SPIN PHENOMENA IN PARTICLE INTERACTIONS

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Preface

Essential growth of research activities related to spin phenomena in high energy physics and their theoretical interpretations has been observed in recent years. In 80's considerable progress occurred in the experimental studies of spin effects at high energies. Spin investigations became oriented and systematic ones. Physicists have met here the desirable unexpected results that immediately attracted attention of the theorists. Besides, it became totally clear that spin enigma is not to be considered separately but it is strongly related to quark–gluon structure of hadrons and their interaction dynamics.

Regularly, every two years physicists specialized in experiment and instrumentation, theory, accelerators and united by their interest in the spin studies meet all together at the symposia devoted to spin phenomena and research at high energies. The broad spectrum of specialities presented at such meetings only confirms the complexity of the problems under study.

This book could serve as an introduction to the spin puzzles at high energies. The main focus is spin effects in hadronic processes. Theoretical analysis here is more complicated and less decisive than say for e^+e^- collisions but on the other hand spin effects observed recently are most interesting ones. Of course, the theoretical approaches to the hadron interactions especially at large distances are highly different and as a consequence their coherent account causes some difficulties. This fact can serve as a possible explanation for the too brief discussion of some topics. Nevertheless we consider it is worth to mention the most of the approaches and models developed for explanations of the spin phenomena.

The new results on spin were obtained in the very recent time. So we feel that there are some results missed in the book or considered too briefly. This is also true for the bibliography.

We hope this book will be useful for the graduate students and for those working in the field of polarization physics or interested in the various aspects of strong interaction dynamics.

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Introduction

This book is devoted to the problems of spin phenomena in high energy hadronic interactions.

Prior to discussion of the contents of book and motivations to address the topic of spin phenomena it seems necessary to remind briefly the history of a concept of spin.

The notion of spin entered physics in the mid of twenties when Uhlenbeck and Goudsmit introduced the internal degree of freedom for the electron — spin as a real physical characteristics [1] instead of the so called non–mechanical strength used at first by Pauli under formulation of his famous principle. The idea introduced by Uhlenbeck and Goudsmit also allowed one to provide the classical mechanical interpretation for the new quantum number proposed by Pauli and served as a guideline for the understanding of the anomalous Zeemann effect.

Thomas calculation of the doublet splitting with account for the electron spin precession finally confirmed notion of spin as a conceptual one for the description of electron and the development of atomic theory.

Therefore Pauli formulated requirement for a new quantum number when he admitted the doubling of the states [2] and Uhlenbeck and Goudsmit introduced the intrinsic electron moment — spin — as a physical quantity.

Discovery of the Dirac equation has shown that spin is an inherent property of the relativistic theory [3] free Dirac particle whose wave function obeys the matrix equation

$$\left(\frac{1}{c}\frac{\partial}{\partial t} + \sum_k \alpha_k \frac{\partial}{\partial x_k} + \frac{imc}{\hbar}\beta\right)\psi = 0,$$

has apart of its momentum an additional integral of motion namely the intrinsic moment of motion (spin) which is equal to $\hbar/2$. The Dirac particle may be in the two states which differ by spin projection on the direction of particle momentum.

In fact the notion of spin aroused from an intersection of the classical and quantum physics ideas. Under this the classical rotation was an original interpretation. It should be noted that in a year 1921 Compton already considered the electron as an extended and rapidly rotating object in his calculations. But in its essence spin appeared as a quantum concept when it was stated the quantum and minimal value of the orbital momentum equal to $\hbar/2$.

The Pauli principle and the concept of spin served as a starting point for the appearance of such fundamental notions as symmetry of the wave function and statistics. According to C. N. Yang the spin of electron is a fundamental manifestation (not understood completely yet) of the space–time structure.

Till recently it was believed that high energy physics could avoid the dynamical implementations of particle spins. In spite of the fact that all fundamental constituents of matter (quarks, leptons and mediators of the fundamental interactions) have a non–zero spin:

$$\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}, \begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \quad - \; s = 1/2,$$

$$\gamma, \quad W^\pm, \quad Z^0, \quad g \; - s \; = 1,$$

as a rule, the respective effects were treated only by means of underlying combinations when composing the state vectors and of appropriate factors introduced into the amplitudes. The dynamical implementations of spin degrees of freedom were currently ignored.

Of course, the use of $SU(6)$–symmetry for the hadronic wave functions and representation for instance of the proton state vector in the form

$$| \, p \uparrow \rangle = [2u \uparrow u \uparrow d \downarrow -(u \uparrow u \downarrow +u \downarrow u \uparrow) d \uparrow]/\sqrt{6},$$

allows one to systematize the data on magnetic moments and on the relative values of hyperon polarizations in inclusive processes. Besides, an assumption on the spin dependence of quark–quark interaction potential allows one to develop a non–relativistic phenomenology of quarkonium similar to the spectrum line splitting in atomic transitions. However the above approaches treat the hadron as a loosely bound system of valence quarks only and therefore they lead to the definite limitations for variety of the processes and effects under consideration.

It should be also noted that the experiments at high energies related to the measurements of spin observables were considered in general as a traditionally steamed from low–energy physics and in its turn, the respective theoretical insights as simple exercises resulted in tedious complications that in addition prevent understanding the origin of the phenomena occurred.

On the other hand it is natural to expect that the role of spin is to be essential under the interactions of quarks and leptons. It has been just proved that the experimental studies on spin provide strong influence on the theoretical considerations and models in the range of high energies.

The observation of a nonzero polarization of the recoil nucleon in the pion charge exchange reaction

$$\pi^- + p \to \pi^0 + n$$

appeared to be highly crucial for the Regge pole model of that time.

The number of the new results obtained in 80's and especially at high $p_\perp$ values:

- the strong dependence of *pp*-scattering angular distribution on the relative orientation of spins in the initial state:

$$d\sigma(\uparrow\uparrow)/d\sigma(\uparrow\downarrow) = 4,$$

- the large value of Λ–hyperon polarization observed in the inclusive process

$$p + p \to \Lambda + X,$$

- the significant asymmetries observed in elastic scattering and binary reactions as well as in inclusive meson production,

stimulated analysis and account for spin degrees of freedom under consideration of the interaction dynamics. These results at the same time were challenging ones for the Quantum Chromodynamics (QCD), or to be more specific, for its perturbative sector pretending to describe the processes at large momentum transfers.

In the framework of perturbative QCD the polarization of individual quark in hard subprocesses appears to be small owing to the vector type of the QCD interaction which leads to the chirality conservation. The quark helicity is conserved therefore with an accuracy up to the terms $O(m/\sqrt{s})$. The phase difference for the different helicity amplitudes required to explain the observed asymmetries

$$A \sim \mathrm{Im}(F_{nf}F_f^*)$$

is not provided by the leading–twist interactions at small distances. Apparently a nonperturbative dynamics is responsible for the observed significant spin effects.

In the recent time a considerable attention has been devoted to the discussion of the nucleon longitudinal spin structure and in particular to the role of quarks and gluons in the proton spin balance:

$$s_p = s_q + s_g + \langle L \rangle.$$

As it follows from the experiments performed at SLAC and CERN, the total contribution of gluonic component and/or of the orbital momentum for both quarks and gluons has a significant value. Evidently the new experiments on the measurement of proton and neutron spin structure functions are needed to make more definite conclusions.

The theoretical studies and interpretations of the already existing data and the results of new experiments will provide deep insight to the nature of a nucleon spin.

The permanent interest the spin phenomena and hadronic spin structure is related to the recognition of the important role of the spin effects for the analysis of hadron interaction dynamics and elaboration of the theory.

The aim of this book is to give a systematic introduction to the problem of account for the spin degrees of freedom in high energy physics. The most interesting spin effects observed at high energies and that are crucial ones for the development of the theory of hadronic interactions are described.

This defines in large extent the content of the book and the composition of the material.

Chapter 1 is devoted to an introduction of the concept of spin. The relevant group rotation representations are also considered.

Almost all the formulas for the amplitudes with account for spin could be written in general form but spin is particularly interesting by its appearance as extremely subtle instrument to check the theoretical constructions. That is why the phenomenological analysis of the experimental data is to play a significant role under discussions of the spin phenomena in particle interactions.

In Chapter 2 the key experimental results obtained under the studies of spin effects in high energy collisions are discussed.

Chapter 3 deals with the theoretical models for the description of spin phenomena at fixed momentum transfers. The essential role of the models is related to interpretation of the experimental results as well as verification of some theoretical concepts. Both these problems are equally important and are closely interpenetrating ones in high energy physics where a parallel development of theoretical ideas and of experiments occurs.

In Chapter 4 the theory of spin phenomena in the framework of the perturbative quantum chromodynamics is considered.

Chapter 5 is devoted to discussions of the models constructed to describe spin phenomena in hard exclusive processes.

In Chapter 6 the approaches related to the spin phenomena in inclusive processes are analyzed.

Nucleon spin structure and the recent results on deep inelastic structure functions are considered in Chapter 7.

Perspectives in spin phenomena investigations with the use of future accelerators are discussed in Chapter 8.