3.3 Proton-Proton Scatterirng at T_L = 3 - 10 GeV

Abstract. The spin-orbit component phase-shifts and the spin-orbit eikonals of *p*-*p* scattering are determined from the solutions of the phase-shift analyses of the experimental data at 3, 6 and 12 GeV/*c*, respectively. An existence of short-range ($\lesssim$ 0.5 fm) repulsive spin-orbit interaction and its remarkable change with energy are suggested. Its implications in the first order phase transition of subnuclear medium indicated in the *p*-*p* scattering in this energy region are discussed in relation to the result of SMC experiment at CERN. (Prog. Theor. Phys. **93** (1995), 1059.)

3.3.1 Introduction

In the late 1970's at Argonne National Laboratory a series of polarized-beam experiments of elastic proton-proton scattering was performed in the incident momentum region P_L=2 -12 GeV/c. Some direct effects of quantum chromodynamics (QCD) have been expected by many groups to appear in those double- and triple-spin-correlation data. We have, however, considered that a QCD-effect will be found not on a particular observable, but on all observables in such a manner as a phase transition takes place. In this case, we should concentrate our efforts for the determination of scattering amplitudes.

A concept of phase transition in the particle physics has been introduced by Nambu[73] as an analogy of the superconductivity. It means that the symmetry satisfied at high temperature is spontaneously broken down with decreasing temperature of the system. This point of view may be said to have been a pathfinder for gauge theory and subsequently, for scenarios of universe-evolution, that is, the four phase-transitions in the early universe[74].

A phase transition is a phenomenon found by the dynamic statistics of many body system in the statistical mechanics. The phase transitions in the cosmology mean that an interaction medium of particles changes into another medium at a critical temperature (T_c) in the process of dropping the temperature of the universe. There may be two types of the phase transitions, i.e., the first and second order ones. The first order transition is catastrophic around at T_c and the second order one is smooth and continuous in the wide range of temperature. It has been inferred that the 4th phase transition in the Big Bang cosmology is a weak first order phase transition from quark-gluon plasma to hadron plasma at $T_c = 150 - 200$ MeV[75]. This temperature range is in the region of collision-energy generated by several tens of GeV proton-synchrotron accelerator, as is shown later.

We made the phase-shift analyses (PSAs) of *p*-*p* scattering in the incident momentum region P_L=1 $-$ 12GeV/c[16, 17, 18, 19, 20, 22, 42, 72, 76]. At 6 and 12GeV/c, we developed the modified PSA of *p*-*p* scattering on the basis of the so-called correspondence principle and succeeded in performing the same detailed study of spin-dependent nuclear interaction[16, 17, 18, 19, 20, 22, 77] as that at low energies. An evidence of a strong repulsive spin-orbit force in the short distance b<0.5 fm was obtained in our previous work[20]. However, our ordinary explanation about the energy dependence of spin-orbit P-wave phase shift may be open to question because of too drastic energy-dependence of new short-range force.

In the next subsection, we reanalyze the results of *p*-*p* scattering data at P_L = 3, 6 and 12 GeV/c. In subsection 3.3.3, as regards the energy-dependence of the obtained spin-orbit phase shifts, we suggest an existence of short-range repulsive spin-orbit interaction with a strong energy dependence. Its implications in the first order phase transition of subnuclear medium indicated in *p*-*p* scattering in this energy region are discussed in the final subsection.

3.3.2 Phase-shift analyses of *p-p* scattering at P_L=3, 6 and 12 GeV/c

In order to analyze a plenty of data measured at Argonne and Saclay, we have proposed a study of nucleon-nucleon interaction in which the scattering amplitudes are determined on the basis of the following correspondence principle. This method is a relativistic extension of Taketani's way[2, 3] of studying nuclear force.

Principle I The peripheral part of the amplitude of nucleon-nucleon scattering in the outer region of the distance $r \gtrsim 2.5$ fm is provided with the one-pion-exchange(OPE) contribution[4, 55].

Principle II In the region $2.5 \gtrsim r \gtrsim 1.0$ fm, the scattering amplitude is evaluated by the modified one-boson-exchange(OBE) contributions[31]. The modification of the OBE-amplitude of nucleon-nucleon scattering is

$$\frac{g^2}{m^2-t} \longrightarrow \frac{g^2}{m^2}[\frac{\Lambda^2}{\Lambda^2-t/n}]^n, \tag{3.18}$$

where t is the squared momentum transfer of nucleons and m the observed mass of the exchanged boson, and g, Λ and n are parameters peculiar to boson. The full amplitude of nucleon-nucleon scattering is represented by

$$M = \sum_{J<J_0}[f_J(\delta_J,\eta_J)] + \sum_{J_0\leq J\leq J_1}[f_J(\delta_J(\mathrm{OBE}),\eta_J)] + M_{\mathrm{OBE}}(J>J_1). \tag{3.19}$$

Here $[\ f_J(\delta_J,\eta_J)]$ is the contribution from the phase shift δ_J and the reflection parameter η_J for the angular momentum J. $\delta_J(\mathrm{OBE})$ are the phase shifts obtained from the modified OBE-amplitudes M_{OBE} by the K-matrix method. The boundary angular momentum J_0 and J_1 are chosen by their corresponding impact parameters b, which are equal to about 1.0 and 2.5 fm, respectively.

Principle III The partial wave amplitudes $[f_J(\delta_J,\eta_J)]$ with the angular momentum $J < J_0$ reflect dynamics in the inner region $r \lesssim 1$ fm. They are determined together with the amplitudes $[f_J(\delta_J(\mathrm{OBE}),\eta_J)]$ and M_{OBE}, by means of the PSA.

The modified OBE-amplitudes are calculated with the well-known bosons π, σ, ρ and ω, the observed masses of which are taken as 135, 400, 770 and 770 MeV, respectively. σ-meson is still not observed, but is known to represent the effect of two-pion-exchange between nucleons.

The experimental data in the region P_L=2−5 GeV/c, except for those at 2 and 3 GeV/c, are not enough to obtain any useful solutions of the PSAs. We have made the energy-dependent PSAs in this energy region by an interpolation of the experimental data at the neighbouring energies by means of Spline-function method, and reported the result in Ref. [22, 77].

Analysis of experimental data at 3 GeV/c

Recently, the double- and the triple-spin correlation parameters of elastic *p-p* scattering were measured at Saturne in the region P_L=1.5 − 3.5 GeV/c. The experimental data at

P_L=3 GeV/c have been considerably accumulated[78]. We make a single energy PSA at this energy by using the total number of data 417: 1 σ_t, 1 σ_r, 1 $\Delta\sigma_T$, 1 $\Delta\sigma_L$, 1 α, 114 $d\sigma/dt$, 34 P, 39 $D_{ij} = (i,0;j,0)$, 149 $A_{ij} = (i,j;0,0)$, 33 $K_{ij} = (i,0;0,j)$, 18 $H_{ijk} = (i,j;0,k)$ and 23 the other three-spin-correlation data. Here the spin- correlation parameters are represented by the spin directions (beam, target; scattered, recoil) in the laboratory system, and i, j, k denote the three directions of measured spin (N, L and S), and 0 indicates unpolarized. The forward amplitudes $\mathrm{Re}F_2 = P_L \mathrm{Re}\Phi_2|_{t=0}/\sqrt{\pi}$ and $\mathrm{Re}F_3 = P_L \mathrm{Re}(\Phi_1 - \Phi_3)|_{t=0}/\sqrt{\pi}$ evaluated by the dispersion relation are also used. The energy bins of the selected data on differential cross section and polarization are 20 MeV, and those of data on spin-correlation parameters are about 100 MeV, respectively. The experimental normalization parameters of spin- correlation data measured at Saturne were reported to be still undetermined and have some ambiguities. If J_0 is taken as 5, the number of the floating parameters is 44 with 10 $\delta_J, 2\times 2\rho_J, 22\eta_J$ and 8 boson parameters.

Analysis of experimental data at 6 GeV/c

The experimental data at this energy are the same as those used in our previous analysis[16, 17, 18, 19, 20]. The total number of them is 387: 1 σ_t, 1 σ_{el}, 1$\Delta\sigma_T$, 1 $\Delta\sigma_L$, 1 α, 82 $d\sigma/dt$, 147 P, 45 D_{ij}, 133 A_{ij}, 29 K_{ij}, 34 H_{ijk} as well as $\mathrm{Re}F_2$ and $\mathrm{Re}F_3$. We reanalyze these data with some corrections and have obtained the solution by taking the previous solution β as the initial values of variable parameters. If J_0 is taken as 7, the number of the floating parameters is 66 with 14 δ_J, 2×3 ρ_J, 38 η_J and 8 boson parameters.

Analysis of experimental data at 12 GeV/c

Following our previous analysis[18], the spin-correlation data measured at Argonne were published in 1986. The total number of experimental data[79] used in the present analysis is 260: 1 σ_t, 1 σ_{el}, 1 $\Delta\sigma_L$, 1 α, 1 $\mathrm{Re}F_2$, 1 $\mathrm{Re}F_3$, 67 $d\sigma/dt$, 67 P, 6 D_{ij}, 90 A_{ij}, 12 K_{ij}, and 12 H_{ijk}. Starting from the previous solution[18], we execute a PSA of these data with the floating variables 95 with 22 δ_J, 2×5 ρ_J and 55 η_J for J_0=11 as well as 8 boson parameters.

3.3.3 *p-p* spin-orbit interaction

Spin-orbit component of the phase shifts

In the assumption of negligibly small quadratic spin-orbit and q-square terms[80], the triplet-odd (real) phase shift $\delta_{\ell,J}$ is decomposed into the three components,

$$\delta_{\ell,J} = \delta_C^\ell + (S_{12})_{\ell,J}\delta_T^\ell + (\boldsymbol{L}\cdot\boldsymbol{S})_{\ell,J}\delta_{LS}^\ell, \quad (J = \ell-1, \ell, \ell+1). \tag{3.20}$$

Here $\delta_C^\ell, \delta_T^\ell$ and δ_{LS}^ℓ are the central, tensor and spin-orbit phase-shifts, respectively. The values of obtained component phase-shifts continue consistently to the established values at lower energies. The solution of δ_{LS}^ℓ is stable and reliable. But the solution of δ_C^ℓ is relatively unstable for reflection of the ambiguity of s-wave phase-shift. It is rather difficult to determine the s-wave phase-shift by the available data at present, because the s-wave

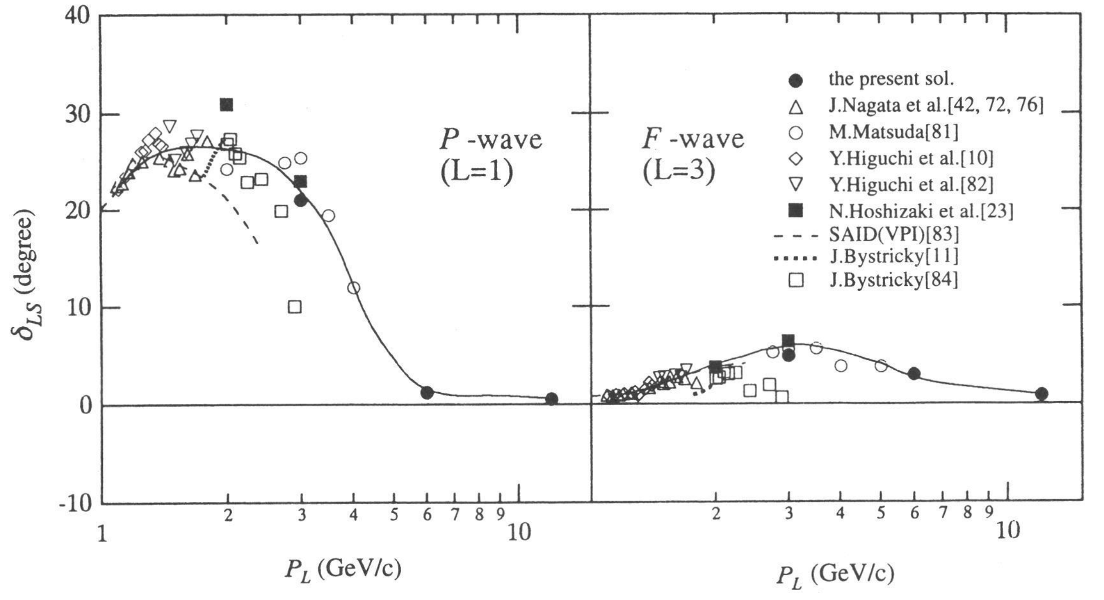

Figure 3.5: The spin-orbit phase-shifts of P- and F-waves. The solid lines are the ones given by interpolating our solutions in Refs. [42, 72, 76, 81], and the present.

amplitude contributes uniformly to the observables at all angles. In spite of such unstability, on the whole, the energy dependence of δ_C^ℓ suggests the existence of a soft cores[20] which has appeared as a hard core in the phenomenology at low energies. The instability of δ_T^ℓ may be caused by the neglection of quadratic spin-orbit term. Both of the tensor and the quadratic spin-orbit term contribute to the transition amplitude between triplet states from $\ell = J \mp 1$ to $\ell = J \pm 1$, but the spin-orbit term does not[80]. The values of δ_T^ℓ are negative and show a tendency to be zero at the higher energies[20].

The obtained solutions of δ_{LS}^1 and δ_{LS}^3 at 3, 6 and 12 GeV/c are shown in Fig. 3.5 together with the solutions of energy-dependent phase-shift analyses. The energy- dependence of spin-orbit phase-shifts indicates that there exists a repulsive spin-orbit interaction which is so strong as to be superior to the attractive one due to the one vector-boson exchanges, and the repulsion of such an interaction becomes prominent at the range r$\lesssim$0.5 fm.

Spin-orbit component of the eikonal

The scattering matrix M in the two-proton spin space is determined by a PSA of p-p scattering at each energy. In the eikonal model, the scattering matrix has an impact parameter representation in terms of the eikonal $\chi(\boldsymbol{b})$ as follows:

$$M(\boldsymbol{q}) = i(p/2) \int [1 - \exp(i\chi(\boldsymbol{b}))] \exp(-i\boldsymbol{q} \cdot \boldsymbol{b}) d^2\boldsymbol{b}, \tag{3.21}$$

where $\boldsymbol{b}$ is the impact parameter, $\boldsymbol{q}$ is the momentum transfer $\boldsymbol{q} = \boldsymbol{p}' - \boldsymbol{p}$, and $\boldsymbol{p}$ and $\boldsymbol{p}'$ are the incident and scattered momenta in the c.m. system, respectively. The eikonal is numerically evaluated by Fourier-Bessel transformation of the scattering matrix $M(\boldsymbol{q})$ of the PSA solutions[20]. The obtained spin-orbit components of eikonal χ_{LS} at 3, 6 and 12 GeV/c

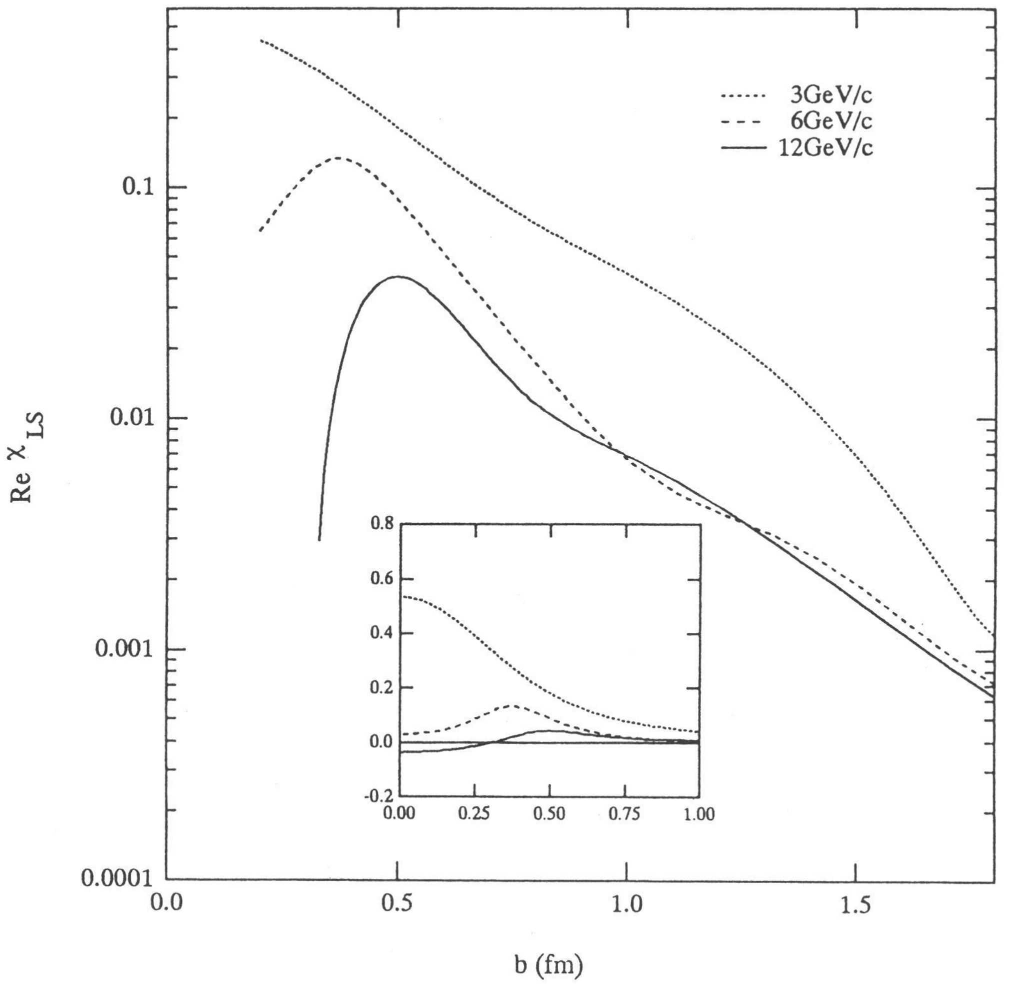

Figure 3.6: The real part of the spin-orbit eikonals Reχ_{LS} obtained from the solutions of the present PSA, where $\boldsymbol{b}$ is the impact parameter in fm-unit.

are shown in Fig. 3.6, respectively. Because Re$\chi_{LS}(b)$ is proportional to $-\int_{-\infty}^{+\infty} V_{LS}(r)dz$, where $V_{LS}(r)$ is the spin-orbit part of a local optical potential and $r = (\boldsymbol{b}^2 + z^2)^{1/2}$, Re χ_{LS} presents the information on the b-dependence of the spin-orbit interaction[20]. The solutions of Reχ_{LS} at 3, 6 and 12 GeV/c agree among them in the outer region $b \gtrsim 1.0$ fm, which represent the force due to peripheral mesonic contribution. In the region of 0.5−1.0 fm, Reχ_{LS} exhibits the nonstatic effect due to the modified one-boson-exchange interaction. In the inner region of $b \lesssim 0.5$ fm, Reχ_{LS} gives new indication on an existence of a short-range repulsive force with a strong energy dependence.

3.3.4 Possible explanation of results as phase transition in subnuclear medium

At a glance, the p-p spin-orbit interaction seems to have two characteristics as follows:

(1) In the region $b \gtrsim 1$ fm, there is a long-range attractive force which represents mainly the force due to peripheral mesonic ingredients in our analysis through the modified one-boson-exchange terms.

(2) At the short distance of $b \lesssim 0.5$ fm, $\mathrm{Re}\chi_{LS}$ suggests the existence of an extremely strong and short-range repulsive force, the strength of which increases progressively with energy. This might be, however, understood to give a suggestion of "shrinkage" of the spin-orbit force in its short-range repulsive term.

It is also to be noted that the spin-orbit component phase shifts have a tendency to tend to zero progressively with energy. These found results can be never understood by the usual hadron physics. Our only possible explanation is that a phase transition takes place in the incident energy region of proton T_L=3 − 10 GeV. The threshold radius for the "shrinkage" of the spin-orbit force is about 0.5 fm, which almost agrees with the bag-radius predicted by the MIT bag model[85].

The critical temperature for the transition from the quark-gluon-plasma phase to the hadron phase is estimated as 150−200 MeV by using the Gibbs condition, provided that the transition is approximately the same to that from the massless quark-gluon gas to the massless pion gas. The energy density of plasma at this critical point is $\epsilon_c = 0.9 - 2.5$ GeV/fm^3[86].

In the next, we calculate the energy density of plasma in high energy collision of two nuclei in the c.m. system by means of Landau's fire ball model. Both of two nuclei are supposed to have the same atomic mass A. The incident energy of one nucleon is given by $E_{cm} = W/A$, where W is the incident energy of nucleus. The incident two nuclei are thin disks owing to the Lorenz contraction, the thickness of which is $2R/\gamma$. Here R is the nuclear radius: $R = 1.2A^{1/3}$[fm] and γ is the Lorenz factor: γ=E_{cm}/m_N. Two nuclei are closed in the volume occupied by two disks at the moment of collision. The energy density of this fire ball is given by

$$\epsilon = \frac{W}{\pi R^2} \Big/ \frac{4R}{\gamma} = \frac{E_{\mathrm{cm}}^2}{2\pi \times 1.2^3 m_N}. \tag{3.22}$$

If this is equal to the energy density of quark-gluon plasma at the critical point, i.e., $\epsilon = \epsilon_c$, the incident energy per nucleon in the c.m. system is evaluated as $E_{\mathrm{cm}} = 1.5$−2.5 GeV, which corresponds to the critical temperature T_c= 100−150 MeV. The incident laboratory-momentum of nucleon corresponding to the value of E_{cm} is evaluated as 3.5−12 GeV/c. The values calculated by the simple model agree with the energies of our discovered catastrophic transition of the spin-orbit force.

The various theoretical arguments[87] and computer simulations[88] suggest the possibility that the early universe has undergone a first-order phase transition associated with QCD effects at a temperature of order 100 MeV. Witten[75] suggested that a true second-order QCD phase transition in cosmology is implausible because in nature there are no exact chiral symmetry and no exact criterion for confinement, and provided an explanation for the dark matter in terms of QCD effects in assumption of $T_c = 100 - 200$ MeV.

Recently, the proton, neutron and deuteron spin dependent structure functions have been measured in the SMC experiment at CERN[89]. It was reported that the quark spin contribution to the nucleon spin is unexpectedly small. This result called "spin crisis" seems to be in accordance with our discovered "shrinkage" of the spin-dependent nuclear force. A possible explanation of these observed results is that the spin-symmetry of constituent quarks of nucleon has been recovered at higher temperature $T > T_c$ and have the random spin-directions so as to result in no contribution to nucleon spin, which is consistent with the free Parton model. At low temperature $T \lesssim T_c$, nucleon spin is understood to be generated by the constituent quark-spins due to the spontaneous broken-symmetry.

Now we have a favorable opportunity to realize our desire of understanding a generation mechanism of nucleon in the early universe.