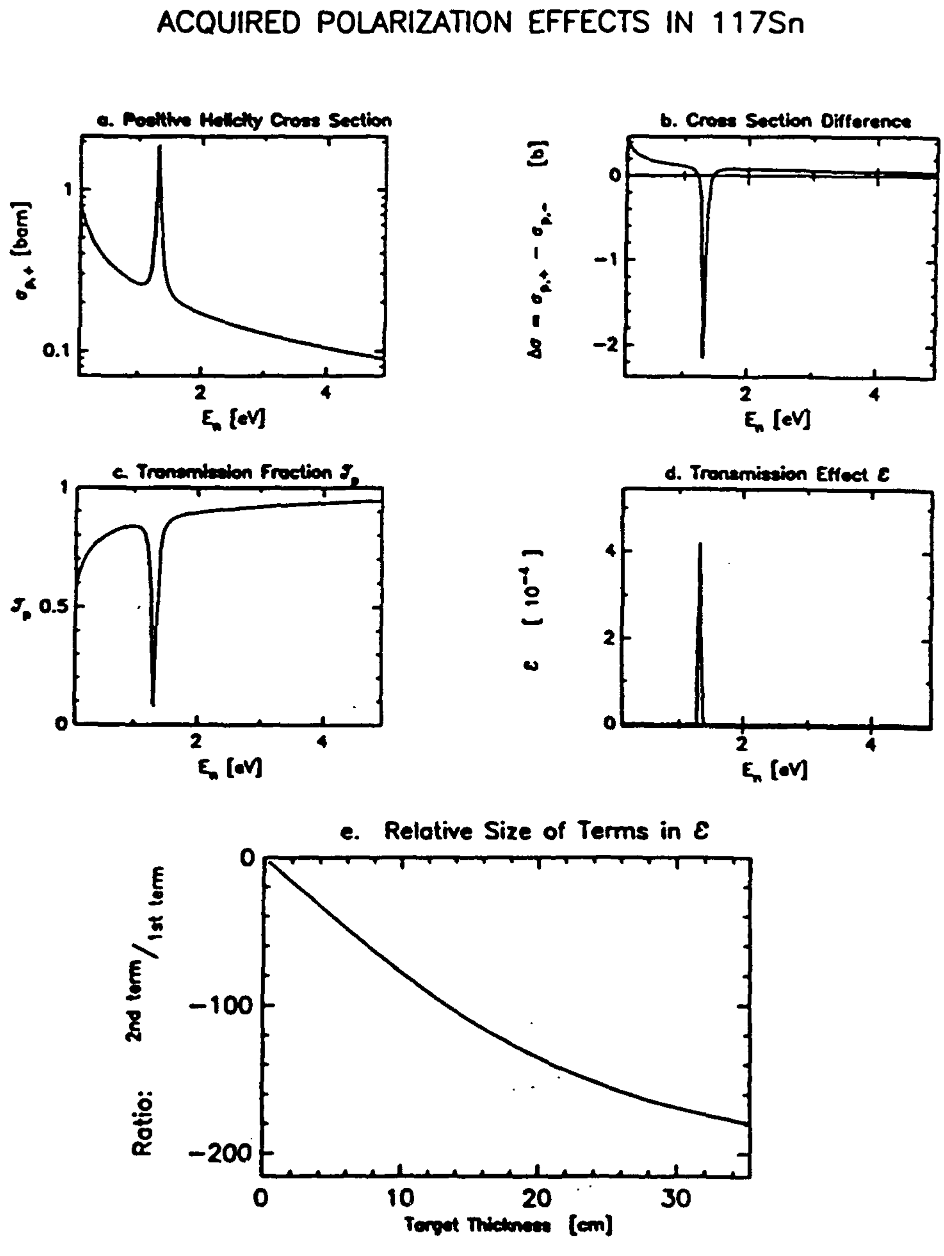

Figure 3.1.2 Acquired polarization effects in Tin-117. The thick-target acquired polarization effects are 200 times larger than the thin target contribution for any practical target thickness.

ACQUIRED POLARIZATION EFFECTS IN 103Rh 34

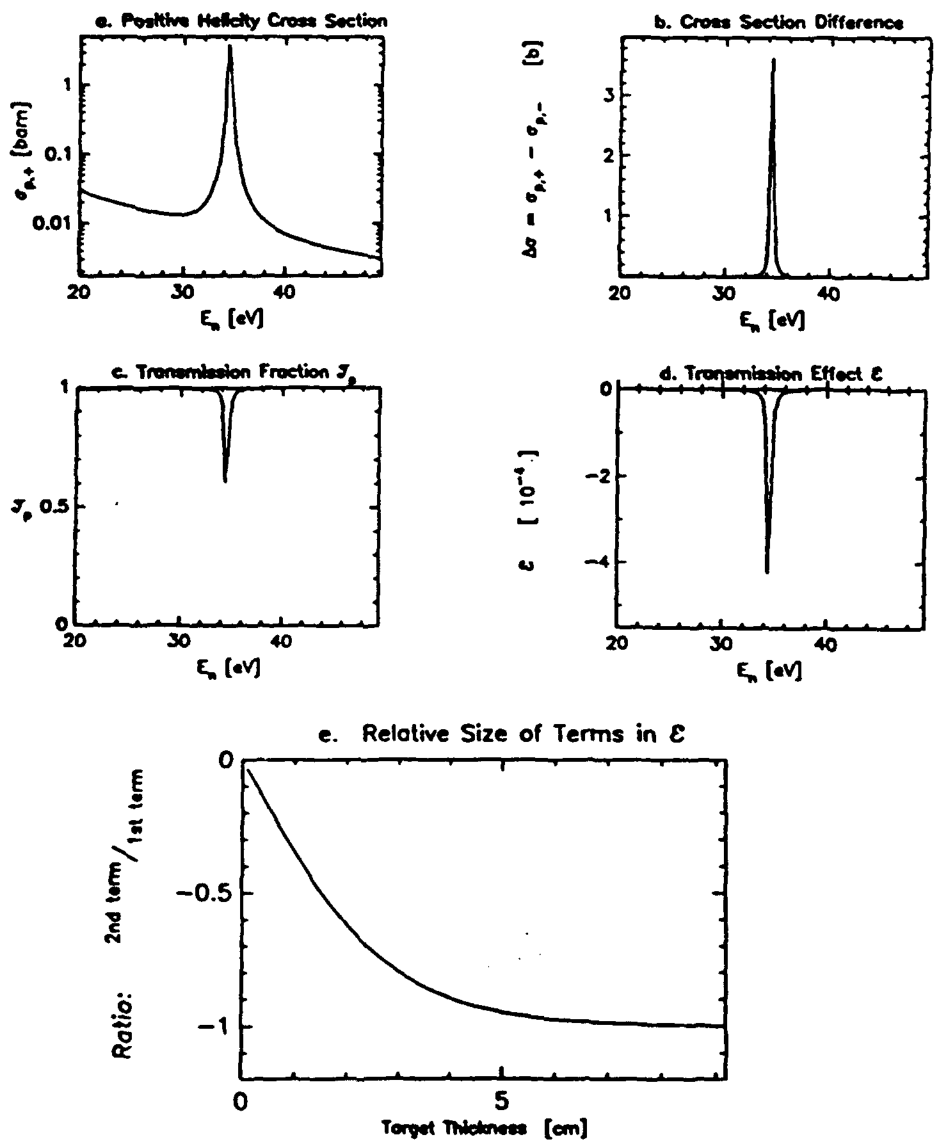

Figure 3.1.3 Acquired polarization effects in Rhodium-103. The asymptotic limit is unity and is fixed by the channel spin mixing angle.

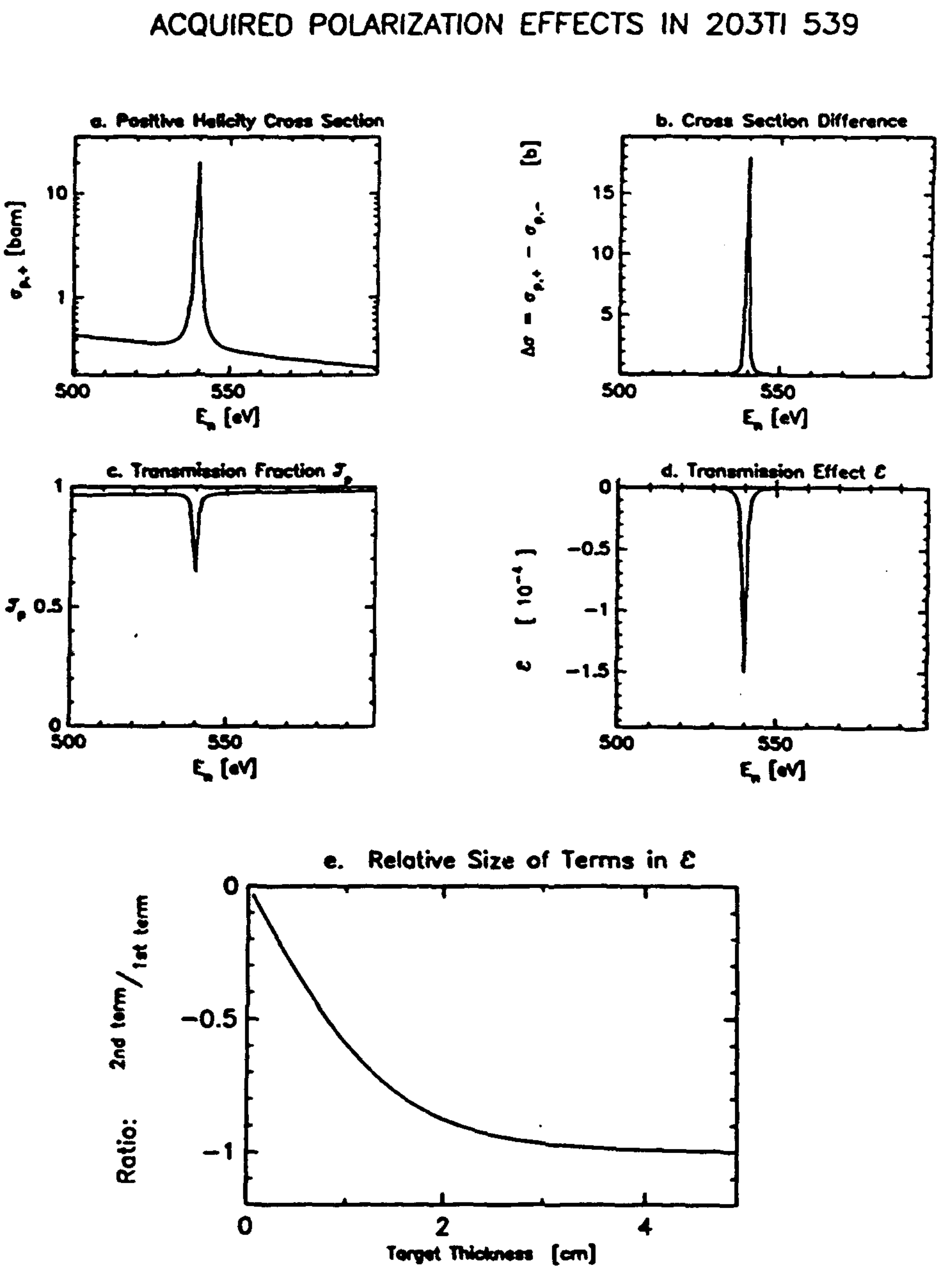

Figure 3.1.4 Acquired polarization effects in Thallium-203.

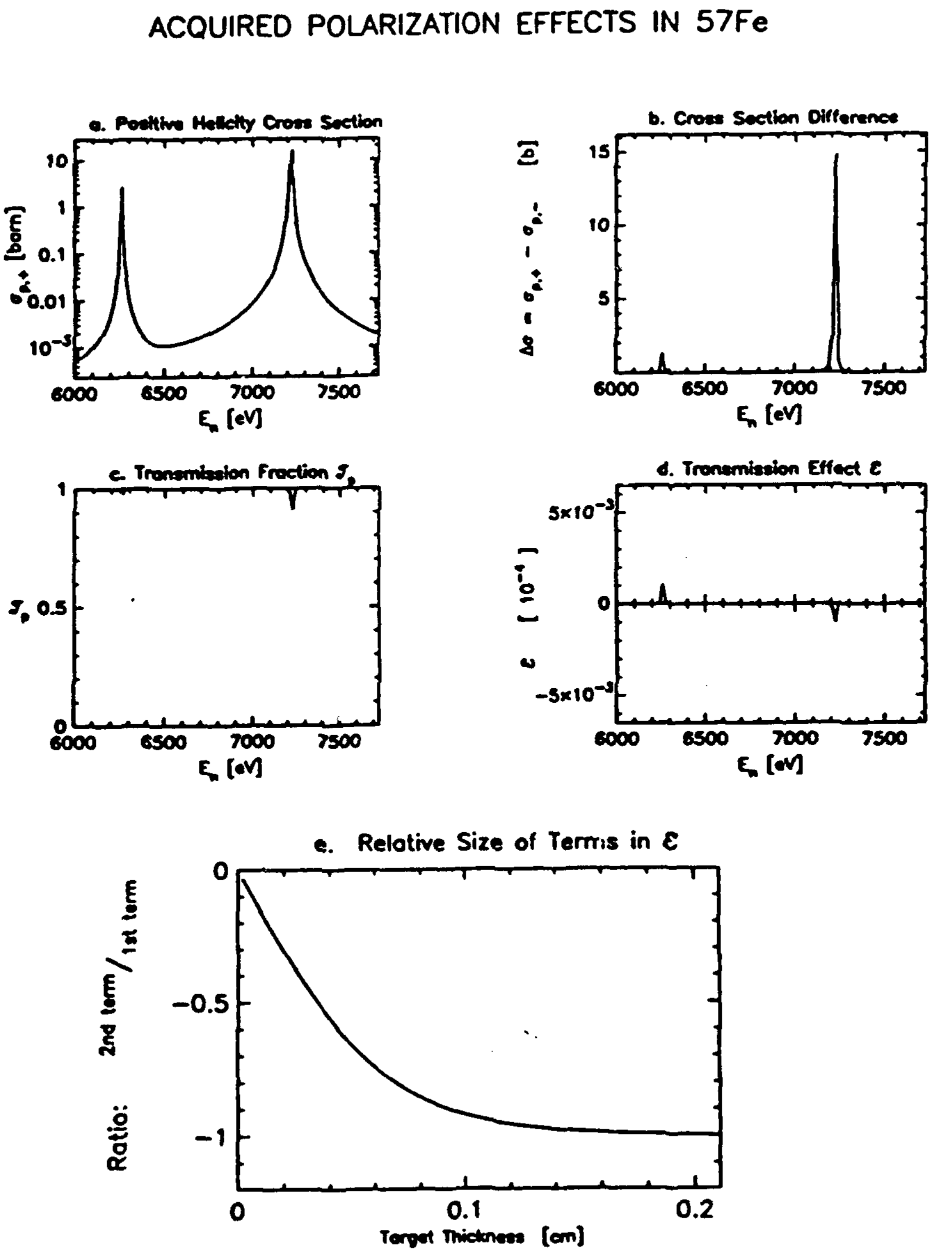

Figure 3.1.5 Acquired polarization effects in Iron-57.

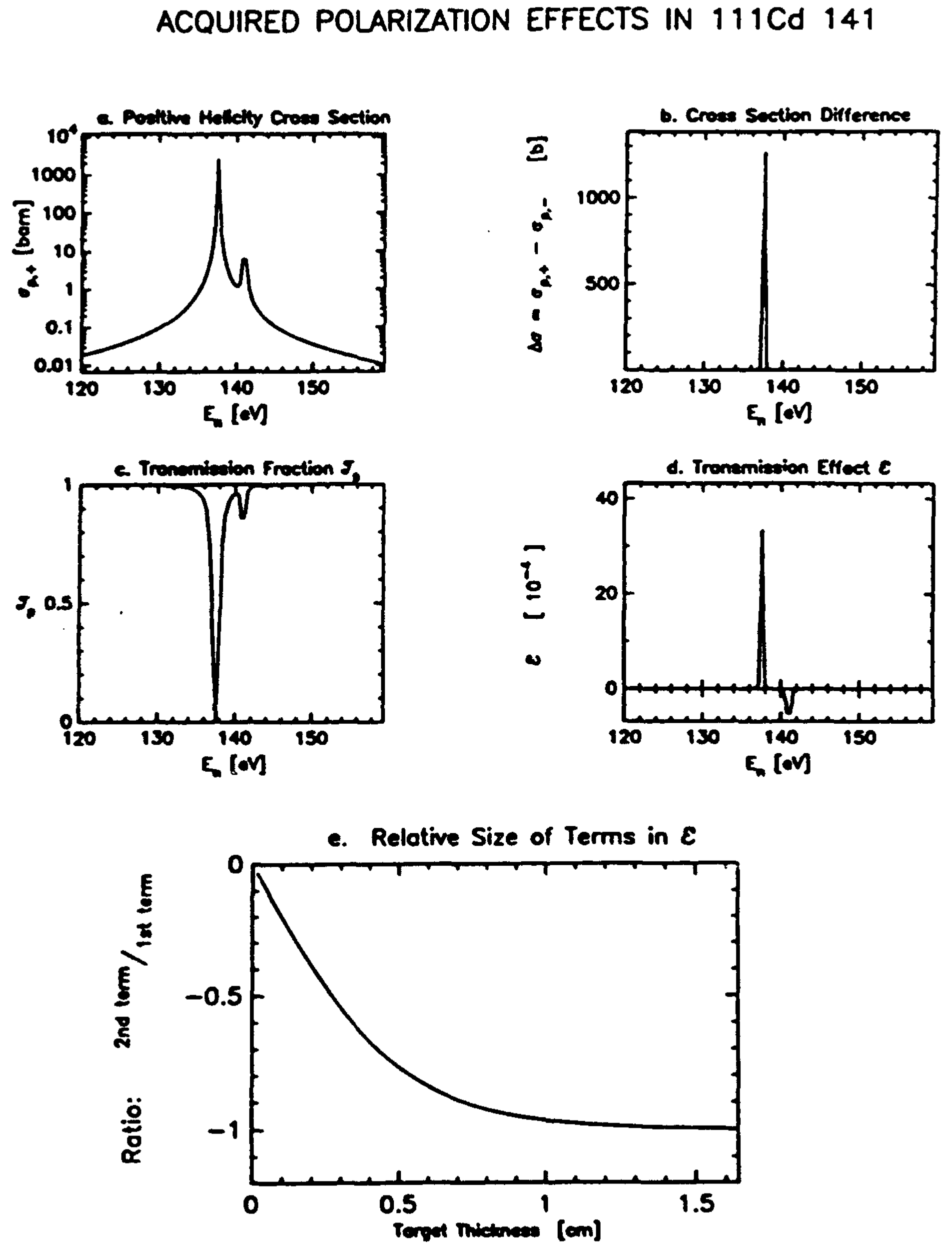

Figure 3.1.6 Acquired polarization effects in Cadmium-111.

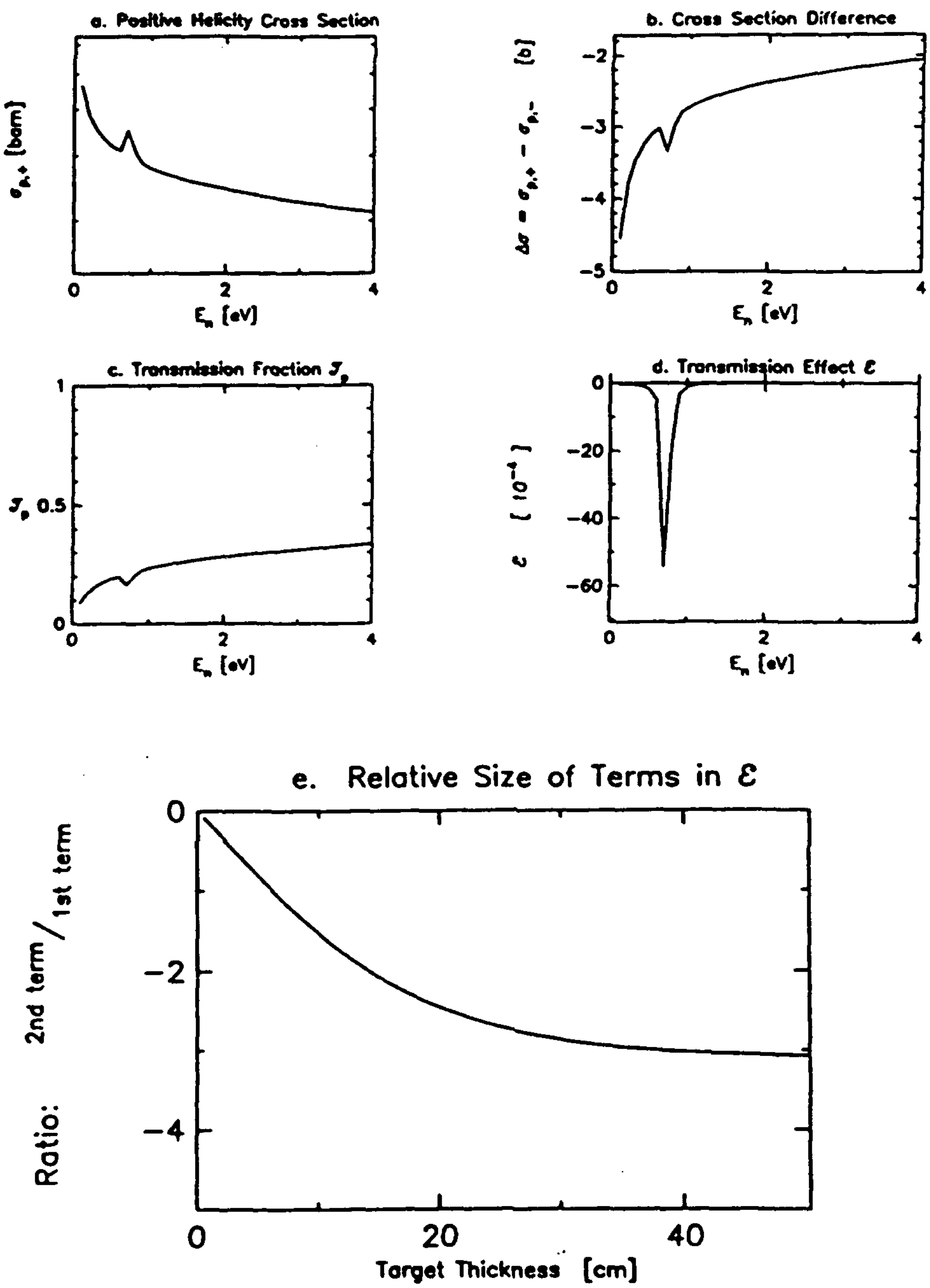

Figure 3.1.7 Acquired polarization effects in Lanthanum-139. The behavior of the transmission effects in higher spin targets (spin 7/2) is exactly the same as in the case of spin 1/2 discussed in detail earlier.

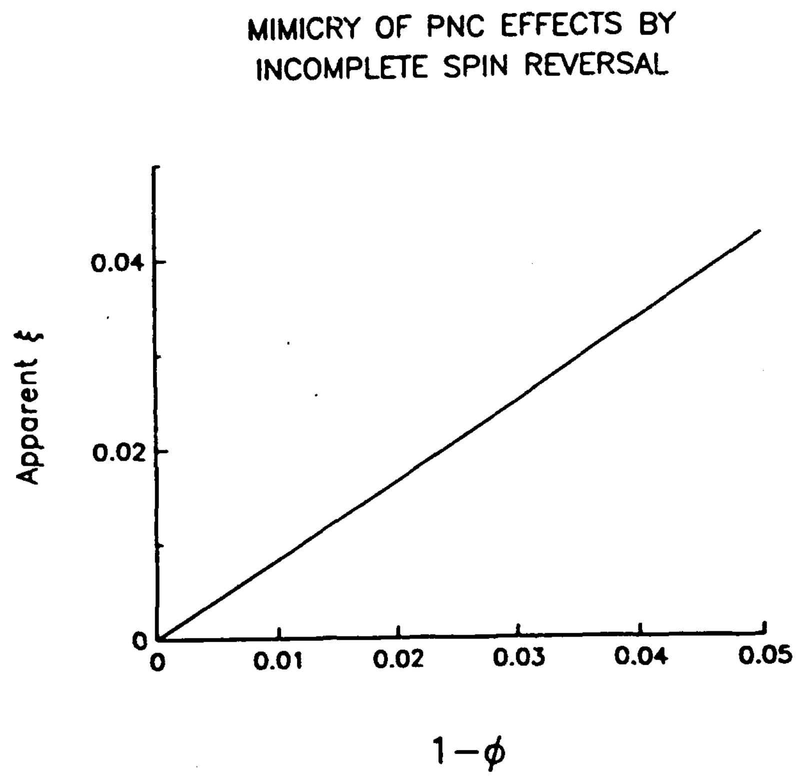

Figure 3.2.1 Effects of improper reversal of target orientation for ^{113}Cd. If the orientation of the target is not exactly reversed during a PNC experiment, a systematic effect will arise which mimics a true parity violation. Orientation errors of ≈3% mimic the size of the true transmission effect calculated earlier.

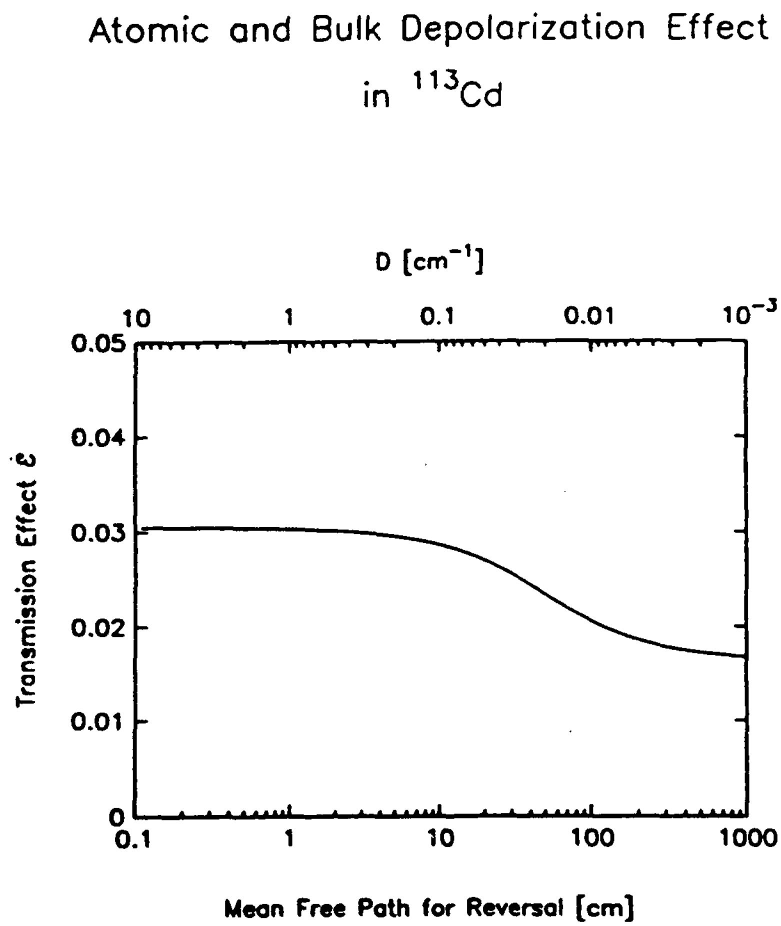

Figure 3.3.1 Effects of atomic and bulk depolarization on experimental results for ^{113}Cd. A target thickness of two mean-free-paths is assumed. No depolarization corresponds to D = 0. Contrary to what one might expect, depolarization does not wash out the observable effects.

Table 3.1.1 Resonance Parameters for Spin 1/2 Nuclei

Target Nucleus	E_s [eV]	Γ_s^n [meV]	Γ_s [meV]	E_p [eV]	Γ_p^n [μeV]	Γ_p [meV]	Mixing Angle[a] [deg]
^{57}Fe	6260.	345.	450.	7220.	1.7e+6	2000.	90.
^{103}Rh	187.	38.3	145.	179.	180.	174.	90.
^{103}Rh	1.259	0.51	156.	34.5	016.	150.	90.
^{111}Cd	137.6	12.	90.	141.	380.	100.	90.
^{113}Cd	0.178	0.38	100.	7.0	0.103	160.	256.
^{117}Sn	-29.	3.5	100.	1.33	0.10	50.	325.
^{203}Tl	238.	4000.	4000.	37.91	25.	500.	90.
^{203}Tl	238.	4000.	4000.	539.	3200.	500.	90.

a) Mixing angle for all nuclei except 113Cd and 117Sn has been artificially set to 90 degrees in order to make the "b" and "c" terms of the cross section equal.

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Appendix A. Experimental setup at LANL

Currently, fundamental symmetry experiments with neutron beams are under development at Los Alamos National Laboratories (USA), Dubna (USSR), and KEK (Japan). A typical experimental setup (the one at LANL) is described below [Fr 91].

The process begins with a 800 MeV LINAC accelerator which has the ability to produce polarized H- and high intensity H+ ions for use in various other parts of the Los Alamos Manufactured Proton Facility (LAMPF). See figure A1 for a diagram of the LAMPF facility. The LANSCE (Los Alamos Neutron Scattering Center) facility is supplied by the H- ions. The ions are sent in a beam of 725us wide pulses at a spacing of 8.33 ms to the proton storage ring.

For the experiments taking place at the facility, a much narrower beam pulse is needed. The proton storage ring serves this function by compressing the pulses to 250ns. The ring also serves to strip the H- ions of their electrons, resulting in a proton beam. This process is 92% efficient, with the remaining 8% going to a beam dump.

From the proton storage ring, the protons are then sent to a neutron production target. The neutrons are produced by a process called spallation. In this process, protons are fired at a heavy, neutron rich target, in this case tungsten, in order to free the neutrons from the target. At LANSCE, approximately 25 neutrons are produced for every incident proton. These neutrons have a very high energy, so they must be moderated to a lower energy by a combination of water and gadolinium-boron shields. Once moderated, the beams have the proper energy and flux for use in experiments.

From the neutron production target, an unpolarized neutron beam is fed to the PNC experiments. First, the beam must be polarized. This is accomplished by using a neutron spin filter, which consists of $La_2Mg_3(NO_3)_{12} - 24H_2O$ (0.5% ^{142}Nd doped), also called LMN, crystals which are polarized in a large cryostat. To polarize the crystals a large magnetic field is applied to them using a superconducting magnet which is cooled by the liquid helium in the cryostat. Once the magnetic field has been applied, the crystals are then bombarded by microwaves to polarize them. These polarized crystals serve to allow only neutrons oriented in the same direction to pass through, therefore polarizing the neutron beam.

Since the experiment measures the difference in transmissions for a positive helicity versus a negative helicity beam, a spin flipper is needed in order to quickly reverse the spin of the polarized neutron beam. The spin flipper is a set of coils and solenoids which creates a magnetic field which can be either parallel or antiparallel to the neutron beam. When the beam passes through it, the neutrons will either continue at their current polarization if parallel o. flip their spins if antiparallel. The efficiency of these flips is near 100%, but some neutrons will not reverse spin.

From this point, the beam is monitored to make sure it maintains required polarization levels as it is incident upon the target. Various targets can be used, such as ^{139}La, ^{81}Br, ^{232}Th, etc.. The portion of the beam that is transmitted through the target is then detected further down the flight path by a set of Li glass neutron detectors, which then feed their signals to the control room for analysis. See figure A2 for a complete picture of the flight path used in the PNC experiments.

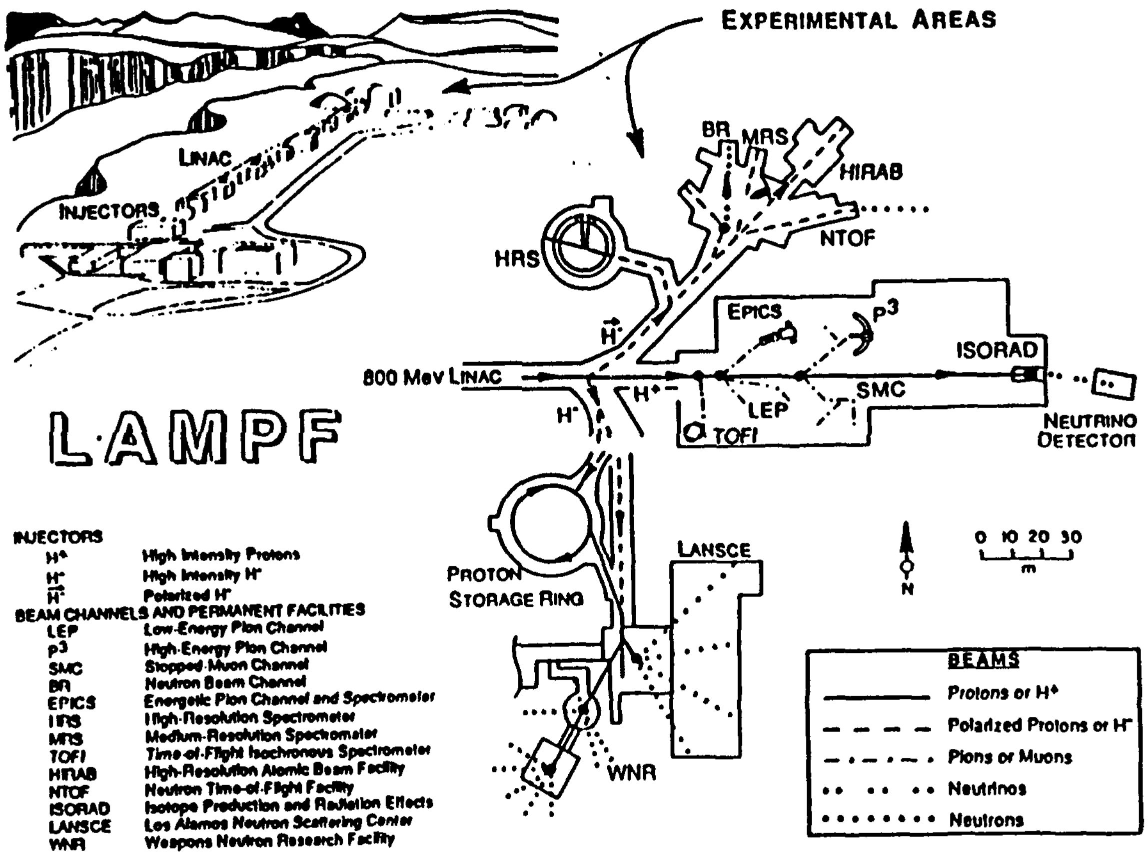

Figure A.1 Experimental facilities at LAMPF. Protons are accelerated to 800 MeV and shot into a Tungsten neutron production target. Figure used courtesy LANL.

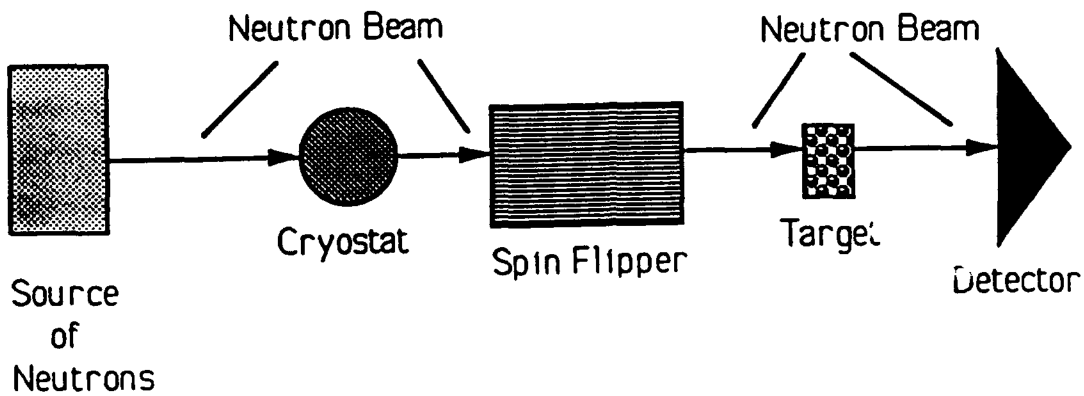

Figure A.2 Experimental beamline for polarized neutron on unpolarized target PNC experiments at LAMPF.

Appendix B. Cross Sections

B.0 Theory of Cross Sections

The differential cross section is the probability per unit angle that a particle will be scattered into that angle. In the calculations discussed in this paper, the total cross section is used. This is the probability that a particle will be scattered in any direction. In short, the cross section of a nucleus can be used to predict both transmission and scattering possibilities. These cross sections are responsible for the resonances that occur in the transmission percentages because they are a function of energy.

To truly understand cross sections, the interaction of the particle and the nucleus must be looked at closely. In any particle-nuclear interaction, there is an ingoing particle and an outgoing particle. Each of these particles, as well as the nucleus, can be represented as a wavefunction. These wavefunctions, in turn, can be described as a superposition of the spin states that are possible. By a combination of these spin states in a coupling scheme, the entire process can be described and a result of the initial interaction can be predicted.

The combination of all possible spin states for the incident beam and the target nucleus forms the basis of the angular correlation function. This is done mathematically through the use of tensors [Fe 65]. Once the angular correlation function has been summed over all angles, the total cross section can be calculated, which is a simpler form for determining scatttering probabilities.

The cross section for a spin 1/2 target can be expressed as four terms, two of which are parity non-conserving terms. It takes the following form:

$$\sigma = a + bP_z^n + cP_z^T + dP_z^TP_z^n$$

The "a" term is parity conserving and is not affected by spin interactions. The "b" term is parity non conserving and is affected by the beam helicity. The "c" term is also parity non conserving, but is affected by the polarization of the target. Lastly, the "d" term is parity conserving, and it is affected by the interaction of the beam helicity with that of the target. As for the spin equlas zero case, the extended expressions for a, b, c, and d are given in section B.1 of this appendix.

B.1 Spin 1/2 Target Parameters

The angle-integrated total cross section for neutrons on spin 1/2 targets may be written [Va 90] as

$$\sigma = a + b P_z^n + c P_z^T + d P_z^n P_z^T$$

where the coefficients in the expression are given by:

$$a = \pi \lambda\!\!\!^{-2} \, \frac{3}{4} \left[\frac{\Gamma_s \Gamma_s^n}{(E_s - E)^2 + (\Gamma_s/2)^2} + \frac{\Gamma_p \Gamma_p^n}{(E_p - E)^2 + (\Gamma_p/2)^2} \right]$$

$$b = \pi \lambda\!\!\!^{-2} \, \frac{\sqrt{3}}{2} \, V^{PNC} \, \frac{1}{[S]^2 [P]^2} \sqrt{\Gamma_s^n} \sqrt{\Gamma_p^n} \, (x - \sqrt{2}\, y) \left[\Gamma_s \Delta E_p + \Gamma_p \Delta E_s \right]$$

$$c = - \pi \lambda\!\!\!^{-2} \, \frac{\sqrt{3}}{2} \, V^{PNC} \, \frac{1}{[S]^2 [P]^2} \sqrt{\Gamma_s^n} \sqrt{\Gamma_p^n} \, (x + \sqrt{2}\, y) \left[\Gamma_s \Delta E_p + \Gamma_p \Delta E_s \right]$$

$$d = \pi \lambda\!\!\!^{-2} \, \frac{1}{2} \left[\frac{1}{2} \, \frac{\Gamma_s \Gamma_s^n}{(E_s - E)^2 + (\Gamma_s/2)^2} + \frac{\Gamma_p \Gamma_p^n}{(E_p - E)^2 + (\Gamma_p/2)^2} \left(-\frac{3}{2} x^2 + \frac{5}{4} y^2\right) \right]$$

and where $[S]^2 = (E_s-E)^2 + (\Gamma_s/2)^2$, $[P]^2 = (E_p-E)^2 + (\Gamma_p/2)^2$, $\Delta E_s = E_s-E$, $\Delta E_p = E_p-E$, $x = \cos\delta$, and $y = \sin\delta$. In this scheme, the other variables are defined as follows: E is the energy of the incident neutron, E_s is the resonance energy value where the s-wave occurs, E_p is the resonance energy value where the p-wave occurs, λ is the reduced neutron wavelength, $\Gamma_s{}^n$, $\Gamma_s{}^T$, $\Gamma_p{}^n$, and $\Gamma_p{}^n$ are the resonance widths of the s or p wave resonances for the total (T) or neutron (n), and δ – the channel spin mixing ratio angle. This mixing ratio angle is the difference between the b and c terms, as they are the same otherwise. Its value will determine the size of the ratio of b to c.

B.3 Extension of Techniques to a Spin 7/2 Target

The same principles used to derive the expression for the spin 1/2 target can be used to come up with an expression for the spin 7/2 target. The expression takes the following form:

$$\sigma = a\rho^T_{00}\rho^n_{00} + b\rho^T_{10}\rho^n_{00} + c\rho^T_{20}\rho^n_{00} + d\rho^T_{00}\rho^n_{10}$$
$$+ e\rho^T_{10}\rho^n_{10} + f\rho^T_{20}\rho^n_{10} + g\rho^T_{30}\rho^n_{10}$$

Where a, b, c, d, e, f, and g take on forms similar to that of a, b, c, and d for the spin 1/2 case, but much more complex, and the various ρ's are spin 7/2 density tensors.

The various terms above can be grouped together to come up with the following expression:

$$\sigma = (a+c)+(d+f)P_z{}^n + bP_z{}^T + (e+g)P_z{}^T\, P_z{}^n$$

which takes on the same form as the spin 1/2 target:

$$\sigma = a' + b'P^n_z + c'P^T_z + d'P^T_zP^n_z$$

The meaning interpretation of each term is slightly different in this case. For example, the "b'" term should be interpreted as that part of the cross section which changes sign only because the neutron spin was flipped. As a result, a spin 7/2 target can be treated in much the same way as a spin 1/2 target, with adjustments made for the different complexities of each of the four terms.

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