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COSY Letter of Intent

- Title of Experiment: Study of ϕ-meson production in interactions of polarized protons with a polarized proton target.
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- Type of beam: Polarized p
- Type of target: Polarized target (storage cell)
- Momentum range: 3400 ± 100 MeV/c
- Intensity: $5 \cdot 10^{10}$ $\vec{p}$ in the ring
- Total number of beam particles needed:
- Earliest date of installation: Beginning of 1998
- Equipment from KFA/IKP: 0^0 Facility

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1 Introduction

We propose to measure ϕ-meson production in the interaction of a polarized proton beam with a polarized proton target

$$\vec{p} + \vec{p} \longrightarrow p + p + \phi \tag{1}$$

at projectile energies in the vicinity of the threshold for ϕ production at $T_{\rm th} = 2.59$ GeV.

It is predicted [1] that the ϕ production should be enhanced for parallel spins of both nucleons in the initial state and suppressed for the antiparallel configuration.

This prediction is based on the assumption of the existence a substantial (on the level of a few percent) admixture of strange quarks in the nucleon wave function even at small momentum transfer. Recent results of experiments with stopped antiprotons at LEAR (CERN) (for a review, see [2]) show a strong dependence of ϕ production on the quantum numbers of the initial state. This effect was interpreted [1] as a manifestation of the polarized intrinsic nucleon strangeness.

The experimental verification of the effects caused by the intrinsic nucleon strangeness is important for the understanding of fundamental properties of the nucleon.

2 Physical motivation

2.1 Strong violation of the OZI rule

Recent results from the experiments on the ϕ-meson production in the annihilation of stopped antiprotons, performed at LEAR(CERN), have demonstrated a significant violation of the Okubo-Zweig-Iizuka (OZI) rule (by a factor of 30-50). The OZI rule [3] forbids creation of new flavors confined in only one particle. Thus, if hadrons A, B and C consist of light quarks only, then the reaction

$$A + B \longrightarrow C + s\bar{s} \tag{2}$$

is strictly forbidden. This means that if the ϕ meson was a pure $\bar{s}s$ state, it cannot be produced in the interaction of non-strange hadrons. However, the ϕ and ω are mixtures of SU(3) singlet and octet and the ϕ can be created in hadron interactions due to a small admixture of the light quarks in its wave function. Then the ratio between the cross sections of ϕ and ω meson production should be

$$R = \frac{\sigma(A + B \to \phi X)}{\sigma(A + B \to \omega X)} = \tan^2(\Theta - \Theta_i) \cdot f \ . \tag{3}$$

Here f is a kinematical phase space factor, Θ and Θ_i are the physical and ideal ($\Theta_i = 35.3^0$) mixing angles, respectively.

Since the vector mesons are practically ideally mixed, the difference $\delta = \Theta - \Theta_i$ is small: the mixing angle from the quadratic Gell-Mann-Okubo mass formula is $\Theta = 39^0$ and from the linear one it is $\Theta = 36^0$. Substituting these values in Eq. (3) one obtains for $f = 1$:

$$R = 4.2 \cdot 10^{-3} \quad \text{for the quadratic mass formula and} \tag{4}$$

$$R = 0.15 \cdot 10^{-3} \qquad \text{for linear the mass formula.} \tag{5}$$

In Fig.1 the ratio $R = \phi X/\omega X$ multiplied by 10^3 is plotted for different reactions at different momenta. One can immediately realize that for pp, πp interactions and $\bar{p}p$ annihilation in flight the deviation from the OZI prediction is small. However, for $\bar{p}p$ annihilation at rest the violation of the OZI rule is rather dramatic.

Figure 1: The ratio $R = \phi X/\omega X \cdot 10^3$ for different reactions at different momenta.

The strong OZI rule violation was observed in the experiments of the ASTERIX, OBELIX and Crystal Barrel collaborations at LEAR [4]-[7]. It was seen in the following channels:

$$\bar{p} + p \rightarrow \phi + \gamma \tag{6}$$
$$\bar{p} + p \rightarrow \phi + \pi^0 \tag{7}$$
$$\bar{n} + p \rightarrow \phi + \pi^+ \tag{8}$$
$$\bar{p} + n \rightarrow \phi + \pi^- \tag{9}$$

for annihilation in liquid and gaseous hydrogen and deuterium targets. The values of the ϕ/ω ratio are significantly higher than the OZI-rule predictions. The largest deviation is for the $\phi\gamma$ channel where $\mathrm{R}(\phi/\omega) \cdot 10^3 = 243 \pm 86$, i.e. about 50 times larger than the OZI prediction $R(\phi/\omega) \cdot 10^3 = 0.15 - 4.2$.

Thus, the very existence of the strong deviation from the OZI rule in the annihilation of stopped antiprotons is a firmly established experimental fact seen by different groups in various reactions.

It is interesting that the OZI rule violation strongly depends on the quantum numbers of the initial state. The conservation of P and C parities strictly fixes the possible quantum numbers of the $N\bar{N}$ initial state in binary reactions of ϕ production. Thus, the $\phi\pi$ final state is only possible either from the spin triplet $^3S_1$ state or from the spin singlet $^1P_1$ state. The ASTERIX collaboration observed [4] that the $\phi\pi$ channel from the $^3S_1$ initial state has the branching ratio $B.R.(\bar{p}p \to \phi\pi^0) = (4.0 \pm 0.8)\cdot 10^{-4}$ and the ratio $R(\phi/\omega)\cdot 10^3 = 76.9 \pm 17.1$. However, no ϕ's were seen in the same channel for annihilation from the $^1P_1$ initial state with the upper limit of $3 \cdot 10^{-5}$.

The large difference in $\phi\pi$ production for annihilation from S and P waves is a very important feature of ϕ production in $N\bar{N}$ annihilation. The key to the understanding of the nature of OZI-rule breaking may be provided by the explanation of this experimental fact. A number of theoretical models were developed for the explanation of these data. It is interesting that the approaches based on the traditional concepts seem to be unable to reproduce all features of the ϕ production observed now (for review, see [2]). At the same time, unconventional ideas like polarized intrinsic strangeness in the nucleon [1] offer a rather natural explanation of the observed facts and suggest a number of new effects to be measured.

All models of the OZI rule violation in annihilation of antiprotons assume that the OZI rule itself is valid. The violation is only apparent and could be regarded as a signal of non-trivial dynamics of the processes considered.

2.2 Polarized intrinsic nucleon strangeness

It was assumed [8, 9] that the abundant ϕ meson production could be the consequence of an admixture of $\bar{s}s$ pairs in the nucleon. At a first glance, the intrinsic strangeness of the nucleon should lead to the same enhancement of the ϕ production in all annihilation channels. That is contrary to the experimental data.

An explanation of the different degree of the OZI-rule violation in different channels of $\bar{p}p$ annihilation can be obtained under the hypothesis of polarized strangeness in the nucleon [1]. Indeed, the results from the deep inelastic lepton-nucleon experiments indicate that strange quarks and antiquarks in the nucleon have a net polarization opposite to the proton spin [10]:

$$\Delta s \equiv \int_0^1 dx[q_\uparrow(x) - q_\downarrow(x) + \bar{q}_\uparrow(x) - \bar{q}_\downarrow(x)] = -0.10 \pm 0.03. \tag{10}$$

It should be noted that it is impossible to directly apply this result from the deep inelastic region to the description of ϕ production at small momentum transfers. This polarization may decrease with decreasing momentum transfer (see, for instance [11]).

Moreover, there are well-motivated expectations that within the chiral quark model it is possible to connect the significant strangeness content in the proton, the negative sign of the strange quark polarization and the recently observed $\bar{u}$-$\bar{d}$ asymmetry in the nucleon[12].

Adopting the interpretation from the deep inelastic region one may ask what happens if the nucleon wave function, even at small momentum transfers, contains an admixture of $\bar{s}s$ pairs with spins of both strange quarks oriented opposite to the nucleon spin.

Let us consider $\bar{p}p$ annihilation from a spin–triplet initial state in which the $\bar{p}$ and p spins are parallel (see, Fig.2). In this case the $\bar{s}$ and s quarks in both nucleons will also have parallel spins. If the rearrangement diagram of Fig.2 is dominant and the polarization of the strange quarks is not changed during the annihilation, then the $\bar{s}$ and s quarks will have parallel spins in the final state as in the quark-model wave function of the ϕ meson. If the $p\bar{p}$ initial state is an S wave, the $\bar{s}s$ pair will probably also be in an S wave as in the ϕ meson. Therefore, the maximum enhancement of ϕ production is expected in the $^3S_1$ channel, as observed in the $\phi\pi$ final state. This model also predicts weaker enhancements in the $^1S_0$ channel, as observed.

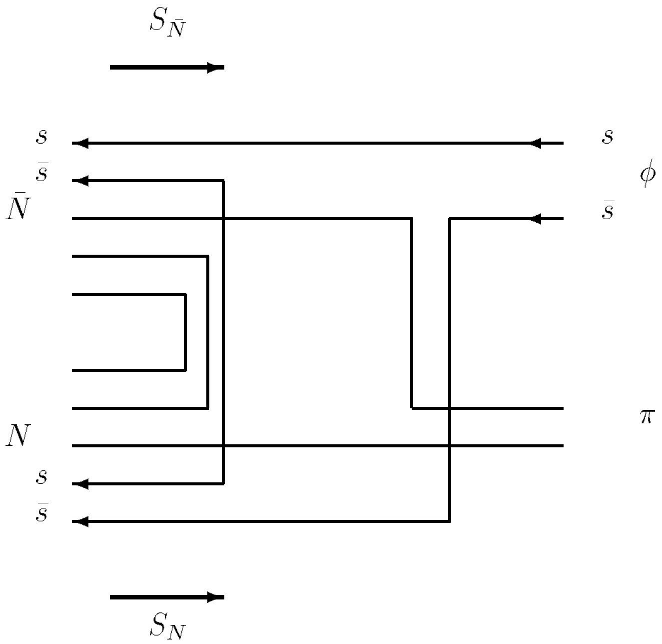

Figure 2: Annihilation of $\bar{N}N \to \phi\pi$ from the spin triplet state. The arrows show the direction of nucleons and strange quark spins.

This model also suggests qualitatively why ϕ production may be more enhanced in $\bar{p}p$ annnihilation at rest than in other hadronic interactions. The reason is that higher–energy collisions involve an increasing admixture of partial waves, implying that the S–wave state "rearrangement" which favours ϕ production becomes progressively more diluted. On the contrary, in the $\bar{p}p$ annihilation at rest only one pure spin state $^3S_1$ is possible for $\phi\pi$ production in S–wave annihilation. To reproduce this situation, for instance in a proton-proton interaction, one should collide a 100% polarized beam with a 100 % polarized target.

The idea that the $\bar{s}s$ in the proton are polarized has interesting implications for reactions with polarized protons, such as

$$\vec{p} + \vec{p} \longrightarrow p + p + \phi \qquad (11)$$

If the idea is correct, ϕ meson production in this reaction should be maximal when the beam and the target nucleons have parallel polarizations, and minimal when they are antiparallel.

An important feature of the intrinsic strangeness effect is the prediction that the spin-triplet initial state will lead to enhanced ϕ production irrespectively of the fact of transverse or longitudinal orientation of the beam-target polarization. Only the value of the total spin of the initial state is relevant.

The important advantage of studying ϕ production in proton-proton collisions (11) is that it is possible to extract the dependence on the spin of the initial state. For annihilation of stopped antiprotons binary reactions of ϕ production are allowed from fixed combinations of spin AND angular momentum of the initial state. Thus, strictly speaking it is impossible to infer that the suppresion of the $\phi\pi^0$ channel from the $^1P_1$ state is due to the antiparallel orientation of the $\bar{s}$ and s quarks in the spin-singlet but not due to different conditions in annihilation from the P wave.

3 The experimental setup

3.1 Experimental layout

Let us consider the typical kinematical features of final state particles in the reaction

$$\begin{array}{rll} \vec{p}+\vec{p} \longrightarrow & p+p+ & \phi \\ & & \rightarrow K^+ + K^- \end{array} \qquad (12)$$

near the threshold for ϕ production $T_{\text{th}} = 2.593$ GeV. Let us take for definiteness a projectile kinetic energy of 2.6 GeV, i.e. 7 MeV above threshold. Then:

- The final state protons are within a very narrow forward cone of 2.8^0. Their typical momenta are around 1 GeV/c.
- Kaons from the ϕ decay have momenta in the range $p_K = 0.37 - 0.84$ GeV/c. The maximum angle between two kaons is around 15^0.

These kinematical features nicely match the abilities of the 0° Facility (ZDF) which now is under construction and where space is available for the integration of a polarized storage-cell target. The experimental layout is shown in Fig.3.

The K^+ from reaction (12) can be measured by the system of telescopes for K^+ identification and the wire chambers of the ZDF spectrometer. Two fast protons can be detected and indentified by the Forward Detector (FD) system.

GEANT simulations of the acceptances and experimental conditions for reaction (12) show that near threshold both protons are within the FD effective acceptance. It means that in principle it is possible to select reaction (12) as a peak at the ϕ mass in the missing-mass spectrum of the two protons. The simulated resolution for the missing mass is rather high (about 1.3 MeV FWHM). So, on the first glance, it might be possible to identify reaction (12) already on the basis of missing mass of two protons in the region of ϕ. However, as it was measured by the SPES3 collaboration [13], the pion background in the ϕ-mass region is high. Therefore, it is obligatory to measure at least one kaon.

Figure 3: Sketch of the experimental setup at the 0° Facility. The with K^+pp mesons will be detected in the side-detection system and the two protons in the forward detectors between the dipoles D2 and D3. The position of the polarized gas target is also indicated.

This possibility exists at the ZDF for K^+ mesons. The array of telescopes for study of subthreshold K^+ production is under construction (see Fig.3). It covers a momentum range of 150-600 MeV/c. The simulated geometrical acceptance for the detection of the K^+ and two protons is $\epsilon_g = 0.23$. The simulated efficiency of the detectors for identifying K^+ mesons is $\sim 15\%$ (including kaon decays between target and detectors). The π^+/K^+ separation was tested for a prototype and is better than 5 orders of magnitude [14]. It is planned to study reaction (12) with the trigger on K^+ in coincidence with the signals from two the protons in the forward detector. Then selection of reaction (12) will be possible by measuring the momenta of two the protons and the K^+.

3.2 Rate estimate

The expected rate of reaction (12) was estimated under the following assumptions:

- Cross-section σ: the cross-section of ϕ production in the few-GeV region is not known. The lowest measured point is at 10 GeV/c [15], where $\sigma = 1.0 \pm 0.4$ μb. We used for an estimation

$$\sigma = 0.5 \ \mu\text{b}.$$

- Polarized beam: we expect an intensity

$$N_{\text{beam}} = 3 \cdot 10^{10} \ \text{s}^{-1}.$$

of the polarized COSY beam

- Polarized target: the polarized gas-target cell for the ZDF is under design now. A cell of 40-50 cm length should provide a target density up to 10^{14} atom $\cdot$ cm^{-2}. We used

$$N_{\text{target}} = 5 \cdot 10^{13} \ \text{atom} \cdot \text{cm}^{-2}.$$

- Acceptance: the simulated geometrical acceptance for K^+pp detection is around 23%. Bearing in mind the efficiency of K^+ registration of 15 % the total acceptance is $\epsilon = 0.23 \cdot 0.15 = 3 \cdot 10^{-2}$. We take conservatively

$$\epsilon = 2 \cdot 10^{-2}.$$

Then the rate R is

$$\begin{aligned} R &= \sigma \cdot N_{\text{beam}} \cdot N_{\text{target}} \cdot \epsilon \cdot T \cdot f(K^+K^-) \\ &= 5 \cdot 10^{-31} \cdot 3 \cdot 10^{10} \cdot 5 \cdot 10^{13} \cdot 2 \cdot 10^{-2} \cdot 1.6 \cdot 10^{6} \cdot 0.49 \ \text{s}^{-1} \\ &= 1.2 \cdot 10^{-2} \ \text{s}^{-1} \approx 40(\text{hour})^{-1} \end{aligned} \tag{13}$$

Here T is the frequency of the COSY beam $T = 1.6 \cdot 10^6$ s^{-1} and $f(K^+K^-)$ is the fraction of the ϕ decaying into K^+K^-.

Typical statistics of ϕ events in the experiments with antiprotons at LEAR is on the level of a total of 10^3 ϕ's. At COSY it is possible to acquire the same statistical accuracy in a reasonable time.

3.3 Background

The main sources of background come from the reactions with pion production, like:

$$p + p \longrightarrow p + p + \pi^+ + \pi^- \tag{14}$$

and non-resonant kaon production, as

$$p + p \longrightarrow p + p + K^+ + K^- \ . \tag{15}$$

$$p + p \longrightarrow p + p + K^+ + \bar{K}^0 + \pi^- \tag{16}$$

Misidentified pions from the reaction (14) being treated as kaons would spread up the narrow signal from the ϕ. However, the K^+-detector system which is being built for subthreshold K^+ studies has a π^+/K^+ separation on the level of 10^5 [14].

The kaon-pair production of (15-16) is unavoidable physical background. In principle, some asymmetry can exist in the production of two kaons in these reactions from spin-parallel and spin-antiparallel initial states of the pp system. To take into account this effect one should perform a control measurements below the threshold of ϕ production. A comparison with the results obtained above the ϕ threshold will help to select the signal from ϕ production. At the proton energies higher than the ϕ threshold, it is also possible to measure the asymmetry outside the ϕ mass region to take into account the effect of the background.

3.4 Expected effect

The magnitude of the expected asymmetry in the ϕ production Y_ϕ

$$A = \frac{Y_\phi(\uparrow\uparrow) - Y_\phi(\uparrow\downarrow)}{Y_\phi(\uparrow\uparrow) + Y_\phi(\uparrow\downarrow)}$$

in the $\vec{p}\vec{p}$ interaction is not known.

Some impressions about the magnitude of the possible effect one can be obtained from the results on ϕ production in $\bar{p}p$ annihilation at rest. It was measured by the OBELIX collaboration [16] that the $\phi\pi^0$ yield from the spin triplet is

$$Y_\phi(^3S_1) = (4.36 \pm 0.4) \cdot 10^{-4}$$

whereas from the spin singlet the $\phi\pi$ channel is absent with the limit

$$Y_\phi(^1P_1) \leq 1.3 \cdot 10^{-5}, \quad 95\% C.L. .$$

Thus, the difference between the ϕ production from different initial spin states in this case is about a factor of 10.

4 Conclusions

It is proposed to measure ϕ-meson production in the interaction of a polarized proton beam with a polarized proton target

$$\vec{p} + \vec{p} \longrightarrow p + p + \phi \tag{17}$$

near threshold of the ϕ production at $T_{\mathrm{th}} = 2.59$ GeV.

The predicted enhancement of the ϕ yield for the spin-triplet initial pp state [1] reflects polarization of the intrinsic nucleon strangeness at small momentum transfer.

The consideration of the possibility for studying this reaction at the COSY 0° Facility (ZDF) show that the apparatus which is under construction for the approved proposals COSY-18 and COSY-20 is also able to detect and select ϕ mesons from the reaction (17). The planned intensity of the polarized COSY beam and ZDF polarized target parameters could provide suitable rates of the reaction to be investigated.

The experimental test of the predictions discussed in this Letter of Intent is important for understanding the fundamental properties of the nucleon.

5 References

References

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