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DIRECT MEASUREMENT OF THE TENSOR POLARIZATION OF A POLARIZED DEUTERON TARGET

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Abstract

The tensor alignment p_{zz} of a polarized deuteron target was measured directly for the first time. The measurement utilizes the tensor analyzing power T_{20} of the πd to 2p reaction at 90° (c.m.), which is well determined from partial wave analysis and consistent theoretical predictions. The resulting value of p_{zz} agrees well with that calculated from the vector polarization p_z obtained from NMR techniques.

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1. Introduction

Recently at TRIUMF, a tensor polarized deuteron target was employed for the first time to measure the tensor analyzing power, T_{20}, in the πd elastic scattering reaction [1]. Considerable attention was paid to the measurement of the tensor polarization achieved in the polarized deuteron target. A method was sought which would provide a direct measurement of the target tensor polarization (p_{zz}), independent of the more usual NMR technique. The NMR technique measures the amount of vector polarization (p_z) of the target, from which p_{zz} can be deduced. The possibility of obtaining p_{zz} directly from a measurement of the πd to 2p reaction at 90° (c.m.) was first pointed out by Niskanen [2]. He observed that (in his reference frame) the tensor analyzing power T_{20} converges to a known, non-zero value in this reaction at 90° (c.m.) providing a unique opportunity for calibration of tensor polarized targets. In the reference frame defined by the Madison convention, which is the frame accessible to experiment, Niskanen's result is only approximately valid. However, as we shall see in section 3.3, the value of T_{20} at this kinematic point is well determined from partial wave analysis and theoretical predictions. Of all the possible spin observables in all the different channels available to πd, only T_{20} in pion absorption at 90° (c.m.) has this feature. Therefore, a measurement of T_{20} in the πd to 2p reaction at 90° (c.m.) effectively provides a direct measurement of the target tensor polarization. We report in this article the results of a calibration experiment in which p_{zz} was measured using the πd to 2p reaction at 90° (c.m.)

2. NMR Techniques

The usual methods for determining the vector polarization, p_z, of a polarized deuteron target involve measurements of the area and asymmetry of the deuteron nuclear magnetic resonance (NMR) signal. Assuming that the relative populations of the magnetic substates of the deuteron are given by a Boltzmann distribution, and that the effects of the deuteron quadrupole moment are negligible, the target tensor polarization is related to the target vector polarization according to the expression

$$p_{zz} = 2-\sqrt{4-3p_z^2}\ . \tag{1}$$

Both the above assumptions are generally considered reasonable. The quadrupole interaction energy is characterized by the frequency 20 kHz, whereas the deuteron Larmour frequency is 16.6 MHz.

2.1 NMR signal area

The magnitude of p_z may be obtained from a measurement of the deuteron NMR signal area by comparing the area of the thermal equilibrium (TE) NMR signal to that of the dynamically polarized NMR signal. Typical TE and dynamic NMR signals are shown in fig. 1. The TE polarization is calculable from a knowledge of the temperature and magnetic field according to

$$p_z(\mathrm{TE}) = \frac{4\tanh\left(\frac{\mu H}{2kT}\right)}{3+\tanh^2\left(\frac{\mu H}{2kT}\right)} \tag{2}$$

where μ is the deuteron magnetic moment, and k is Boltzmann's constant. For typical values of H (2.549 T) and T (0.750 K) the TE (vector) polarization is 0.000791. Application of microwaves of 70.820 GHz dynamically polarizes the target to values in excess of 0.3. The area of the deuteron NMR signal is proportional to the amount of polarization, the proportionality constant being determined from the TE measurement. This technique relies on the gain of the NMR system being linear over the range of amplification required for the TE and dynamically polarized signals. A further requirement is that the background underneath the NMR signal be well understood. Finally, the value of p_{zz} is deduced from p_z using eq. (1).

2.2 NMR signal asymmetry

A second technique of obtaining p_z involves a measurement of the NMR signal asymmetry [3]. The interaction of the deuteron quadrupole moment with the electric field in the C-D and O-D molecular bonds has the effect of shifting the energy levels by an amount which depends on the angle between the magnetic field and the electric field of the bond. This angular dependence smears out the resulting pair of transitions, one of which is proportional to the intensity of the m=+1 to 0 transition and the other to the intensity of the m=0 to -1 transition. Therefore a measurement of the NMR signal asymmetry provides a measure of the target vector polarization. In practice this is accomplished by forming the ratio R of the intensities of the two transitions, from which p_z can be obtained via $p_z=(1-R^2)/(1+R+R^2)$. This technique has an advantage over the area technique in that the difficult measurement of the tiny TE NMR signal can be avoided. The former requirement of linear gain over a large dynamical range ($\sim 10^3$) in amplification is replaced by the requirement of frequency independent gain over the range of frequencies spanned by the NMR signal. The background underneath the NMR signal must again be known, however the influence of this background on the results is different from that of the NMR signal area technique. Again, the value of p_{zz} is deduced from p_z in this technique using eq. (1).

3. Direct measurement of P_{zz}

Both of the above techniques involve difficult measurements of the deuteron NMR signal. Stringent requirements on the linearity of the system must be met in order to achieve meaningful results. Furthermore, in the end p_{zz} must be deduced from the measurements of p_z. In order to verify the results obtained from the above techniques, a direct measurement of p_{zz} was performed using a nuclear reaction.

3.1 Formalism

In order to extract the tensor analyzing power T_{20}, the target magnetic field (spin alignment axis) is oriented longitudinally with respect to the incident beam. In the πd to 2p reaction at 90° (c.m.), T_{20} is known, therefore one can obtain p_{zz} from a measurement of the πd to 2p differential cross sections with the target polarized and unpolarized according to

$$p_{zz} = \frac{\sqrt{2}}{T_{20}} \left(\frac{\sigma(\mathrm{pol})}{\sigma(\mathrm{unpol})} - 1 \right) \qquad (3)$$

Since this simple expression contains only the ratio of differential cross sections; contributions from the target thickness, solid angle, and counter efficiencies cancel out, and only relative differential cross sections need be measured. The relative differential cross section is given by

$$\sigma = \frac{\mathrm{Yield}}{N_{\mathrm{beam}} * \varepsilon} \qquad (4)$$

where Yield is the number of πd to 2p events measured, N_{beam} is the number of incident beam particles, and ε is the efficiency of the data acquisition system.

3.2 Value of T_{20} implied by A_{yy} in the pp to πd Reaction

Two techniques were used to determine the precise value of T_{20} at the energy of this measurement (80 MeV). For one technique the value of T_{20} was extracted from measurements of A_{yy} at 90° (c.m.) in the pp to πd reaction. It can be shown [4] that for the orthogonal geometry being considered (90° (c.m.) in the πd to 2p reaction) there is a relationship between T_{20} and A_{yy} given by

$$T_{20} = \sqrt{2}\,\frac{3A_{yy}-1}{4} \qquad (5)$$

Using this relationship and the measured value of $A_{yy}=-0.86\pm0.04$ [4] at Tp=447 MeV in the pp to πd reaction, one obtains a value for T_{20} at $T\pi$=80 MeV in the πd to 2p reaction of $T_{20}=-1.27\pm0.05$.

3.3 Value of T_{20} extracted from a PWA

Blankleider and Afnan [5] show that, assuming dominance of the a_2 amplitude (feeding the singlet $^1D_2$ p-p wave) for the $\pi d \rightarrow 2p$ reaction, T_{20} is given by:

$$T_{20} = \frac{-\sqrt{2}}{70}\,\frac{(70+25*P_2(\cos\theta)+108*P_4(\cos\theta))}{1+P_2(\cos\theta)}$$

where the $P_j(\cos\theta)$ are the Legendre polynomials. For $\cos\theta=0$, T_{20} is then $-\sqrt{2}$. In practice, although the rest of the amplitudes are certainly not zero, enough cancellation occurs near $\theta=90°$ for the value to be close to $-\sqrt{2}$, especially for energies near 150 MeV (pion kinetic energy). In fig. 2 are shown the results of calculations of this quantity based on partial wave amplitudes calculated from the unitary theories of ref. 5 and 6, as well as partial wave amplitudes obtained from fits to the existing data base. The fitted partial wave amplitudes were obtained both from published fits [7], as well as two sets of fitted amplitudes obtained ourselves, using somewhat different assumptions regarding the high-order fixed amplitudes (which were fixed to theory) than were used in ref. [7]. The fitting technique which we employed incorporated calculations of the spin-dependent observable T_{20}, using the formalism of ref. [5], into the CERN Minuit system.

As is evident from fig. 2, the predicted value of T_{20} at 145 MeV is very close to the value $-\sqrt{2}$, independent of whether one uses the theoretical values of the partial wave amplitudes, or fitted ones (as expected for energies near the value where the relative contribution of the a_2 amplitude dominates). For lower energies, the predicted value decreases due to the increasing role played by the other amplitudes, and an increasing spread between the predictions of the different amplitude sets develops. This spread demonstrates the increasing sensitivity to the exact nature of the interference between these small amplitudes and the larger a_2 amplitude.

It is interesting to note that over this energy range the amplitudes of ref. [6] yield values in better agreement with experiment than do those of ref. [5]. Since none of the different unitary theories currently available yield spin-dependent observables which are in agreement with experiment, it is not surprising that the predictions for T_{20} arising from use of the various fitted PWA amplitude sets cluster more closely to each other than do the theoretical predictions.

The fitting algorithms of ref. [7] are designed to yield a smooth energy dependence. This is accomplished by incorporating systematic errors in the experimental data when the amplitudes are fitted. Our fitting routines, on the other hand, accept the experimental data as published. The two techniques thus provide somewhat different values for both T_{20} and A_{yy}, reflecting the somewhat different values assumed for the input data.

The value of T_{20} at 90° from three sets of fitting procedures yielded values between -1.248 and -1.256 for the energy of this experiment (80 MeV). However, since the system accepted a range of 2.5° in polar angle (c.m.) about 90°, the variation of T_{20} over this angular range had to be considered. This results in a decrease in the magnitude of the value of T_{20} by 0.015.

Allowing for possible systematic errors in the existing spin-dependent observables, a value of $T_{20} = -1.28 \pm 0.03$ at 80 MeV (450 MeV for the time-reversed $p + p \rightarrow d + \pi$ reaction) is considered a reasonable estimate on the basis of the results illustrated in fig. (2). It is noted that this value is in good agreement with the value extracted from the A_{yy} data (given earlier), as expected since this A_{yy} data was included in the data set employed in the partial wave fitting routine. Since the partial wave technique fits all the experimental data at a given energy in a global fashion, it should be expected that the extracted value for T_{20} should be somewhat more accurately determined by this technique than that based on a single observable (the A_{yy} technique).

4. Experimental Arrangement

4.1 Polarized deuteron target.

The polarized deuteron target consisted of a mixture of 95% fully deuterated N-butyl alcohol and 5% D_2O into which EHBA-(Cr^V) was dissolved to a molecular density of 6×10^{19}/ml. This material was in the form of frozen 1 mm diameter beads contained in a thin walled teflon basket measuring $16 \times 16 \times 5$ mm^3. The basket was immersed in a mixture of $^3He/^4He$ in the mixing chamber of a dilution refrigerator and was oriented to present the 16 × 16 mm^2 surface perpendicular to the pion beam.

The 2.5 T polarizing field was provided by a superconducting split pair magnet with field axis parallel to the beam direction. The split pair provided an opening of ±12.5° at 90° to the incident beam for the escape of the πd to 2p reaction products. The target was polarized by irradiating the target beads with approximately 1 mw of microwave power. The time required to polarize to 90% of maximum was typically three hours.

A series tuned NMR circuit, with the coil wound directly on the target basket, was used to measure the target polarization [8]. A voltage controlled capacitor, located in the refrigerator mixing chamber, was swept to keep the NMR circuit near resonance throughout the RF frequency sweep, and so permit measurement of the resistive component of the NMR signal. Analysis of the NMR signals yielded an average target polarization of p_z=-0.333 ± 0.015.

4.2 Detection system

The πd to 2p spin dependent cross sections were measured on the M11 pion beamline at TRIUMF. The incident pion energy was chosen to be 80 MeV. Although the πd to 2p cross sections are more difficult to measure and the T20 characterizing the reaction is less well determined at this energy than at energies closer to the (3,3) resonance, the geometry of the polarized target magnet coils constrained the incident energy to less than about 90 MeV. The target magnet coils effectively shield the target between lab angles of 50° to 77.5° and 102.5° to 130°. As the bombarding energy rises, the outgoing 90° (c.m.) protons are thrown more and more forward in the lab system. Above 90 MeV, the outgoing 90° (c.m.) protons are completely blocked by the target magnet coils. The selection of precisely 80 MeV incident energy was made

because extensive spin-dependent data for the inverse reaction exist at the equivalent center of mass energy. The A_{yy} and PWA determination of T_{20} require such data.

The experimental arrangement is shown in fig. 3. The incident beam was counted directly in scintillators S1 and S2. The size of S2 (9 x 37 x 2 mm^3) was chosen small enough that beam particles which passed through S2 also passed through the polarized target. A differential degrader located midway between the M11 channel dipole magnets removed most of the contaminant protons in the beam. Remaining protons were eliminated from the recorded events by upper level pulse height requirements on S1 and S2. The spatial stability of the incident beam was monitored by means of a split scintillator hodoscope located 3 m downstream of the polarized target. This device was sensitive to shifts in the vertical or horizontal beam position of as little as 100 microns.

The detector arrangement consisted of scintillator telescopes and delay line readout multi-wire proportional chambers for each of the outgoing protons, which were detected in coincidence. The central trajectory through each of the detector arms was at an angle of ±80° with respect to the incident beam. Wire chambers WCL1 and WCR1 were 20 × 20 cm^2 in area, and placed 40 cm from the target center. Following these chambers were scintillators L1 and R1, which were 8 × 20 × 0.3 cm^3, and 60 cm from the target center. The second pair of wire chambers, WCL2 and WCR2, were 30 x 30 cm^2 in area and 81 cm from the target. Just behin these chambers were scintillators L2 and R2, which were 9.4 × 27.9 × 0.6 d cm^3. The solid angles defined by the scintillators L2 and R2 were 33.9 msr and 35.5 msr, respectively. The trigger for the experiment consisted of the coincidence S1*S2*R1*R2*L1*L2.

4.3 Analysis of πd to 2p results.

At the bombarding energy and c.m. angle of interest, a significant background from quasi-free pion absorption on ^{12}C was present. Therefore, explicit measurements of the background associated with the polarized target were made by replacing the polarized deuteron target material (C_4D_9OD) with non-deuterated material (C_4H_9OH). This choice of background target is ideal, since it has the same form (1 mm diameter spheres) as the foreground target, and consists of the same nuclei except for the substitution of Hydrogen, from which absorption events do not arise. By subtracting the appropriately normalized background data from the foreground data, it was possible to study absorption events arising solely from the polarized (and unpolarized) deuterons in the target.

Two methods of data analysis were pursued. One method consisted of examining histograms of the vertical coplanarity of the reaction as calculated from the data provided by the four vertical wire chamber planes. Typical foreground, background, and background subtracted histograms of the coplanarity are shown in fig. 4. From this figure, it is clear that the absorption events from heavier nuclei, broadened due to the ensuing three-body final state, are removed by the background subtraction. The yield of absorption events from deuterium was obtained by integrating the background subtracted coplanarity histograms over the central peak.

A second independent method of obtaining the πd to 2p yield was also used. This method consisted of examining the TOF spectra from the scintillators, and was thus independent of possible systematic errors introduced by the wire chamber efficiencies, etc. A typical spectrum of the TOF difference between scintillators L2 and R2 is shown in fig. 5. Again, explicit measurements of the background were used to eliminate all contributions to the yield except those arising from the deuterium in the target.

5. Results

A total of 10,000 πd to 2p events were recorded for each state of target polarization (on or off). The result of the coplanarity analysis (assuming a value of -1.28 ± 0.03 for T_{20} as mentioned earlier) was $p_{zz}=0.098\pm0.024$. The result of the TOF analysis was consistent with this value, namely $p_{zz}=0.10\pm0.022$. The rather large uncertainties associated with these results arise from the statistical uncertainty of the measured cross sections after background subtraction, coupled with the small magnitude of target tensor polarization achieved.

These results may be compared to the values of p_{zz} obtained indirectly from the analysis of the deuteron NMR signals acquired at the same time the πd to 2p data were obtained. The result of the NMR signal area analysis was $p_{zz}=0.083\pm0.008$, and the result of the NMR signal asymmetry analysis was $p_{zz}=0.095\pm0.008$. These results are in good agreement within the quoted uncertainties with those obtained via the measurement of the πd to 2p reaction. The results are summarized in table 1.

5.1 Results for rf burned target.

Although the independent measurement of the deuteron target tensor polarization described above was the primary objective of this experiment, a further investigation was performed with a "burned" deuteron target. The burning process [9] consists of irradiating the target with rf over a narrow range of frequencies, effectively "burning" away a portion of the deuteron NMR spectrum. This procedure is known [9] to increase the deuteron tensor polarization dramatically. However the relaxation times characterizing this enhancement are thought to be quite small. Furthermore, as the ensemble of deuteron spins is no longer in a state of equilibrium after rf-burning, it is unclear how to extract the degree of polarization from analysis of the deuteron NMR signals. In order to investigate the average target tensor polarization over roughly an 18 hour period, the πd to 2p measurements were performed after rf-burning as well. Three measurements were made, each after separate rf irradiations of the target. One of the πd to 2p measurements was made with the target magnetic field at 1.25 T, the other two measurements were made at 2.5 T. In all three cases the target was in frozen spin mode (no microwaves applied). The results of the analysis of the πd to 2p data taken with the rf-burned target are also summarized in table 1. The average of these results indicates that $p_{zz}=0.10\pm0.017$ (TOF analysis) and $p_{zz}=0.11\pm0.018$ (coplanarity analysis). These results are consistent with those obtained without rf-burning, indicating either that no substantial enhancement of the tensor polarization was achieved by rf-burning, or that the decay time of tensor polarization produced by rf-burning is substantially faster than that produced by microwave irradiation. In either case, the measurements indicate that rf-burning is unsuitable for producing enhanced target tensor polarizations for scattering experiments, which require known polarizations for periods typically several hours long.

6. Summary

The first direct measurement of the tensor polarization of a polarized deuteron target has been made using the reaction πd to 2p at 90° (c.m.) and at a bombarding energy of 80 MeV. The results of the measurement are consistent with those obtained using NMR signal analysis. Furthermore, a study of the enhancement of the target tensor polarization from rf-burning indicated that no substantial enhancement exists over an 18 hour period.

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References

[1] G.R. Smith, et al. Phys. Rev. Lett. 57, (1986) 803.

[2] J.A. Niskanen, Phys. Lett. 82B, (1979) 187.
Note that the reference frame used in this reference is not consistent with the Madison convention, therefore the t_{kq} are in general not the same as those used here.

[3] K. Guckelsberger and F. Udo, Nucl. Inst. and Meth. 137, (1976) 415.
O. Hamada, S. Hiramatsu, S. Isagawa, S. Ishimoto, A. Masaike, and K. Morimoto, Nucl. Inst. and Meth. 189, (1981) 561.

[4] E. Aprile-Giboni, et al., Nucl. Phys. A415, (1984) 391.
Note that there are several typographical errors in this reference. Eq. (9) should read $T_{20} = \sqrt{2}/4\ (3A_{yy}-1)$, and the second row of table 5 should begin with $T_{20}(90^{o})$.

[5] B. Blankleider and I.R. Afnan, Phys. Rev. C24, (1981) 1572.
B. Blankleider and I.R. Afnan, Nucl. Phys. A437, (1985) 534.

[6] Y. Avishai and T. Mizutani, Phys. Rev. C27, (1983) 312.

[7] D.Bugg, J. Phys. G10 (1984) 717.

[8] G.D. Wait et al., Contributed paper to the International Workshop on Polarized Sources and Targets, Montana, Jan. 13, 1986.

[9] W. de Boer, CERN report 'Dynamic Orientation of Nuclei at Low Temperatures', May 13, 1974.

Table I. The results of the πd to 2p measurements of p_{zz} are tabulated for each of the analysis techniques used.

B(target)	RF-burned	p_{zz} from TOF analysis	p_{zz} from coplanarity analysis
2.50T	No	0.101 ± 0.022	0.098 ± 0.024
2.50T	Yes	0.109 ± 0.026	0.113 ± 0.029
2.50T	Yes	0.073 ± 0.029	0.082 ± 0.031
1.25T	Yes	0.135 ± 0.032	0.134 ± 0.035
average (rf-burned)		0.104 ± 0.017	0.108 ± 0.018

Figure Captions

Fig. 1 Typical TE (a) and dynamically polarized (b) NMR spectra are shown. The value of TE polarization was 0.005, and the value of the dynamic polarization was 0.36.

Fig. 2 The tensor analyzing power T_{20} in the πd to 2p reaction at 90^0 (c.m.) is plotted on the vertical axis vs incident proton (pion) energy on the lower (upper) horizontal axis. The energy dependence of the phase shift solutions is shown in the solid curves (this work) and the dotted curves (ref. [7]). The results of predictions based on Faddeev calculations is shown as dashed (ref. [6]) and dash-dot (ref. [5]) curves. The single point at T_π=80 MeV corresponds to the value of T_{20} deduced from existing A_{yy} data according to eq. 5 (ref. [4]).

Fig. 3 The experimental layout is shown, with the pion beam incident from the top. The meaning of the various detectors is explained in the text.

Fig. 4 Typical spectra of the vertical coplanarity are shown as measured with the polarized deuteron target (a), and the background target (b). The resulting background subtracted spectrum is shown in (c).

Fig. 5 A typical spectrum of the TOF difference between scintillators L2 and R2 is shown.

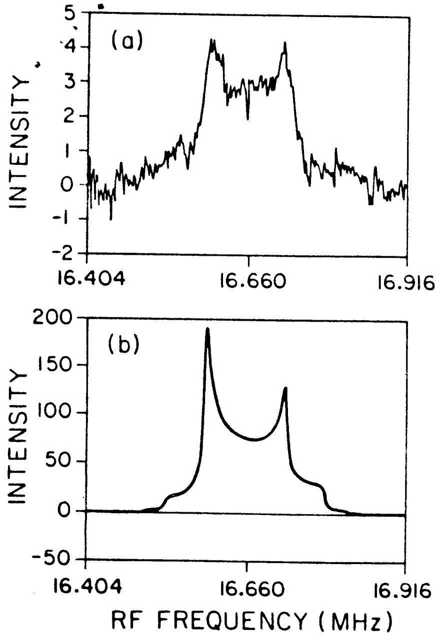

Fig. 1

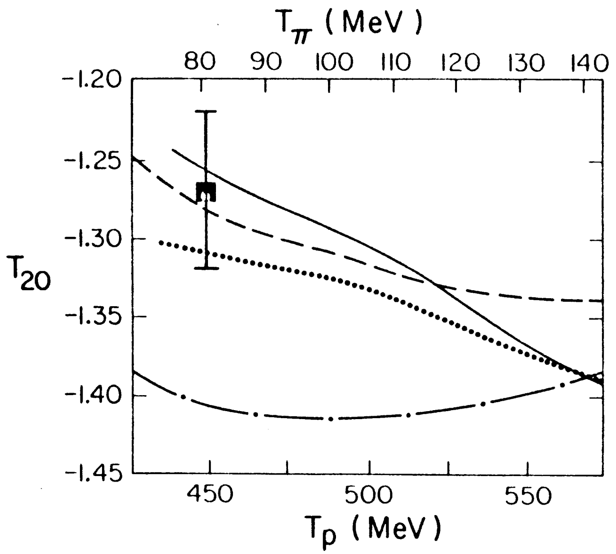

Fig. 2

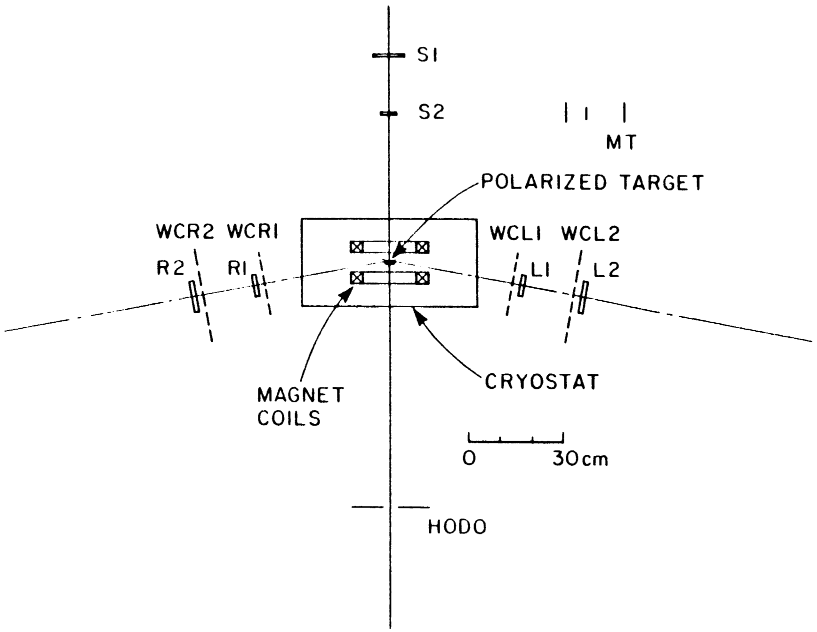

Fig. 3