

Origin of Elastic pp Polarization at Large Angles

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We propose a simple mechanism to generate a sizable analyzing power in high-energy pp elastic scattering at large angles. Our predictions are of direct interest for the experimental program in progress at Brookhaven National Laboratory and for near-future experiments which will be undertaken elsewhere.

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The spin dependence of two-body processes at high energies is known to probe hadronic interactions at a rather refined level and allows us to ask detailed questions about hadron structure which cannot be answered from the knowledge of unpolarized cross sections only. Over the last ten years or so, a large selection of spin measurements for this class of reactions have been performed. They cover mainly the region of small momentum transfer, and the corresponding "soft" physics has been discussed in a comprehensive review of polarization phenomena in hadronic reactions.¹ Clearly, to test our understanding of color quark dynamics at very short distances, one must investigate large-momentum-transfer processes at high energies. For inclusive reactions, in the framework of perturbative QCD, the basic quark asymmetries resulting from the helicity-conserving nature of the theory imply large *double-spin* asymmetries at the hadron level, but these interesting predictions² have not yet been tested for lack of experimental data.

On the other hand, large-angle pp elastic scattering is one of the best known reactions and it is worth recalling the existence of a striking spin dependence which has been already discovered at the maximum energy of the Argonne National Laboratory zero-gradient synchrotron. The transverse spin-spin correlation parameter A_{NN} was found to climb up to the large value 0.59 ± 0.09 at $\theta_{c.m.} = 90^\circ$ for $p_{lab} = 12.75$ GeV/c.³ In terms of the five nucleon-nucleon helicity amplitudes ϕ_i , this physical observable reads

$$\sigma_0 A_{NN} = \text{Re}(\phi_1 \phi_2^* - \phi_3 \phi_4^* + 2|\phi_5|^2), \quad (1)$$

where

$$\sigma_0 = \frac{1}{2} (|\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 + 4|\phi_5|^2). \quad (2)$$

If one tries to use perturbative QCD to describe pp elastic scattering in this energy range,⁴ the helicity-conservation rule⁵ implies that the single- and double-flip amplitudes vanish, i.e., $\phi_2 = \phi_5 = 0$ at large angles. In addition, from symmetry arguments at 90° we have

$\phi_3 = -\phi_4$ and from the quark interchange model $\phi_1 = \frac{1}{2}\phi_3$. As a result, one gets $A_{NN}(90^\circ) = \frac{1}{3}$,⁴ which is definitely in disagreement with the above experimental result. Of course one can always assume the existence of additional contributions related to nonperturbative effects which will die out as the energy increases. In that case one expects, from the future data at the Brookhaven National Laboratory alternating-gradient synchrotron, a value of $A_{NN}(90^\circ)$ that decreases towards the value $\frac{1}{3}$.

In the theoretical approach of the massive quark model (MQM) and its extension to the quark geometrodynamics (QGD),⁶ the physics of large-angle two-body reactions has been analyzed in detail in a series of papers.⁷⁻⁹ In this model the scattering amplitudes are obtained by folding of the hadron vertex functions with the elementary quark-quark amplitudes at large angles. The vertex functions are constructed with the assumption that the two baryons, before and after the scattering, have in common two spectator quarks which conserve spin (not helicity), momentum, and the internal degrees of freedom. We also assume that two spin- $\frac{1}{2}$ quarks can exchange in addition to transverse vector states, behaving like a "gluon," a pseudoscalar and a longitudinal vector state; this set constitutes a richer spin structure than in perturbative QCD. This leads to a specific $\theta_{c.m.}$ dependence, while the energy dependence is such that we must recover in the high-energy limit the observed behavior of the hadron form factors. By using the set of N - N amplitudes given in Table I of Ref. 8, one finds a larger value for $A_{NN}(90^\circ)$ which should go up to 0.97 at asymptotic energies, in contrast with the perturbative QCD value of $\frac{1}{3}$. A new potential physics will emerge with the advent of the polarized proton beam at the Brookhaven National Laboratory alternating-gradient synchrotron and hopefully this important question will be answered soon.

We now turn to the simplest spin-dependent observ-

able, the analyzing power A , whose expression is

$$\sigma_0 A = \text{Im}[(\phi_1 + \phi_2 + \phi_3 - \phi_4) \phi_5^*], \quad (3)$$

and see that it will vanish at large angles in perturbative QCD because $\phi_5 = 0$. In the MQM-QGD approach we do not have this constraint, but all the amplitudes are expected to be real as in perturbative QCD and for this reason we also anticipate $A = 0$ at large angles. However, if at high momentum transfer t , there is a remnant of the imaginary diffractive nonflip amplitude which is known to dominate at small t , then there will be interesting interference effects with the MQM-QGD spin-dependent real amplitudes, which might persist up to very large scattering angles. This is precisely the mechanism that we will invoke to generate a sizable analyzing power at large angles.

Some years ago we presented a satisfactory phenomenological analysis of pp elastic scattering with a new impact picture for low and high energy.¹⁰ These predictions have been extended¹¹ and were found to be in good agreement with recent data at the CERN SPS collider. We therefore consider that this impact-picture amplitude provides an accurate representation of "soft" scattering up to reasonable values of the momentum transfer. If we combine it with the MQM-QGD hard-scattering amplitudes described above and properly normalized to the cross section near $\theta_{c.m.} = 90^\circ$, we expect to get a good description of the differential cross section up to very large values of the scattering angle. For example, we have checked that at $p_{\text{lab}} = 28 \text{ GeV}/c$ and $\theta_{c.m.} = 45^\circ$, we have $d\sigma/dt = 4 \times 10^{-7} \text{ mb/GeV}^2$, which is consistent with the expectations of Krisch.¹² If we now calculate the analyzing power for $\theta_{c.m.}$ above 45° from the resulting set of amplitudes, we find that A is very large, starting around 50% and decreasing slowly towards zero for

$\theta_{c.m.} = 90^\circ$. Our predictions for pp are shown in Fig. 1 where we have plotted A vs $\theta_{c.m.}$ for two different values of p_{lab} , 28 and 50 GeV/c . There is a slight uncertainty about these results due to the fact that we do not know the exact value of $d\sigma/dt$ in this kinematic region. For $p_{\text{lab}} = 24 \text{ GeV}/c$ at the largest angle measured, corresponding to $|t| = 6.72 \text{ GeV}^2$, we get $d\sigma/dt = 1.1 \times 10^{-6} \text{ mb/GeV}^2$, to be compared with the experimental value¹³ of $(8.49 \pm 0.51) \times 10^{-7} \text{ mb/GeV}^2$.

We have also calculated A_{NN} at two different energies, which is shown in Fig. 2. Let us discuss the energy dependence that we have found. In the impact picture we have $\phi_1 \sim \phi_3$ and $\phi_2 \sim -\phi_4$, and ϕ_2 is smaller than ϕ_1 . So A is essentially given by

$$A \sim (-\text{Im}\phi_1 \text{Re}\phi_5) / [(\text{Im}\phi_1)^2 + 2(\text{Re}\phi_5)^2], \quad (4)$$

where $\text{Im}\phi_1$ is the imaginary part of the diffractive amplitude and $\text{Re}\phi_5$ the real part of the flip MQM amplitude.¹⁴ In the large-angle region, it is known from the impact picture that $\text{Im}\phi_1$ is negative¹⁵ while $\text{Re}\phi_5$ given by the MQM is positive. As a result, A is positive. In the kinematic region under consideration in Fig. 1, i.e., $\theta_{c.m.} > 45^\circ$ and $28 \text{ GeV}/c \leq p_{\text{lab}} \leq 50 \text{ GeV}/c$, since the MQM amplitude dominates, the ratio in Eq. (4) reduces to $-\text{Im}\phi_1/\text{Re}\phi_5$. At fixed angle, when the energy increases, since the hard-scattering contribution drops faster than the impact-picture amplitude, it is clear that A will increase. However, this behavior is limited because, as a result of the fast decrease of the MQM contribution, one will ultimately reach an energy where $\text{Im}\phi_1$ dominates over $\text{Re}\phi_5$ and the ratio of Eq. (4) will then become $-\text{Re}\phi_5/\text{Im}\phi_1$ which is going to zero for asymptotic energies. Using the same arguments, one can understand the energy behavior in Fig. 2. We expect A_{NN} to decrease at fixed

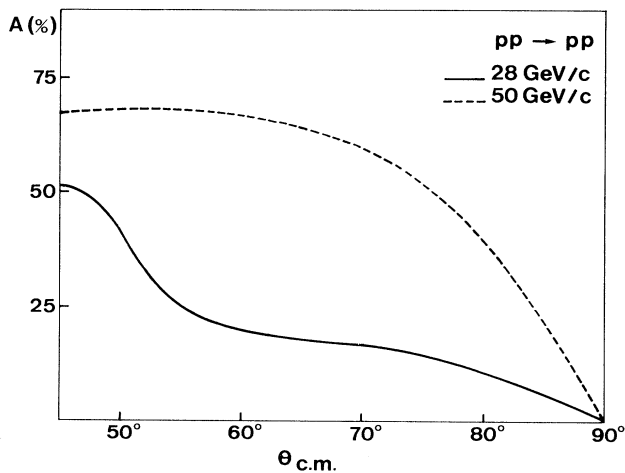


FIG. 1. Predictions for the pp analyzing power A vs $\theta_{c.m.}$ at two different energies.

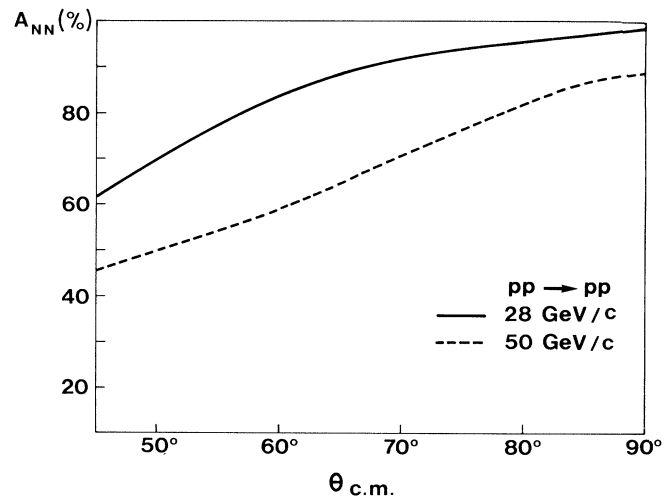


FIG. 2. Our predictions for the A_{NN} parameter in pp elastic scattering vs $\theta_{c.m.}$ at two different energies.

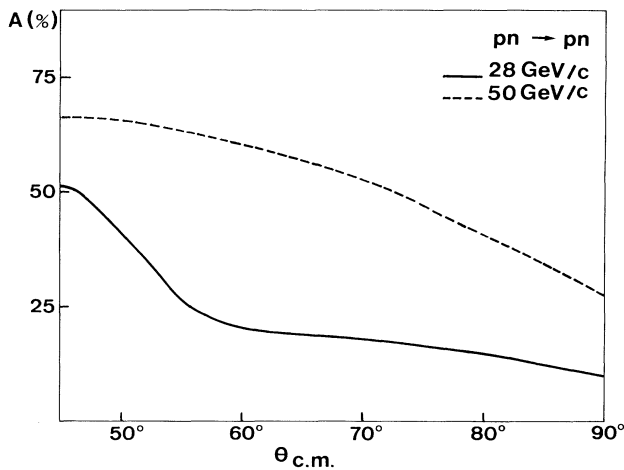


FIG. 3. Our predictions for the pn analyzing power A vs $\theta_{c.m.}$ at two different energies.

angle, since $A_{NN} \sim [(\text{Re}\phi_1)^2 + \text{Im}\phi_1\text{Im}\phi_2]/\sigma_0$ and in the impact picture $\text{Im}\phi_2$ is found positive.

Experimentally this kinematic region, $\theta_{c.m.} \geq 50^\circ$, has not yet been investigated, but there is a strong indication of this effect from a recent result of Raymond *et al.*¹⁶ at Brookhaven National Laboratory. At $p_{\text{lab}} = 28 \text{ GeV}/c$ and $p_{\perp}^2 = 6.56 (\text{GeV}/c)^2$, they find that $A = (51 \pm 17)\%$, and this is perhaps the beginning of a new domain where large values of A result from a maximum interference mechanism between soft- and hard-scattering amplitudes which are strongly out of phase.¹⁷ We have also calculated A for pn elastic scattering and the results are presented in Fig. 3. The pn analyzing power is similar to that of pp , except near $\theta_{c.m.} = 90^\circ$ where it does not vanish from symmetry arguments. We would like to stress that if these predictions turn out to be verified by experiment they would confirm the correctness of the phase of the impact picture and they would indicate the presence of a large hard-scattering flip amplitude.

We would like to indicate that a similar calculation has been done with use of the perturbative QCD amplitudes⁴ and one finds much smaller results, partly because of the fact that $\phi_2 = \phi_5 = 0$. Moreover, the calculation is only reliable near 90° because for $\theta_{c.m.} \leq 70^\circ$ the hard QCD cross section blows up very quickly and its extrapolation is totally unrealistic.

In conclusion, we believe that the elastic nucleon-nucleon analyzing power at large angles is very impor-

tant to measure because its determination is a real challenge to our knowledge of spin dependence at short distances.

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