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## Threshold $J/\psi$ production in nucleon–nucleon collisions

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**Abstract.** We analyse  $J/\psi$ -production in nucleon–nucleon collisions near threshold in the framework of a general model-independent formalism, which can be applied to any reaction  $N + N \rightarrow N + N + V^0$ , where  $V^0 = \omega, \phi$  or  $J/\psi$ . Such reactions show large isotopic effects: a large difference for pp and pn collisions, which is due to the different spin structure of the corresponding matrix elements. The analysis of the spin structure and of the polarization observables is based on symmetry properties of the strong interaction. Using existing experimental data on the different decays of the  $J/\psi$  meson, we suggest a model for  $N + N \rightarrow N + N + J/\psi$ , based on  $t$  channel  $\eta + \pi$  exchanges. We predict polarization phenomena for the  $n + p \rightarrow n + p + J/\psi$  reaction and the ratio of cross sections for np and pp collisions. For the processes  $\eta(\pi) + N \rightarrow N + J/\psi$  we apply two different approaches: vector meson exchange and local four-particle interaction. In both cases we find larger  $J/\psi$  production in np collisions than in pp collisions.

### 1. Introduction

It is well known that the  $J/\psi$  meson has been observed in two different reactions: in  $p + \text{Be}$  collisions [1] and  $e^+e^-$  [2].

Since that time experimental and theoretical studies of  $J/\psi$  production have been going on. As a result of high statistics and high-resolution experiments, a large amount of information on the properties of the  $J/\psi$  meson, on its production processes and on its numerous decays has been collected. From a theoretical point of view, the interpretation of the data, in particular in the confinement regime, is very controversial. As an example, the c-quark mass is too large, if

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compared to predictions from chiral symmetry, but for theories based on the expansion of heavy quark mass (heavy quark effective theory), this mass is too small [3]. In principle, all data on  $J/\psi$  should be explained in the framework of QCD. For example, theoretical considerations of charm production (open or hidden) should unify different steps: the parton-level hard process with production of  $c\bar{c}$  pairs, the hadronization of  $c\bar{c}$  into  $J/\psi$  or into charmed hadrons (mesons and baryons), and the final-state interaction of the produced charmed hadrons with other particles. The relatively large transferred momenta involved in most processes of  $J/\psi$  production in hadron–hadron collisions allow us to treat the first step in the framework of perturbative QCD, but the applicability of QCD is not so straightforward for the description of the c-quark hadronization.

This is correct especially for exclusive reactions, such as  $J/\psi$  production in nucleon–nucleon collisions:  $N + N \rightarrow N + N + J/\psi$ . Note that the threshold for this reaction is large:  $E_{th} = 12.24$  GeV which corresponds to  $\sqrt{s} = 2m + m_{J/\psi} \simeq 5$  GeV, whereas experimental data about  $p + p \rightarrow J/\psi + X$  are available for  $\sqrt{s} \geq 6.7$  GeV [4]. Therefore the experimental study of  $N + N \rightarrow N + N + J/\psi$  near threshold is an important part of the programme for the future accelerator facility at GSI [5].

Precise measurements of threshold  $J/\psi$  production will bring important information with respect to the following issues. First of all the threshold meson production in NN collisions gives deeper insight into the reaction mechanisms as shown by recent experiments on  $p + p \rightarrow p + p + \omega(\phi)$  [6]–[14],  $p + p \rightarrow \Lambda(\Sigma^0) + K^+ + p$  [15]–[18] and  $p + p \rightarrow p + p + \eta(\eta')$  [7]–[12, 19]–[27]. In this respect,  $J/\psi$  production has a specific interest: the production and the propagation of charm in ion–ion collisions has been considered as one of the most promising probes of quark–gluon plasma (QGP) formation [28]. The productions of charmonium (hidden strangeness) and D ( $D^*$ ) mesons (open charm) are equally important. The suppression of charmonium production in heavy-ion collisions has been indicated as a signature of QGP [29], but in order to state the evidence of a clear signal, it is necessary to analyse in detail all possible mechanisms for  $J/\psi$  production in ion–ion collisions and also all other processes which are responsible for the dissociation of the produced  $J/\psi$  meson, such as  $J/\psi + N \rightarrow \Lambda_c + D$ , for example.

The aim of this paper is to study  $J/\psi$  production in the simplest NN reactions:  $p + p \rightarrow p + p + J/\psi$  and  $n + p \rightarrow n + p + J/\psi$ . In the near-threshold region there is no experimental information about a possible difference between pp and np collisions. There are no theoretical predictions for such exclusive processes, which are very difficult to treat in the framework of QCD. It is possible to find some phenomenological parametrizations [30] of the energy dependence of the total cross section for  $p + N \rightarrow J/\psi + X$ , without any consideration of possible isotopic effects. However, previous experience with light meson production [31]–[34],  $N + N \rightarrow N + N + \omega(\phi)$ , showed an essential difference in np and pp cross sections, in particular in the near-threshold region, and there is no physical reason for a different behaviour in  $J/\psi$  production. It is evident that knowledge of the elementary process  $p + N \rightarrow p + N + J/\psi$  is very important for a realistic calculation of  $J/\psi$  production in nucleus–nucleus collisions.

In principle the ‘elastic’  $J/\psi$  production in NN collisions can be treated in full analogy with processes of light vector meson production. All symmetry properties of the strong interaction, such as the Pauli principle, the isotopic invariance and the  $P$  invariance, which have been successfully applied to light vector meson production in NN collisions [35], hold for  $J/\psi$  production, too. A formalism can be built, which is particularly simplified in the threshold region, where final particles are produced in the S state. Simple considerations indicate that this region is quite wide: the effective proton size, which is responsible for charm creation, has to be quite small,  $r_c \simeq 1/m_c$ , where  $m_c$  is the c-quark mass [36]. Therefore the S-wave picture can be

applied for  $q \leq m_c$ , where  $q$  is the  $J/\psi$  three-momentum in the reaction centre of mass (CMS).

This paper is organized as follows. In section 2 we establish the spin structure of the threshold matrix for the two NN processes:

$$\begin{aligned} p + p &\rightarrow p + p + J/\psi, \\ p + n &\rightarrow p + n + J/\psi \end{aligned}$$

in terms of partial S-wave amplitudes, and calculate the simplest polarization observables in terms of these amplitudes. In section 3 we treat the dynamical issue in terms of  $t$ -channel exchange mechanisms by light mesons. We give numerical predictions in the framework of a  $\pi + \eta$  model. The experimental data about different hadronic decays of the  $J/\psi$  meson may give constraints on our predictions.

## 2. Spin structure of threshold matrix elements and polarization phenomena

In the general case, the spin structure of the matrix element for the process  $N+N \rightarrow N+N+V^0$  is described by a set of 48 independent complex amplitudes, which are functions of five kinematical variables [37]. The same reaction, in coplanar kinematics, is described by 24 amplitudes, functions of four variables. In collinear kinematics the number of independent amplitudes is reduced to seven and the description of this reaction is further simplified in the case of threshold  $V^0$ -meson production, where all final particles are in the S state.

Applying the selection rules following from the Pauli principle, the  $P$  invariance and the conservation of the total angular momentum, it is possible to prove that the threshold process  $p + p \rightarrow p + p + V^0$  is characterized by a single partial transition:

$$S_i = 1, \ell_i = 1 \rightarrow j^P = 1^- \rightarrow S_f = 0, \quad (1)$$

where  $S_i$  ( $S_f$ ) is the total spin of the two protons in the initial (final) states,  $\ell_i$  is the orbital momentum of the colliding protons,  $j$  is the total angular momentum, and  $P$  is the parity for the colliding pp system. In the CMS of the considered reaction, the matrix element corresponding to transition (1) can be written as:

$$\mathcal{M}(\text{pp}) = 2f_{10}[\tilde{\chi}_2 \sigma_y \vec{\sigma} \cdot (\vec{U}^* \times \hat{k}) \chi_1] (\chi_4^\dagger \sigma_y \tilde{\chi}_3^\dagger), \quad (2)$$

where  $\chi_1$  and  $\chi_2$  ( $\chi_3$  and  $\chi_4$ ) are the two-component spinors of the initial (final) protons;  $\vec{U}$  is the three-vector of the  $V^0$ -meson polarization,  $\hat{k}$  is the unit vector along the three-momentum of the initial proton;  $f_{10}$  is the S-wave partial amplitude, describing the triplet–singlet transition of the two-proton system in  $V^0$ -meson production and  $\vec{\sigma} = (\sigma_x, \sigma_y, \sigma_z)$  are the standard Pauli matrices.

In the case of np collisions, applying the isotopic invariance for the strong interaction, two threshold partial transitions are allowed:

$$\begin{aligned} S_i = 1, \ell_i = 1 &\rightarrow j^P = 1^- \rightarrow S_f = 0, \\ S_i = 0, \ell_i = 1 &\rightarrow j^P = 1^- \rightarrow S_f = 1, \end{aligned} \quad (3)$$

with the following spin structure of the matrix element:

$$\mathcal{M}(\text{np}) = f_{10}[\tilde{\chi}_2 \sigma_y \vec{\sigma} \cdot (\vec{U}^* \times \hat{k}) \chi_1] (\chi_4^\dagger \sigma_y \tilde{\chi}_3^\dagger) + f_{01}(\tilde{\chi}_2 \sigma_y \chi_1) [\chi_4^\dagger \vec{\sigma} \cdot (\vec{U}^* \times \hat{k}) \sigma_y \tilde{\chi}_3^\dagger], \quad (4)$$

where  $f_{01}$  is the S-wave partial amplitude describing the singlet–triplet transition of the two-nucleon system in V-meson production. In the general case, the amplitudes  $f_{10}$  and  $f_{01}$  are

complex functions, depending on the energies  $E$ ,  $E'$  and  $E_V$ , where  $E(E')$  and  $E_V$  are the energies of the initial (final) proton and of the produced  $V^0$ -meson, respectively.

Note that  $f_{10}$  is the common amplitude for pp and np collisions, due to the isotopic invariance of the strong interaction. This explains the presence of the coefficient 2 in equation (2). The parametrizations (2) and (4) are model-independent descriptions of the spin structure for threshold production of any vector meson in NN collisions,  $N + N \rightarrow N + N + V^0$ , from the light  $\rho$ ,  $\omega$  and  $\phi$  to  $J/\psi$ ,  $\psi'$ ,  $\psi''$ , including the vector bottomium:  $\Upsilon(1S)$ ,  $\Upsilon(2S)$  and even the hypothetical exotic vector toponium states. All dynamical information is contained in the partial amplitudes  $f_{01}$  and  $f_{10}$ , which are different for the different vector particles. On the other hand, some polarization phenomena have common characteristics, essentially independent of the type of vector meson. For example, vector mesons produced in pp and np threshold collisions are transversally polarized, and the elements of the density matrix  $\rho$  are independent of the relative values of the amplitudes  $f_{01}$  and  $f_{10}$ :  $\rho_{xx} = \rho_{yy} = \frac{1}{2}$ ,  $\rho_{zz} = 0$ . Therefore, the angular distribution shows a  $\sin^2 \theta_P$  dependence for the subsequent decay  $V^0 \rightarrow P + P$  (where P is a pseudoscalar meson) and the  $(1 + \cos^2 \theta)$  dependence for the decay  $V^0 \rightarrow \mu^+ + \mu^-$ , where  $\theta$  ( $\theta_P$ ) is the angle between  $\hat{k}$  and the  $\mu^-$  ( $P$ ) momentum (in the rest system of  $V^0$ ). Possible deviations from this behaviour have to be considered as an indication of the presence of higher partial waves in the final state.

All other one-spin polarization observables, related to the polarizations of the initial or final nucleons, identically vanish, for any process of  $V^0$ -meson production.

The dependence of the differential cross section for threshold collisions of polarized nucleons (where the polarization of the final particles is not detected) can be parametrized as follows:

$$\frac{d\sigma}{d\omega}(\vec{P}_1, \vec{P}_2) = \left(\frac{d\sigma}{d\omega}\right)_0 (1 + \mathcal{A}_1 \vec{P}_1 \cdot \vec{P}_2 + \mathcal{A}_2 \hat{k} \cdot \vec{P}_1 \hat{k} \cdot \vec{P}_2), \quad (5)$$

where  $\vec{P}_1$  and  $\vec{P}_2$  are the axial vectors of the beam and target nucleon polarizations,  $d\omega$  is the element of phase-space for the three-particle final state. The spin correlation coefficients  $\mathcal{A}_1$  and  $\mathcal{A}_2$  are real and they are different for pp and np collisions:

$$\begin{aligned} \vec{p} + \vec{p} \rightarrow p + p + V^0 : \mathcal{A}_{1pp} = 0, \mathcal{A}_{2pp} = 1, \\ \vec{n} + \vec{p} \rightarrow n + p + V^0 : \mathcal{A}_{1np} = -\frac{|f_{01}|^2}{|f_{01}|^2 + |f_{10}|^2}, \mathcal{A}_{2np} = \frac{|f_{10}|^2}{|f_{01}|^2 + |f_{10}|^2}, \end{aligned} \quad (6)$$

with the following relations  $-\mathcal{A}_{1np} + \mathcal{A}_{2np} = 1$  and  $0 \leq \mathcal{A}_{2np} \leq 1$ .

Defining  $\mathcal{R}$  as the ratio of the total (unpolarized) cross section for np and pp collisions, taking into account the identity of final particles in  $p + p \rightarrow p + p + V^0$ , we find:

$$\mathcal{R} = \frac{\sigma(np \rightarrow npV^0)}{\sigma(pp \rightarrow ppV^0)} = \frac{1}{2} + \frac{1}{2} \frac{|f_{01}|^2}{|f_{10}|^2}. \quad (7)$$

So the following relation holds:

$$\mathcal{A}_{1np} = -1 + \frac{1}{2\mathcal{R}}.$$

The polarization transfer from the initial neutron to the final proton ( $\vec{n} + p \rightarrow n + \vec{p} + V^0$ ), can be parametrized as follows:

$$\vec{P}_f = \mathcal{P}_{1np} \vec{P}_1 + \mathcal{P}_{2np} \hat{k} (\hat{k} \cdot \vec{P}_1), \quad (8)$$

with a simple expression, which relates the real coefficients  $\mathcal{P}_{1np}$  and  $\mathcal{P}_{2np}$  to the partial amplitudes  $f_{01}$  and  $f_{10}$ :

$$\mathcal{P}_{1np} = -\mathcal{P}_{2np} = \frac{2\text{Re}f_{01}f_{10}^*}{|f_{01}|^2 + |f_{10}|^2} = \cos\delta \frac{\sqrt{2\mathcal{R} - 1}}{\mathcal{R}}, \quad (9)$$

where  $\delta$  is the relative phase of  $f_{01}$  and  $f_{10}$ , which is non-zero, in the general case.

For the process  $p + p \rightarrow p + p + V^0$  the relation  $\mathcal{P}_{1pp} = \mathcal{P}_{2pp} = 0$  holds, for any vector meson  $V^0$ .

### 3. The dynamics of the $t$ channel

The parametrization of the spin structure of the threshold matrix elements given above is based on fundamental symmetry properties. It is therefore model independent and can be applied to any reaction mechanism. Following the standard way of describing the nucleon–nucleon interaction, we will apply  $t$ -channel  $\pi^0$ ,  $\eta$ ,  $\sigma$  and  $\rho(\omega)$  meson exchanges to  $J/\psi$  production, too. Such an approach has been used to describe the production of light vector mesons such as  $\phi$  and  $\omega$  [30]–[34]. The reaction threshold for  $p + p \rightarrow p + p + J/\psi$  in the laboratory system (LAB) is quite large. However, the formalism of Pomeron exchange cannot be applied here, even at such large energies, because the Regge picture is valid when not only the initial energy is large, but also the excitation energy: the quantity  $(W - W_{th})/W_{th}$  (where  $W$  is the total energy) has to be essentially larger than unity.

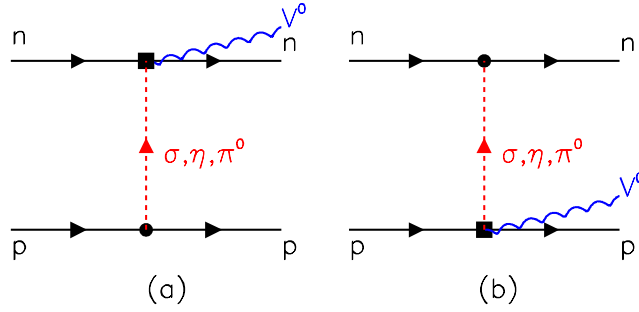
Another important kinematical variable is the momentum transfer squared,  $t = (p_2 - p_4)^2$ , where  $p_2$  and  $p_4$  are the four-momenta of the target and of the scattered nucleon. At threshold, one can find that the variable  $t$  has only a fixed value,  $t = -mm_V$ , where  $m$  is the nucleon mass and  $m_V$  is the  $V$ -meson mass. So, for  $J/\psi$  production this momentum is large:  $t \simeq -3 \text{ GeV}^2$ , therefore all the propagators corresponding to the light mesons are of comparable magnitude ( $t - m_\pi^2 \simeq t - m_\eta^2 \simeq t - m_\sigma^2 \simeq t - m_\rho^2$ ). In such a situation it is not possible to justify the dominance of a particular exchange mechanism, so we have to conclude that threshold heavy  $V^0$ -meson production in NN collisions is determined by the exchange of the coherent sum of many different mesons, with different masses.

But what about the quantum numbers,  $\mathcal{J}^P$ , of these exchanges ( $\mathcal{J}$  is the spin and  $P$  is the parity of the corresponding meson)?

We can use the parametrizations (2) and (4), which are exact and model-independent results, with definite selection rules, from the point of view of the  $s$  channel for  $N + N \rightarrow N + N + V^0$  to understand the  $t$  channel  $\mathcal{J}^P$  picture. Using the Fierz transformations (in two-component form), let us rewrite the general parametrization of the matrix element, see equations (2) and (4), as a  $t$ -channel parametrization:

$$\begin{aligned} (\tilde{\chi}_2 \sigma_y \chi_1) [\chi_4^\dagger \vec{\sigma} \cdot (\vec{U}^* \times \hat{k}) \sigma_y \chi_3^\dagger] &= \frac{1}{2} (\chi_3^\dagger \chi_1) [\chi_4^\dagger \vec{\sigma} \cdot (\vec{U}^* \times \hat{k}) \chi_2] + \frac{1}{2} [\chi_3^\dagger \vec{\sigma} \cdot (\vec{U}^* \times \hat{k}) \chi_1] (\chi_4^\dagger \chi_2) \\ &+ \frac{1}{2} [(\chi_3^\dagger \vec{\sigma} \cdot \vec{U}^* \chi_1) (\chi_4^\dagger \vec{\sigma} \cdot \hat{k} \chi_2) - (\chi_3^\dagger \vec{\sigma} \cdot \hat{k} \chi_1) (\chi_4^\dagger \vec{\sigma} \cdot \vec{U}^* \chi_2)]. \end{aligned} \quad (10)$$

Each term in equation (10) has a precise dynamical interpretation, as it corresponds to  $t$ -channel meson exchange (figure 1) with a definite spin and parity,  $\mathcal{J}^P$ . The first two terms describe a scalar exchange, where the spin structure  $\vec{\sigma} \cdot (\vec{U}^* \times \hat{k})$  (in one vertex) corresponds to the matrix element of the process  $\sigma^* + N \rightarrow V^0 + N$  ( $\sigma^*$  is a virtual scalar meson) at its threshold. The other vertex, corresponding to the  $\sigma$ NN interaction has a structure of the type  $\chi^\dagger \mathcal{I} \chi$ . The last



**Figure 1.** Feynman diagrams for the process  $n + p \rightarrow n + p + V^0$ , describing  $t$ -channel exchanges by neutral  $\sigma$ ,  $\eta$  and  $\pi^0$  mesons.

two terms describe the exchange by neutral pseudoscalar mesons ( $\pi^0$  or  $\eta$ ) with the  $\vec{\sigma} \cdot \hat{U}$ -spin structure of the matrix element for the subprocess  $\pi^{0*}(\eta^*) + N \rightarrow V^0 + N$  at threshold, and with the  $\vec{\sigma} \cdot \hat{k}$  structure for the vertex  $NN\pi(\eta)$ . The same considerations hold for the  $f_{10}$  partial amplitude.

Therefore we can conclude that  $t$ -channel exchanges with  $\mathcal{J}^P = 0^+$  (scalar mesons) and  $\mathcal{J}^P = 0^-$  (pseudoscalar mesons) can be considered as the most probable mechanisms to describe the threshold dynamics of  $J/\psi$  production in NN collisions. Let us consider these mechanisms in detail.

### 3.1. $\sigma$ exchange

The matrix element  $\mathcal{M}_\sigma$ , corresponding to the two diagrams of figure 1, can be written as:

$$\mathcal{M}_\sigma = \mathcal{M}_{1\sigma} + \mathcal{M}_{2\sigma},$$

with the following expression for the matrix element  $\mathcal{M}_{1\sigma}$ , corresponding to figure 1(a):

$$\mathcal{M}_{1\sigma} = -\frac{g_{\sigma NN}}{t - m_\sigma^2} \mathcal{N}(\chi_3^\dagger \mathcal{I} \chi_1) \{ \chi_4^\dagger [i h_{1\sigma} \hat{k} \cdot \vec{U}^* + h_{2\sigma} \vec{\sigma} \cdot (\hat{k} \times \vec{U}^*)] \chi_2 \}, \quad (11)$$

where  $g_{\sigma NN}$  is the  $\sigma NN$  coupling constant,  $\mathcal{I}$  is the unit  $2 \times 2$  matrix,  $\mathcal{N} = 2m(E + m) = m(m_V + 4m)$  is a normalization factor, which arises from the transformation of the invariant matrix element for the considered process (in terms of the four-component spinors for the initial and final nucleons) to the two-component form, which is better adapted to the description of threshold spin structure in the CMS of the considered process. We used the following formula for the threshold energy of the initial nucleons,  $E = W/2 = m + m_V/2$ . The complex amplitudes  $h_{1\sigma}$  and  $h_{2\sigma}$  describe two possible threshold partial transitions in  $\sigma^* + N \rightarrow V^0 + N$ :  $\ell_\sigma = 1 \rightarrow \mathcal{J}^P = 1/2^-$  and  $3/2^-$ , where  $\ell_\sigma$  is the orbital momentum of the initial  $\sigma N$  system. One can find that:

$$h_{1\sigma} = h_{1/2} + 2h_{3/2}, \quad h_{2\sigma} = h_{1/2} - h_{3/2},$$

where  $h_{1/2}$  and  $h_{3/2}$  are the partial amplitudes corresponding to the two possible values of the total angular momentum in  $\sigma^* + N \rightarrow V^0 + N$ .

Comparing the spin structure of the matrix elements for the processes  $n + p \rightarrow n + p + V^0$ , equation (4) and  $\sigma + N \rightarrow N + V^0$ , equation (11), one can see that only the amplitude  $h_{2\sigma}$  has to be kept, because it generates transversally polarized  $V^0$  mesons. First of all, this means that the



cross sections of the processes  $n + p \rightarrow n + p + V^0$  and  $\sigma + N \rightarrow N + V^0$  are determined by different combinations of the amplitudes  $h_{1\sigma}$  and  $h_{2\sigma}$ . This is a result of the following formulae for the corresponding cross sections:

$$\frac{d\sigma}{d\Omega}(\sigma N) \simeq |h_{1\sigma}|^2 + 2|h_{2\sigma}|^2, \quad \frac{d\sigma}{d\omega}(np \rightarrow npV) \simeq |h_{2\sigma}|^2.$$

Therefore these cross sections must be independent. Moreover, both amplitudes  $f_{01}$  and  $f_{10}$ , for  $n + p \rightarrow n + p + V^0$  in the case of  $\sigma$  exchange, being proportional to  $h_{2\sigma}$ , have to satisfy simple relations. In such a case, definite numerical values can be derived for the polarization observables in  $V$ -meson production for  $np$  collisions. To prove this, let us transform the matrix element (11) into the 'standard' parametrization of equation (4), in terms of definite quantum numbers of the  $s$  channel:

$$-(\chi_3^\dagger \chi_1) (\chi_4^\dagger \vec{\sigma} \cdot \vec{A} \chi_2) = \frac{1}{2} [-(\tilde{\chi}_2 \sigma_y \vec{\sigma} \cdot \vec{A} \chi_1) (\chi_4^\dagger \sigma_y \tilde{\chi}_3^\dagger) + (\tilde{\chi}_2 \sigma_y \chi_1) (\chi_4^\dagger \vec{\sigma} \cdot \vec{A} \sigma_y \tilde{\chi}_3^\dagger) + i\epsilon_{ikl} A_i (\tilde{\chi}_2 \sigma_y \sigma_l \chi_1) (\chi_4^\dagger \sigma_k \sigma_y \tilde{\chi}_3^\dagger)], \quad (12)$$

where  $\vec{A} = (\hat{k} \times \vec{U}^*)$ . From equation (12) one can see that  $\mathcal{M}_{1\sigma}$  contains not only the structures which are allowed by symmetry selection rules, but also a contribution which corresponds to a triplet–triplet transition in the  $np$  system (last term in equation (12)). Such a transition is forbidden by the generalized Pauli principle, following from the isotopic invariance of the strong interaction, and should not appear in the total matrix element  $\mathcal{M}_\sigma$ .

Let us consider in a similar way the matrix element  $\mathcal{M}_{2\sigma}$ :

$$\mathcal{M}_{2\sigma} = -\frac{g_{\sigma NN}}{t - m_\sigma^2} \mathcal{N} \{ \chi_3^\dagger [i h_{1\sigma} \hat{k} \cdot \vec{U}^* + h_{2\sigma} \vec{\sigma} \cdot (\hat{k} \times \vec{U}^*)] \chi_1 \} (\chi_4^\dagger \mathcal{I} \chi_2), \quad (13)$$

where we applied the following relations:  $g_{\sigma pp} = g_{\sigma nn} = g_{\sigma NN}$ ,  $h_{i\sigma}(\sigma n \rightarrow n V^0) = h_{i\sigma}(\sigma p \rightarrow p V^0)$ ,  $i = 1, 2$ , which follow from the isotopic invariance of the strong interaction, in the case of an isoscalar vector meson. Note that here we use the same propagator as in equation (11). This is correct in threshold conditions, because any different propagator will generate higher waves in the initial and final states. Summing the two contributions in the matrix element,  $\mathcal{M}_\sigma$ , the wrong term corresponding to the triplet–triplet transition in  $n + p \rightarrow n + p + V^0$  is exactly cancelled:

$$\mathcal{M}_{1\sigma} + \mathcal{M}_{2\sigma} = -(\tilde{\chi}_2 \sigma_y \vec{\sigma} \cdot \vec{A} \chi_1) (\chi_4^\dagger \sigma_y \tilde{\chi}_3^\dagger) + (\tilde{\chi}_2 \sigma_y \chi_1) (\chi_4^\dagger \vec{\sigma} \cdot \vec{A} \sigma_y \tilde{\chi}_3^\dagger).$$

Therefore, for  $\sigma$  exchange, one finds:

$$f_{10}^{(\sigma)} = -f_{01}^{(\sigma)} = -\frac{g_{\sigma NN}}{t - m_\sigma^2} \mathcal{N} h_{2\sigma}. \quad (14)$$

Independently of the numerical values of the coupling constant  $g_{\sigma NN}$  and of the partial amplitude  $h_{2\sigma}$  for the process  $\sigma + N \rightarrow N + V^0$ , the polarization observables for the process  $n + p \rightarrow n + p + V^0$  and the ratio  $\mathcal{R}$  (see equation (7)), take the following values (in the framework of  $\sigma$  exchange):

$$2\mathcal{A}_{1np}^{(\sigma)} = \mathcal{P}_{1np}^{(\sigma)} = -1 \quad \text{and} \quad \mathcal{R}^{(\sigma)} = 1. \quad (15)$$

Note that introducing phenomenological form factors in the expression for  $\mathcal{M}_\sigma$  affects the absolute value of the cross section, but cannot change the relation  $f_{10}^{(\sigma)} = -f_{01}^{(\sigma)}$  and therefore the results (15).



### 3.2. $\eta$ exchange

Similarly to  $\sigma$  exchange, the  $\eta$  exchange is characterized by two diagrams (figure 1) and the matrix element is the sum of two matrix elements, corresponding to figures 1(a) and (b):

$$\mathcal{M}_\eta = \mathcal{M}_{1\eta} + \mathcal{M}_{2\eta},$$

where the matrix element  $\mathcal{M}_{1\eta}$  can be written as:

$$\mathcal{M}_{1\eta} = -\frac{g_{\eta NN}}{t - m_\eta^2} \left( \frac{k}{E + m} \right) \mathcal{N} \{ \chi_3^\dagger [h_{1\eta} \vec{\sigma} \cdot \vec{U}^* + h_{2\eta} \vec{\sigma} \cdot \hat{k} \vec{U}^* \cdot \hat{k}] \chi_1 \} (\chi_4^\dagger \vec{\sigma} \cdot \hat{k} \chi_2), \quad (16)$$

where  $h_{1\eta}$  and  $h_{2\eta}$  are two independent partial amplitudes, which describe the threshold spin structure for the subprocess  $\eta^* + N \rightarrow V^0 + N$ . These amplitudes correspond to two allowed threshold partial transitions (in  $\eta^* + N \rightarrow V^0 + N$ ):  $\ell_i = 0 \rightarrow j^P = 1/2^-$  and  $\ell_i = 2 \rightarrow j^P = 3/2^-$ . The factor  $k/(E + m) = \sqrt{m_V/(m_V + 4m)}$  arises from the transformation from the relativistic expression of the  $\eta NN$  vertex,  $\bar{u}(p_2) \gamma_5 u(p_1)$ , to the two-component form in the CMS of the  $n + p \rightarrow n + p + V^0$  reaction,  $\vec{\sigma} \cdot \hat{k}$ .

Again, one can prove that only the sum  $\mathcal{M}_{1\eta} + \mathcal{M}_{2\eta}$  generates the correct spin structure for threshold matrix element  $\mathcal{M}_\eta$  (again taking into account the isotopic invariance for both vertexes of the considered diagrams:  $\eta NN$  and  $\eta + N \rightarrow N + V^0$ ,  $N = p$  or  $n$ ):

$$\mathcal{M}_{1\eta} + \mathcal{M}_{2\eta} = \frac{g_{\eta NN}}{t - m_\eta^2} \mathcal{N} \sqrt{\frac{k}{E + m}} h_{1\eta} [(\tilde{\chi}_2 \sigma_y \vec{\sigma} \cdot \vec{A} \chi_1) (\chi_4^\dagger \sigma_y \tilde{\chi}_3^\dagger) + (\tilde{\chi}_2 \sigma_y \chi_1) (\chi_4^\dagger \vec{\sigma} \cdot \vec{A} \sigma_y \tilde{\chi}_3^\dagger)], \quad (17)$$

with the following relation for the partial amplitudes for  $n + p \rightarrow n + p + \eta$ :

$$f_{10}^{(\eta)} = f_{01}^{(\eta)} \quad (18)$$

and definite numerical predictions for the polarization phenomena and for the ratio  $\mathcal{R}$ :

$$\mathcal{A}_{\text{inp}}^{(\eta)} = -\frac{1}{2}, \quad \mathcal{P}_{\text{inp}}^{(\eta)} = 1 \quad \text{and} \quad \mathcal{R}^{(\eta)} = 1. \quad (19)$$

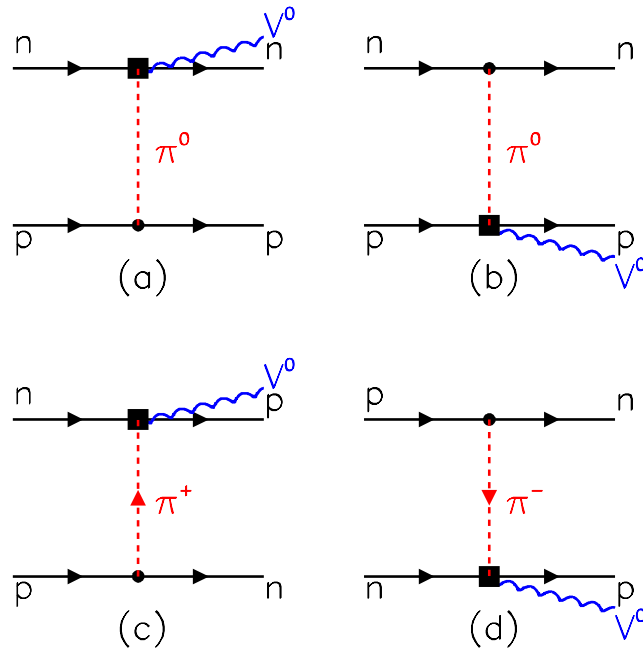
So, only the coefficient  $\mathcal{P}_{\text{inp}}^{(\eta)}$  can discriminate between  $\eta$  and  $\sigma$  exchanges.

### 3.3. $\pi$ exchange

Due to the isotopic invariance of the strong interaction, it is necessary to consider four Feynman diagrams, corresponding to the exchange of neutral and charged pions in  $n + p \rightarrow n + p + V^0$  (see figure 2). Taking into account the isotopic relations between different coupling constants in  $NN\pi$  vertexes and different amplitudes for the processes  $\pi + N \rightarrow N + V^0$ , one can find the following expressions for the amplitudes  $f_{10}^{(\pi)}$  and  $f_{01}^{(\pi)}$ :

$$f_{10}^{(\pi)} = -\frac{g_{\pi NN}}{t - m_\pi^2} h_{1\pi} \mathcal{N} \sqrt{\frac{m_V}{4m + m_V}}, \quad f_{01}^{(\pi)} = -3f_{10}^{(\pi)}, \quad (20)$$

and the single amplitude  $f_{10}^{(\pi)}$  for the process  $p + p \rightarrow p + p + V^0$  is equal to  $2f_{10}^{(\pi)}$  ( $np \rightarrow npV^0$ ). Note that the spin structure for the processes  $\pi + N \rightarrow N + V^0$  and  $\eta + N \rightarrow N + V^0$  has to be similar.



**Figure 2.** Pion exchange for the process  $n + p \rightarrow n + p + V^0$ .

Independently of the concrete model for the amplitude  $h_{1\pi}$  of the process  $\pi + N \rightarrow N + V^0$ , the relations (20) allow us to predict definite values for the polarization observables and for the ratio  $\mathcal{R}$ :

$$\mathcal{A}_{1np}^{(\pi)} = -\frac{9}{10}, \quad \mathcal{P}_{1np}^{(\pi)} = -\frac{3}{5} \quad \text{and} \quad \mathcal{R}^{(\pi)} = 5 \quad (21)$$

which are very different from the previous cases of pure  $\sigma$  or  $\eta$  exchanges.

### 3.4. 'Realistic model': $\pi + \eta$ exchange

Based on the previous results for  $t$ -channel exchanges, we can build a more realistic model, combining the contributions of different mesons. As an example, let us consider the case of  $\pi + \eta$  exchange, with the following expressions for the allowed threshold partial amplitudes  $f_{10}$  and  $f_{01}$  of the process  $n + p \rightarrow n + p + V^0$ :

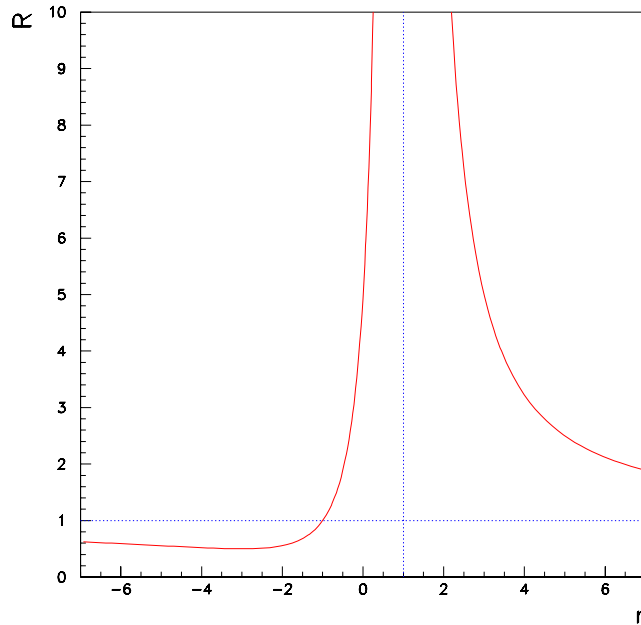
$$f_{10} = -f_{\pi}(1 - r), \quad f_{01} = f_{\pi}(3 + r), \quad (22)$$

where  $f_{\pi} = [g_{\pi NN}/(t - m_{\pi}^2)]\sqrt{m_V/(m_V + 4m)}h_{1\pi}$  and the ratio

$$r = (g_{\eta NN}/g_{\pi NN})(h_{1\eta}/h_{1\pi})(t - m_{\pi}^2)/(t - m_{\eta}^2)$$

characterizes the relative role of  $\eta$  and  $\pi$  exchanges in  $n + p \rightarrow n + p + V^0$ . Therefore, we can find the following results for the polarization observables in  $n + p \rightarrow n + p + V^0$  and for the ratio  $\mathcal{R}$  of the total cross section for  $n + p$  and  $p + p$  collisions:

$$\begin{aligned} \mathcal{A}_{1np} &= -\frac{9 + 6\mathcal{R}e r + |r|^2}{2(5 + 2\mathcal{R}e r + |r|^2)}, & \mathcal{P}_{1np} &= -\frac{3 - 2\mathcal{R}e r - |r|^2}{5 + 2\mathcal{R}e r + |r|^2}, \\ \mathcal{R} &= \frac{5 + 2\mathcal{R}e r + |r|^2}{|1 - r|^2}. \end{aligned} \quad (23)$$



**Figure 3.** Dependence of  $\mathcal{R}$  on  $r$ .

This primarily means that, in the framework of the considered model, two independent parameters  $\mathcal{R}er$  and  $|r|^2$  enter into the definition of three observables. Therefore a simultaneous measurement of  $\mathcal{P}_{1np}$  and  $\mathcal{A}_{1np}$  can determine uniquely  $\mathcal{R}er$  and  $|r|^2$  (with the evident condition  $|\mathcal{R}er| < |r|$ ):

$$\mathcal{R}er = -1 - 2\frac{1 + 2\mathcal{A}_{1np}}{1 - \mathcal{P}_{1np}}, \quad |r|^2 = -3 + 4\frac{3 + 2\mathcal{A}_{1np}}{1 - \mathcal{P}_{1np}}. \quad (24)$$

The situation is simplified if the ratio  $r$  is a real parameter. This is the case in the framework of the effective Lagrangian approach for the processes  $\eta(\pi) + N \rightarrow N + V^0$ , near threshold, where the corresponding pole Feynman diagrams originate the real amplitudes  $h_{1\eta}$  and  $h_{1\pi}$ . It is also the case for the  $s$  channel  $N^*$  contribution, which is common to  $\eta + N$  and  $\pi + N$  interactions. For  $J/\psi$  production the first case seems to be the most probable.

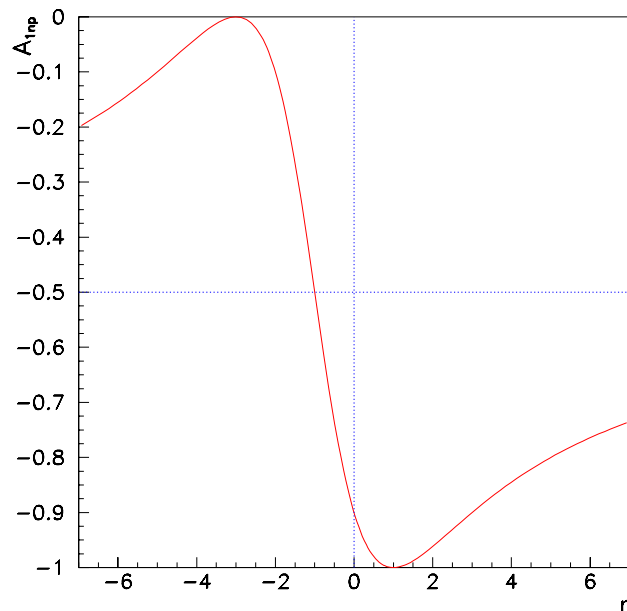
For a real value of  $r$ , the following quadratic relation between polarization observables  $\mathcal{P}_{1np}$  and  $\mathcal{A}_{1np}$  holds:

$$4\mathcal{A}_{1np} + 4\mathcal{A}_{1np}^2 + \mathcal{P}_{1np}^2 = 0. \quad (25)$$

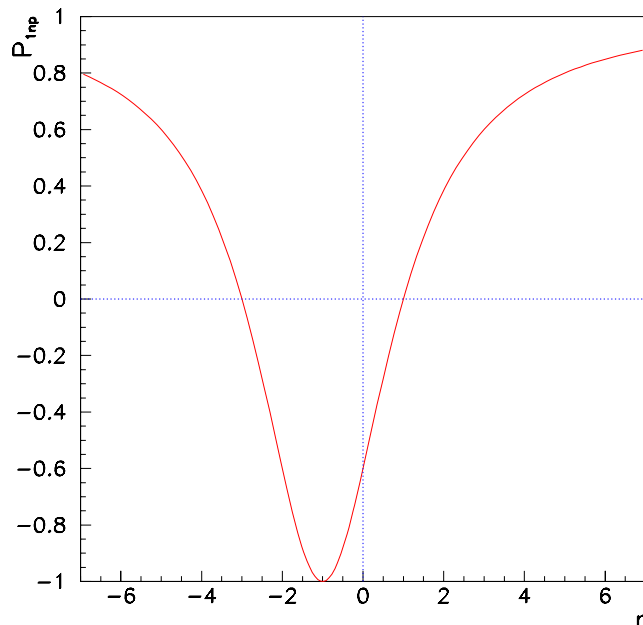
After measuring the ratio  $\mathcal{R}$  (of total cross sections for np and pp interactions) it should be possible to find two different values for  $r$ :

$$r_{\pm} = \frac{\mathcal{R} + 1}{\mathcal{R} - 1} \pm 2\frac{\sqrt{2\mathcal{R} - 1}}{\mathcal{R} - 1}.$$

Knowing  $r$ , it is straightforward to predict any polarization observable for the process  $n + p \rightarrow n + p + V^0$ . The behaviour of  $\mathcal{R}$ ,  $\mathcal{A}_{1np}$  and  $\mathcal{P}_{1np}$  as functions of  $r$ , (when  $r$  is real) are shown in figures 3–5. One can see a strong dependence of the ratio  $\mathcal{R}$  on  $r$  in the region  $-1 \leq r \leq 3$ , where  $\mathcal{R} > 1$ , i.e. with strong isotopic effects. Only for  $r < -1$  do we have  $\mathcal{R} < 1$ , with a weak dependence on the parameter  $r$ . The coefficients  $\mathcal{A}_{1np}$  and  $\mathcal{P}_{1np}$  show particular sensitivity to  $r$ .



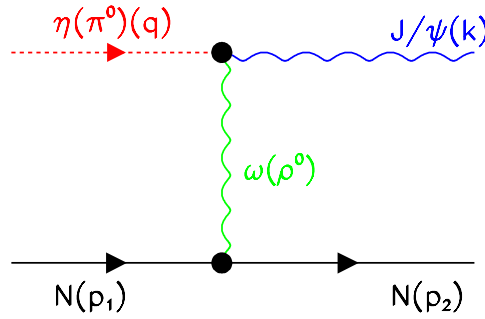
**Figure 4.** Dependence of  $\mathcal{A}_{1np}$  on  $r$ .



**Figure 5.** Dependence of  $\mathcal{P}_{1np}$  on  $r$ .

### 3.5. Attempts to estimate $r$

The previous analysis is based on the most general properties of threshold vector meson production in NN collisions and  $t$ -channel exchanges. In the last case, we used only properties related to the quantum numbers of the corresponding  $t$ -channel mesons: spin, parity and isotopic spin. All previous results are valid for any isoscalar vector meson production,  $\omega$ ,  $\phi$  or  $J/\psi$ . The properties, which are specific to a definite  $V^0$ -meson reaction, appear first of all in the



**Figure 6.** Feynman diagram for  $t$ -channel  $\omega(\rho)$  exchange for the process  $\eta(\pi) + N \rightarrow N + N + J/\psi$ .

kinematics, in particular in the different  $V^0$ -meson masses, and in the values of the partial amplitudes for the binary subprocess,  $M^* + N \rightarrow N + V^0$ , where  $M^* = \sigma, \eta, \pi$  is a virtual meson (with space-like four-momentum). So, for the considered  $(\eta + \pi)$  model, all dynamical information, which is necessary for the calculations of such observables as  $\mathcal{R}$ ,  $\mathcal{A}_{1np}$  and  $\mathcal{P}_{1np}$ , is contained in one complex parameter  $r$ , which characterizes the ratio of the threshold amplitudes for  $\eta(\pi) + N \rightarrow N + V^0$  processes. Therefore the identity of the  $V^0$  production is also contained in the ratio  $r$ .

Let us estimate this ratio in the case of  $J/\psi$  production. To do this, we refer to the existing experimental information about the different hadronic decays of the  $J/\psi$  meson. For example, the following branching ratios [38]:

$$\begin{aligned} \text{BR}(J/\psi \rightarrow \rho^0 \pi^0) &= (4.2 \pm 0.5) \times 10^{-3}, \\ \text{BR}(J/\psi \rightarrow \omega \eta) &= (1.58 \pm 0.16) \times 10^{-3}, \end{aligned}$$

allow us to determine  $r$  in the framework of a simple vector exchange model for the process  $\eta(\pi) + N \rightarrow N + N + J/\psi$  (see figure 6). The nice property of this model is that all the coupling constants are known. The  $\rho$ -exchange mechanism for  $J/\psi$  production in  $\pi N$  collisions has been considered earlier [39, 40]. The corresponding matrix element can be written in the following form:

$$\mathcal{M} = \frac{g_{PVV'}}{t - m_{V'}^2} \frac{\epsilon_{\mu\nu\rho\sigma} U_\mu k_\nu q_\rho J_\sigma}{m_{J/\psi}}, \quad (26)$$

$$J_\sigma = \bar{u}(p_2) \left[ \gamma_\sigma F_1 - \frac{\sigma_{\sigma\nu} (k - q)_\nu}{2m} F_2 \right] u(p_1) = \bar{u}(p_2) \left[ \gamma_\sigma (F_1 + F_2) - \frac{p_{1\sigma} + p_{2\sigma}}{2m} F_2 \right] u(p_1), \quad (27)$$

where  $F_1$  and  $F_2$  are the Dirac and Pauli form factors of the  $V'NN$  vertex of the considered diagram. At the reaction threshold, the matrix element, equations (26) and (27), can be simplified as:

$$\mathcal{M} \simeq \frac{g_{PVV'}}{t - m_{V'}^2} (F_1 + F_2) \chi_2^\dagger (\vec{\sigma} \cdot \vec{U}^* - \vec{\sigma} \cdot \hat{k} \hat{k} \cdot \vec{U}^*) \chi_1. \quad (28)$$

Taking into account VDM predictions for the  $(F_1 + F_2)$  term, which in the case of the  $\omega NN(\rho NN)$  vertex, is proportional to the isoscalar,  $\mu_p + \mu_n$ , (isovector,  $\mu_p - \mu_n$ ), magnetic moment of the nucleon, one can find:

$$r = \frac{g_{\eta NN} (\mu_p + \mu_n)}{g_{\pi NN} (\mu_p - \mu_n)} \frac{g(J/\psi \rightarrow \eta\omega)}{g(J/\psi \rightarrow \pi^0 \rho^0)} \simeq \frac{g_{\eta NN}}{g_{\pi NN}} \frac{0.88}{4.8} \sqrt{\frac{\Gamma(J/\psi \rightarrow \eta\omega)}{\Gamma(J/\psi \rightarrow \pi^0 \rho^0)}} \simeq \frac{1}{7} \left| \frac{g_{\eta NN}}{g_{\pi NN}} \right|,$$

where  $g(\Gamma)$  is the corresponding coupling constant (decay width). All existing analysis of threshold  $\eta$ -meson photoproduction on protons [41] indicates that  $g_{\eta NN} \ll g_{\pi NN}$ . Therefore, in the framework of such a model, we have  $|r| \ll 1$ . From these considerations we cannot determine the sign of the ratio  $r$ , but the small value of  $|r|$  indicates that the np cross section can be essentially larger than pp cross section, in the case of  $J/\psi$  production.

However, conclusions could be different if one takes another set of experimental data about  $J/\psi$  decays [38]:

$$\begin{aligned} \text{BR}(J/\psi \rightarrow p\bar{p}\eta) &= (2.09 \pm 0.18) \times 10^{-3}, \\ \text{BR}(J/\psi \rightarrow p\bar{n}\pi^-) &= (2.00 \pm 0.10) \times 10^{-3}. \end{aligned} \quad (29)$$

Evidently both these decays can be considered as crossed channels of the processes  $\eta(\pi) + N \rightarrow N + J/\psi$ . Generally, each decay  $J/\psi \rightarrow N + \bar{N} + P$  ( $P$  is the pseudoscalar meson,  $P = \pi$  or  $\eta$ ) is characterized by a complicated spin structure—with six independent scalar (and complex) amplitudes, which are functions of two independent kinematical variables. It is not possible to restore the full spin structure, from a knowledge of the branching ratio alone (with unpolarized particles). Moreover, there is the delicate problem of the extrapolation from the decay region of the kinematical variables (of the process  $J/\psi \rightarrow N + \bar{N} + P$ ) to the scattering region (of the process  $P + N \rightarrow N + J/\psi$ ). To overcome this problem, let us consider the oversimplified assumption that the two types of processes  $J/\psi \rightarrow N + \bar{N} + P$  and  $P + N \rightarrow N + J/\psi$  are driven by an effective contact four-particle interaction, with a single coupling constant. The exact spin structure of this interaction is not important for our considerations. In such an approximation the ratio  $r$  can be estimated from the following formula:

$$r = \frac{g_{\eta NN} (t - m_\pi^2)}{g_{\pi NN} (t - m_\eta^2)} \left[ \frac{\text{BR}(J/\psi \rightarrow N\bar{N}\eta)}{\text{BR}(J/\psi \rightarrow N\bar{N}\pi^-)} \right]^{1/2} \simeq \frac{g_{\eta NN}}{g_{\pi NN}} < 1.$$

Again the sign of  $r$  cannot be determined by such considerations, but, again the value of  $r$  which has been derived is in the range where the ratio  $\mathcal{R}$  is very sensitive to the value of  $r$ . Note that the dependence of the polarization observables  $\mathcal{A}_{1np}$  and  $\mathcal{P}_{1np}$  is also quite large, in this region of  $r$ .

In the previous considerations, the effects of the final-state interaction in the produced NN $J/\psi$  three-particle system were not taken into account. In the near-threshold region, the NN interaction is well known, in terms of the corresponding scattering energies and effective radius. It is not the case for the  $J/\psi$ N interaction. Note in this connection, that the total  $J/\psi$ N cross section is not well known at present [42]. For example, photoproduction data give values of 3–4 mb [43]–[45], while the analysis of charmonium absorption on nucleons (at relatively high momentum) in  $p + A$  and  $A + A$  reactions suggests larger values, 6–7 mb [46, 47]. These larger values can be explained in the framework of effective Lagrangian approaches [48]–[50]. Different methods have been suggested for a direct measurement of this quantity, through the processes  $\pi + d \rightarrow J/\psi + p + p$  [39, 40],  $\bar{p} + d \rightarrow J/\psi + n$  [51] and charmed meson production in  $\bar{p} + A$  collisions [52].

Note that, in the general case, it is necessary to define two different  $J/\psi$  cross sections corresponding to transversal and longitudinal  $J/\psi$  polarization. For example, the data about  $\gamma + N \rightarrow J/\psi + N$  are sensitive to  $\sigma_T(J/\psi N)$  cross sections, with transversal  $J/\psi$  polarization, if the VDM hypothesis is correct. Another possible method is to determine the average  $\sigma_{Av}(J/\psi N)$  cross section, obtained by averaging over the  $J/\psi$  polarization. In the case of interest here, in the near-threshold  $J/\psi$  production in nucleon–nucleon collisions,  $N + N \rightarrow N + N + J/\psi$ , the

possible effects of the  $J/\psi N$  interaction are given by the  $\sigma_T(J/\psi N)$  cross section alone, because we showed that the kinematical conditions are such that the  $J/\psi$  is produced with transversal polarization, only. To avoid double counting in the calculation of the  $J/\psi N$  final interaction, one has to take into account only the  $J/\psi N$  interaction with a nucleon spectator, produced in the vertex  $\pi NN$ .

Let us compare the cross sections for the  $\phi$  and  $J/\psi$  production in pp collisions—in the framework of the same approach, namely for  $\pi$  exchange in  $N + N \rightarrow N + N + V^0$  and  $\rho$  exchange for the subprocess  $\pi + N \rightarrow N + V^0$ , with  $V^0 = \phi$  or  $J/\psi$ . For the same value of  $Q = \sqrt{s} - 2m - m_V$ , we can write (in the near-threshold region):

$$R(J/\psi, \phi) = \frac{\sigma(\text{pp} \rightarrow \text{pp}J/\psi)}{\sigma(\text{pp} \rightarrow \text{pp}\phi)} \simeq \frac{g^2(J/\psi \rightarrow \pi\rho)}{g^2(\phi \rightarrow \pi\rho)} \left( \frac{t_\phi - m_\pi^2}{t_{J/\psi} - m_\pi^2} \right)^2 \left[ \frac{F(t_{J/\psi})}{F(t_\phi)} \right]^2,$$

where  $g(V \rightarrow \pi\rho)$  is the coupling constant for the decay  $V \rightarrow \pi\rho$ ,  $t_V = -mm_V$  is the threshold value of the momentum transfer squared,  $F(t)$  is a phenomenological form factor for the vertex  $\pi^* \rho^* V^0$ , with virtual  $\pi$  and  $\rho$ . Using the existing experimental data about the decays  $J/\psi \rightarrow \pi + \rho$  and  $\phi \rightarrow \pi + \rho$ , one can find  $g^2(J/\psi \rightarrow \pi\rho)/g^2(\phi \rightarrow \pi\rho) \simeq 10^{-4}$ , so that  $R(J/\psi, \phi) \simeq 10^{-5} [F(t_{J/\psi})/F(t_\phi)]^2$ . Taking into account that  $\sigma(\text{pp} \rightarrow \text{pp}\phi) \simeq 300$  nb at  $p_L = 3.67$  GeV [6], one can find that  $\sigma(\text{pp} \rightarrow \text{pp}J/\psi) \simeq 0.03$  nb  $[F(t_{J/\psi})/F(t_\phi)]^2$ . This value is too small, when compared with the existing experimental value for the lowest  $\sqrt{s} = 6.7$  GeV, namely [4]  $\sigma_{exp}(\text{pp} \rightarrow \text{pp}J/\psi) = 0.3 \pm 0.09$  nb.

Note that the  $\rho$ -exchange model for  $\sigma(\pi N \rightarrow J/\psi)$  gives a cross section one order of magnitude smaller than other possible theoretical approaches [53]–[55]. One possibility is to explain the value of  $\sigma_{exp}(\text{pp} \rightarrow \text{pp}J/\psi)$ . Another possibility is to take  $[F(t_{J/\psi})/F(t_\phi)]^2 \simeq 10$ , which could be plausible, because the  $J/\psi = c\bar{c}$  system must have a smaller size than  $\phi = s\bar{s}$ . This can be realized by the following form factor:

$$F_V(t) = \frac{1}{1 - \frac{t}{\Lambda_V^2}},$$

with  $\Lambda_V \simeq m_V$ .

#### 4. Conclusions

Let us summarize the main results concerning the theoretical analysis of  $J/\psi$  production in nucleon–nucleon collisions in the threshold regime.

- We established the spin structure of the threshold matrix element in terms of a limited number of partial transitions, corresponding to S-wave production of final particles in the process  $N + N \rightarrow N + N + J/\psi$ .
- We proved the essential role of isotopic effects for  $J/\psi$  production in pp and np collisions. The two reactions present very different characteristics concerning:
  - \* the number of independent partial transitions,
  - \* the spin structure of the threshold matrix elements,
  - \* the value of the absolute cross sections,
  - \* the polarization phenomena.

Note that all these differences are generated by a common mechanism: the origin of the essential difference has to be found in the different role of the Pauli principle for pp and pn collisions in the near-threshold region.



- This model-independent analysis shows the universality of theoretical considerations of threshold production of different vector mesons in nucleon–nucleon collisions, starting from *light*  $\rho$ ,  $\omega$ ,  $\phi$  to charmed mesons.
- Only one polarization observable, the  $J/\psi$  polarization, is identical for pp and pn collisions: the  $J/\psi$  meson is transversally polarized—even in collisions of unpolarized nucleons. The experimental determination of the ratio of the total cross sections for np and pp collisions is important for the identification of the reaction mechanism. Polarization phenomena, which are trivial for threshold pp collisions, will be very useful for np collisions. The polarization transfer coefficients show the largest sensitivity to the nature (quantum numbers) of  $t$ -channel exchanges.
- The existing experimental data on the specific decays of  $J/\psi$ , such as  $J/\psi \rightarrow \rho\pi$ ,  $J/\psi \rightarrow \omega\eta$ ,  $J/\psi \rightarrow N\bar{N}\pi$ ,  $J/\psi \rightarrow N\bar{N}\eta$ , constrain a possible model for the threshold  $J/\psi$  production in nucleon–nucleon collisions. These data show, in a transparent way, the link between the possible reaction mechanisms on one side, and the physics of  $J/\psi$  decays in the usual hadrons ( $N$ ,  $\bar{N}$ ,  $\pi$ ,  $\rho$  . . .), on the other side.

In this paper we stress the importance of np collisions in the threshold production of  $J/\psi$ , due to the large sensitivity to the underlying reaction mechanisms. Therefore a polarized neutron beam of corresponding energies or a polarized target are potentially very interesting, in this respect. In the planned GSI facility, the possibility of having polarized targets has not been excluded. Moreover, the unpolarized GSI beams will allow us to determine the intensity of singlet and triplet amplitudes through the comparison of np- and pp-induced cross sections.

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