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SEARCH FOR EFFECTS OF THE OZI RULE VIOLATION IN φ AND ω MESONS PRODUCTION IN POLARIZED DEUTERON BEAM INTERACTION WITH POLARIZED PROTON TARGET (PROJECT DPHE3)

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It is proposed to verify the predictions of the intrinsic polarized nucleon strangeness model by investigation of the reaction $\vec{d}+\vec{p}\to {}^3\mathrm{He}+\varphi$ with different deuteron and proton spin orientations. This reaction is very convenient to make such a test because of large momentum transfer and since the substantial OZI rule violation has been already found for this reaction at SATURNE II for the non-polarized proton and deuteron. The predictions of the model are very clear: the φ production should be increased with parallel deuteron and proton spins orientation and suppressed with antiparallel one. We propose to perform measurements using the polarized deuteron beam from the JINR Nuclotron and the BES spectrometer with a movable polarized proton target.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

Поиск эффектов нарушения правила ОЦИ в рождении φ- и ω-мезонов во взаимодействии пучка поляризованных дейтронов с поляризованной протонной мишенью (проект DPHE3)

В.Ю.Алексахин и др.

Предлагается проверка предсказаний модели поляризованной внутренней странности в нуклоне с помощью изучения реакции $\vec{d}+\vec{p}\to {}^3\mathrm{He}+\varphi$ с различными ориентациями спинов дейтрона и протона. Изучение этой реакции имеет ряд преимуществ для проверки предсказаний этой модели, а именно: сильное нарушение правила ОЦИ с неполяризованными начальными частицами уже обнаружено в экспериментах на САТУРН II. Предсказания модели очень четкие: выход φ должен быть усилен при параллельной ориентации спинов дейтрона и протона и подавлен при их антипараллельной ориентации. Предлагается использовать пучок поляризованных дейтронов от нуклотрона ОИЯИ и спектрометр БЕС с передвижной поляризованной протонной мишенью.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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1. Physical Motivation

According to the naive quark models, the proton wave function contains just two u quarks and one d quark. This model gives a good general picture of the hadron structure at large distances, while probes of a shorter distance reveal more constituents like a sea of $\bar{q}q$ ($q = u, d, s$) pairs and gluons, qualitatively as expected on the basis of perturbative QCD. However, there are now some experimental indications that the proton wave function can contain a substantial fraction of $\bar{s}s$ pairs.

The presence of $\bar{s}s$ pairs in the nucleon was first indicated by measurements of the charm production in the deep-inelastic neutrino scattering and low energy πN scattering data on the σ term. The magnitude of the strange quark contribution varies for different nucleon matrix elements. Thus the fraction of the nucleon momentum carried by the strange quarks is $(4.08 \pm 0.41)\%$ [1]. The contribution of the strange quarks in the nucleon mass is surprisingly high $m_s\langle \bar{s}s \rangle = 190 \pm 60$ MeV [1]. Recently the EMC and successor experiments (SMC, E142, E143) have not only confirmed the indication that such pairs are present, but also indicated that they are polarized. This latter observation has stimulated great theoretical interest (for review, see [1]—[3]). A number of competing explanations appeared and attention was drawn back to some old problems.

Thus the presence of a substantial amount of strange quarks in the nucleon arouses a problem of applicability of the Okubo–Zweig–Iizuki (OZI) rule [4] to processes involving baryons. The OZI rule predicts that diagrams with disconnected quark lines should be suppressed as compared to connected quark diagrams. If there are no strange quarks in the nucleon, then production of the φ meson, for instance in $\bar{p}p$ annihilation, should look like in Fig.1(a). The $\bar{s}s$ pair should be created in the final state, which is absent in the initial state, so φ production is described by the disconnected diagram and should be suppressed. On the contrary, production of the ω meson, which contains only light quarks, could be described by the diagram of Fig.1(b), where the quark lines of the initial state are connected with the final state ones. Therefore, no suppression is expected for ω meson production.

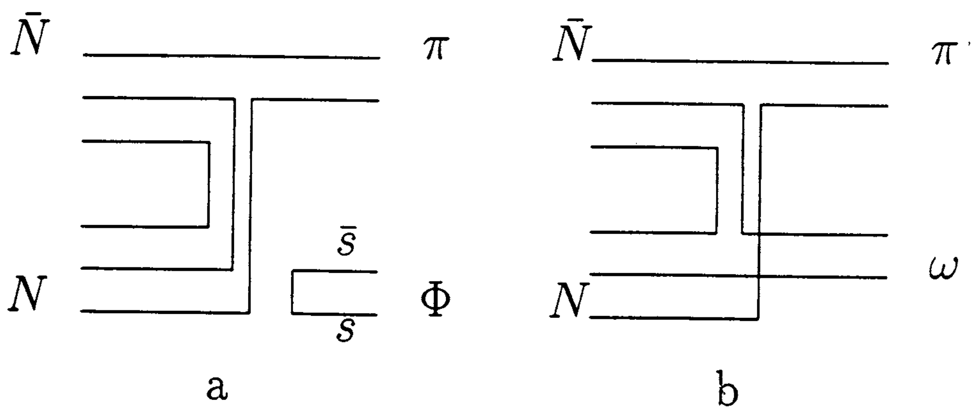

Fig.1. Disconnected quark diagram of φ meson production in $\bar{N}N$ interaction (a). Diagram of ω production in the same process (b)

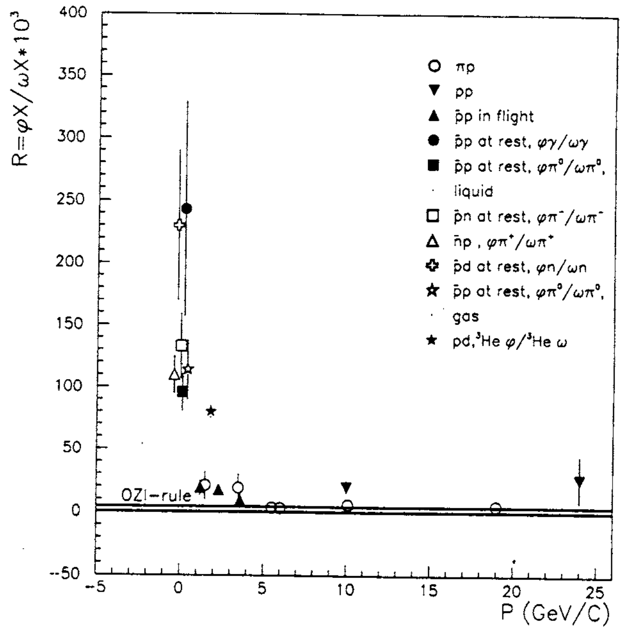

Fig.2. Ratio $R = \varphi X/\omega X$ multiplied by 10^3 for different hadronic interactions

The OZI rule was tested in a number of experiments. The results of these tests are shown in Fig.2, where the ratio $R = \varphi X/\omega X$ multiplied by 10^3 is plotted. One can immediately realize that for *pp*, πp interactions and $\bar{p}p$ annihilations in flight no strong deviations from the OZI rule prediction was found. However, strong violation of the OZI rule was observed in recent experiments with stopped antiprotons at LEAR (CERN).

The very existence of strong deviation from the OZI rule in annihilation of stopped antiprotons is a firmly established experimental fact seen by different groups in different reactions (for a review, see [5]).

The most striking feature of the OZI rule violation found in the experiments at LEAR is its strong dependence on the quantum numbers of the initial state.

For instance, the OBELIX collaboration have studied the channel $\bar{p}p \to \varphi\pi^0$ for annihilation in hydrogen targets with different densities [6], [7] and not only a large ratio φ/ω was found (30 times higher than the naive OZI rule prediction), but also it turned out that the φ production is 50 times more prominent for annihilation from the triplet initial state than from the singlet one.

Some attempts were made to explain the strong OZI rule violation in $\bar{p}p$ annihilation at rest [8]—[10] on the basis of the traditional ideas, but these approaches are unable to reproduce all the features of φ production observed now. On the contrary, the model of the polarized intrinsic nucleon strangeness [11] provides the physically transparent explanation of the observed spin dependence of the φ yield and predicts some definite tests.

1.1. Polarized Intrinsic Nucleon Strangeness. First of all, it is assumed that the OZI rule itself is valid. Its violation is only apparent and could be regarded as a signal of a complicated nucleon structure. It is supposed [11], [12] that the abundant φ meson production could be the consequence of an admixture of $\bar{s}s$ pairs in the nucleon. In this case the φ production in *NN* or $\overline{N}N$ interactions is described by the diagarms with connected *s*-quark lines.

At first glance, the intrinsic strangeness of the nucleon should lead to the same enhancement of the φ production in all annihilation channels. This is in contradiction with the experimental data. To solve this principal difficulty it was assumed [11] that the $\bar{s}s$ component in the nucleon is polarized.

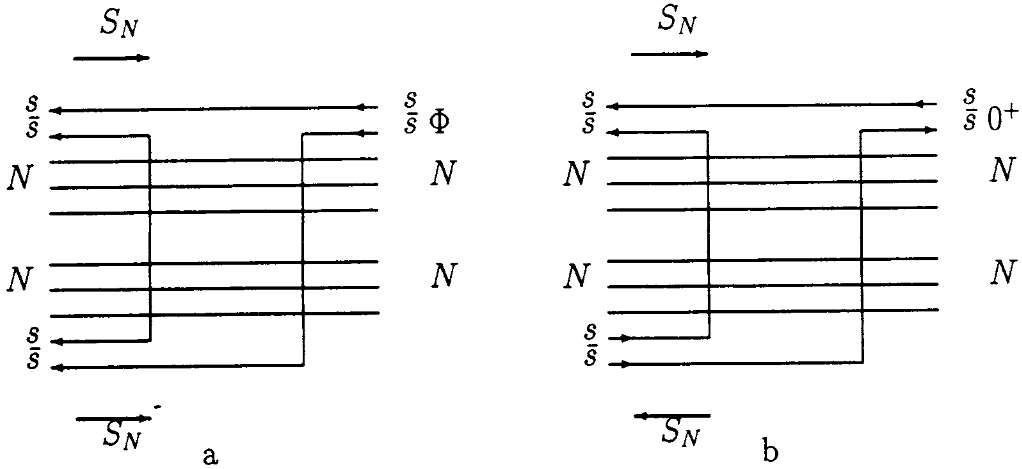

Fig.3. Production of the φ meson in *NN* interaction from the spin-triplet (a) and spin-singlet (b) states. The arrows show the direction of nucleons and strange quark spins

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 [13]:

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

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

Let us consider *NN* interaction from a spin-triplet initial state in which the nucleon spins are parallel (see Fig.3). In this case the $\bar{s}$ and s quarks in both nucleons will also have parallel spins. If the rearrangement diagram of Fig.3 is dominant and the polarization of the strange quarks is not changed during the interaction, 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 *NN* initial state is an *S* state, 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 $\bar{p}p \to \varphi\pi$ channel. If the initial *NN* state is spin singlet, then the rearrangement diagrams like that in Fig.3b may lead to the system in the final state also in the spin-singlet state, but that is not a φ meson.

This model also qualitatively suggests why φ production may be more enhanced in $\bar{p}p$ annihilation at rest than in other hadronic interactions. The reason is that higher energy collisions involve an increasing admixture of partial waves, implying that the «rearrangement» into the $\bar{s}s$ spin-triplet *S*-wave state of the φ meson 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 $\varphi\pi$ production in S-wave annihilation.

An important step was made in [12], where arguments were given on the basis of chiral symmetry that the $\bar{s}s$ pair in the nucleon wave function might be in a $^3P_0$ state.

We would like to stress that all tests of the predictions of this model [11] performed up to date gave positive results (for review, see [5]).

1.2. $\vec{d}+\vec{p}\to {}^3\text{He}+\varphi$ *as a Test of the Polarized Proton Strangeness Model.* The spin dependence of the φ yield should manifest itself in polarized proton interactions with polarized deuterons

$$\vec{p}+\vec{d}\to {}^3\text{He}+\varphi. \qquad (2)$$

It is predicted [11] that φ production will be enhanced when spins of the proton and deuteron are parallel. When spins of the beam and target particles are oppositely directed, the φ production is predicted to be suppressed.

The φ (and ω) yields in reaction (2) were measured at SATURNE II with the unpolarized beam and target combination [14]. A large deviation from the OZI rule prediction was revealed: $R(\varphi/\omega)=(80\pm 3^{+10}_{-4})\cdot 10^{-3}$.

These results are promising and give credence to study the polarization effects of the OZI rule violation in these processes. The main physical advantage of ^{3}He production reactions (2) is that they provide a possibility of studying OZI rule violation in the high-momentum transfer region.

Recently the $pd\to {}^3\text{He}+X$ processes were considered in [16], [17] on the assumption that the meson X production is going on via a two-step mechanism involving the subprocesses $pp\to d\pi$ and $\pi N\to XN$. In this scheme the φ production occurs not in NN interaction but in πN one.

Numerically, the calculations of [16] underestimate the cross sections of φ and ω production by a factor of 2.4. In [17] it is stressed that the absolute value of the cross section is very sensitive to the spin structure of the elementary amplitudes and underestimates the cross sections of φ and ω production by a factor of 10. Thus, one could conclude that this simple two-step mechanism alone is responsible for ^{3}He production. In principle, there are different possibilities of matching high momentum transfer of ^{3}He with the deuteron formfactor.

It is remarkable that the «standard» two-step model of ^{3}He production in reaction (2) predicts completely different behavior of the φ yields. It was calculated [17] that if vector mesons are created via the $pp\to d\pi$ and the $\pi N\to XN$ chain, then they should be produced mainly from the antiparallel orientation of the proton and deuteron spins. The value of the asymmetry

$$A=\frac{Y(\uparrow\uparrow)-Y(\uparrow\downarrow)}{Y(\uparrow\uparrow)+Y(\uparrow\downarrow)} \qquad (3)$$

(where Y is the ^{3}He yield for the parallel and antiparalel orientations of the spins of protons and deuterons) near the threshold is expected to be $A = -0.95$. The intrinsic polarized strangeness model predicts that A should be positive. Thus, it would be extremely interesting to perform these measurements.

It is important to compare characteristics of φ production with those for ω meson. The effects of nuclear dynamics of ^{3}He formation with φ and ω mesons should be rather similar. The ω production would be a nice reference point providing information on standard mechanisms of the vector meson production.

It is expected that the ratio of φ/ω cross sections should be high and the asymmetry (3) would be positive and large for the φ production.

2. The Experimental Apparatus

2.1. Selection of the Reactions with φ(ω) Mesons. The polarized deuteron beam with a proper momentum of about 5 GeV/c will be available at the JINR Nuclotron. The polarized proton target was already installed and the first experiments with it have been done [18], [19].

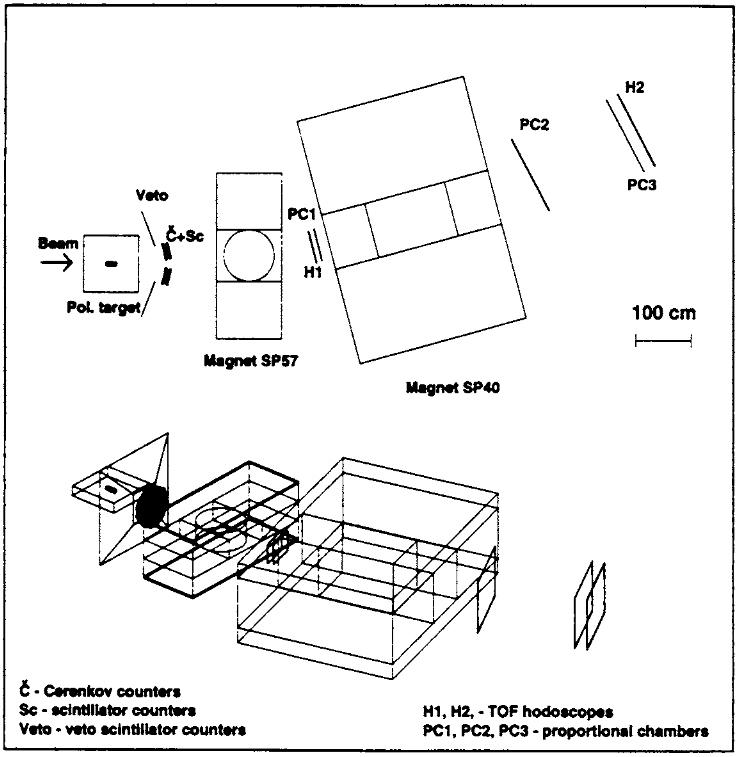

Fig.4. General layout of the proposed apparatus

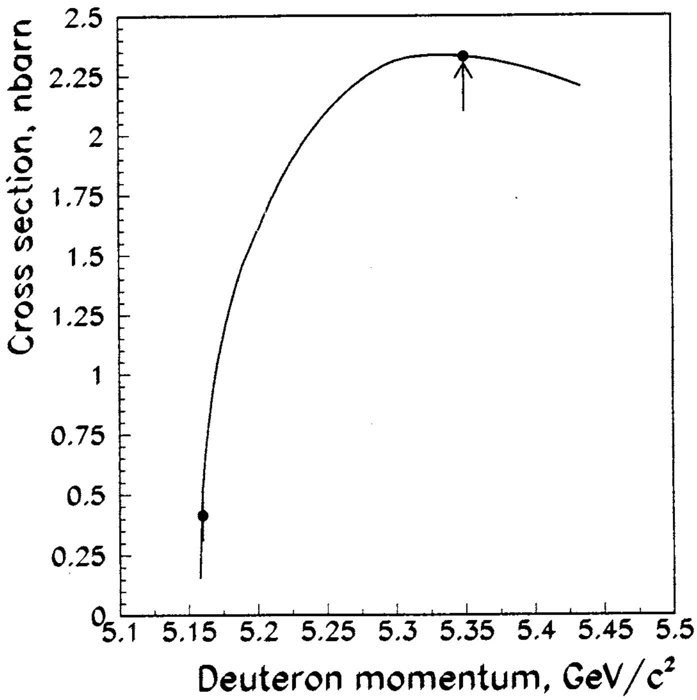

Fig.5. Cross section of the $dp \to {}^3\mathrm{He}\varphi$ reaction as a function of the deuteron momenta scaled in accordance with the experimental data (see the text). The arrow indicates the chosen point

The BES magnetic spectrometer [20], which is under development at LHE JINR, will be used for measurements of ^{3}He in the reactions:

$$\vec{d} + \vec{p} \to {}^3\mathrm{He} + \varphi, \tag{4}$$

$$\vec{d} + \vec{p} \to {}^3\mathrm{He} + \omega. \tag{5}$$

The general layout of the apparatus is shown in Fig.4. It consists of magnets SP57 and SP40, proportional chambers, TOF hodoscopes, scintillator and Cherenkov counters.

The binary reactions (4), (5) will be selected by a peak in the missing mass spectrum of ^{3}He.

As a working point we choose the deuteron momentum 5.35 GeV/c. In [17] the cross section of reaction (2) as a function of the beam energy was calculated. This dependence for reaction (2) as a function of incident deuteron momentum was scaled in accordance with the experimental data [14] and shown in Fig.5. The arrow indicates the chosen point on momentum.

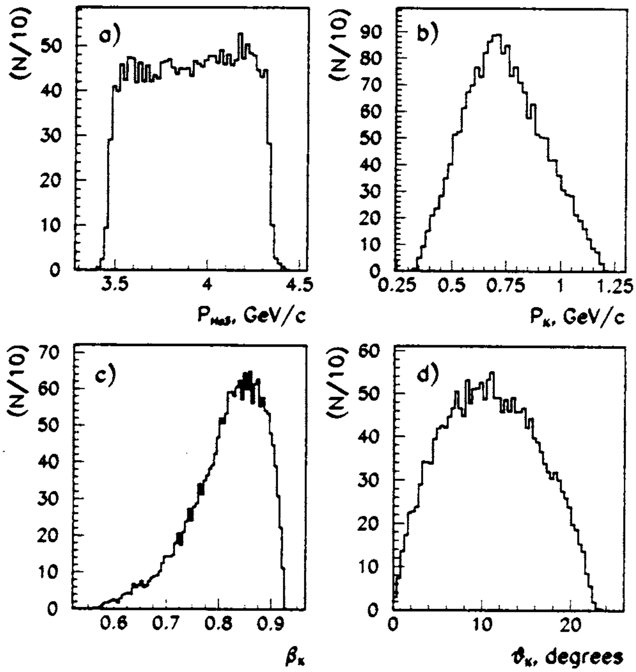

Fig.6. Kinematic characteristics of the φ production reaction: (a) ^3He momentum distribution; (b) kaon momentum distribution; (c) distribution on β for kaons; (d) distribution in scattering angles for kaons

One could see that the cross section reaches its maximum just at this point. This momentum in the laboratory system corresponds to the c.m.s. momentum of 258 MeV/c in the φ production reaction (4). The same c.m.s. momentum for ω production (5) corresponds to the initial deuteron momentum of 4.37 GeV/c.

In Fig.6. the kinematic characteristics of the φ production reaction (4) are shown. The momentum distribution of ^3He is shown in Fig.6(a), the ^3He momenta are in the range 3.5—4.4 GeV/c. The momentum distribution of kaons from the φ decay is shown in Fig.6(b). It is peaked at 700 MeV/c. The corresponding distribution in the velocity β of the kaons is shown in Fig.6(c). One can see that most kaons have $\beta < 0.9$. The angular distribution of the kaons is shown in Fig.6(d). The kaon scattering angles are confined within 20°.

It is assumed to detect the ^3He nucleus and to measure its angle and momentum. Then φ(ω) mesons could be selected by the peak in the missing mass spectrum.

The Monte-Carlo simulation of the reactions under investigation was performed. The momentum resolution of the BES spectrometer was assumed to be 1% and the angular resolution was taken as 0.1°.

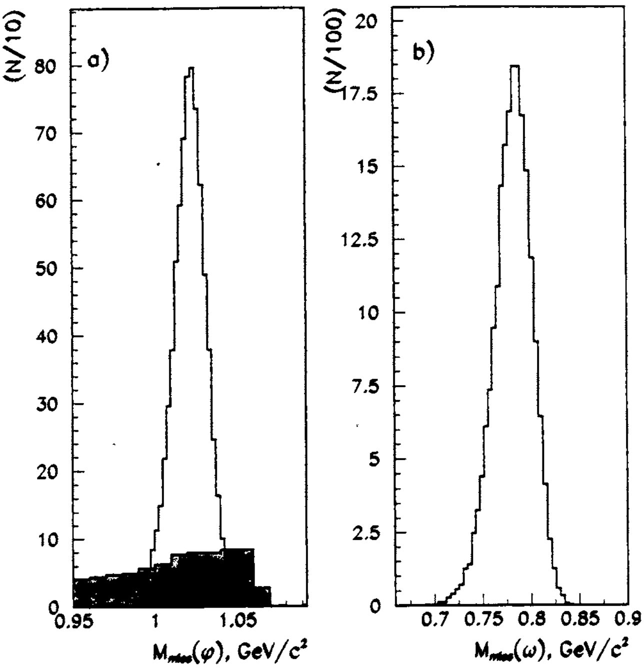

Fig.7. Missing mass distribution: (a) in the φ production reaction, the hatched area corresponds to the reaction on the bound nucleus; (b) in the ω production reaction

In Fig.7 the simulated missing mass spectra for reactions (4), (5) are shown. One could see that smearing of the φ and ω peaks due to the detector resolution and energy losses in the 20-cm-thick polarized target is not dramatic. The narrow peaks with $\sigma_\varphi = 9 \pm 1$ MeV and $\sigma_\omega = 25 \pm 1$ MeV (when fitted by a Gaussian) are seen.

The ^{3}He nuclei will be separated from the background with the time-of-flight and charge identification systems of the BES spectrometer.

2.2. *Analysis of the Background Reactions.* As was pointed out, the φ and ω mesons should manifest themselves as the peaks in a missing mass spectrum with respect to ^{3}He. However, there is a significant background from other reactions, particularly from the reaction $\vec{d} + \vec{p} \to {}^3\text{He} + n \cdot \pi$. To evaluate the background a Monte–Carlo simulation of one of the most important background channels

$$\vec{d}\,\vec{p} \to {}^3\text{He}\,\pi^+\pi^-\pi^0\pi^0 \qquad (6)$$

has been done. In Fig.8(a) the pion momentum distribution is shown. The pions from reaction (6) have a rather broad distribution peaked at 300 MeV/c. The corresponding distribution in the velocity β is shown in Fig.8(c). Though the low-β tail for pions is not

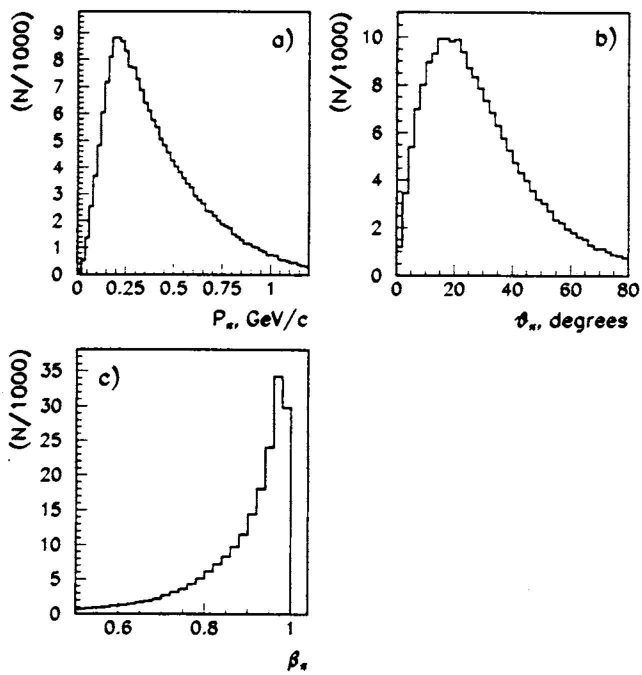

Fig.8. Momentum distribution of pions in the background reaction (a), distributions in scattering angle (b) and β (c)

negligible, most of them have $\beta > 0.9$, while most of kaons from φ decay have $\beta < 0.9$ (Fig.6(c)). The distribution of the pion scattering angles is shown in Fig.8(b). It is significantly broader than the corresponding distribution for the kaons (Fig.6(d)). Thus, it is quite natural to use angular, velocity and multiplicity cuts for the background suppression.

We also investigated reaction (2) on bound, not polarized protons. It appears that the peak from the φ meson in the missing mass spectra is strongly smeared because of the Fermi motion (see Fig.7(a), hatched area). Our estimations show that the signal from the reaction on a free proton is about 14 times higher than from the reaction on bound proton, if both distributions are integrated within the $m_\varphi \pm 3\sigma$ interval.

The practical scheme of the background suppression is proposed as follows. The array of the Cherenkov counters followed by a similar array of thin scintillator counters is placed downstream the target in front of the BES spectrometer. This detector array covers the scattering angle range $5° < \theta < 20°$. It allows one to select events with two slow charged particles within the defined angular range. Besides this detector system, a veto detector covering the angular range $\theta > 20°$ is installed. This detector will reject background events with charged particles scattered at large angles.

It is proposed to use the total internal reflection to construct the Cherenkov detector, because the velocity threshold was chosen as 0.9, which corresponds to $n = 1.11$. Only gases and aerogels could have such a refractive index, but construction of gas counters is difficult

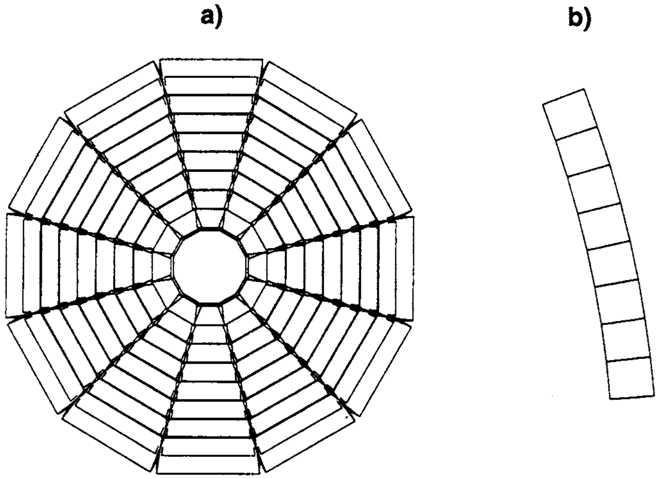

Fig.9. Array of the Cherenkov counter as seen from the beam direction (a) and the lateral view of a single counter (b)

and aerogels with the needed n are not available. The proposed Cherenkov detector (see Fig.9) will consist of twelve trapezoids. It will be placed downstream the target around the beam axis leaving a hole for the beam passage.

Each trapezoid will be made of one-piece plexiglas and specially machined to give it a complex shape, namely it will consist of nine segments each covering 1.7° in θ-angle and having its own slope angle to the beam axis to provide the best discrimination in β. The slope angles for each segment were optimized by our Monte-Carlo simulation.

The trapezoids will have a reflective front side (viewing the target) and their both lateral sides will be in contact with two adjoining trapezoids. All trapezoids will be attached to the photomultiplier tubes from the external side. The similar structure — a set of 10-mm-thick plastic scintillator detectors — will be placed just behind the Cherenkov counter. This structure will cover the angular range $5° < \theta < 20°$. The rest of the solid angle will be covered by the veto detector. It consist of four 10-mm-thick plastic scintillator segments.

The trigger will require the presence of a ^{3}He nucleus and the absence of signals in the veto counters, while in the off-line analysis we will take events with two signals in the scintillator counters and without signals in the Cherenkov counter.

The performance of the proposed set-up was estimated by the Monte-Carlo simulation. To evaluate the suppression factor we generated $2 \cdot 10^6$ events of the background channel (6) and the same number of events for this reaction on bound nucleons.

Just 0.05% of the events from the reaction (6) and 0.025% from reaction on bound nucleons pass through the set of cuts on the velocity ($\beta < 0.9$), multiplicity ($N = 2$), angles $5° < \theta < 20°$ and the requirement of ^{3}He nucleus detection. The channels with higher multiplicity have lower cross sections and the channels with lower multiplicity have fast

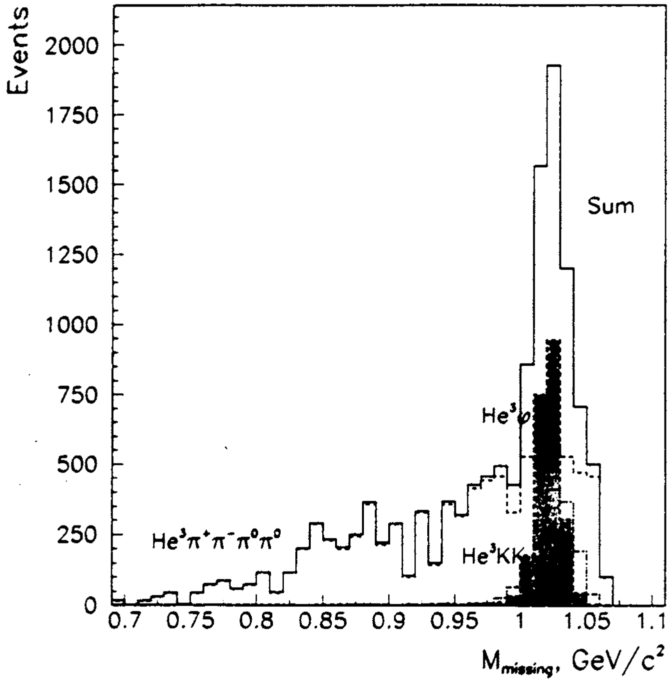

Fig.10. Expecting missing mass distribution for the φ production reaction and background reactions after selection cuts on the velocity and multiplicity

pions and will be suppressed by the Cherenkov detector more strongly. Therefore the background suppression of $10^3 - 10^4$ seems to be feasible.

In Fig.10 the missing mass distribution for the φ production reaction is compared with the background reactions (6) and $dp \to {}^3\text{He}\,K^+K^-$. It was assumed that $\sigma(\varphi) = \sigma(K^+K^-) = 10^{-3}\sigma(4\pi)$. The above-mentioned cuts were applied to all reaction channels.

A clear peak from φ is evident.

3. Requests for the Beamline, Polarized Target and Accelerator Time

The possible event rate for $p_d = 5.35$ GeV/c was estimated. Assuming the polarized beam intensity $N_d = 10^8\ \text{s}^{-1}$, the polarized target $C_3H_8O_2$ ($L = 20$ cm, $\rho = 0.7$ g/cm^3) and the cross section $\sigma = 2.3$ nb, the expected number of φ events is

$$N_\varphi = N_d \cdot \rho_p \cdot L \cdot \sigma \cdot R_{\varphi \to KK} \cdot \varepsilon \cdot d \approx 1160/\text{day},$$

where $R_{\varphi \to KK} = 0.49$ is the probability of φ decay into K^+K^-, $\rho_p = 4.4 \cdot 10^{22}$ is the number of free protons in 1 cm^3, $\varepsilon = 0.150 \pm 0.003$ is the registration efficiency, $d = 0.9$ is the duty factor.

The statistical accuracy of the asymmetry measurements was estimated. To obtain ~ 10000 events (2), 9 days of polarized deuteron beam with the intensity $N_d = 10^8\ s^{-1}$ are needed.

A discussion about possibility of the moving Medium Resolution Spectrometer (MRS) [21] from Los-Alamos to JINR is going on. We would like to stress that the MRS could be used to our investigations.

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