SELECTED ASPECTS OF SCATTERING AND ANNIHILATION REACTIONS

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Model independent properties of the spin density matrix and of polarization observables for electron hadron scattering and electron positron annihilation in specific channels are presented. Particular attention is devoted to the extraction and the properties of hadron form factors, as well as to the reaction mechanism.

1 Introduction

Scattering and annihilation reactions involving leptons and light hadrons constitute unique probes to learn about hadron structure and hadron spectroscopy. We developed a model independent formalism which can be applied to elastic electron scattering on hadrons and to the crossed channels. This formalism allows to express the spin structure of the matrix element in terms of the relevant amplitudes (in general complex functions of kinematical variables) and then, to calculate the differential cross section and the polarization observables. The number and the structure of the amplitudes depend on the reaction mechanism, with evident simplification if one assumes that the reaction occurs through one photon exchange. The amplitudes are expressed as functions of hadron electromagnetic form factors (FFs). Definite prescriptions for their analytical extension from space-like (SL) to time-like (TL) regions allow to find coherent results and/or predictions for the experimental observables in the full kinematical region. A review of the general formalism, focused on the threshold region can be found in Ref. [1]. The reactions involving electron and protons have been derived in Refs. [2]. Here we give specific examples of application of such formalism to reactions involving deuteron and spin one particles: $e^- + d \to e^- + d$, $e^+ + e^- \to d + \bar{d}$ [3, 4] $(\rho + \rho)$ [5] assuming one photon exchange.

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The process of e^+e^- annihilation into four (or more) pions was firstly detected in Frascati, later on in Novosibirsk, and recently in Babar ([6] and Refs. herein). The achievable luminosity and the modern detectors allow to characterize the intermediate states. The present formalism constitutes a useful tool for a global understanding of the hadron dynamics, providing a unified description in SL and TL regions.

2 Electron-deuteron system

The deuteron, the only bound two–nucleon system, has been extensively studied theoretically and experimentally. In particular, models based on impulse approximation where the deuteron can be understood as a system of two nucleons interacting via nucleon–nucleon interaction, compete with QCD inspired models where quark degrees of freedom should be explicitly taken into account. Assuming P and C parities conservation, a spin one particle is fully described in terms of three FFs. Their experimental determination and the comparison to the theory is an important test of our understanding of the dynamical structure of the hadrons.

During the last years, it has become possible to measure not only cross sections, but also spin observables, due to the developments of polarized electron beams, polarized deuteron targets and polarimeters. Large progress has been made from the experimental side. The outgoing–deuteron polarization has been measured in a secondary analyzing scattering. For vector polarization up to a few GeV, an inclusive measurement on a carbon target as $d+C \rightarrow$ *one charged particle* $+X$ is sufficient, when the charged protons from deuteron break up are eliminated with help of an absorber. For tensor polarization, however, only exclusive reactions as elastic $d+p$ scattering or charge exchange [7] give sufficient efficiency and analyzing powers. In particular, recent polarization data for electron–deuteron elastic scattering allowed the individual determination of the deuteron charge and quadrupole FFs up to a value of the momentum transfer squared $-q^2 = Q^2 =$ 1.8 GeV^2 (for a review see, for instance, [8]).

The interaction of electrons with deuterons is usually assumed to occur through the exchange of a virtual photon (one–photon exchange approximation) due to the smallness of the electromagnetic fine structure constant, which suppress two -or more- photon exchange. However, a few decades ago it was suggested [9] that the two–photon exchange mechanism may be significant in the region of large momentum transfer. More recently, the contribution of two–photon exchange to elastic electron–deuteron scattering was discussed in Refs. [4].

The knowledge of electromagnetic FFs in the TL region of momentum transfer gives additional important information about the internal composite structure of the hadron. Deuteron FFs are real functions of the momentum transfer squared, while they are complex in TL region. This is the main difference between $e^-+d \to e^-+d$ and $e^++e^- \to d+\bar{d}$, which are related by crossing symmetry and therefore described by the same amplitudes acting in different kinematical regions. The complex nature of the deuteron FFs in TL region leads to non–zero single–spin observables (at the level of the Born approximation) in the $e^+ + e^- \to d + \bar{d}$ reaction. The component P_y (orthogonal to the reaction plane) of the deuteron polarization (all other particles are unpolarized) is non zero. The single–spin asymmetry A_y (when the deuteron target is polarized) in the elastic ed–scattering vanishes in the Born approximation. A_y can be non zero in case of the interference between one– photon and two–photon exchange amplitudes. The same arguments hold for the spin correlation coefficient due to the longitudinal polarization of the electron beam and to the tensor polarization of the deuteron. To determine three deuteron FFs, in the case of the elastic ed– scattering, it is necessary to measure the unpolarized cross section and one polarization observable. In TL region the deuteron FFs are complex and one has to determine not only the moduli of the deuteron FFs but also their relative phases. The measurements of a single polarization observable is not sufficient for the $e^+ + e^- \to d + \bar{d}$ reaction, where, besides the measurement of the unpolarized cross section, it is necessary to measure four polarization observables.

Measurements are certainly very difficult in the TL region, due to the steep decreasing of the cross section, however, other mechanisms, as the presence of a two–photon contribution, could favor a larger cross section.

Let us recall general and model independent expressions for the reaction $e^-(k_1) + e^+(k_2) \to d(p_1) + \bar{d}(p_2)$ where the momenta of the particles are indicated in brackets. In the reaction CMS the unpolarized differential cross section can be written as

$$\frac{d\sigma^{un}}{d\Omega} = \frac{\alpha^2\beta^3}{4q^2}D,\ D = \tau(1+\cos^2\theta)|G_M|^2 + \frac{3}{2}\sin^2\theta\left(|G_C|^2 + \frac{8}{9}\tau^2|G_Q|^2\right), \qquad (1)$$

where θ is the angle between the momenta of the deuteron ($\vec{p}$) and the electron beam ($\vec{k}$), $\alpha = 1/137$ is the electromagnetic constant, $\beta = \sqrt{1-4M^2/q^2}$ is the deuteron velocity in the reaction center of mass system (CMS), $\tau = q^2/(4M^2)$ where M is the deuteron mass and q is the four momentum of the virtual photon, $q = k_1 + k_2 = p_1 + p_2$. The standard deuteron electromagnetic FFs are G_C (charge monopole), G_M (magnetic dipole) and G_Q (charge quadrupole).

Integrating (1) over the angle, one obtains for the total cross section:

$$\sigma_{tot}(e^+e^- \to \bar{d}d) = \frac{\pi\alpha^2\beta^3}{3q^2}\left[3|G_C|^2 + 4\tau(|G_M|^2 + \frac{2}{3}\tau|G_Q|^2)\right]. \qquad (2)$$

The angular asymmetry, R, with respect to the differential cross section measured at $\theta=\pi/2, \sigma_0$ is:

$$\frac{d\sigma^{un}}{d\Omega} = \sigma_0(1+R\cos^2\theta), \text{ with } R = \frac{2\tau(|G_M|^2 - \frac{4}{3}\tau|G_Q|^2) - 3|G_C|^2}{2\tau(|G_M|^2 + \frac{4}{3}\tau|G_Q|^2) + 3|G_C|^2}. \qquad (3)$$

This observable which does not require polarized particles, is very sensitive to the different assumptions on deuteron FFs.

The cross section can be written, in the general case, as the sum of unpolarized and polarized terms, corresponding to the different polarization states and polarization directions of the incident and scattered particles:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma^{un}}{d\Omega}\left[1 + P_y + \lambda P_x + \lambda P_z + P_{zz}R_{zz} + P_{xz}R_{xz} + P_{xx}(R_{xx}-R_{yy}) + \lambda P_{yz}R_{yz}\right],$$

where P_i (P_{ij}), $i,j=x,y,z$ are the components of the polarization vector (tensor) of the outgoing deuteron, and R_{ij}, $i,j=x,y,z$ the components of the quadrupole polarization tensor of the outgoing deuteron in its rest system.

As in SL region, the measurement of the angular distribution of the outgoing deuteron determines the modulus of the magnetic FF, but the separation of the charge and quadrupole FFs requires the measurement of polarization observables.

3 Hadron form factors

Explicit expressions for all experimental observables are given in Ref. [3] for e^+e^- annihilation in $d\bar{d}$ and in Ref. [5] for $\rho^+\rho^-$ production, respectively. Their calculation requires a model for the hadron FFs.

In Ref. [10] a generalization of the nucleon model from Ref. [11] has been successfully applied to the deuteron case. Its extension to TL region is straightforward.

The basic idea of this parametrization is the presence of two components in the hadron structure: an intrinsic structure, very compact, characterized by a dipole (monopole) q^2 dependence and a meson cloud. A very good description of all known data on deuteron electromagnetic FFs has been obtained, with as few as six free parameters applying evident physical constraints. As an example, we show in Fig. 1 the results obtained for

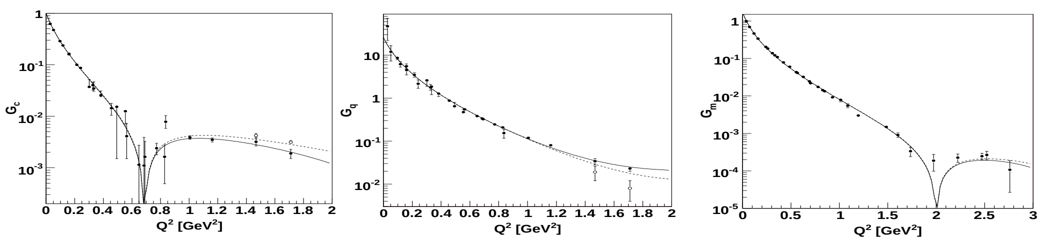

Figure 1: Fit to deuteron form factor data. The solid and dashed lines correspond to two different fits for the data (solid and empty circles).

the deuteron FFs. This parametrization has a better χ^2, fewer number of parameters and more evident physical content, with respect to the other available parameterizations. Moreover, it has the necessary analytical properties that allow its application to the TL region (see Ref. [10] and Refs. herein).

In case of ρ-meson FFs in TL region, their experimental determination is in principle possible at e^+e^- rings, such as Babar, Frascati, Novosibirsk and Beijing. In Ref. [5] we introduced a simple VMD parametrization for ρ–meson FFs, where the parameters were adjusted in order to reproduce the existing theoretical predictions in SL region from a model based on light–front formalism with constituent quarks [12]. The parametrization was then analytically extended to the TL region.

4 Conclusions and perspectives

Quantitative estimations require the knowledge of the hadron FFs, in the corresponding kinematical region. Data for deuteron are absent in the whole TL region, and also in SL region, at large momentum transfer squared. Therefore, we used simple parametrizations in SL region, with analytical continuations to TL region, keeping in mind that they are poorly constrained. Polarization effects either vanish or are large and measurable.

The obtained expressions hold for any value of the incident energy, they are model independent, assuming C and P conservation, and that the interaction proceed through one photon exchange. One can therefore apply the formalism to the recent results obtained by the Babar collaboration on $e^+ + e^- \to \rho^+ + \rho^-$ [6]. These data could, in particular, constrain the parametrization of FFs, at $\sqrt{s}$=10.58 GeV, which has been adjusted on a theoretical calculation in a moderate q^2 SL region.

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