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ANALYSIS OF ELASTIC ANTIPROTON SCATTERING AT INTERMEDIATE
ENERGIES USING THE RELATIVISTIC IMPULSE APPROXIMATION

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ABSTRACT

Elastic scattering of antiprotons by several closed shell nuclei are studied using the relativistic impulse approximation. The input parameters are obtained from different $N\bar{N}$ potential models and the model dependence is studied. The results for the spin observables are found to be sensitive to the different potential models for the $N\bar{N}$ interaction as well as to the relativistic effects.

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I. INTRODUCTION

In recent years the relativistic models for nucleon-nucleus have developed considerably and the interest in the study of relativistic effects in nuclear physics is rapidly growing^{1),2)}. The application of Dirac approach³⁾⁻⁶⁾ to elastic proton nucleus scattering at intermediate energies has met with considerable success. It is now quite clear that traditional approaches based on multiple scattering theory⁷⁾ are inadequate^{8),9)} to describe the elastic scattering of protons, in particular the spin observables. On the other hand it is now well established that the relativistic impulse approximation⁴⁾ describes all the essential features of the elastic proton scattering observables in a parameter-free way.

It has been shown recently¹⁰⁾ that the main effect arises due to the inclusion of intermediate negative energy states of the projectile, i.e., the $\bar{N}N$ pair terms. The virtual pair creation and annihilation effects are implicitly included in Dirac formalism which leads to systematic improvement over the non-relativistic approach. It is not clear at present whether the success of the relativistic impulse approximation is simply a superior treatment of the NN amplitudes in multiple scattering or whether it is truly due to the relativistic effect associated with antiparticles. Since the Dirac approach treats the particles and antiparticles on equal footing it is tempting to apply the Dirac formalism to study the antiproton-nucleus scattering as a more severe test of this approach.

The recent experimental data¹¹⁾ from LEAR on antiproton-nucleus scattering provide such an opportunity. Several analyses¹²⁾ have been reported for the antiproton-nucleus scattering using the standard techniques of nucleon-nucleus scattering (i.e., using the non-relativistic microscopic optical potentials as well as relativistic approaches). Recent calculations¹³⁾ using the relativistic impulse approximation (RIA) reproduce fairly well the $\bar{p}$ - ^{12}C angular distribution data at 47.8 MeV and the difference between the results of the non-relativistic impulse approximation (NRIA) using the same inputs are found to be small in this case. This feature is observed even at higher energies^{2),14),15)}. The relativistic effects are found to be smaller than that due to the different input parameters of the calculations¹⁴⁾.

The successes of the relativistic impulse approximation and the standard non-relativistic optical model calculations indicate that the nuclear medium effects due to Fermi motion and correlations are probably not important for

antiproton scattering¹³⁾. The antiproton annihilates with nucleons into meson channels and does not penetrate the nucleus even at higher energies. The interaction occurs at the surface. The nucleus appears as a black disc for the antiprotons beyond a certain radius.

The key ingredients for constructing the first order $\bar{p}$ -A optical potential in the relativistic and non-relativistic calculations are the basic two-body $\bar{N}N$ amplitudes and the nuclear density. In the absence of empirical $\bar{N}N$ amplitudes the former are generally derived from the existing $\bar{N}N$ potential models¹⁶⁾⁻¹⁸⁾ whereas the latter is fairly well known from the electron scattering data and relativistic mean field calculations¹⁹⁾. However, the t -matrices generated from the $\bar{N}N$ potential models are not sufficiently constrained due to lack of experimental information. Hence systematic analysis of $\bar{p}$ -A scattering data using different $\bar{N}N$ model amplitudes in the Dirac approach may provide some additional constraints on the $\bar{N}N$ interaction.

In the present study we use the relativistic impulse approximation for analyzing the elastic $\bar{p}$ -A scattering data by several closed shell nuclei ^{12}C , ^{16}O and ^{40}Ca , using different $\bar{N}N$ potential models. The current $\bar{N}N$ potential models which describe the existing $\bar{N}N$ data differ mainly in their treatment of the strong short-range absorptive potential of the $\bar{N}N$ interaction. The Dover-Richard model¹⁶⁾ (DR) assumes the annihilation potential to be independent of the $\bar{N}N$ intrinsic spin and isospin and takes them to be of Wood-Saxon form with depth of several GeV. The Paris group¹⁷⁾ (PARIS) uses a more flexible phenomenological form to fit the $\bar{N}N$ data and takes the annihilation potential to be state-dependent, characterized by a range of the order of $(2m)^{-1}$ and is much stronger in the spin-singlet than in the spin-triplet states. In contrast, the Nijmegen group¹⁸⁾ adopts a coupled channel approach, and assumes that the coupling potentials of the $\bar{N}N$ system and mesonic channels depend on isospin but are independent of spin. In the present work we use the DR¹⁶⁾ and PARIS¹⁷⁾ models to generate the $\bar{N}N$ amplitudes. Both models derive the real t -channel meson exchange $\bar{N}N$ potential via G-parity transformation of the NN PARIS potential²⁰⁾ and differ in the spin dependence of the annihilation potential. Due to strong spin dependence of the short-range annihilation potential of the two-body $\bar{N}N$ interaction the PARIS model predicts²¹⁾ much larger cross-sections for inelastic iso-scalar spin-flip transitions in ^{12}C compared to that given by the DR model. Due to lack of experimental data it has not been verified as yet¹²⁾. Besides, the few parameters of the DR model are almost fixed by the experimental data. On the other hand, in the PARIS model the strengths of the various spin

components of the annihilation potentials cannot be well determined since only few data are available with large error bars for the forward polarisation measurements. Hence systematic study of the $\bar{p}$ -A scattering using the two different models would provide information on the spin dependence of the absorptive part of the $\bar{N}N$ interaction. Besides the model dependence the comparison between relativistic and non-relativistic impulse approximation with the experimental data would enable us to study the relativistic effects in the $\bar{p}$ -A scattering.

In Section 2 we briefly recall the formalism for the construction of Dirac optical potentials in terms of invariant amplitudes. In Section 3 the results are presented together with discussions and the conclusions are given in the last section.

2. THE IMPULSE APPROXIMATION: CONSTRUCTION OF THE DIRAC OPTICAL POTENTIALS

The basic premise of the impulse approximation is that the free two-body t-matrix provides a reasonable estimate of the effective interaction needed to generate the optical potential. The relativistic impulse approximation⁴⁾ (RIA) makes use of the five-term Lorentz invariant two-body scattering amplitude²²⁾

$$F(s, t) = F_S \mathbf{1}_1 \mathbf{1}_2 + F_P \gamma_1^5 \gamma_2^5 + F_V \gamma_1^\mu \gamma_{2\mu} + F_A \gamma_1^5 \gamma_1^\mu \gamma_2^5 \gamma_{2\mu} + F_T \sigma_1^{\mu\nu} \sigma_{2\mu\nu} \quad (1)$$

where the subscripts 1 and 2 refer to the incident and the target nucleons respectively, $\mathbf{1}$, γ^5 , γ_μ and $\sigma_{\mu\nu}$ are the Dirac γ -matrices²³⁾. On-shell, the Dirac amplitudes F_S (scalar), F_P (pseudoscalar), F_V (vector), F_A (axial vector) and F_T (tensor) are functions of the two Lorentz invariants s and $t = -q^2$. They are related by a matrix transformation²²⁾ to the two-body scattering amplitude in the Pauli spin-matrix representation

$$(2ik_c)^{-1} f_c = A + B \vec{\sigma}_1 \cdot \vec{\sigma}_2 + C q \cdot (\vec{\sigma}_1 + \vec{\sigma}_2) + D \vec{\sigma}_1 \cdot \vec{q} \vec{\sigma}_2 \cdot \vec{q} \quad (2) \\ + E \sigma_{1z} \sigma_{2z}$$

Here, f_c is the non-relativistic scattering amplitude, A, B, C, D, E are the Wolfenstein amplitudes, and k_c is the momentum in the c.m. frame and $\sigma_{1x} = \sigma_1 \cdot \hat{x}$, $\hat{n} = (\mathbf{k} \times \mathbf{k}') / |\mathbf{k} \times \mathbf{k}'|$, $\mathbf{q} = \mathbf{k} - \mathbf{k}'$ is the momentum transfer, $\mathbf{k}$ and $\mathbf{k}'$

being the incident and outgoing two-body cm momenta respectively. The amplitudes A, B, C, D and E are functions of energy and momentum transfer and are derived directly from experimental phase shifts in the standard manner. In the impulse approximation the coefficients of the two-body amplitudes are evaluated at a fixed optimal²⁴⁾ energy and the amplitude is obtained off shell from the on-shell amplitude by assuming each coefficient to be a function of momentum transfer only. Assuming the five term representation to be adequate, one can obtain the familiar leading order 'tp' form of the optical potential for use in the Dirac equation. In momentum space the local optical potential is then given by

$$U_{opt}(r) = - \frac{4\pi i k}{m} \langle 0 | \sum_{i=1}^A e^{i \vec{q} \cdot \vec{r}_i} F | 0 \rangle \quad (3)$$

where k is the projectile-nucleus centre of mass momentum wave number and F is the invariant amplitude given by Eq. (1). For a spin-saturated, spherically symmetric nucleus the scalar, tensor and the timelike component of the vector term contribute. Neglecting the tensor term^{25),26)} which plays a minor role the optical potential becomes

$$U_{opt}(r) = - \frac{4\pi i k}{m} [F_s(r) \rho_s(r) + F_v(r) \rho_v(r)] \quad (4)$$

where ρ_s and ρ_v are the scalar and the vector density terms given by

$$\rho_s(r) \equiv \sum_{i=1}^A \langle 0 | e^{i \vec{q} \cdot \vec{r}_i} | 0 \rangle \quad (5a)$$

$$\rho_v(r) \equiv \sum_{i=1}^A \langle 0 | e^{i \vec{q} \cdot \vec{r}_i} \gamma_1^0 | 0 \rangle. \quad (5b)$$

When defined this way the densities are roughly equal. The Fourier transform of Eq. (4) yields the potentials in co-ordinate space. These are used in the fixed energy Dirac equation

$$[\vec{\alpha} \cdot \vec{p} + \beta (m + S(r)) + V(r)] \bar{\Psi}_{\vec{k},s}(\vec{r}) = E \bar{\Psi}_{\vec{k},s}(\vec{r}) \quad (6)$$

where $E = (m^2 + k^2)^{\frac{1}{2}}$ is the relativistic energy, and S(r) and V(r) are the local Lorentz scalar and vector potentials respectively. $\vec{k}, s$ denote the momentum and the spin orientation of the projectile. The relativistic projectile-nucleus scattering amplitudes and observables are obtained by solving this time-independent Dirac equation.

3. RESULTS AND DISCUSSIONS

We have calculated the elastic scattering cross-sections and spin observables for 180 MeV antiprotons scattered by ^{12}C , ^{16}O and ^{40}Ca using the relativistic impulse approximation. The Dirac equation was solved in the eikonal limit²⁷⁾. For simplicity, the vectors and scalar densities are taken to be equal. Since the geometries of the scalar and vector potentials resemble²⁸⁾ that of the nuclear density we parametrized the densities as follows:

$$S(r) = (S_R + iS_I) f_s(r) \quad (7a)$$

$$V(r) = (V_R + iV_I) f_v(r) \quad (7b)$$

where f_s and f_v are taken to have Wood-Saxon form and are given by

$$f_{s,v}(r) = \left\{ 1 + \exp \left[(r - c_{s,v}) / a_{s,v} \right] \right\}^{-1} \quad (8)$$

The values of the parameters c and a of the radial forms given by Eq. (8) are obtained from the phenomenological fit of the electron scattering data and the charge r.m.s. radii for each nucleus²⁹⁾. The strengths of the scalar and vector potentials were obtained from the t -matrices³⁰⁾ derived from the different NN potential models using proper kinematics. The central values of the potentials deduced from the different models for ^{40}Ca are given in Table 1 together with the other potential parameters. The scalar and vector potentials obtained are seen to have large values for the real part and with opposite sign for the scalar and vector potentials²⁾ as in the nucleon-nucleus case.

In Fig. 1 we display the results of the DR and Paris models for $\bar{p}$ - ^{40}Ca elastic scattering observables at 180 MeV, together with the experimental data¹¹⁾ for the angular distribution. Both models provide the overall features of the angular distribution fairly well and tend to deviate from the experimental data at large angles and predict deeper minima compared to the experimental ones. The difference between the two models are hardly noticeable in the angular distribution except at the minima where the DR model predicts deeper minima than the PARIS results. This is not so for the polarization results where the difference between the two models is clearly visible.

Similar features are observed for ^{12}C and ^{16}O . In case of ^{12}C and ^{16}O the position of the minima as predicted by the two models occurred at larger angles (3° - 5° for ^{16}O and ^{12}C respectively) than the experimental ones. The potential strengths were increased by 1.12 and 1.2 respectively to fit the position of the diffraction minima for ^{16}O and ^{12}C respectively. The results are shown in Figs. 2 and 3 together with the experimental data¹¹⁾ at 180 MeV. For ^{40}Ca the agreement to the angular distribution data is fairly good considering that no parameters were varied in our calculation.

In contrast to the angular distributions the spin observables $A_y(\theta)$ and $Q(\theta)$ in the elastic $\bar{p}$ -A scattering show pronounced sensitivity to the different $\bar{N}N$ models. It provides a clear distinction between the different $\bar{N}N$ amplitudes used in the calculation. This can be seen in Figs. 1-3 (bottom part) where the analyzing powers are displayed for comparison. Similar effects are obtained for the spin rotation functions. In Fig. 3 (bottom) the polarization measurements³¹⁾ for ^{12}C are shown together with the results of the two models. The few data points favour the DR model. However, the experimental data are few and one cannot yet draw firm conclusions.

The difference between the results of polarization as obtained by the two models may be attributed to the specific spin components of the two-body $\bar{N}N$ amplitude of the DR and PARIS models. The spin-dependent components are quite different in the two models whereas the spin-independent amplitudes are not so. In Fig. 4 the spin-dependent amplitudes and the spin-independent amplitudes as obtained from the two models are shown for comparison for the $\bar{p}n$ case. Results (not shown) for $\bar{p}p$ scattering are similar. In the standard multiple scattering theory for a spin-saturated nuclei the first order spin-independent and spin-orbit potentials depend linearly on A and C amplitudes respectively. By contrast, the potential which induces the spin precession in the Dirac case depends non-linearly on all the five amplitudes of Eq. (2), particularly the single spin flip amplitude C. The contributions from the other amplitudes B, D and E are known to be very small³⁾. Hence the difference between the results of the analysing powers are mainly due to the spin-dependent part of the $\bar{N}N$ interaction.

In Fig. 5 we compare the results of the relativistic impulse approximation with that of the non-relativistic⁵⁾ case for ^{40}Ca using the PARIS model. The two curves for the differential cross-section are hardly distinguishable whereas the analyzing powers show sensitivity to the relativistic effects with more pronounced structure appearing in the region of the diffraction minima. This agrees with previous findings^{2),15)}. Similar results are obtained using the DR model. In order to understand the qualitative difference between the RIA and NRIA we consider the Schrödinger equivalent form of the Dirac Eq. (6) obtained in the usual way with central and spin-orbit potentials

$$U_c = S(r) + \frac{E}{m} V(r) + \frac{S^2(r) - V(r)^2}{2m} \quad (9a)$$

$$U_{so} = \frac{1}{2m [E + m + S(r) - V(r)]} \frac{1}{r} \frac{d}{dr} [S(r) - V(r)] \quad (9b)$$

The non-relativistic limit is reached by dropping the $S-V/2m$ terms in these equations. The closeness of the curves for the angular distribution, as shown in Fig. 5, is due to the fact that second and higher order terms in $S-V/2m$ are small compared to unity and the terms non-linear in density are suppressed considerably in the $\bar{N}N$ interaction. This indicates that nuclear medium effects are relatively small at this energy. The enhancement of the spin orbit force due to the denominator term of the spin-orbit force is mainly responsible for the difference in the relativistic and non-relativistic results for the analyzing power, Fig. 5 (bottom) as in the proton-nucleus scattering.

4. CONCLUSIONS

Our analysis shows that the $\bar{p}$ -nucleus elastic angular distributions are insensitive both to the different current $\bar{N}N$ potentials as well as to relativistic dynamics. On the other hand the spin observables are sensitive to the $\bar{N}N$ interaction models and they are also dependent on relativistic effects.

The difference between the DR and PARIS models is clearly reflected in the analyzing power. The spin observables are also sensitive to the relativistic effects. The few data points for polarisation results in $\bar{p}$ - ^{12}C elastic scattering are in better agreement with the DR model. However, present data do not allow one to draw a definite conclusion in favour of any particular model.

The success of the impulse approximation in describing the angular distribution for the $\bar{p}$ -A scattering at low and intermediate energies indicates that medium effects are unimportant for $\bar{p}$ -nucleus scattering. This is also seen in other calculations based on high energy approximation³²⁾ which show similar fits to the angular distribution even at lower energies. Eikonal and non-adiabatic corrections are small as a consequence of the extremely strong forward peak in the $\bar{p}$ -N scattering.

The Dirac approach enables one to gain information on $\bar{N}N$ interaction and provide additional constraints for the $\bar{N}N$ interaction assuming the other ingredient of the calculation, the nuclear density to be known fairly well. The spin dependence of the different models can be largely determined from the study of elastic $\bar{p}$ -A scattering observables.

Fairly good fits to the angular distribution for $\bar{p}$ -⁴⁰Ca are obtained with the two models without varying any parameters of the Dirac potential. For the two lighter nuclei ¹²C and ¹⁶O the strengths of the vector and the scalar potentials were increased by 1.2 and 1.12 to fit the positions of the minima of the angular distribution.

Our present knowledge of the $\bar{N}N$ interaction is rather limited due to the lack of enough experimental data. The present situation is quite puzzling due to the unknown role of the annihilation which gave rise to different predictions such as existence of bound and resonant states in the $\bar{N}$ -N and $\bar{N}$ -nucleus systems³³⁾⁻³⁴⁾. The strong annihilation makes it rather difficult to distinguish between the relativistic effects and model effects. Due to strong absorption of the antiprotons the nuclear interaction is mostly peripheral and hence medium corrections become negligible. As a consequence of absorption the distorted waves are wiped out even at lower energies and the terms of higher order in $S-V/2m$ of the Dirac potentials gets suppressed considerably.

Different experiments with the antiprotons are needed to study the spin dependence of the $\bar{N}N$ interaction, and to constrain the different spin-isospin parameters of the $\bar{N}N$ annihilation potential. Our study indicates that polarization measurements in the $\bar{p}$ -nucleus scattering may be one of them which will provide useful constraints on specific components of the $\bar{N}$ -N interaction, since spin observables are sensitive to the different $\bar{N}N$ potential models.

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Model	S_R, S_I (MeV)	V_R, V_I (MeV)	c (fm)	a (fm)
PARIS	-438, -34	+394, -112	3.55	0.64
Dover-Richard	-297, -68	257, -102	"	"

TABLE - Dirac optical potential parameters
for ^{40}Ca at 180 MeV

REFERENCES

- 1) B.D. Serot, "Medium Energy Nucleon and Antinucleon Scattering" (1985), edited by H.V. von Geramb (Springer Verlag), p. 413 and references therein;
R. Brockmann and R. Machleidt, "Medium Energy Nucleon and Antinucleon Scattering" (1985), edited by H.V. von Geramb (Springer Verlag), p. 459.
- 2) B.C. Clark, "Proc. Medium Energy Nucleon and Antinucleon Scattering" (1985), edited by H.V. von Geramb (Springer Verlag), p. 391 and references therein.
- 3) B.C. Clark, S. Hama, R.L. Mercer, L. Ray and B.D. Serot, Phys. Rev. Lett. 50 (1983) 1645.
- 4) J.A. McNeil, J.R. Shepard and S.J. Wallace, Phys. Rev. Lett. 50 (1983) 1439.
- 5) J.R. Shepard, J.A. McNeil and S.J. Wallace, Phys. Rev. Lett. 50 (1983) 1443.
- 6) L. Ray and G.W. Hoffmann, Phys. Rev. C31 (1985) 538.
- 7) A.K. Kerman, H. McManus and R.M. Thaler, Ann. of Phys. (N.Y.) 8 (1959) 551.
- 8) G.W. Hoffman, L. Ray, M.L. Barlett, R. Fergerson, J. McGill, E.C. Milner, K.K. Seth, D. Barlow, M. Bosko, S. Iverson, M. Kaltka, A. Saha and D. Smith, Phys. Rev. Lett. 47 (1981) 1436;
L. Ray et al., Phys. Rev. C23 (1981) 828.
- 9) R.D. Amado, J. Pickarewicz, D.A. Sparrow and J.A. McNeil, Phys. Rev. C28 (1983) 2180.
- 10) M.Y. Hynes, A. Dicklesimer, P.C. Tandy and R.M. Thaler, Phys. Rev. C31 (1985) 1438.
- 11) D. Garreta, P. Birien, G. Burge, A. Chaumeaux, D.M. Drake, S. Janouin, D. Legrand, M.C. Lemaire, B. Mayer, J. Pain, J.C. Peng, M. Berrada, J.P. Bocquet, E. Mommad, J. Mougey, P. Perrin, E. Aislandes, O. Bing, A. Erell, J. Lichtenstadt and A.I. Yavin, Phys. Lett. 135B (1984) 2266;
ibid., Phys. Lett. 149B (1984) 64; Phys. Lett. 151B (1985) 473.
- 12) M.C. Lemaire, "Medium Energy Nucleon and Antinucleon Scattering" (1985), edited by H.V. von Geramb (Springer Verlag), p. 285. This contains a review of theoretical and experimental work on antiproton scattering.
- 13) B.C. Clark, S. Hama, J.A. McNeil, R.L. Mercer, L. Ray, B.D. Serot, D.A. Sparrow and K. Stricker Bauer, Phys. Rev. Lett. 53 (1984) 1423.
- 14) A. Picklesimer, P.C. Tandy, J.A. Tjon, Los Alamos preprint (1985).
- 15) A.T.M. Aerts, "Proceedings of the VIIth European Symposium of Antiproton Interactions Durham", edited by M.R. Pennington. Int. of Phys. Conf. series No. 73 (1984), Adam & Hilger Ltd. Bristol and Boston (1985), p. 491.

- 16) C.B. Dover and J.M. Richard, Phys. Rev. C21 (1980) 1466.
- 17) J. Coté, M. Lacombe, B. Loiseau, B. Moussallam, R. Vinh-Mau, Phys. Rev. Lett. 48 (1982) 1319.
- 18) P.H. Timmers, W.A. Vander Sanden and J.J. Swart, Phys. Rev. D29 (1984) 1928;
ibid., Phys. Rev. D30 (1984) 1995.
- 19) J.W. Negele and J.L. Friar, "Advances in Nuclear Physics", edited by E. Vogt and M. Baranger (Plenum, New York, 1975), Vol. 8, p. 219.
- 20) M. Lacombe, B. Loiseau, J.M. Richard, R. Vinh Mau, J. Coté, P. Pirés and R. de Tourreil, Phys. Rev. C21 (1980) 861.
- 21) G.B. Dover, M.A. Farney, W.G. Love, M.E. Saino and G. Walker, Phys. Lett. 143B (1984) 45.
- 22) J.A. McNeil, L. Ray and S.J. Wallace, Phys. Rev. C27 (1983).
- 23) J.D. Bjorken and S.D. Drell, Relativistic 2123 Quantum Mechanics (McGraw Hill, New York, 1964);
- 24) S.A. Gurvity, J.P. Dedonder and R.D. Amado, Phys. Rev. C19 (1979) 142.
- 25) L.D. Miller, Phys. Rev. Lett. 51 (1983) 1807C.
- 26) B.C. Clark, S. Hama, J.A. McNeil, R.L. Mercer, L. Ray, G.W. Hoffmann, B.D. Serot, J.R. Shepard and S.J. Wallace, Phys. Rev. Lett. 51 (1983) 1809C.
- 27) R.D. Amado, J. Pickarcvycz, D.A. Sparrow and J.A. McNeil, Phys. Rev. C28 (1983) 1663.
- 28) B.C. Clark, S. Hama and R.L. Mercer, AIP Conference Proc. No. 97: The Interaction between Medium Energy Nucleons in Nuclei - 1982, edited by H.O. Meyer (A.I.P. Press, New York, 1983) 260.
- 29) I. Sick, Nucl. Phys. A218 (1974) 509;
C.J. Horowitz and B.D. Serot, Nucl. Phys. A368 (1981) 503.
- 30) The PARIS and DR t-matrices were kindly supplied by Dr. S. Saino (private communications).
- 31) R. Birsas et al., CERN preprint EP/85-28 (1985);
C.I. Beard et al., in Proc. of Third LEAR Workshop on Physics with Antiprotons at LEAR in the ACOL ERA, edited by U. Gastaldi, R. Klapisch, J.M. Richard and J. Tran Thanh Van (1985) 239.
- 32) O.D. Dalkarov and V.A. Karmanov, Phys. Lett. 147B (1984) 1.
- 33) C.B. Dover and J.M. Richard, Ann. Phys. 121 (1979) 70;
J.A. Niskanen and A.M. Green, Nucl. Phys. A431 (1984) 593.
- 34) E.H. Auerbach, C.B. Dover and S.H. Kahana, Phys. Rev. Lett. 46 (1981) 702;
A.M. Green and S. Wycech, Nucl. Phys. A377 (1982) 441.

FIGURE CAPTIONS

- Fig. 1 Differential cross-section (top) and analyzing power (bottom) for ^{40}Ca at 180 MeV. The solid (dashed) line in the PARIS (Dover-Richard) calculation. The data are from Ref. 11).
- Fig. 2 Same as in Fig. 1 but for ^{16}O .
- Fig. 3 Same as in Fig. 1 but for ^{12}C .
- Fig. 4 The components of the spin-independent amplitudes and the spin-dependent amplitudes due to PARIS and DR models for the $\bar{p}n$ scattering. The dashed (dot-dashed) line is the PARIS (DR) result.
- Fig. 5 Differential cross-sections (top) and analysing power (bottom) for the PARIS model with RIA (-----) and NRIA (-----) calculations for ^{40}Ca at 180 MeV are shown together with the experimental data of Ref. 11).

- Fig. 1 -

- Fig. 2 -

- Fig. 3 -

- Fig. 4 -

- Fig. 5 -