POSSIBLE EXPERIMENTS WITH POLARIZED NEUTRONS AT THE ZGS AND AT FNAL

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I. INTRODUCTION

Experiments with polarized neutrons at high energy have interested me recently for at least five reasons as follows: (1) Our Michigan group has over the past decade evolved a program of hadronic physics with neutron beams at the Bevatron, the ZGS, the AGS, and at FNAL so that we feel quite familiar with the problems and techniques in this area[1]. (2) The Argonne ZGS has discussed plans to accelerate polarized deuterons; the neutrons from the stripped deuteron beam will provide a collimated, intense, reasonably monochromatic polarized neutron beam of up to 6 GeV. (3) The observed polarization of inclusively-produced Λ°s by Overseth's group at FNAL and CERN begs the investigation of polarization in other inclusive phenomena such as neutron production[2]. (4) J. Rosen et al. have recalled[3] that the Schwinger Effect[4] can produce up to 100% polarization of neutrons in elastic scattering at very small angles at high energies and outlined possible experiments at Fermilab. (5) During the winter and spring of this year I was a guest of Westfield College (London) where Elliot Leader stimulated my interest in various polarization phenomena accessible though small angle neutron scattering.[5] Drawing these factors together has lead to the conception of a series of possible experiments at both Argonne and Fermilab which I will sketch herein.

Fundamental to the class of experiments I am discussing is the interference between the electromagnetic

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(here magnetic) scattering and the nuclear scattering. As E. Leader has noted most succinctly[6], polarization effects are maximal where these amplitudes are equal at a value of transverse momentum $p^\circ_\perp$ in elastic scattering given by

$$p^\circ_\perp = \frac{4\pi\alpha Z\mu}{m\sigma_T(nA)}$$

for neutrons of mass m on a nucleus of charge Z and mass number A. For hydrogen and lead, $p^\circ_\perp \cong 1.8$ MeV/c, and for uranium, $p^\circ_\perp \cong 2.0$ MeV/c. It is convenient to define $q = p_\perp/p^\circ_\perp$. At very small angles, the magnetic scattering is proportional to $(-t)^{-1}$ while the nuclear term is nearly constant, so that the polarization varies with q as

$$P = \frac{2q}{1+q^2}$$

In Figure 1 we have plotted P vs. q and q^2 (proportional to -t). It is convenient that P falls only slowly for $q > q_0$ so that $\bar{P} \cong 0.7$ for $1 \le q \le 4$ and $\bar{P} \cong 0.4$ for $3 \le q \le 10$ (averaged over $p_\perp$, not t). In order to design an experiment, we want to consider the fraction of the incident flux which may be scattered into a range of t useful for polarization analysis. The relevant quantity is

$$\frac{1}{\sigma_T}\left(\frac{d\sigma_e}{dt}\right)\delta t\ .$$

A useful, conservative assumption is to consider a target 1/3 of an interaction mean free path thick. In this case, the fraction of incident flux scattered into certain ranges of δt from hydrogen and lead targets

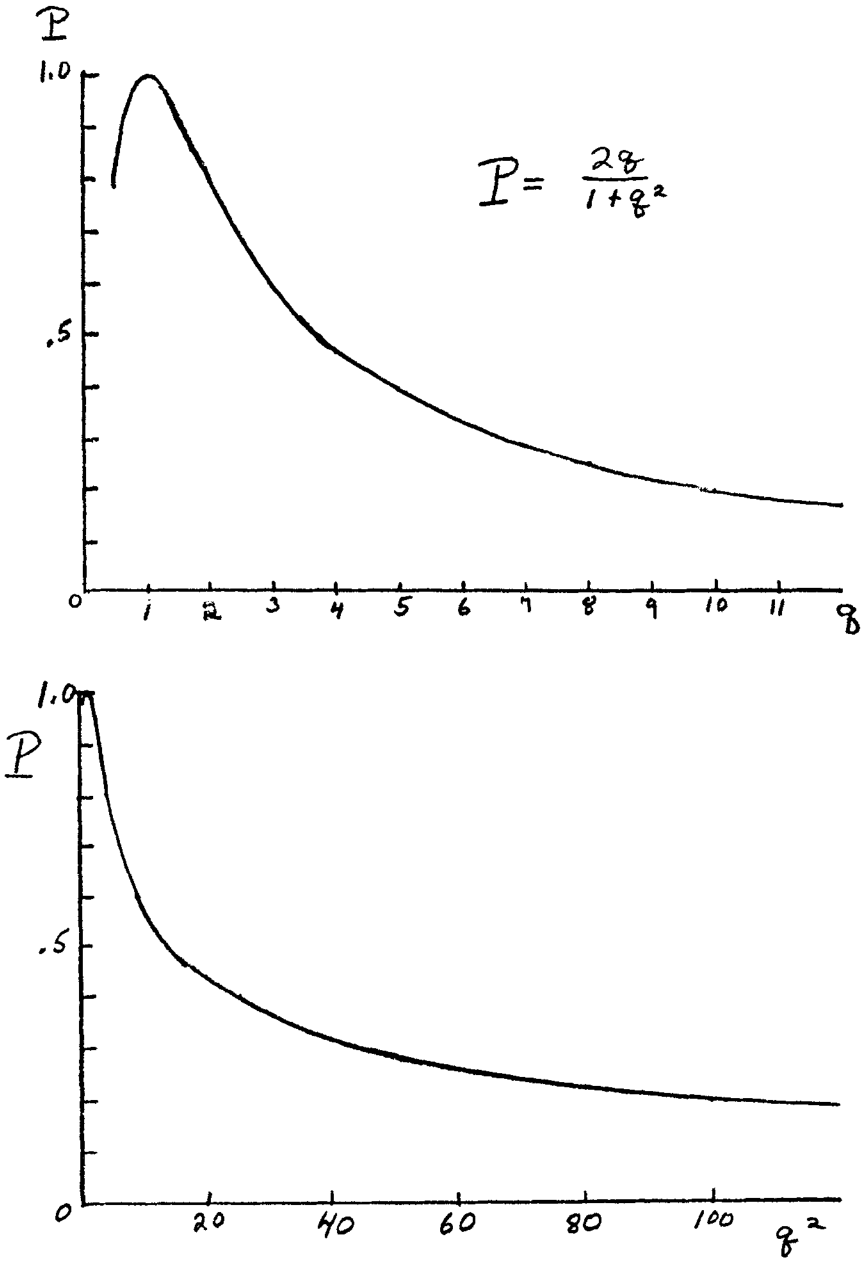

Figure 1. Plot of P vs. q and q^2 where $P = 2q/(1+q^2)$.

is indicated in Table I.

TABLE I

Fraction of incident flux elastically scattered into given ranges of q for 1/3 λ targets of H and Pb

q	A	$\bar{P}$	$1/3\left[\frac{1}{\sigma_T}\left(\frac{d\sigma_e}{dt}\right)\delta t\right]$
1-4	H	.7	2×10^{-5}
1-4	Pb	.7	2×10^{-3}
3-10	H	.4	1.2×10^{-4}
3-10	Pb	.4	1.2×10^{-2}

II. ZGS EXPERIMENTS

It is expected that the ZGS will produce a beam of polarized deuterons of about 5×10^9 per ZGS pulse at 12 GeV. From the analysis of W.T. Meyer[7] electromagnetic stripping occurs at this energy with a forward cross section $d\sigma/d\Omega \cong 10^{-21}$ cm^2/sr. In this case both the neutron and proton leave the stripping target, so that neutrons may be tagged by coincidence detection of the protons. Alternatively, nuclear stripping may be used wherein one nucleon is absorbed in the target and the other continues. This occurs with about ten times the cross section of EM stripping. As our proposed experiments do not require tagging it seems that the larger cross section is appropriate to use.

For a beam defined at an angle corresponding to q=1 at 6 GeV/c, $\theta \simeq (2\text{ MeV/c})/(6\text{ GeV/c}) = 3 \times 10^{-4}$ rad, so that $\delta\Omega \simeq 10^{-7}$ sr. (Strictly speaking, this θ could be the half-angle of the beam cone from a point source, however it is probably more realistic to assume a beam stripper target or neutron source of size comparable to the scattering target so that the angle subtended by the scattering target from each point at the source is 10^{-7} sr and the incident angles range over $\theta = \pm 3 \times 10^{-4}$ rad.) With a lead or uranium stripper of $1/3\lambda$ thickness a beam of 10^{-4} n per incident d would be contained in this solid angle, or about 5×10^{5} polarized neutrons per pulse. A possible experimental program at the ZGS might proceed as follows:

A. Verify the Schwinger Effect, develop polarimeter, and measure the neutron beam polarization. The beam as defined above and incident on a lead target of $\lambda/3$ length could then be detected by a neutron spatial detector in a plane downstream from the scatterer a distance equal to the distance between the stripping and scattering targets, as in Figure 2. A beam plug would be useful to block out the central (unscattered) beam; this could be a steel rod 4 or 5 feet in length (8 or 10 λ). If the incident deuteron beam spot on the stripping target were 1cm diameter and the scattering target the same, the two targets would be separated by about 30 m. The detector would then be 30 m beyond the scattering target, and the beam plug would be just over 2 cm diameter. A larger collimator of about 10 cm diameter concentric with the plug would be useful to keep down counting rates from events scattered at larger, less interesting angles. The neutron detector could be the same apparatus used in our group's experiments on np and nd elastic scattering at the ZGS and subsequently at FNAL.[8] This detector is an assembly of alternating magnetostrictive wire spark chambers and 0.5 inch Zn converter plates in addition to several trigger scintillators. The system records the tracks of secondaries from converted neutrons and, after extrapolating to the vertex,

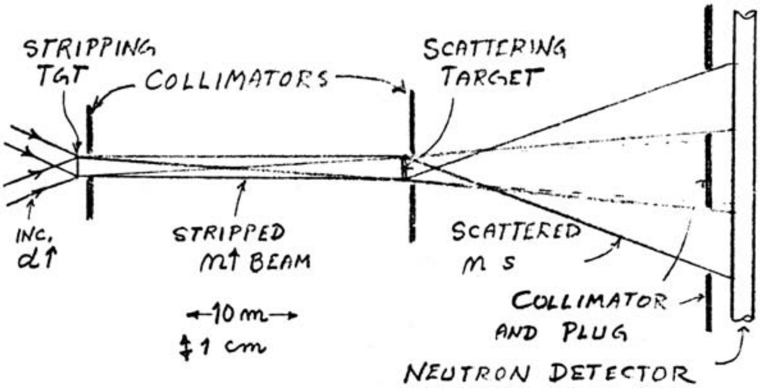

Figure 2. Experiment to study Schwinger Effect at the ZGS. Not shown are magnets to sweep charged particles and to rotate neutron polarization. Note 500:1 ratio of horizontal to vertical scales.

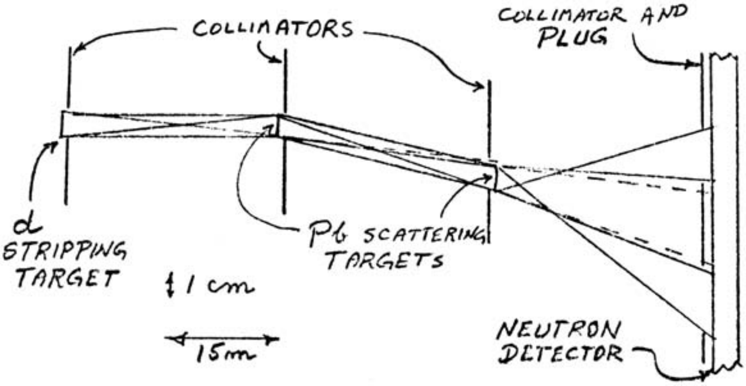

Figure 3. Double scattering experiment to unambiguously verify the Schwinger Effect. The first Pb scattering target produces polarized neutrons incident on the second lead scattering target.

was proven capable of a neutron vertex resolution of ≤0.1cm. While the technique is readily adaptable to a proportional chamber system, the rates in most of these experiments are sufficiently modest to not require a faster detector. This detector is not energy sensitive, nor is energy sensitivity necessary at the ZGS.

Scattered neutrons would be detected in the solid angle of this apparatus at a rate of about 10^3 per pulse (single scattered) permitting rapid data accumulation of polarization. As the average polarization should be 70%, even an hour of running would overkill the polarization determination. It would be necessary to check the centering of all beam elements (collimators, targets, etc.) and it would also be desirable to rotate the plane of polarization of the neutrons with magnets either before or after the scattering target, or both.

The beam could be defined to a much finer pencil (stripping and scattering targets both about 2 mm diameter) at a sacrifice of a factor of 5^4(or 625) in rate but a gain in the scattering angle precision. This would obviate the need to fold the scattering angular distribution over the beam divergence in the data analysis and would make for a cleaner, simpler analysis.

Of course this experiment actually sums over both the neutron beam polarization and the analyzing power of the scattering process. To quantitatively and uniquely check the Schwinger Effect, it would be desireable to do a double scattering experiment. Here a two cm aperture centered at $q \cong 2$ in the plane of the collimator would redefine the now-polarized scattered beam; a second scatterer would replace the neutron detector, and the neutron detector would then be moved 30 m further down stream, again behind a beam plug and collimator (Figure 3). With 10^3 neutrons scattered into the plane of the second scatterer, only about 50 neutrons pass through the second collimator and hence only one neutron in ten pulses is scattered into the range $1 \leqslant q \leqslant 4$ by the second scatterer. Of course opening up the aperture of first and second collimators to accept twice the range of $p_\perp$ would increase the rate of detected neutrons by a factor of 16, with a corresponding loss of polarization.

B. The polarized neutrons could be scattered from an unpolarized hydrogen target, and the recoil neutron distribution in φ near $q = 1$ analyzed to determine ρ. This is not terribly attractive, as $P \propto (1+\rho^2)^{-\frac{1}{2}}$, and even $\rho = 0.3$ produces only a 5% decrease in P from its value (100%) when $\rho = 0$.

C. A more challenging experiment, and potentially a very interesting one, might be a double scattering experiment wherein a liquid hydrogen target is the first scatterer and a lead scatterer serves as an analyzer in a second scattering as in Figure 4. Here it would be necessary to open up the collimators to accept a beam solid angle corresponding to $\Delta q \sim 3-5$. Specifically, if the beam were collimated to 5 cm diameter at the hydrogen target and the scattered beam also to 5 cm at the Pb "analyzer", and again if each scatterer were $\lambda/3$ thick the rate would be about one double-scattered neutron per pulse. This experiment would permit one to measure the depolarization parameter D_{LS}, and hence ρ, directly.

The larger bite of q in each scatter would reduce the sensitivity of the measurement for the sake of

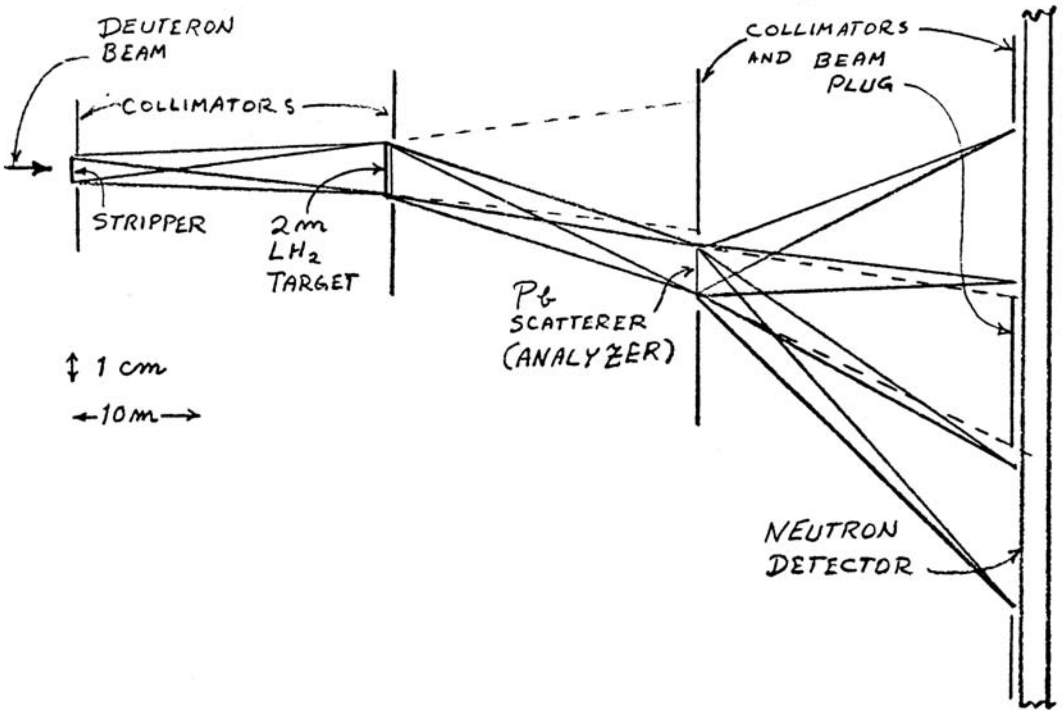

Figure 4. Geometry for determination of D_{SL} by double scattering on first liquid hydrogen and second lead.

counting rate, and an optimum found which would maximize the precision in determination of a physical parameter (e.g. ρ) in a given data collection time.

D. Scattering from a polarized target. Even a long polarized target contains only about 1g cm^{-2} of hydrogen, so that the fraction of the incident flux scattered into $1 \leq q \leq 4$ by protons in a polarized target would be about one per pulse with an incident beam of 5×10^5 polarized neutrons per pulse. Again, rates could be improved by opening collimators at the expense of reduced polarization sensitivity. This type of measurement would permit direct determination of A_{SL} and A_{LS}, and hence $Re(\Phi_1 - \Phi_3)$ and $Re\ \Phi_2$.

E. Double scattering from a polarized target. This is sheer blue sky, wherein a polarized target would be substituted for the liquid hydrogen target of B(above). The rates would be very low indeed; even with gimmicks it would be hard to reach one detected event per pulse.

III. FERMILAB EXPERIMENTS

We have routinely employed a neutron beam at Fermilab (beam M3 in the Meson Lab) containing a flux from 10^5 to 10^7 per pulse in a solid angle between 10^{-8} and 10^{-10}sr[9]. This beam is nominally unpolarized; its polarization has never been explored, or even questioned. However it is produced by a proton beam incident on a Be target at angles of 0.5 to 1.75 mr (variable), and recent developments have permitted larger targeting angles. It seems likely that neutrons are polarized to the extent that $\Lambda°$s have been found to be, e.g. $P \simeq 0.15p_\perp$ for $0.4 < x < 0.7$. If so, 300 GeV neutrons ($p_\perp \sim .15-.5$ GeV/c) might be polarized by up to several percent.

This polarization is a major uncertainty in the design of Fermilab experiments.

The Fermilab neutron beam is a "white" spectrum so that an energy-sensitive detector would be necessary. Our group has routinely used an ionization calorimeter with a 12% FWHM resolution at 300 GeV.[10] We have not so far combined this with a vertex detector (chamber) although this should be straightforward. At least several experiments suggest themselves.

A. Study of beam polarization. The beam polarization could be analyzed by employing the Schwinger Effect directly, using a 1/3 λ lead scatterer and a configuration as sketched in Figure 2. At Fermilab the beam target is 1/16 inch and may be collimated to 1/16 inch at 600 ft corresponding to $\theta = \pm 1.7\text{x}\ 10^{-5}$. The detector at 1250 feet (under the mezzanine) could then explore the scattered beam asymmetry. As at the ZGS magnets could be used to rotate the neutron beam polarization in order to cancel some systematic errors. (It is fortunate here that the spin precession is independent of momentum.) There would be $10^2 - 10^3$ neutrons scattered per pulse into $1 \leqslant q \leqslant 4$ near the peak of the neutron spectrum in this experiment. I have assumed in this discussion that the Schwinger Effect and scattering in a lead analyzer would have already been studied and verified in experiments at the ZGS, so that a double scattering experiment would not be necessary.

If polarization of the inclusively-produced neutron beam is found, it would be of obvious interest to explore it quantitatively, as functions of target as well as neutron x and $p_\perp$. This experimental program would be analogous to the studies of Λ° polarization in inclusive production.

B. Production of a polarized beam and study of $\Delta\sigma$

If the beam polarization were 10% or greater, it could be used as a polarized beam directly to study such quantities as $\Delta\sigma_L$ and $\Delta\sigma_S$ using a polarized proton target and a simple transmission experiment. If $\Delta\sigma/\sigma \cong 1\%$ and P(beam) = 10% the 1 g cm^{-2} of the polarized target would lead to a $2.4x10^{-5}$ change in transmission when the target or beam polarization is reversed. The systematic uncertainties in seeing such a small effect may be difficult but not impossible. If the beam polarization is too small, a polarized beam could be achieved by scattering on lead. With $q \simeq 3.$ a beam flux of the order of 10^2 to 10^3 per pulse could be achieved, with $P \geqslant 50\%$. This flux is still sufficient to study $\Delta\sigma_L$ and $\Delta\sigma_S$ as long as the systematic effects can be controlled.

C. Double scattering experiments.

Experiments to determine D_{SL} as under IIC above could be carried out at Fermilab. Here a long hydrogen target would be used to scatter the neutron beam and the polarization of the scattered neutrons could be determined from a second scattering on lead. Either the incident beam would be sufficiently polarized, in which case the numbers are analogous to the ZGS case (with the incident beam higher and incident polarization smaller by about an order of magnitude) or it would be necessary to effect an initial scattering on lead to polarize the beam, with a corresponding sacrifice in intensity and necessitating opening the various apertures as discussed earlier. The overall

M3 beam length, over 2000 ft, seems sufficient for the triple scattering.

D. Scattering on a polarized target

Again the arguments and numbers as in IID for the ZGS case, and as in IIIC above, the same caveats concerning the incident beam intensity and polarization pertain.

E. Other experiments

Double scattering on a polarized target (as in IIE) is an obvious but difficult possibility. It is also clear that the polarization in "normal" ($-t \geqslant 0.1(\text{GeV}/c)^2$) elastic scattering could be studied. These and further studies made possible given a polarized neutron beam are obvious interesting extensions of an experimental program.

TABLE II

Physics Experiments with Polarized Neutrons

Experiment		Reaction[a]	Determine[b]
I.	ZGS		
	A. Schwinger Effect	$n\uparrow Pb \to n(\theta,\varphi)Pb$	
	B. Hydrogen Scattering	$n\uparrow p \to n(\theta,\varphi)p$	ρ
	C. Double Scattering	$n\uparrow p \to n\uparrow\downarrow(\theta,\varphi)p$	D_{SL}, ρ
	D. Scattering on a Polarized Target	$n\uparrow p\uparrow\downarrow \to n(\theta,\varphi)p$	A_{SL}, A_{LS}
	E. Double Scattering on a Polarized Target	$n\uparrow p\uparrow\downarrow \to n\uparrow\downarrow(\theta,\varphi)p$	
II.	FNAL		
	A. Analyze Beam	$pBe \to n\uparrow(\theta,\varphi)X$ $n\uparrow Pb \to n(\theta,\varphi)Pb$	
	B. Cross Section Beam	$n\uparrow p\uparrow\downarrow \to$ anything	$\Delta\sigma_L$ $\Delta\sigma_S$
	C. Double Scattering	$n\uparrow p \to n\uparrow\downarrow(\theta,\varphi)p$	D_{SL}, ρ
	D. Scattering on a Polarized Target	$n\uparrow p\uparrow\downarrow \to n(\theta,\varphi)p$	A_{SL}, A_{LS}

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[a] The arrows represent known polarization, longitudinal or transverse, of the preceeding particle.

[b] The notation follows E. Leader, refs. 5 and 6.

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