IFT Instituto de Física Teórica
Universidade Estadual Paulista

July/94

IFT P.024/94

I

Medium effects on spin observables of proton knockout reactions

G. Krein

Instituto de Física Teórica
Universidade Estadual Paulista
Rua Pamplona 145
01405-900 - São Paulo, S.P.
Brazil

and

Th. A. J. Maris, B. B. Rodrigues, E. A. Veit

Instituto de Física
Universidade Federal do Rio Grande do Sul
Caixa Postal 15051
91501-970 - Porto Alegre, R.S.
Brazil

Instituto de Física Teórica
Universidade Estadual Paulista
Rua Pamplona, 145
01405-900 – São Paulo, S.P.
Brazil

Telephone: 55 (11) 251.5155
Telefax: 55 (11) 288.8224
Telex: 55 (11) 31870 UJMFBR
Electronic Address: LIBRARY@IFT.UESP.ANSP.BR
47553::LIBRARY

Medium effects on spin observables of proton knockout reactions

G. Krein

Instituto de Física Teórica - Universidade Estadual Paulista
Rua Pamplona, 145 - 01405-000 São Paulo - Brazil

Th.A.J. Maris, B.B. Rodrigues and E.A. Veit

Instituto de Física - Universidade Federal do Rio Grande do Sul
Caixa Postal, 15051 - 91501-970 Porto Alegre - Brazil

Abstract

Medium modifications of the properties of bound nucleons and mesons are investigated by means of medium energy quasi free proton knockout reactions with polarized incident protons. The sensitivity of the spin observables of these reactions to modifications of the nucleon and meson properties is studied using the Bonn one-boson exchange model of the nucleon-nucleon interaction. A method proposed to extract the *pp* analysing power in medium from the $(\vec{p}, 2p)$ asymmetries indicates a reduction of this quantity compared to its free space value. This reduction is linked to modifications of masses and coupling constants of the nucleons and mesons in the nucleus. The implications of these modifications for another spin observable to be measured in the future are discussed.

I. INTRODUCTION

In recent years the question of medium modifications of nucleons and mesons properties has received a great deal of attention [1–12]. There have been speculations on modifications of nucleon and meson masses and sizes, and of meson-nucleon coupling constants. These speculations have been motivated from a variety of theoretical points of view, which include renormalization effects due to strong relativistic nuclear fields, deconfinement of quarks, and chiral symmetry restoration. Independently of the theoretical explanation, it is important to have different experiments which might provide information on this issue.

Quasi-free (x,xN) reactions represent probably the most direct manner to measure single-particle properties in nuclei. Hence, it is a suitable tool to observe medium modifications of nucleons and mesons properties and their consequences on physical observables of these experiments. In this paper we propose to use quasi-free $(\vec{p}, 2p)$ reactions[1] with polarized incident protons to investigate medium modifications of bound nucleons.

In a quasi-free $(p, 2p)$ scattering an incident proton of medium energy (200 ∼ 1000 MeV) knocks out a bound proton [13]. The only violent interaction of this process occurs between the incident particle and the ejected one. The incoming and outcoming nucleons wave functions are just distorted while traversing the nucleus. By measuring in coincidence the energies and momenta of the emerging nucleons, these processes provide a direct information on single-particle separation energy spectra and momentum distributions. In the last three decades quasi-free scattering experiments have been performed with this basic purpose. For an overview of this topic see Ref. [14,15].

The formalism generally used to describe quasi-free reactions is based on the impulse approximation to describe the violent quasi-free collision, whereas initial- and final-state interactions, or distortions, are described by complex optical potentials. The cross section of $(p, 2p)$ reactions is sensitively dependent on these distortions. In particular, the imaginary

---

[1] The arrow over p indicates a polarized incident beam.

part of the optical potentials, representing the multiple scattering, may reduce the quasi-free cross section by an order of magnitude. As a consequence a relatively small change in the somewhat uncertain imaginary optical potentials may spoil a good description of an experimental result. In other words, a good fit to an experimental result may partly be due to a fortunate adjustment of the distorting potential. A new perspective in this field has been opened by the possibility of exploring spin and isospin degrees of freedom [16,17], specially due to the fact that comparing different processes (by changing the spin or isospin variable) in a single kinematical and geometrical situation, the uncertainties related to the distortions may to a large extent be eliminated [18]. Hence, using this kind of comparison one may check whether and to which extent the medium modifications of nucleon and mesons properties are reflected in the spin observables of quasi free scattering. One such a case is given by coplanar quasi-free scattering with polarized incident protons in a single kinematical and geometrical situation by varying the polarization of the incident proton.

The effect of medium modification of the nucleon and mesons masses on the differential cross sections and on spin observables of proton-nucleus elastic scattering has been recently investigated in Ref. [6] by using the Brown and Rho hadronic scaling law [7]. The modification of the meson masses removes the nuclear radius discrepancy which persistently occurred in analysis with the non-relativistic impulse approximation (NRIA) when empirical nuclear densities obtained from eletron scattering are employed. Moreover, the modified meson masses do not spoil the successes achieved with the relativistic impulse approximation (RIA) of Ref. [19] on spin observables.

The relative successes in accessing medium modifications by means of elastic [20] and quasi-elastic [21,22] proton scattering motivated us to consider quasi free $(\vec{p}, 2p)$ scattering to investigate the medium effects on the spin observables [23,24]. Compared with elastic nuclear scattering, the quasi-free processes are very simple; while the first one deals with the superposition of scattering amplitudes of all nucleons of the nucleus, the last one deal basically with the scattering amplitude of a single nucleon in the nucleus.

Medium effects have been introduced [25] in the treatment of quasi-free processes using the density dependent t matrix interaction by Von Geramb and Nakano. It was found that they increase the cross sections somewhat, but scarcely change the analysing powers. In the present paper we are essentially concerned with the analysing powers since there seem to exist discrepancies between the experimental results and theoretical predictions [26].

A recent new development in the treatment of $(\vec{p},2p)$ reaction is the use of relativistic distorted impulse approximations (RDIA) [27]. The relativistic calculations include elastic distortions described by relativistic optical potentials with complex vector and scalar potentials, and Dirac Hartree like mean field potentials for the nuclear structure. More recently [28], recoil effects have been incorporated in the RDIA calculation. The general result of the relativistic calculations is that they clearly improve the theoretical description of several aspects of the reactions. However, there remain discrepancies mainly related to spin observables at some geometries. In this sense, our study is complementary to the relativistic calculations and might indicate the importance of medium modifications of the basic nucleon properties to be included in a complete calculation.

In the following section we briefly review the usual formalism for treating quasi-free $(\vec{p},2p)$ scattering and compare the experimental data with the theoretical predictions. In section III we use the one boson exchange Bonn [29,30] potential model to investigate the influences which the different mesons play for the spin observables relevant to quasi-free scattering. The effects of modifications of the masses of the nucleons and mesons and of the meson nucleon coupling constants on the spin observables are investigated in section IV. There we also study the implications of these modications for the interpretation of the available experimental data. Our conclusions and future perspectives are presented in section V.

II. QUASI-FREE $(\vec{p},2p)$ SCATTERING

In this section we briefly summarize the formalism generally used to calculate the quasi-free correlation cross section [14,15] to make the present paper self contained and to clarify our later arguments. Therefore, we focus our attention just on those aspects relevant to these purposes. We also show that in some special cases the pp analysing power in medium is directly given by the asymmetries of the $(\vec{p},2p)$ reactions. At the end of this section we discuss the experimental data used to detect nuclear medium modifications of nucleon and meson properties.

The correlation cross section for quasi-free scattering in the factorized distorted wave impulse approximation (DWIA) is given by:

$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE} = KF\,\frac{d\sigma_{pp}}{d\Omega}\,(E_0, \theta, P_{eff})\;P_S(\vec{k}_3)\,. \qquad (1)$$

Here KF is a kinematical factor. The indices 0, 1 and 2 refer to the incoming and the two emerging particles, respectively, and 3 to the nuclear (ejected) proton. The nucleon-nucleon cross section, $\frac{d\sigma_{pp}}{d\Omega(E_0, \theta, P_{eff})}$, is taked at energy E_0 and angle θ defined in the center of mass system corresponding to the quasi-free collision. $P_S(\vec{k}_3)$ is the distorted momentum distribution of the nuclear proton, with $\vec{k}_3 = \vec{k}_1 + \vec{k}_2 - \vec{k}_0$ (equating the negative recoil momentum of the residual nucleus) by momentum conservation.

In the impulse approximation, one assumes that the nuclear medium does not affect the violent nucleon-nucleon knockout process. In this case, $\frac{d\sigma_{pp}}{d\Omega}$ is the center of mass free cross section for nucleons 0, 1 and 2 with their actual momenta and polarizations in the laboratory system, while the ejected nucleon, 3, has an effective polarization inside the nucleus, represented by P_{eff}.

A free pp cross section has been used to calculate the quasi free cross sections along the years [14,15,18]. In this paper we perform an exploratory study about the consequences of relaxing the impulse approximation by using a medium modified pp cross section. An attempt in this direction, made by Kudo and Miyazaki [25] by introducing medium effects using a density dependent t-matrix, has scarcely changed the analysing power.

In the derivation of the cross section (Eq.(1)) besides the impulse approximation for the scattering matrix element of the knockout process, also the factorization assumption has been used. That is, fixed average values for the nucleon nucleon matrix elements have been taken, in spite of the fact that, because of the distortion, the momentum and energy values of the nucleon-nucleon collision in the nucleus have a certain spread around the asymptotic ones. For nucleon-nucleon quasi-free scattering at a few hundred of MeV the factorization approximation has been shown to be a good approximation, as long as one avoids those parts of the momentum distributions which are mainly made up of multiple scattered nucleons. These are the regions where the undistorted momentum distributions vanish or are very small [18]. This is an important restriction which shall come up again when we analyze the available experimental data.

These and others assumptions and approximations used to deduce the factorized cross section given by Eq.(1) are extensively discussed in the literature. They include the distortions of the incoming and outgoing nucleons, the off-shell effects and short range correlations. From the detailed studies over the years, the picture which comes out is that the most doubtful approximation refers to the strong distortions for the incoming and outgoing nucleons. These have been treated via optical potentials, with or without the spin-orbit term. The distortion may reduce the quasi-free cross section by one order of magnitude! In contrast, in most cases the spin dependence of the distortion is not too strong [31] and the off-shell effects are relatively small [14–18].

To avoid uncertainties caused mainly by the distortion, it is desirable to work with ratios of quasi-free processes with similar geometrical and kinematical conditions. That is the case for different measurements in a single kinematical and geometrical situation by varying the polarization of the incident beam or the isospin of the ejected nucleon [18]. In case the incident polarization is changed, a suitable experimental quantity is the asymmetry defined by

$$A = \frac{d\sigma^{(+)} - d\sigma^{(-)}}{d\sigma^{(+)} + d\sigma^{(-)}} , \qquad (2)$$

where the + and − signs indicate the spin direction of the incoming proton. Using the factorized DWIA, the asymmetry is given entirely in terms of the ratio of proton-proton cross sections, with polarizations P_0 and P_{eff} orthogonal to the scattering plane[2] [32] :

$$\frac{d\sigma}{d\Omega}(\theta, T_{rel}) = I_0(\theta, T_{rel})[1 + (P_0 + P_{eff})P(\theta, T_{rel}) + P_0 P_{eff} C_{nn}(\theta, T_{rel})] . \tag{3}$$

where $I_0(\theta, T_{rel})$ is the free unpolarized pp cross section, and $P(\theta, T_{rel})$ and $C_{nn}(\theta, T_{rel})$ are spin observables for free polarized pp scattering taking at the center of mass angle θ and at the relative kinetic energy T_{rel}. The effective polarization (P_{eff}) of the ejected nucleon, caused by the combined influence of the nuclear spin-orbit coupling and the distortion by multiple scatterings, can be quite large in certain geometrical situations. In such a case the matrix element of the corresponding free scattering is, in general, heavily dependent on the polarization of the incoming proton. In this sense the distortion is a desirable mechanism.

The observables $P(\theta, T_{rel})$ and $C_{nn}(\theta, T_{rel})$ are given in terms of the matrix elements of the Wolfenstein matrix as follow [33]:

$$P(\theta_{cm}, T_{rel}) = \frac{1}{I_0(\theta_{cm}, T_{rel})} Re[a^* e] \tag{4}$$

$$C_{nn}(\theta_{cm}, T_{rel}) = \frac{1}{2I_0(\theta_{cm}, T_{rel})} \left\{ |a|^2 - |b|^2 - |c|^2 + |d|^2 + |e|^2 \right\} . \tag{5}$$

Another spin observable which we consider in section IV is the depolarization tensor, $D_{nn}(\theta, T_{rel})$ which is given by:

$$D_{nn}(\theta_{cm}, T_{lab}) = \frac{1}{I_0(\theta_{cm}, T_{lab})} \left\{ |a|^2 + |b|^2 - |c|^2 - |d|^2 + |e|^2 \right\} . \tag{6}$$

Substituting Eq.(3) in Eq.(2), we obtain for the asymmetry the following expression:

$$A = \frac{P(\theta, T_{rel}) + P_{eff} C_{nn}(\theta, T_{rel})}{1 + P_{eff} P(\theta, T_{rel})} P_0 . \tag{7}$$

Hence, the effective polarization of the nuclear particle involved in the quasi free scattering can be calculated to a good approximation from the experimental asymmetry (A_{exp}) by inverting Eq.(7):

---

[2] *We consider coplanar quasi-free scattering.*

$$P_{eff} = \frac{A_{exp} - P_0 P(\theta, T_{rel})}{P_0 C_{nn}(\theta, T_{rel}) - A_{exp} P(\theta, T_{rel})} . \tag{8}$$

There is a simple prediction which one can make for the case of good shell model nuclei, such as ^{16}O and ^{40}Ca, namely the effective polarizations of the nucleons in two sub-shells split by the spin-orbit interaction should vanish, to a good approximation, that is [34]:

$$(l+1) P_{eff}^{j=l+1/2} + l \, P_{eff}^{j=l-1/2} \sim 0 . \tag{9}$$

This relation agrees with actual distorted wave calculations and is nearly independent of the optical and shell model potentials which generate the distortions and single-particle wave functions.

Up to now we have just reviewed the usual theoretical treatment of quasi free scattering. An interesting point aspect not sufficiently explored in the literature [15,26,36] is to consider special cases for which the effective polarization of the ejected nucleon is zero. In these cases Eq.(7) leads to[3]:

$$P(\theta, T_{rel}) = A_{exp} . \tag{10}$$

This means that it is possible to extract the pp analysing power ($P(\theta, T_{rel})$) in medium from the asymmetries of quasi free $(\vec{p}, 2p)$ reactions. This represents probably the most direct manner to get information of the pp analysing power in medium.

One possibility is to consider the knockout of s-state protons. The effective polarization *of a s state nucleon is zero since there is no spin orbit coupling*. However as the momentum distribution for s states peaks at momentum smaller than for others states, the knockout takes place in less denser regions and we do not expect a large medium effect in these states. Another problem is that working on the steep slope of the s state momentum distribution curve it is not safe to neglect the spin orbit distortion.

Let us consider then other states and look for special kinematical and geometrical conditions such that $P_{eff} = 0$. For a fixed geometry and kinematics the values of θ and T_{rel}

---

[3] For polarized incident beam normalized to 100% ($P_0 = 1$).

necessary to calculate the asymmetries of the $l + 1/2$ and $l - 1/2$ states are not exactly the same, due to the different binding energies of these states. However, since this difference is small and $C_{nn}(\theta, T_{rel})$ and $P(\theta, T_{rel})$ are smooth functions of energy and angle, one has that $C_{nn}^{l+1/2} \approx C_{nn}^{l-1/2}$ and $P^{l+1/2} \approx P^{l-1/2}$ to a good approximation. (Here $C_{nn}^{l+1/2}$ means the value of $C_{nn}(\theta, T_{rel})$ which enters in Eq.(7) to calculate the asymmetry of the $(l + 1/2)$ state, and so on.) Within this approximation, $A_{exp}^{l+1/2} = A_{exp}^{l-1/2}$ implies $P_{eff}^{j+1/2} = P_{eff}^{j-1/2}$, in contradiction with Eq.(9), except when $P_{eff}^{j+1/2} = P_{eff}^{j-1/2} = 0$. Hence, for those kinematical and geometrical conditions for which the asymmetries of quasi-free scattering in two sub-shells split by the spin-orbit interaction are equal ($A_{exp}^{l+1/2} = A_{exp}^{l-1/2}$), the effective polarization of the nucleons involved in the quasi free collision should be to a good approximation equal to zero ($P_{eff}^{j+1/2} \sim P_{eff}^{j-1/2} \sim 0$). One may therefore extract from Eq. (10) the *pp* analysing power in medium from the experimental $(\vec{p}, 2p)$ asymmetries, by looking for those points where the curve for $A_{exp}^{l+1/2}$ crosses the curve for $A_{exp}^{l-1/2}$. At these special points $A_{exp}^{l+1/2} = A_{exp}^{l-1/2} = \tilde{P}(\theta, T_{rel})$ where $\tilde{P}(\theta, T_{rel})$ is the *pp* analysing power in medium.

Kitching et al. [36] has performed an extensive series of measurements of the asymmetry for the $^{16}O(\vec{p}, 2p)^{15}N$ reaction in a coplanar geometry with 200 MeV incoming protons with polarizations orthogonal to the scattering plane (normalized to 100%). Some of the TRIUMF experimental asymmetries [36] for 200 MeV coplanar $(\vec{p}, 2p)$ scattering on ^{16}O, resulting in the j=1/2 ground state and the j=3/2 first excited state of ^{15}N are shown in Fig.1[4]. The reader may see in Fig. 1 that there is an appreciable reduction of the analysing power in medium looking for the special cases where $A_{exp}^{1/2} = A_{exp}^{3/2}$. At these points the asymmetries yield the analysing power in medium, according to Eq.(10). On the other hand, the free $P(\theta, T_{rel})$ values are indicated by the dashed curves in this same figure and it is clear that the in medium value is smaller than the free one for the non symmetrical geometries ($\theta_1 \neq \theta_2$).

---

[4] We select cases for which most of the experimental data are not at the momentum distributions minima, to avoid uncertainties coming from the multiple scatterings [26]

For $\theta_1 = \theta_2$ the free $P(\theta, T_{rel})$ values are anyhow small and not too much can be said.

The effective polarization calculated [26] from these experimental asymmetries using Eq.(8) with P and C_{nn} for free scattering are reproduced in Fig.2. In this figure the effective polarization of the 3/2 state is already multiplied by -2 to check wheter $P_{eff}^{1/2} = -2P_{eff}^{3/2}$ as predicted by Eq.(9). For the cases $\theta_1 = \theta_2$ the agreement is excellent. For $\theta_1 \neq \theta_2$ there are discrepancies. As was remarked, for symmetrical angles, for reasons of symmetry, $P(\theta, T_{rel})$ is small. For asymmetrical angles, $P(\theta, T_{rel})$ is typically 0.3 and the the fits are poor. (See the dashed curves in Fig.1).

In Ref. [26] an empirical observation was made: if one sets arbitrarily $P(\theta, T_{rel}) = 0$ and does not change the value of $C_{nn}(\theta, T_{rel})$, Eq.(8) describes quite well the experimental data for both the asymmetrical and symmetrical cases. In fact, assuming $P(\theta, T_{rel}) \approx 0$ in Eq.(7), for non-vanishing effective polarization, one has ($P_0 = 1$):

$$\frac{A^{l+1/2}}{A^{l-1/2}} = \frac{P_{eff}^{l+1/2} C_{nn}^{l+1/2}(\theta, T_{rel})}{P_{eff}^{l-1/2} C_{nn}^{l-1/2}(\theta, T_{rel})} . \tag{11}$$

This means that the agreement between theory and experiment achieved in Ref. [26] remains true even if $C_{nn}^{l\pm 1/2}(\theta, T_{rel})$ is modified in medium as long as the C_{nn}'s ratio for $j = l + 1/2$ and $j = l - 1/2$ remains approximately equal to unity.

The situation described above is not restricted to the ^{16}O nucleus. The measured asymmetries [37] for the reaction ^{40}Ca$(p, 2p)^{39}$K at 200 MeV indicate also a reduction of $P(\theta, T_{rel})$ in medium for non-symmetrical geometry, as can be seen in Fig.3. Again the values for $A_{exp}^{1/2} = A_{exp}^{3/2}$, which give $P(\theta, T_{rel})$ in medium, are much smaller than the free $P(\theta, T_{rel})$ values. Moreover, the effective polarization extracted from these asymmetries using Eq.(8) show a similar behaviour as for the ^{16}O, that is for the symmetrical angle (small values for $P(\theta, T_{rel})$) Eq.(8) describes well the results while for the asymmetrical situation the agreement is poor, as can be seen in Fig.4.

The asymmetries have also been measured for ^{40}Ca$(\vec{p}, 2p)$ populating the $2s_{1/2}$ hole state in ^{39}K. In this case there is a much smaller reduction (if any) of $P(\theta, T_{rel})$ in medium. However, as has been mentioned, the knockout of $2s$ states occurs in less dense regions of the nucleus and the effect of the nuclear medium is not expected to be large [35].

The analysing powers and cross sections for these reactions have been calculated [27] within the framework of the DWIA, including both the effect of the spin orbit interaction for the distorted waves and off-shell effects in the proton-proton scattering using antisymmetrized t-matrix elements calculated with an effective relativistic Love Franey nucleon-nucleon interaction. The results of the calculations agree reasonably well with the data. However, it appears that for the $^{16}O(\vec{p}, 2p)$ reaction the non-symmetrical geometry considered ($20^0 - 65^0$) shows an agreement of less quality than the two symmetrical ones ($30^0 - 30^0$ and $40^0 - 40^0$). For the $^{40}Ca(\vec{p}, 2p)$ reaction the situation is not so clear. It would be interesting to know the results which one would get with this treatment for the cases showing discrepancies in our analysis ($30^0 - 40^0$ and $30^0 - 45^0$ for ^{16}O, and $30^0 - 54^0$ for ^{40}Ca), as well as for the 2s state in ^{40}Ca.

The experimental evidence of a reduction of $P(\theta, T_{rel})$ in medium sets strong constraints on medium modifications of the nucleon-nucleon interaction, as we shall now discuss. In the next section we use the Bonn one-boson exchange model of the nucleon nucleon interaction to relate the spin observables relevant to quasi-free scattering to the properties of the exchanged mesons.

III. THE NUCLEON-NUCLEON INTERACTION, MESON PROPERTIES AND SPIN OBSERVABLES

The free NN interaction is well described by potentials derived from meson exchange models. In this paper we use one of the most successful meson-exchange models, namely the Bonn potential [30]. For the present purposes, it is sufficient to use the one boson exchange potential (OBEP) which includes $\sigma, \vec{\delta}, \eta, \vec{\pi}, \omega$, and $\vec{\rho}$ meson exchanges.

In order to get some understanding of the contribution of each exchanged meson to the spin observables, we do the following. We use the parameters of the Bonn potential which fit the experimental phase shifts (table 5 of Ref. [29]) and calculate the observables P and C_{nn}.

Then, we recalculate the spin observables setting the coupling constant of a given meson equal to zero, without changing any other parameter. In this way, it is possible to evaluate the importance of any particular meson to P and C_{nn}. The results are shown in Fig.5. The first fact which one learns from this figure is that, not surprisingly, the most important contributions to these observables comes basically from two mesons, from the σ and the ω. (The π meson contributes to the observables at low energies only; mainly to C_{nn}.) The other important conclusion is that the σ meson is the crucial one for P. Although the absence of the ω meson makes the absolute value of P smaller than its experimental value, the absence of the σ changes the sign of P with respect to its true value. The observable C_{nn} is sensitive to both σ and ω mesons; the π meson is relevant at relatively low energies only.

The crucial observation that the σ meson is the most important meson for the observable P may lead us to understand the reduction of P in medium discussed in the section II. The potential generated by this meson has central and spin-orbit components. Since a central potential cannot produce a polarization, it appears that the spin-orbit component of the nucleon-nucleon potential should be much weaker in the nucleus than in free space.

It seems then that a reduction of P in medium may be associated to the change of the properties of the σ meson in the nucleus. It is interesting to note that in a recent relativistic density dependent Hartree approach for finite nuclei, where the coupling constants of the relativistic Hartree lagrangian are made density dependent [11] it was found that $g_{\sigma NN}$ and $g_{\omega NN}$ are of the order of 10% smaller in medium than in free space.

In order to investigate medium effects on P and C_{nn} we use the Bonn potential [30] to generate pp phase shifts to be used in the calculation of P and C_{nn}. However the input parameters (masses and/or coupling constants) are changed according to some prescription.

Although much effort [1–12] has been devoted to the question of medium modifications of the hadronic properties, not too much has been concluded yet. There is a scaling conjecture for hadron properties at finite densities suggested by Brown and Rho [7] based on arguments of partial restoration of chiral symmetry in nuclei which leads to the following scaling law for the masses:

$$\frac{m_N^*}{m_N} \approx \frac{m_\sigma^*}{m_\sigma} \approx \frac{m_\rho^*}{m_\rho} \approx \frac{m_\omega^*}{m_\omega} \approx \frac{f_\pi^*}{f_\pi} \equiv \xi \,,$$
$$\frac{m_\pi^*}{m_\pi} \approx 1 \,, \qquad (12)$$

where f_π is the pion decay constant, m_N, m_ρ, m_ω and m_π are the masses of the nucleon, $\vec{\rho}$, ω and $\vec{\pi}$ mesons, respectively, and m_σ the mass of the effective scalar σ meson. The asterisk denotes the value of these quantities in nuclear medium.

Other authors have also discussed hadronic scaling law for the masses based on QCD arguments [2,4,9,10,12]. Kusaka and Weise [9] have concluded that the Brown and Rho scaling law is not realized for reasonable parameter changes. However Gao *et al.* [12], based on the thermofield dynamical theory, have concluded that for $\rho < 4\rho_0$, where ρ_0 is the saturation density, Brown and Rho conjecture should be correct. Hatsuda and Lee [10] have obtained a linear decrease of the masses as a function of density; their results seem to support Brown and Rho scaling law. Although the validity of Brown and Rho law is still controvertial, we take it as a starting point to investigate the behavior of the observables with changed hadronic mass.

Another open question is the value assumed by ξ in Eq.(12). We have taken it in the range 0.6 to 0.9.

With respect to the variations of coupling constants, the situation is even more controvertial [8,11]. As has been mentioned, it was found by Brockmann and Toki [11] in a relativistic density-dependent Hartree approach that the $g_{\sigma NN}$ and $g_{\omega NN}$ are ~ 10% smaller in medium than in free space. The Banerjee's toy model, based on the chiral confined model, leads to a reduction of $g_{\sigma NN}$ with density, while $g_{\omega NN}$ and $g_{\rho NN}$ increase at some low rate with the density. There is still a scaling law derived by Banerjee [8], using the results of McGovern, Birse and Spanos [5], which leads to an increase of $g_{\sigma NN}$ and $g_{\omega NN}$ in medium. As we do not have a definitive prescription for changing the coupling constants in medium, we assume that $g_{\sigma NN}$ and $g_{\omega NN}$ decrease in medium [11] according to:

$$\frac{g_{\sigma NN}^*}{g_{\sigma NN}} = \frac{g_{\omega NN}^*}{g_{\omega NN}} = \chi \,. \qquad (13)$$

where χ is assumed in the range $0.6 < \chi < 0.9$.

We also consider simultaneous variations of masses and coupling constants by taking Eq.(12) and Eq.(13) simultaneously.

In summary, we consider three prescriptions:

i) only the masses are changed according to Eq. (12).

ii) only the σNN and ωNN coupling constants are changed according to Eq. (13).

iii) the σNN and ωNN coupling constants and masses are changed simultaneously according to Eq.(12) and Eq.(13).

We have not considered medium modifications of masses and/or coupling constants of the mesons $\vec{\rho}$, η and $\vec{\delta}$ since their contributions to P and C_{nn} at the energies we are considering are much smaller than the ones from σ and ω, as can be seen in Fig. 5. With respect to the pion since it is a Goldstone boson, its mass presumably changes only slowly with density [3,6] and modifications on the $g_{\pi NN}$ affect the spin observables only at low energies (Fig. 5). We have checked our results against variations of the pion mass and coupling constant and they do not change our conclusions.

In Fig. 6 we show the effect on the observables P and C_{nn} of changing the masses and/or coupling constants according to the three prescriptions above, taking $\xi = 0.7$ and $\chi = 0.75$. The figures show that in all three prescriptions there is a reduction of $P(\theta, T_{rel})$ in medium compared to the free value. For others values of ξ and χ the results are basically the same except that the curves cross the axis in slightly different places. The reduction increases, as ξ and/or χ decrease. C_{nn} is reduced for $45^0 \lesssim \theta_{cm} \lesssim 135^0$ and enhanced for other values of θ_{cm} in all three prescriptions.

IV. MEDIUM MODIFICATIONS AND QUASI-FREE REACTIONS

In this section we analyse the implications of the medium modifications for the $(\vec{p}, 2p)$ asymmetries.

We have calculated the values of P and C_{nn} with the three prescriptions explained in section III taking $0.6 < \xi, \chi < 0.9$. The effective polarizations are then calculated by using the experimental asymmetries in Eq.(8). A remarkably good agreement between these effective polarizations and the theoretical prediction, Eq.(9), is obtained when one changes simultaneously masses and coupling constants and takes $\xi = 0.7$ and $\chi = 0.75$. The results are shown in Fig. 7 and Fig. 8 for the $^{16}O(\vec{p},2p)^{15}N$ and $^{40}Ca(\vec{p},2p)^{39}K$, respectively.

The conclusion one can draw from these figures is that the modifications of nucleon and meson properties clearly affect the spin observables of the reaction in a significant way. As mentioned in the introduction, although relativistic effects including retardation lead to improvement on the calculated $(\vec{p},2p)$ cross-sections, there still remain discrepancies for spin observables in some geometrical regions. In this sense, the inclusion of medium modifications on the basic interaction process might be worthwhile to be investigated.

As has been mentioned, in Ref. [26] the discrepancies have been eliminated by taking P arbitrarily equal to zero and using the free space value of C_{nn}. In our calculation, for consistency, we assumed that both P and C_{nn} are modified in medium. The value of P turned out to be drastically reduced in medium, but it does not go exactly to zero. The value of C_{nn} is also changed in medium, however it is still a smooth function of energy and angle. As a consequence, the ratio $C_{nn}^{j=l+1/2}/C_{nn}^{j=l-1/2} \approx 1$ and the agreement is achieved rather independently of the free C_{nn} value.

In an early attempt [24] the reduction of P in medium was investigated using a formalism developed by Horowitz and Iqbal [21]. In their formalism, the medium modification are evaluated in a relativistic model where the NN interaction is assumed to depend on the enhancement of the lower components of the nucleon Dirac spinor due to strong scalar and vector components nuclear potentials. Although this formalism also leads to a reduction of the pp analysing power in medium, the effect is too small to eliminate the observed discrepancies. The influence of a depolarization of the incident beam as well as off-shell effects have also been investigated a long time ago [38] and do not explain the discrepancies.

There is still lacking a clear explanation of the fact that in the $2s$-knockout from ^{40}Ca

the reduction of the analysing power is much smaller than in the $1p$ and $1d$-states studied here. Based on the argument that the 2s state knockout occurs in less dense regions of the nucleus one would expect to describe the data with our approach using larger values for ξ and/or λ compared to the values used for p and d states. Our analysis for this case indicates that ξ and λ must be larger than 0.9.

Up to now we have discussed the spin observables which enter in the coplanar $(\vec{p},2p)$ quasi free cross sections, namely P and C_{nn}. We observed that the three prescriptions for hadronic scaling laws affect these observables. However, we do not expect to be able to discriminate between the three prescriptions through these observables solely since the effects go always in the same direction, that is when a prescription leads to an enhancement (*reduction*) *of* P or C_{nn} the other two prescriptions lead to an enhancement (reduction) too.

However, the proposed measurement of $(\vec{p},2\vec{p})$ quasi-free *reaction proposed* at IUCF and TRIUMF will have indirect access to another spin observable, namely the depolarization tensor, D_{nn}. For this observable, in contrast, the effects of the three prescriptions are quite different, as can be seen in Fig.9. It is clear that such a measurement might provide severe constraints on medium modifications of hadron properties[5].

V. CONCLUSIONS

We have used quasi free knockout reactions to investigate medium modifications of bound nucleons. Some *care must be taken when the* factorized[6] quasi-free $(\vec{p},2p)$ cross sections as in this paper are used.

---

[5] Kudo and Tsunoda [39] have *calculated the depolarization* tensors for the $1d_{5/2}$, $1d_{3/2}$ and $2s_{1/2}$ hole states in the ^{40}Ca$(\vec{p},2p)^{39}$K at $E = 200$ MeV.

[6] The quasi-free cross section is factorized into a product of the momentum distribution of the *ejected nucleon times* a *pp cross section at energy* and angles corresponding to the violent interaction.

The factorized form of the cross sections has been often checked[7] and it turned out that the best way is to avoid the minima of the momentum distributions of the ejected nucleon (where a large smearing of the momentum happens) and to work with ratios of quasi-free cross sections to cancel out uncertainties related with the optical potentials. With this care in mind, the factorized cross section shows the advantage of making the physics of the process transparent. For instance, an effective polarization of the ejected nucleon (before the knockout process) is understandable in terms of a combined effect of the spin orbit interaction and the absorption of the ejected nucleon [13]. As for medium energy, in the angular region needed for the absorption effect, the cross section for protons with paralell spins is much larger than the one for opposite spins, an asymmetry is expected (and detected) for $(\vec{p},2p)$ process with polarized incident beams.

There is also a theoretical prediction which relates the effective polarizations for nucleons in two sub-shells split by the spin-orbit interaction. In principle, one could doubt the validity of this prediction since it is based on the factorization approximation. However, it is remarkable that the data agree quite well with this theoretical prediction when the angles of the two emerging particles are equal. When the emerging angles are different some discrepancies show up. These discrepancies have been observed a long time ago [26] and various attempts to explain them have been made on the basis of off shell effects, depolarization of the incident beam [38] as well as by taking into account the nucleon effective mass inside the nucleus [23,24]. To our knowledge, none of these has been successful.

On the basis of a factorized quasi free cross section, we have proposed to extract the pp analysing power in medium (P) through the asymmetries of $(\vec{p},2p)$ processes. In particular, P is equal to the experimental asymmetries for two sub-shells split by the spin-orbit interaction for geometrical and kinematical situations such that $A^{j=l+1/2} = -A^{j=l-1/2}$. From the measured asymmetries for 200 MeV coplanar $(\vec{p},2p)$ on $1p$ states of ^{16}O and $1d$ states

---

[7] see Ref. [18] and references therein.

of ^{40}Ca, we have observed a reduction of P in medium.

A reduction of the pp analysing power in medium is also predicted by the Horowitz and Iqbal relativistic treatment [21] of proton nucleus scattering. In this approach a modified NN interaction in medium is assumed due to the effective nucleon mass (smaller than the free mass) which affects the Dirac spinors used in the calculations of the NN matrix $\mathcal{M}$. Cross sections and spin observables are modified in medium. For instance, the analysing power is found to decrease 10% compared to the free value at 500 MeV for an effective nuclear mass ~ 15% smaller the free value. This treatment is unable to explain the discrepancies under discussion in the quasi-free $(\vec{p},2p)$ asymmetries [23,24].

In this paper we have performed an exploratory study towards a possible explanation of the P reduction observed in $(\vec{p},2p)$ scattering in terms of medium modifications of nucleon and meson properties. The first conclusion is that the ω and specially the σ meson give the main contribution for this observable. The next step was to use hadronic scaling laws in our calculations. As this issue is still controvertial, in this exploratory study we have considered possible modifications of masses and/or coupling constants for the σ and ω mesons, which are the most important for the spin observables. It turned out that by scaling simultaneously masses and coupling constants we have been able to eliminate the discrepancies observed in the asymmetries of $(\vec{p},2p)$ reactions. We do not know of any other explanation for these discrepancies.

Our results show that quasi-free $(\vec{p},2p)$ reactions might be a powerfull tool to investigate medium modifications of bound nucleons and hopefully to discriminate different prescriptions. More experimental data at higher bombarding energies are clearly needed.

ACKNOWLEDGMENTS

Support by Fundação de Amparo à Pesquisa do Estado do Rio Grande do Sul (FAPERGS), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) is acknowledged.

REFERENCES

[1] For a recent review see: T. Hatsuda, Nucl. Phys. A **544**, 27c(1992).

[2] V. Bernard, U.G. Meissner and I. Zahed, Phys. Rev. Lett. **59**, 966(1987).

[3] Y. Nambu, In: K. Winter (ed) **Festival-Festschrift for Val Teledgdi**, New York:Ed. Elsevier, 1988.

[4] B.A. Campbel, Jonh Ellis and K.A. Olive, Phys. Lett. B **235**, 325(1990). Nucl. Phys. **B345**, 57(1990).

[5] J.A. McGovern, M.C. Birse and D. Spanos, J. Phys. G **16**, 1561(1990).

[6] G.E.Brown, A.Sethi, and N.M.Hintz, Phys.Rev.C **44**, 2653(1991).

[7] G.E. Brown and M. Rho, Phys. Rev. Lett. **66**, 2720(1991).

[8] M.K. Banerjee, Phys. Rev. **45**, 1359(1992).

[9] K. Kusaka and W. Weise, Phys. Lett. B **288**, 6(1992).

[10] T. Hatsuda and S.H. Lee, Phys. Rev. C **46**, R34(1992).

[11] R. Brockmann and H. Toki, Phys. Rev. Lett. **68**, 3408(1992).

[12] S. Gao, R-K. Su and P.K.N. Yu, Phys. Rev. C **49**, 40(1994).

[13] Th.A.J. Maris, P.Hillman, and H.Tyrén, Nucl. Phys., **7**, 1(1958); Th.A.J. Maris, Nucl. Phys. **9**, 577(1958/1959).

[14] G.Jacob and Th.A.J. Maris, Rev. Mod. Phys, **38**,121(1966) and **45**, 6(1973).

[15] P. Kitching, W.J. McDonald, Th.A.J. Maris, and C.A.Z. Vasconcellos, Adv. Nucl. Phys. **15**, 43(1985).

[16] P. Kitching, C.A. Miller, D.A. Hutcheon, A.N. James, W.J. McDonald, J.M. Cameron, W.C. Olsen, and G. Roy, Phys. Rev. Lett. **37**, 1600(1976).

[17] A.N. James, W.J. McDonald, J.M. Cameron, C.A. Miller, D.A. Hutcheon, P. Kitching, G.C. Neilson, G.M. Stinson and E.D. Earle, Nucl. Phys. **A324**, 253(1979).

[18] Th.A.J. Maris, M.R.Teodoro, and E.A.Veit, Phys. Rev. C **20**, 446(1979).

[19] J.A. Tjon and S.J. Wallace, Phys. Rev. C **38**, 1085(1987).

[20] D.P. Murdock and C.J. Horowitz, Phys. Rev. C **35**, 1442(1987).

[21] C.J. Horowitz and J. Iqbal, Phys. Rev. C **33**, 2059(1986).

[22] C.J. Horowitz and D.P. Murdock, Phys. Rev. C **37**, 2032(1988).

[23] B.B. Rodrigues, Master dissertation, Universidade Federal do Rio Grande do Sul, 1992 (unpublished).

[24] G. Krein, B.B. Rodrigues, and E.A. Veit, In: D. Dillenburg, G. Jacob, P. Kitching and C.A.Z. Vasconcelos (eds) **Current topics in nuclear physics and quantum field theory**, Festschrift for Prof. Th.A.J. Maris, Porto Alegre:Ed. da Universidade, 1994, 55-72.

[25] Y. Kudo and K. Miyazaki, Phys. Rev. C **34**, 1192(1986).

[26] Th.A.J. Maris, M.R. *Teodoro, and* E.A. Veit, Phys. Lett. **B94**, 6(1980).

[27] E.D. Cooper and O.V. Maxwell, Nucl. Phys. A **493**, 468 (1989); O.V. Maxwell and E.D. Cooper, Nucl. Phys. A **513**, 584 (1990).

[28] O.V. Maxwell and E.D. Cooper, Nucl. Phys. A **565**, 740 (1993).

[29] R. Machleidt, K. Holinde and Ch. Elster, Phys. Rep. **149**, 1(1987).

[30] R. Machleidt, In: K. Langanke, J.A. Maruhn, S.E. Koonin (Eds.) **Computational nuclear physics**, New York: Springer Verler-Verlag, 1993, vol. 2,chap. 1.

[31] C. Schneider, Nucl. Phys. A **300**, 313 (1978); N.S. Chant, P. Kitching,P.G. Ross, and L. Antonuk, *Phys. Lett.* **43**, 495 (1979).

[32] L.Wolfenstein, Ann. Rev. Nucl. Sci. **6**, 43 (1953).

[33] J. Bystrick, F. Lehar and P. Winternitz, J. Phys. (PARIS) **39** (1978)1.

[34] V E.Herscovitz, Th.A.J.Maris and M.R.Teodoro, Phys.Lett. **69B**, 33 (1977).

[35] P. Kitching, In: D. Dillenburg, G. Jacob, P. Kitching and C.A.Z. Vasconcelos (eds) **Current topics in nuclear physics and quantum field theory**, Festschrift for Prof. Th.A.J. Maris, Porto Alegre:Ed. da Universidade, 1994, 31-44.

[36] P.Kitching, C.A.Miller, W.C.Olsen, D.A.Hutcheon, W.J.McDonald and A.W.Stetz, Nucl.Phys. **A340**, 423 (1980).

[37] L. Antonuk, P. Kitching, C.A. Miller, D.A. Hutcheon, W.J. McDonald, G.C. Neilson, and W.C. Olsen, Nucl. Phys. **A370**, 389 (1981).

[38] E.A. Veit, Ph.D. thesis, Universidade Federal do Rio Grande do Sul, 1981 (unpublished).

[39] Y. Kudo and H. Tsunoda, Prog. Theor. Phys. **89**, 89 (1993).

FIGURES

FIG. 1. Experimental asymmetries [36] for 200 MeV coplanar $(\vec{p}, 2p)$ scattering on the p-states of ^{16}O. The dashed curves correspond to the free $P(\theta, T_{rel})$ values.

FIG. 2. The effective polarization calculated [26] from the TRIUMF measurements shown in Fig.1. The effective polarizations of the $j = 3/2$ state are multiplied by -2 to check Eq.(9).

FIG. 3. Experimental asymmetries [37] for 200 MeV coplanar $(\vec{p}, 2p)$ scattering on the d-states of ^{40}Ca. The dashed curves correspond to the free $P(\theta, T_{rel})$ values.

FIG. 4. The effective polarization calculated from the TRIUMF measurements shown in Fig. 3. The effective polarizations of the $j = 5/2$ state are multiplied by -3/2 to check Eq.(9).

FIG. 5. The observables $P(\theta, T_{rel})$ and $C_{nn}(\theta, T_{rel})$ calculated with the Bonn potential with parameters which fit the experimental phase shifts for free scattering on protons (solid curves) and turning off different mesons.

FIG. 6. The observables $P(\theta, T_{rel})$ and $C_{nn}(\theta, T_{rel})$ calculated with the Bonn potential. The solid curves correspond to parameters which fit the experimental phase shifts. The dashed curves correspond to scaling the masses (Eq.(12) with $\xi = 0.7$), dot-dashed curves correspond to scaling coupling constants (Eq.(13) with $\chi = 0.75$) and dotted curves, scaling masses and coupling constants with $\xi = 0.7$ and $\chi = 0.75$.

FIG. 7. Effective polarizations for $1p$ states of ^{16}O obtained from the experimental asymmetries shown in Fig.1 with masses and coupling constants changed according to Eq.(12) ($\xi = 0.7$) and Eq.(13) ($\chi = 0.75$).

FIG. 8. Effective polarizations for $1d$ states of ^{40}Ca obtained from the experimental asymmetries shown in Fig.3 with masses and coupling constants changed according to Eq.(12) ($\xi = 0.7$) and Eq.(13) ($\chi = 0.75$).

FIG. 9. The observables D_{nn} calculated with the Bonn potential. The convention is the same as in Fig.6.

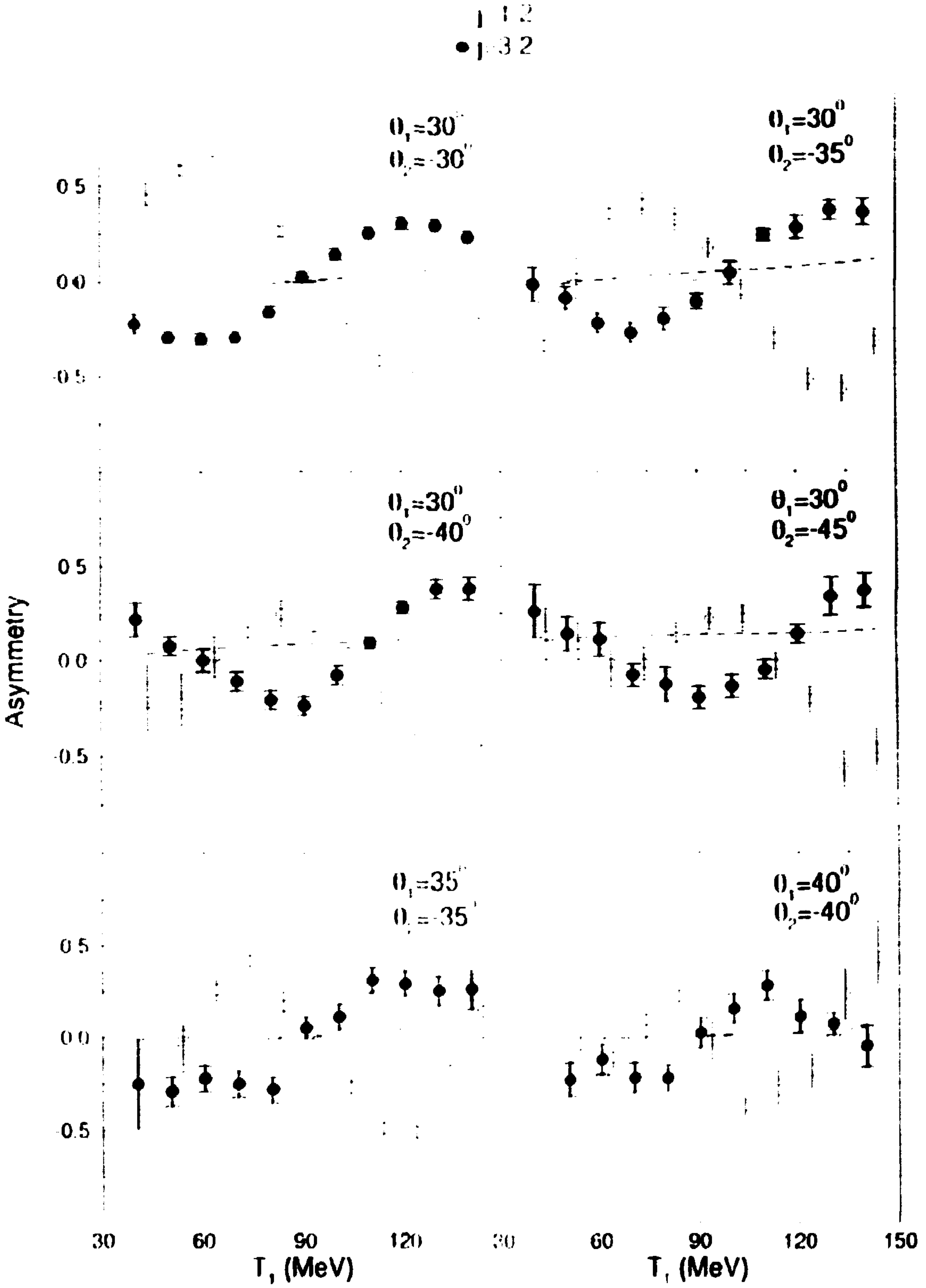
j 1 2
● j 3 2
θ₁=30°
θ₂=-30°
θ₁=30°
θ₂=-35°
θ₁=30°
θ₂=-40°
θ₁=30°
θ₂=-45°
θ₁=35°
θ₂=-35°
θ₁=40°
θ₂=-40°
Asymmetry
0.5
0.0
-0.5
0.5
0.0
-0.5
0.5
0.0
-0.5
30
60
90
120
30
60
90
120
150
T₁ (MeV)
T₁ (MeV)

Fig 1

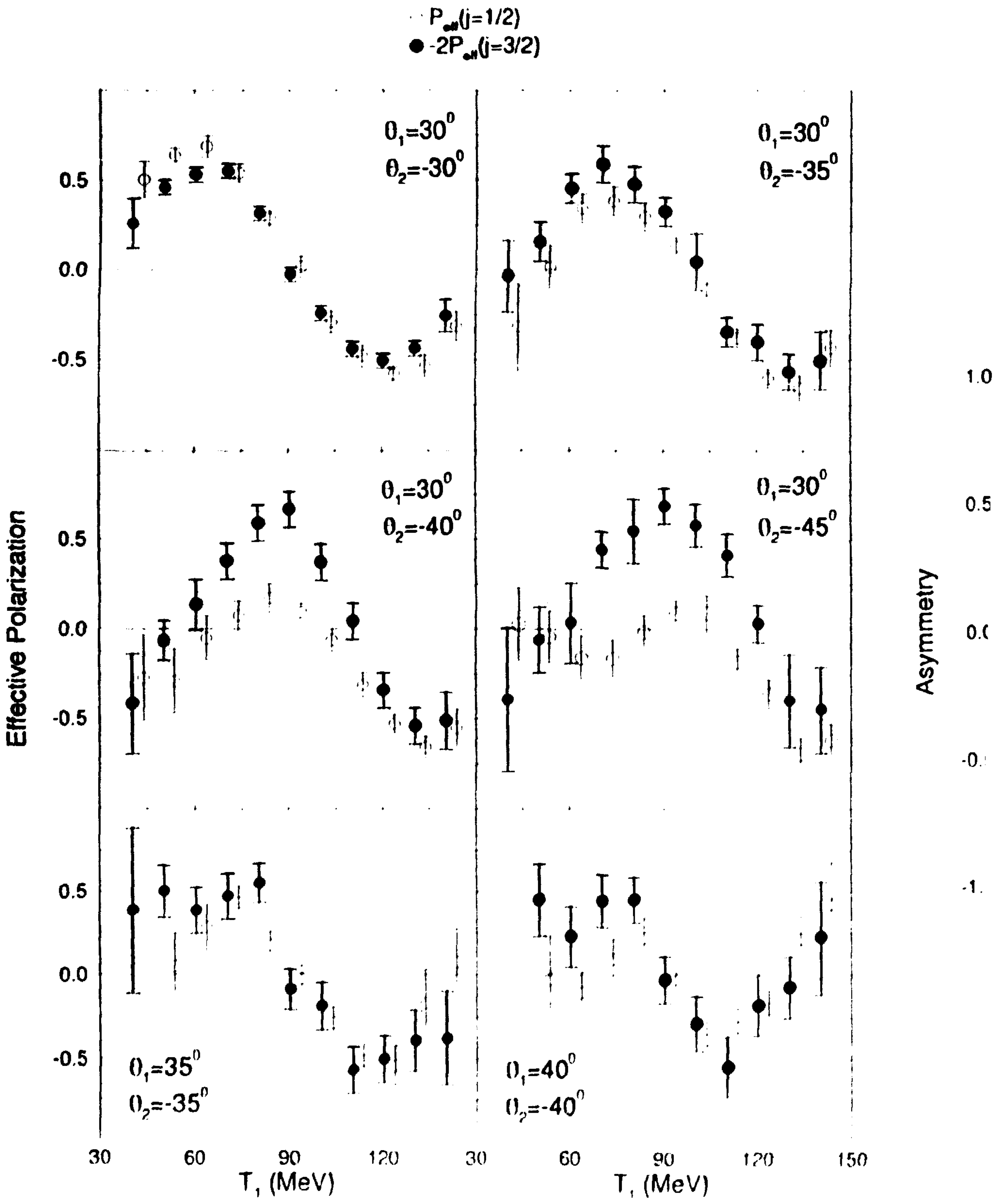
$P_{eff}(j=1/2)$
$-2P_{eff}(j=3/2)$
Effective Polarization
Asymmetry
$\theta_1=30^0$ $\theta_2=-30^0$
$\theta_1=30^0$ $\theta_2=-35^0$
$\theta_1=30^0$ $\theta_2=-40^0$
$\theta_1=30^0$ $\theta_2=-45^0$
$\theta_1=35^0$ $\theta_2=-35^0$
$\theta_1=40^0$ $\theta_2=-40^0$
0.5
0.0
-0.5
1.0
0.5
0.(
-0.
-1.
30
60
90
120
150
T_1 (MeV)
T_1 (MeV)

Fig 2

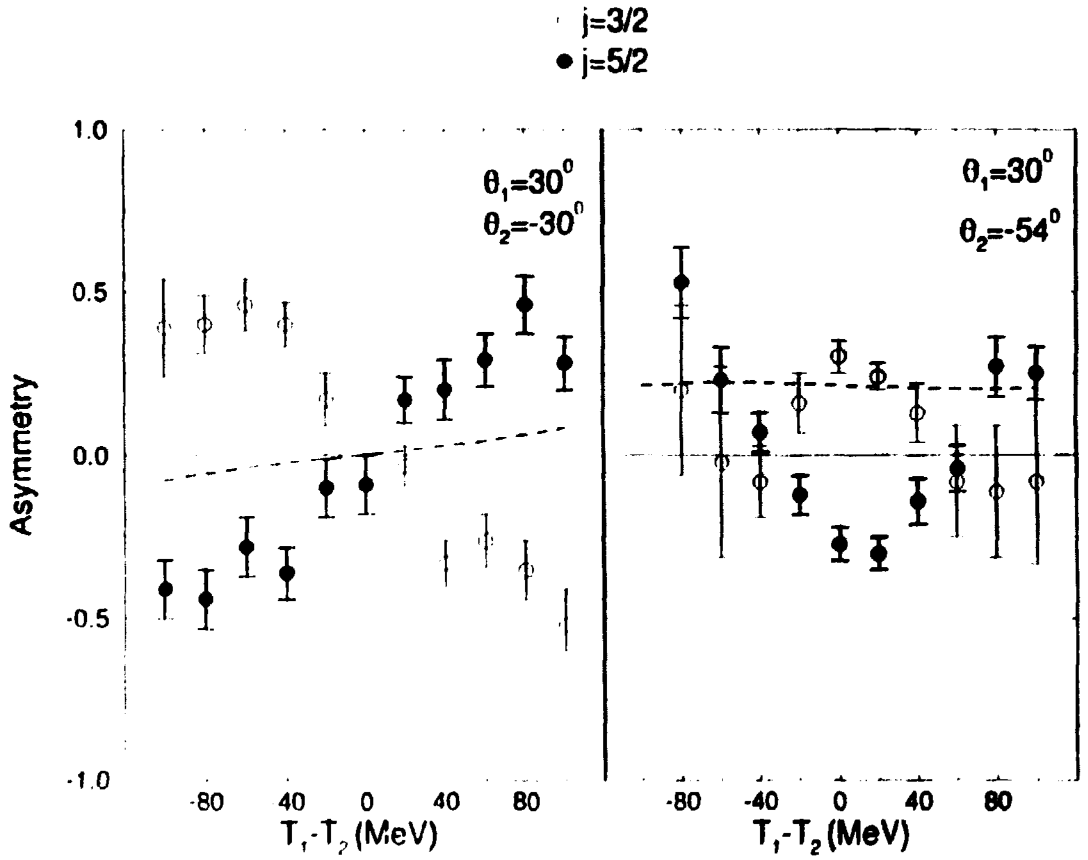
j=3/2
● j=5/2
1.0
0.5
0.0
-0.5
-1.0
Asymmetry
$\theta_1=30^0$
$\theta_2=-30^0$
$\theta_1=30^0$
$\theta_2=-54^0$
-80
40
0
40
80
T_1-T_2 (MeV)
-80
-40
0
40
80
T_1-T_2 (MeV)

Fig 3

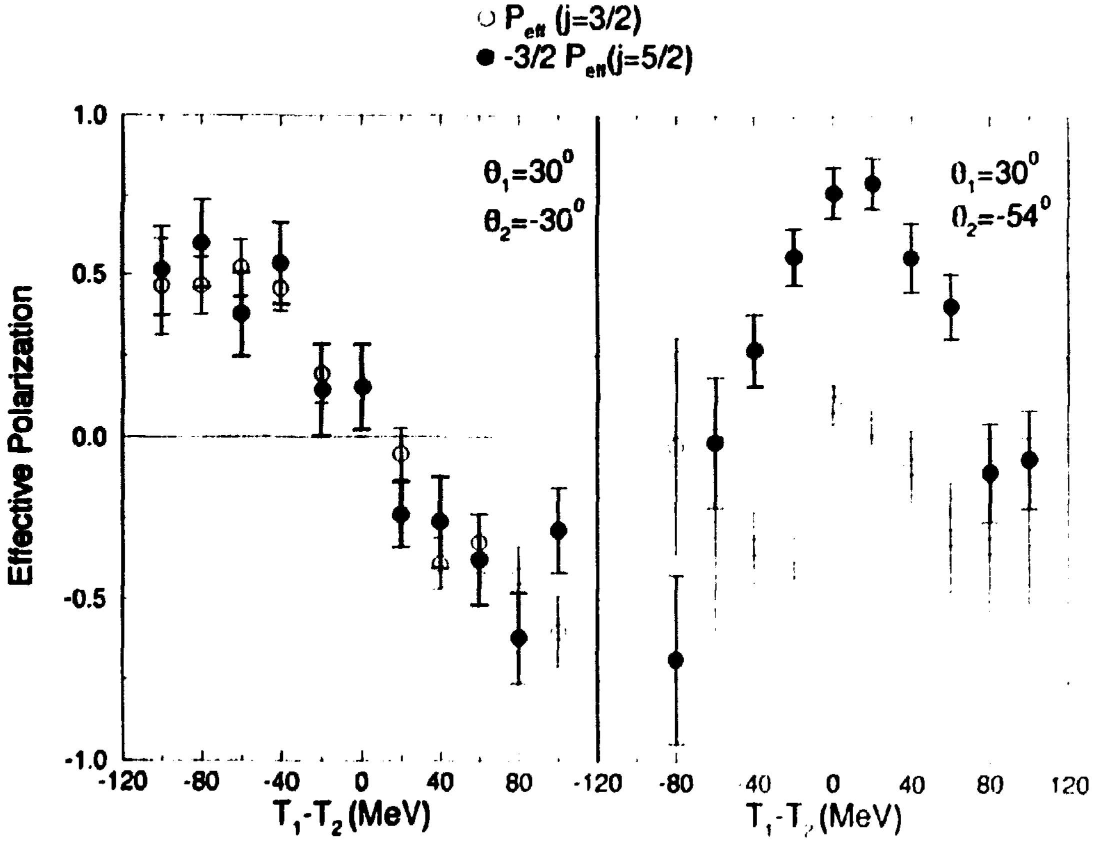
○ P_{eff} (j=3/2)
● -3/2 P_{eff}(j=5/2)
Effective Polarization
1.0
0.5
0.0
-0.5
-1.0
$\theta_1=30^0$
$\theta_2=-30^0$
$\theta_1=30^0$
$\theta_2=-54^0$
-120
-80
-40
0
40
80
-120
-80
40
0
40
80
120
T_1-T_2 (MeV)
T_1-T_2 (MeV)

Fig 4

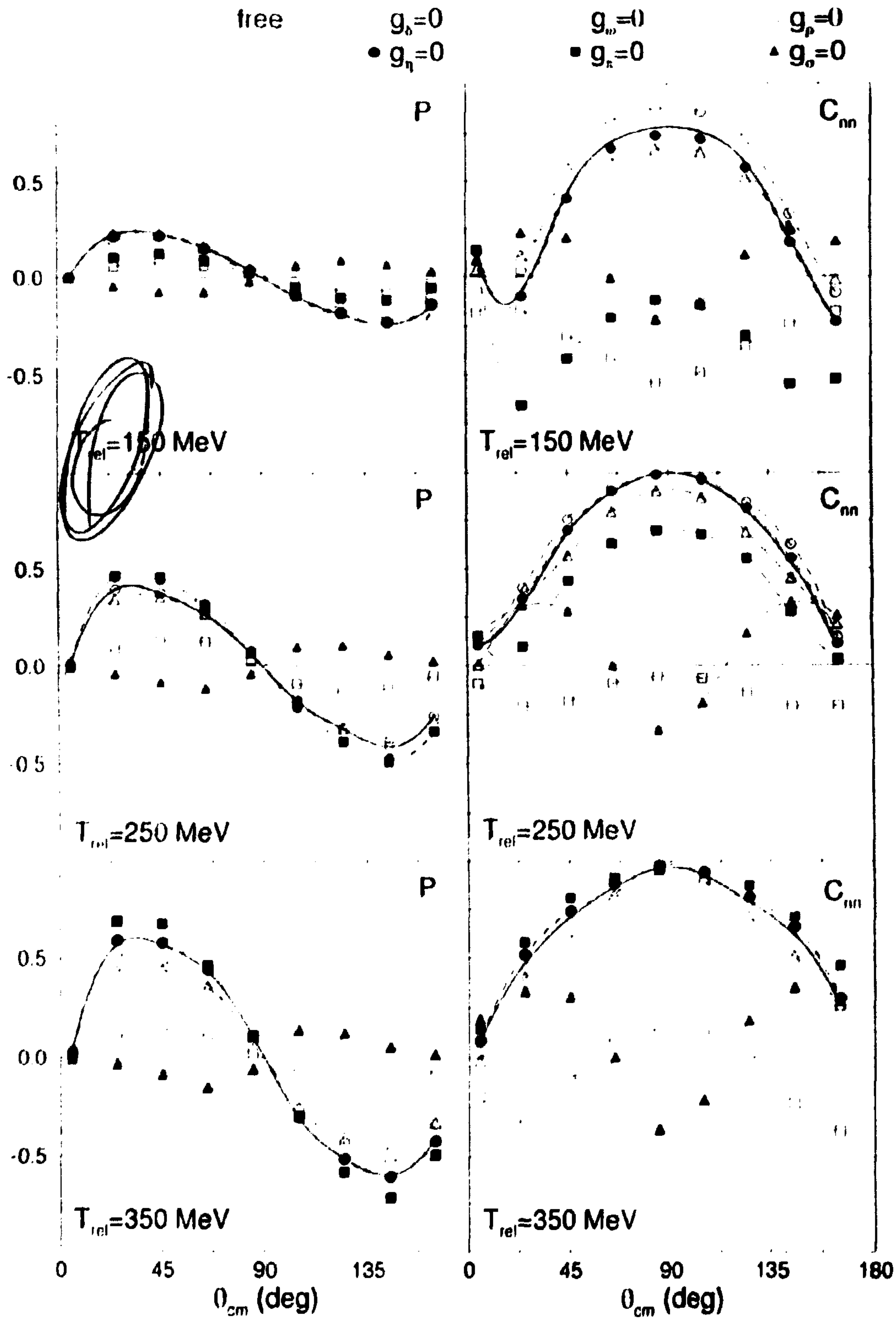
free
g_δ=0
g_ω=0
g_ρ=0
● g_η=0
■ g_π=0
▲ g_σ=0
P
C_nn
0.5
0.0
-0.5
T_rel=150 MeV
T_rel=250 MeV
T_rel=350 MeV
0
45
90
135
180
θ_cm (deg)

Fig 5

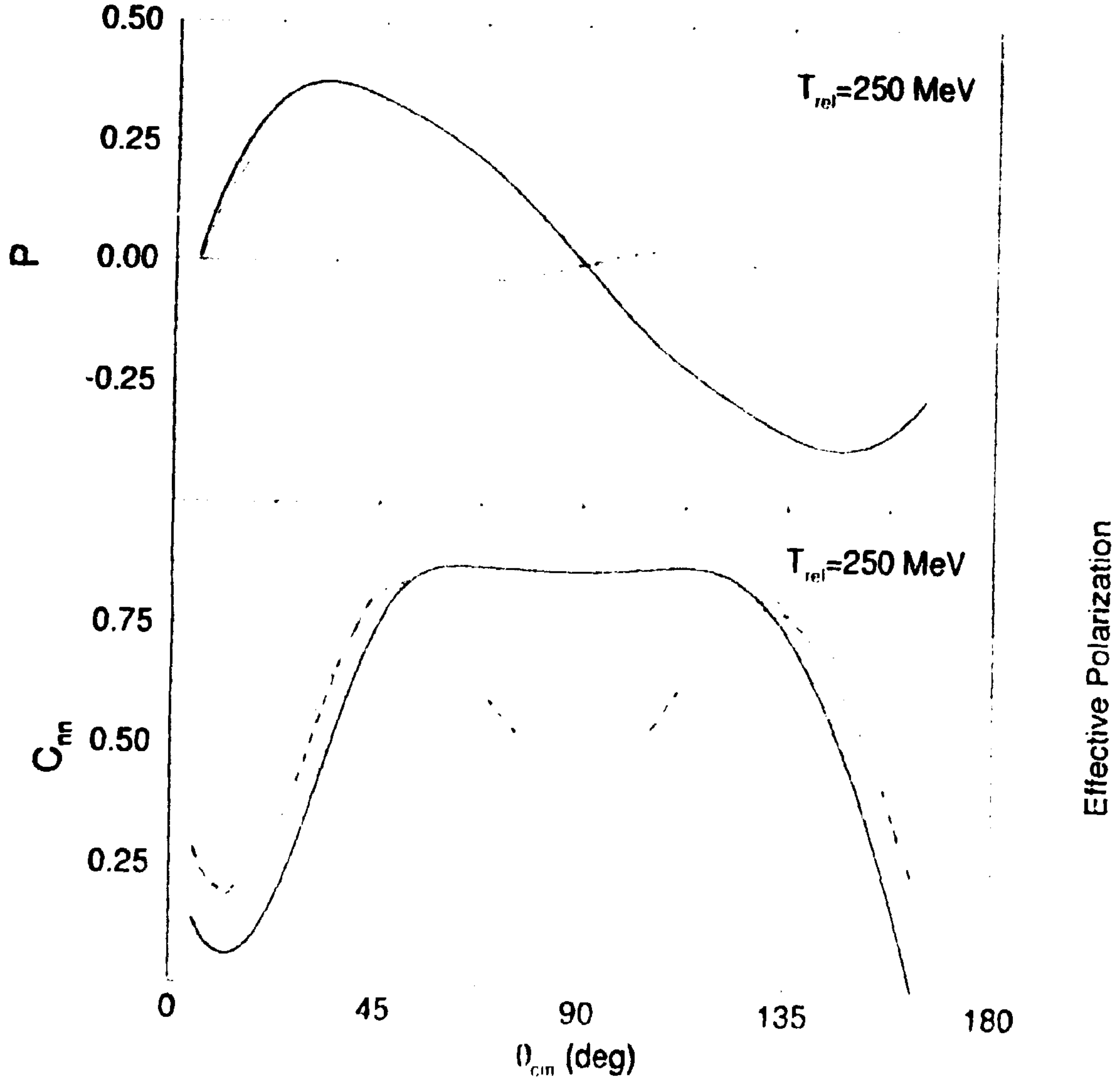
0.50
0.25
P
0.00
-0.25
T_{rel}=250 MeV
0.75
C_{nn}
0.50
0.25
T_{rel}=250 MeV
Effective Polarization
0
45
90
135
180
θ_{cm} (deg)

Fig 6

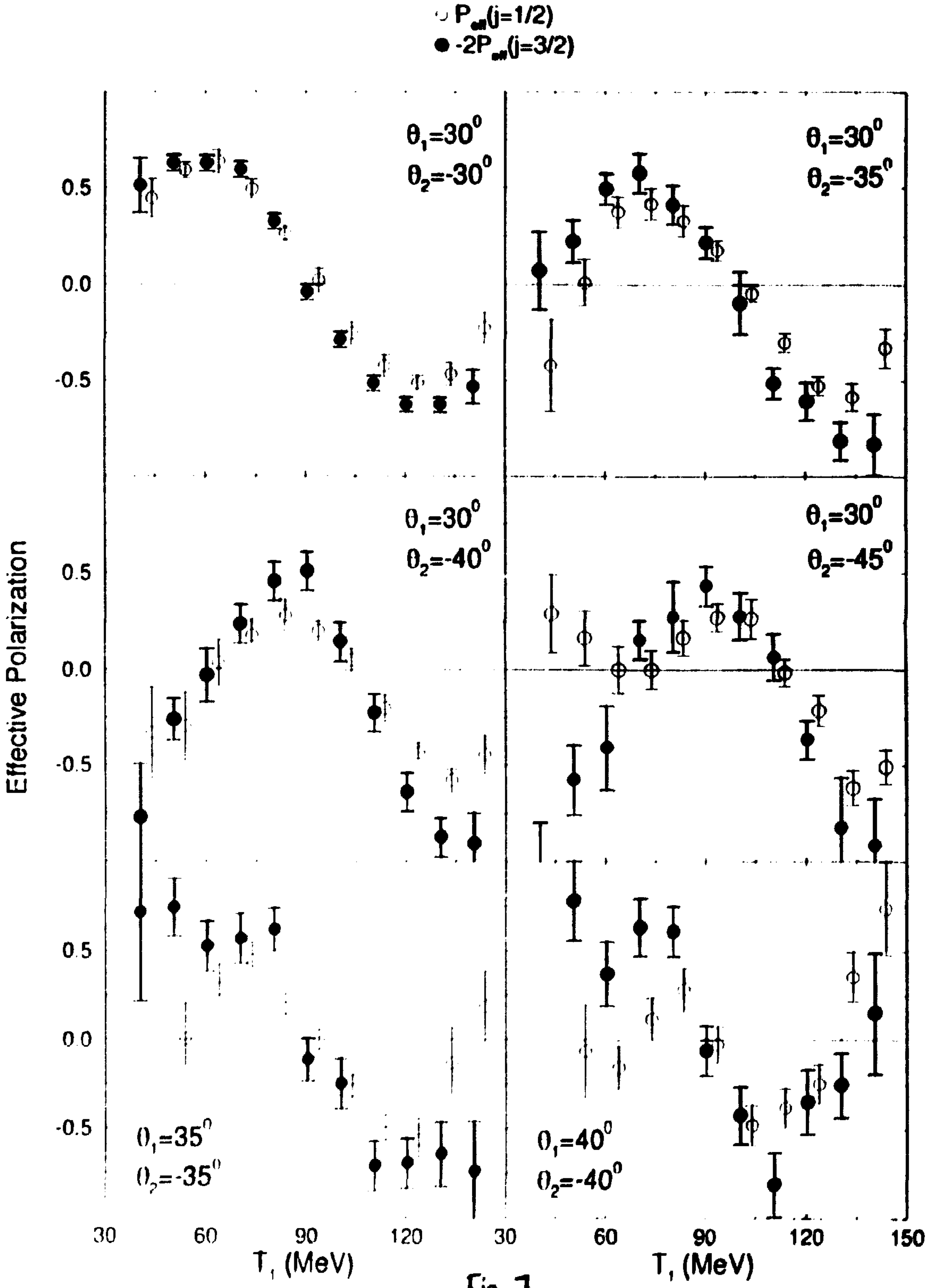
P_eff(j=1/2)
-2P_eff(j=3/2)
Effective Polarization
θ1=30° θ2=-30°
θ1=30° θ2=-35°
θ1=30° θ2=-40°
θ1=30° θ2=-45°
θ1=35° θ2=-35°
θ1=40° θ2=-40°
0.5
0.0
-0.5
30
60
90
120
150
T1 (MeV)

Fig 7

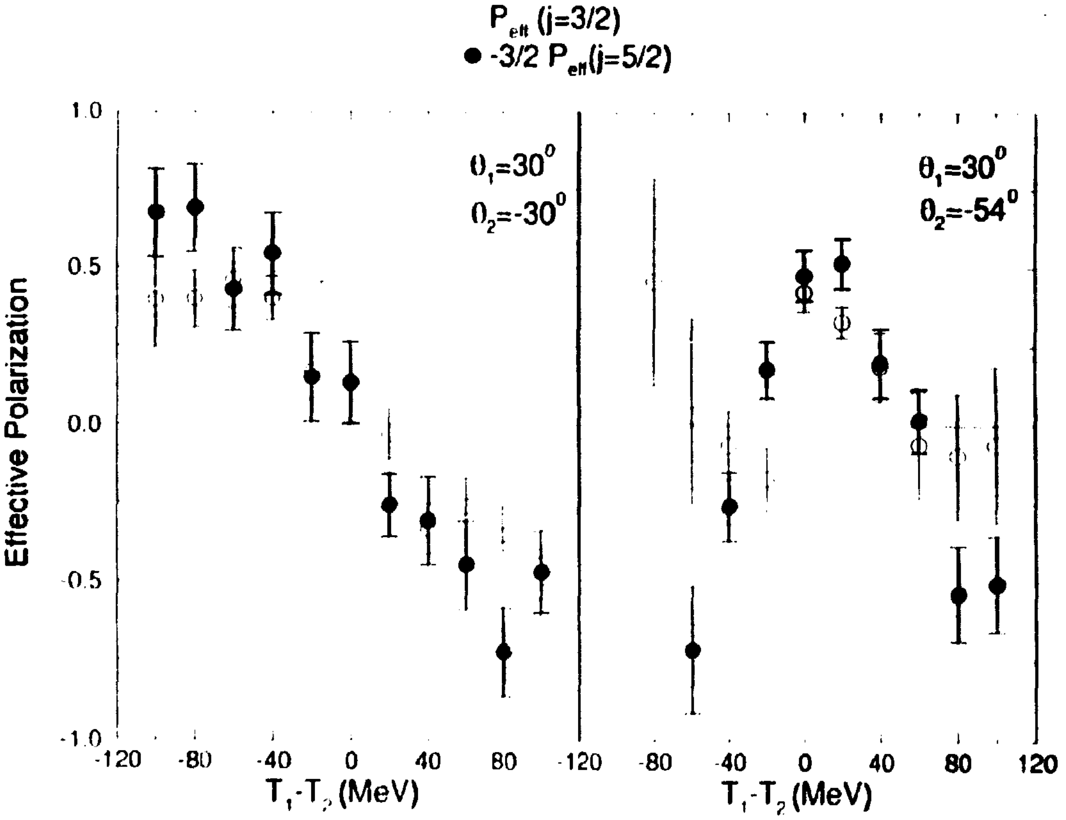
P_{eff} (j=3/2)
● -3/2 P_{eff}(j=5/2)
Effective Polarization
1.0
0.5
0.0
-0.5
-1.0
θ_1=30°
θ_2=-30°
θ_1=30°
θ_2=-54°
-120
-80
-40
0
40
80
120
T_1-T_2 (MeV)
T_1-T_2 (MeV)

Fig 8

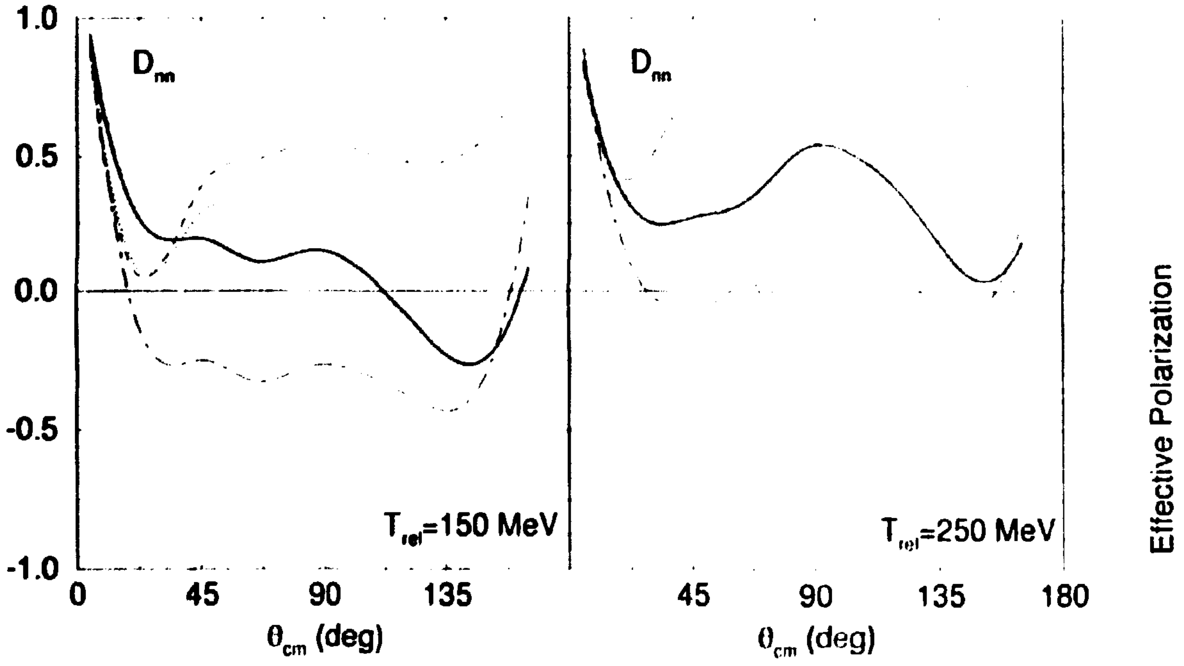
1.0
0.5
0.0
-0.5
-1.0
D_nn
D_nn
T_rel=150 MeV
T_rel=250 MeV
0
45
90
135
45
90
135
180
θ_cm (deg)
θ_cm (deg)
Effective Polarization

Fig 9