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RECENT RESULTS FROM VES EXPERIMENT

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Results obtained in $\pi^- Be$ interactions at 27, 36.6 and 41 GeV/c are presented. Decay $f_1(1285) \to \pi^+\pi^-\pi^0$ is observed; the dominant mechanism of the isospin symmetry violation in this decay is the $a_0(980) - f_0(980)$ mixing. The intensity of this mixing is measured. An upper limit on possible $f_1(1285) - a_1(1260)$ mixing is obtained. Preliminary results of a study of $(\omega\phi)$ system are shown. Plans for coming upgrade of the detector are presented.

Keywords: Meson spectroscopy; isospin violation; scalars.

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1. Introduction

The VES detector is a wide aperture forward spectrometer, which is installed in unseparated beam of negative particles (mainly π^-) from the Serpukhov accelerator. It is equipped with an electromagnetic calorimeter and Cherenkov detectors for identification of beam and charged secondary kaons. It has a fast Data acquisition system (up to 8000 triggers per accelerator spill) and operates with a forward multiplicity trigger. Details of the VES setup can be found elsewhere[1].

2. $f_1(1285) \to \pi^+\pi^-\pi^0$ Decay

The decay $f_1(1285) \to \pi^+\pi^-\pi^0$ violates the isospin symmetry. It can proceed by means of the $f_1(1285) \leftrightarrow a_1(1260)$ mixing and by a direct decay $f_1(1285) \to (\pi^+\pi^-\pi^0)$. The $f_1(1285) \to a_1(1260)$ mixing is driven mainly by the difference of light quark mass $\Delta m = m_d - m_u$[2,3]. Namely, this Δm is responsible for known decays $\omega \to \pi^+\pi^-$, $\phi(1020) \to \pi^+\pi^-$, $\eta \to 3\pi$ and $\eta' \to 3\pi^0$. In the case of $f_1 \leftrightarrow a_1$ mixing it leads to a_1-like final states: $(\rho\pi), (f_0(600)\pi)$. Another effect which can contribute to the decay $f_1(1285) \to \pi^+\pi^-\pi^0$, is the $a_0(980) \leftrightarrow f_0(980)$ mixing predicted in 1979[4]. Qualitatively speaking, loops with virtual K^+K^- and $K^0\bar{K}^0$ pairs should cancel each other, but this cancellation is not perfect due to the difference

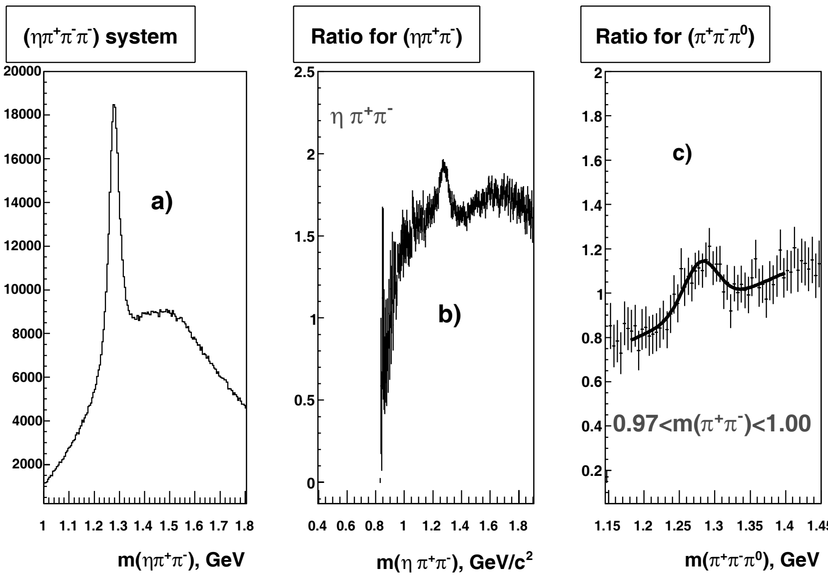

Fig. 1. (a) Invariant mass of $(\eta\pi^+\pi^-)$ system produced in the reaction $\pi^- N \to (\eta\pi^+\pi^-\pi^-)N$; at low t', $|t'| < 0.04\ GeV^2$. There are two entries per event. (b) Ratio of weighted to unweighted $m(\eta\pi^+\pi^-)$ spectra (see text); (c) similar ratio for $m(\pi^+\pi^-\pi^0)$ system.

in mass of charged and neutral kaons. The isospin symmetry violation reaches its maximum in the region between thresholds for pairs of charged and neutral kaons. The amplitude of the isospin violating transition depends on the couplings of scalar mesons with $K\bar{K}$ pairs. Theoretical aspects of the expected $a_0(980) \leftrightarrow f_0(980)$ mixing are discussed in details in recent paper[5], where isospin-violating effects are considered within the unitarized chiral approach to leading order in the quark mass differences and electromagnetism. Several possibilities for its experimental observation were proposed.

Diffractive reaction $\pi^- N \to (f_1\pi^-)N \to (\eta\pi^+\pi^-)\pi^- N$ represents a reach source of the $f_1(1285)$ mesons at low background. The branching ratio of $f_1 \to a_0\pi$ decay is large, $BR = 0.36 \pm 0.07$[6]. Because of these facts the process chain

$$f_1(1285) \to a_0(980)\pi^0 \to f_0(980)\pi^0 \to (\pi^+\pi^-)\pi^0 \qquad (1)$$

is well suitable for a search of expected isospin violation. Fig. 1a demonstrates the $f_1(1285)$ signal in dominant decay mode, $f_1 \to \eta\pi^+\pi^-$ at low momentum transfer region, $|t| < 0.04\ GeV^2$. The estimated number of events in the f_1 peak is 59300 ± 600 in case of of the gaussian shape of the signal. This mode is similar to the sought $(\pi^+\pi^-\pi^0)$ channel from experimental point of view, and it was used for normalization. Selection procedure for both channels is described in[7,8]. As for the f_1 production process, results of the partial wave analysis of $\eta\pi^+\pi^-\pi^-$ system[9] show that dominamt wave has quantum numbers $J^{PC}M\eta = 1^{++}0+$, where J, P, C, M, and η denote the spin, parity, C-parity, spin projection and the exchange

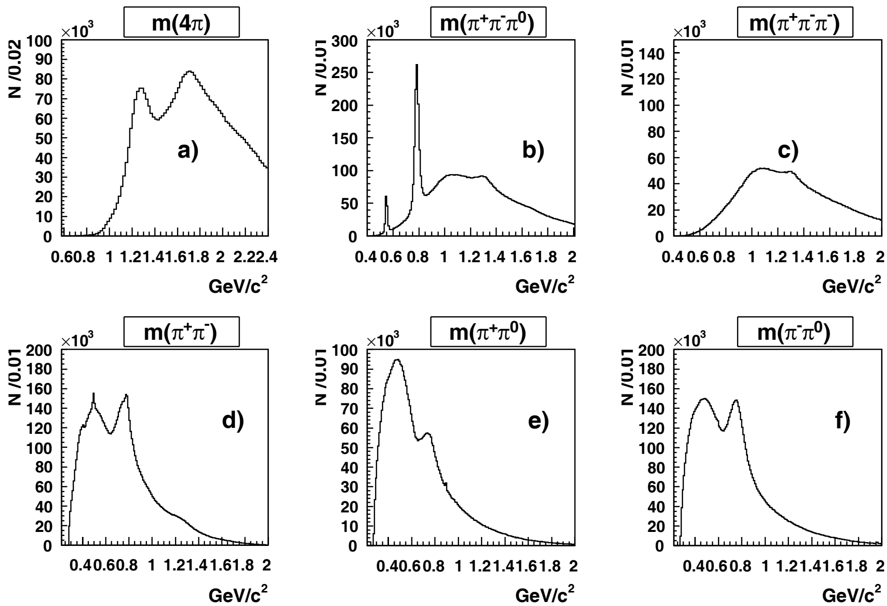

Fig. 2. Invariant masses for $(\pi^+\pi^-\pi^-\pi^0)$ system. (a) Total mass; (b) $m(\pi^+\pi^-\pi^0)$; (c) $m(\pi^+\pi^-\pi^-)$; (d) $m(\pi^+\pi^-)$; (e) $m(\pi^+\pi^0)$; (f) $m(\pi^-\pi^0)$.

naturality, respectively. This intermediate system decays into f_1 and extra π^-. The angular term in the overall amplitude, which describe the f_1 production and the subsequent decay chain $f_1 \to a_0^{+-}\pi^{-+} \to \eta\pi^+\pi^-$, is

$$A = \frac{3}{\sqrt{2}} sin(\theta_1) \cdot \sin(\theta_2) \cdot sin(\phi_0 - \phi_2); \tag{2}$$

(the angles are defined in Ref. 8). The weight $W = |A|^2$ can be used to enhance the f_1 signal. It is demonstrated in Fig. 1b which shows the ratio of $(\eta\pi^+\pi^-)$ invariant mass spectrum weighted with the W (corrected for angular acceptance) to the unweighted one. We note here, that the sought decay signal in $\pi^+\pi^-\pi^0$ final state should also have the angular dependence (2), therefore the weighting with W should cause a similar effect.

Fig. 1 shows different mass spectra for the selected $(\pi^+\pi^-\pi^0\pi^-)$ sample of the reaction under study. Prominent peaks from the $\omega(783)$ and $\eta(550)$ are observed in the $(\pi^+\pi^-\pi^0)$ subsystem (Fig. 1b). Also an accumulation of events is seen in the mass region of the sought $f_1(1285)$ and competitive $a_2^0(1320)$.

To increase the signal to background ratio, the following selection criteria have been applied: a) events at the low momentum transfer, $|t'| < 0.04$, were selected; b) events with a signal detected in the target guard system, i.e. events with photons originating from the target fragmentation were rejected; c) events with $m(\pi^+\pi^-\pi^0) < 0.810\, GeV/c^2$ at any combination were rejected. First two cuts tend to select the diffractive reaction, the third one rejects events with $\omega(780)$ or $\eta(550)$.

If a supplementary requirement on the $m(\pi^+\pi^-)$ is imposed, $0.97 < m(\pi^+\pi^-) < 1.0\ GeV/c^2$ and the angular weight described above is applied, then a clear peak emerges in the ratio of weighted $m(\pi^+\pi^-\pi^0)$ spectrum to the unweighted one (Fig. 1c). The mass and width of this peak are consistent with the $f_1(1285)$ parameters. As a check, the angular weight was applied to the $(\pi^+\pi^-\pi^-)$ subsystem, where the f_1 should not appear. No signal is observed. We conclude that application of angular weight appropriate for known $(f_1\pi^-)$ production-and-decay process indeed extracts the sought f_1 signal in $m(3\pi)$ spectrum. The term "*cusp*" will denote below the observed signal at $m(2\pi)$ close to the kaon pair threshold.

The probability of the $f_1 \to \pi^+\pi^-\pi^0$ decay, which is associated with a signal in two-pion subsystem near 1 GeV, was estimated without angular weight. First, events were selected at the $m(\pi^+\pi^-\pi^0)$ close to the f_1 mass and a mass spectrum $m(\pi^+\pi^-)$ was analysed (Fig. 3a). The K^0_s and $\rho(770) - \omega(780)$ peaks are seen, and another narrow bump in the region of interest, $m(\pi^+\pi^-) \sim 985\ MeV/c^2$. It was checked that the expected signal shape for the $a_0 \to f_0$ transition is close to gaussian and that the experimental resolution dominates in the gaussian width. To filter this signal out of background, the $m(\pi^+\pi^-)$ spectrum was fitted from $0.4\ GeV/c^2$ to kinematic limit by a sum of the gaussian signal and a background function, which was chosen as a cubic polynomial function with free coefficients multiplied by phase space, plus relativistic P-wave Breit-Wigner for the $\rho(770)$, plus gaussians for K^0 and $\omega(783)$. In the fit the masses of K^0, ω, ρ and the ρ width were fixed at the table values, while the K^0 and ω widths were fixed at values estimated from experimental resolution. The yields the gaussian mean value of $m = 983 \pm 3\ MeV$ and the gaussian $\sigma = 15 \pm 4\ MeV$ for the signal, the later one is consistent with the value of $\sigma = 21\ MeV$ expected from Monte Carlo study. The fit $\chi^2/ND = 81.9/(76 - 10)$ and the statistical significance of the deviation of gaussian normalisation parameter from zero is $6.5\,\sigma$.

Then we fix it's gaussian shape of the peak (at $m = 0.983\ GeV/c^2$ and $\sigma = 0.021\ GeV/c^2$) and introduce it into bin-by-bin fit with normalization parameter left free. This time the fit was performed in a wide range of $m(3\pi)$ from 1.15 to $1.45\ GeV/c^2$, that is in thirty equidistant bins, all bins having the width of $10 MeV/c^2$. Dependence of the fitted number of "cusp" events on the $m(\pi^+\pi^-\pi^0)$ is shown in Fig. 3b. Errors at the number of events in individual bins were determined from MINOS procedure in MINUIT[10]. The observed dependence can be fitted by a sum of a Gaussian function and a linear background with free coefficients. This background term absorbs imperfections in the background functions used for the $m(\pi^+\pi^-)$ fits. The fit result is shown in Fig. 3b. The fitted peak has $m = 1287 \pm 2\ MeV$ and the gaussian width $\sigma = 14.7 \pm 2.5\ MeV$, which are in agreement with the table values. The total number of events in gaussian peak is 1400 ± 300. This number of events, taken together with the number of events in $f_1 \to \eta(2\gamma)\pi^+\pi^-$ channel, gives the relative branching ratio. The ratio of the detection efficiencies, $R = \varepsilon(\pi^+\pi^-\pi^0)/\varepsilon(\eta(2\gamma)\pi^+\pi^-)$ was estimated from Monte-Carlo simulation and taken into account, $R = 0.95 \pm 0.05$. It is worth mentioning that the observed signal

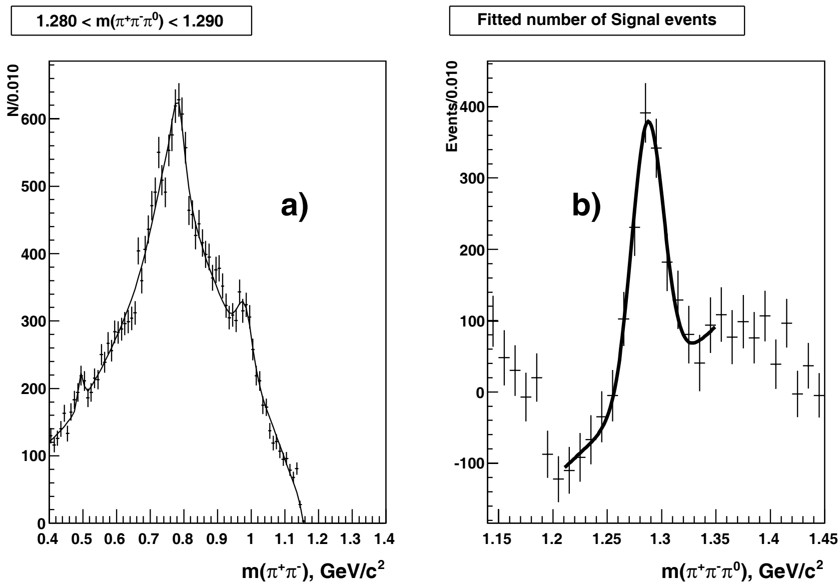

Fig. 3. (a) Mass spectrum $m(\pi^+\pi^-)$, selected combinations with $m(\pi^+\pi^-\pi^0)$ in the mass interval (1.280,1.290) GeV/c^2. (b) Fitted number of signal events as a function of $m(\pi^+\pi^-\pi^0)$, superimposed curve corresponds to a sum of Gaussian signal and a linear background.

is concentrated in rather narrow interval on the two-pion mass, approximately at $0.95 < m(\pi^+\pi^-) < 1.10\ GeV/c^2$.

Experimental data show that the narrow signal at $m(\pi^+\pi^-)$ close to $(K\bar{K})$ threshold matches to the expectation for $a_0(980) \leftrightarrow f_0(980)$ "cusp" and associates with a narrow signal in $m(\pi^+\pi^-\pi^0)$, which is well consistent with the $f_1(1285)$ on its mass and width, and with angular dependencies preferable for $(f_1\pi^-)$ system. So, all elements of the observed pattern fit well with predictions based on the mechanism suggested by Achasov and collaborators in 1979[4]. The relative branching ratio is determined from the observed number of events in the $\eta\pi^+\pi^-$ and $\pi^+\pi^-\pi^0$ channels:

$$\frac{BR(f_1 \to \pi^+\pi^-\pi^0(0.96 < m(\pi^+\pi^-) < 1.01))}{BR(f_1 \to \eta\pi^+\pi^-) \cdot BR(\eta \to \gamma\gamma)} = (2.5 \pm 0.5 \pm 0.5)\%;$$

here statistical and systematic errors are indicated.

Systematic error was estimated by variations of the fixed "cusp" width, $f_1(1285)$ shape (gaussian or Breit-Wigner for both reactions), background parametrisation and the fit range in two-pion mass spectra fits. Uncertainties in the efficiency ratio and in known f_1 branching ratios were also included.

This relative branching ratio is consistent with estimation made by Achasov et al.[11]. With PDG values for $BR(f_1 \to \eta\pi\pi) = 0.52 \pm 0.16$ and $BR(\eta \to \gamma\gamma) = 0.3939 \pm 0.0024$[6,12] it leads to

$$BR(f_1 \to \pi^+\pi^-\pi^0(0.96 < m(\pi^+\pi^-) < 1.01)) = (0.34 \pm 0.15)\%$$

here we take the $BR(f_1 \to \eta\pi^+\pi^-) = \frac{2}{3}BR(f_1 \to \eta\pi\pi)$. From this value we derive the branching of isospin violating decay of neutral $a_0(980)$, $BR(a_0^0(980) \to \pi^+\pi^-) = (2.8 \pm 1.0)\%$ (neglecting the $a_0 \to K\bar{K}$ decay mode).

3. Limit on the $f_1(1285) \leftrightarrow a_1(1260)$ Mixing

Possible $f_1 \leftrightarrow a_1$ mixing should lead to the $(\rho^{+-}\pi^{-+})$ final states. Number of ρ^{+-} events was determined from a fit of a sum of $m(\pi^+\pi^0)$ and $m(\pi^-\pi^0)$ spectra as a function of $m(\pi^+\pi^-\pi^0)$ at different $m(3\pi)$ intervals. Observed ρ^{+-} signal as a function of $m(\pi^+\pi^-\pi^0)$ is shown in Fig. 4. No enhancement at the $f_1(1285)$ mass is observed. A parametrization of the observed ρ^{+-} mass spectrum was performed, assuming a gaussian f_1 signal (with fixed mass and width) and a background. This background was taken a sum of a quadratic function with free coefficients and a Breit-Wigner term which corresponds to the expected a_2 bump. The parametrization gives the number of $f_1 \to \rho^{+-}\pi^{-+}$ events $N_{\rho^{+-}} = -617 \pm 1852$. From this we derive upper limit for the branching fraction

$$BR(f_1(1285) \to \rho^{+-}\pi^{-+}) < 0.62\% \tag{3}$$

at 95% conf. level. Intensity of the $f_1 \to a_1$ transition is determined by polarization operator $\Pi_{f_1 a_1}$[13]:

$$BR(f_1 \to \rho\pi) = \frac{\Gamma_{a_1 \to \rho\pi}}{\Gamma_{f_1}} \frac{\Pi^2_{f_1 a_1}}{|m^2_{a_1} - m^2_{f_1} - i(m_{f_1}\Gamma_{f_1} - m_{a_1}\Gamma_{a_1})|^2} \approx \frac{\Pi^2_{f_1 a_1}}{m^2_{f_1}\Gamma_{f_1}\Gamma_{a_1}}.$$

From 3 we obtain:

$$\Pi_{f_1 a_1} < 0.0070\ GeV^2 \text{ for } \Gamma_{a_1} = 200\, MeV$$
$$\Pi_{f_1 a_1} < 0.0122\ GeV^2 \text{ for } \Gamma_{a_1} = 600\, MeV.$$

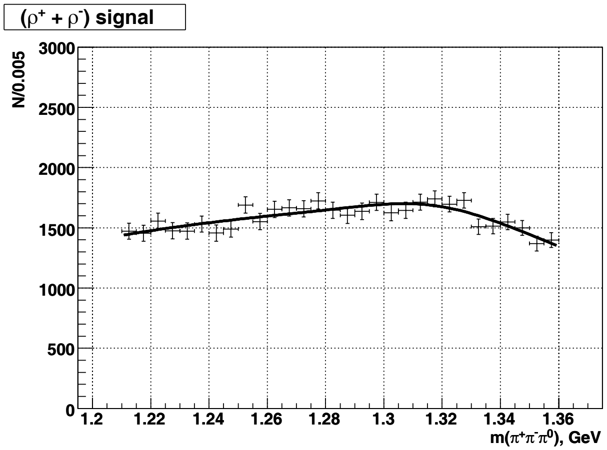

Fig. 4. Fitted number of ρ^{+-} events in different $m(\pi^+\pi^-\pi^0)$ intervals. Superimposed curve corresponds to the fit of the observed ρ^{+-} signal by a sum of Gaussian function for the searched f_1 signal (with fixed mass and width) plus background (see text).

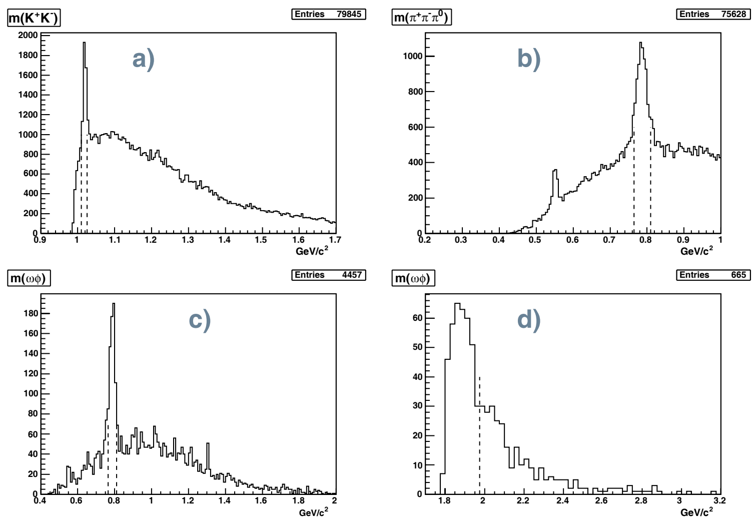

Fig. 5. Invariant masses for $(K^+K^-\pi^+\pi^-\pi^0)$ system: (a) $m((K^+K^-)$; (b) $m(\pi^+\pi^-\pi^0)$; (c) $m(\pi^+\pi^-\pi^0)$, selected events at $1.10 < m(K^+K^-) < 1.025$; (d) selected events at $1.10 < m(K^+K^-) < 1.025$ and $0.765 < m(\pi^+\pi^-\pi^0) < 0.805\ GeV/c^2$.

It doesn't contradict to prediction based on the assumption of universality of charge symmetry breaking in different channels like $\omega \to \pi^+\pi^-$, $\phi \to \pi^+\pi^-$[14]:

$$\Pi_{f_1 a_1} \approx 0.005\, GeV^2.$$

4. A Scalar Object Near the $(\omega\phi)$ Threshold

An interesting scalar object near the $(\omega\phi)$ threshold has been reported by BES Collaboration[15]. A search of a similar object at VES experiment was undertaken. This study is based on the statistics acquired in interactions of a π^- beam at the momentum of 27 GeV/c and 36.6 GeV/c on a Be target, in reaction

$$\pi^- p \to K^+K^-\pi^+\pi^-\pi^0 n. \tag{4}$$

The π^0 mesons were detected in the $\gamma\gamma$ mode. Identification of charged kaons was provided by a wide-aperture Cherenkov detector. The following selection criteria have been applied for the selection of the $(K^+K^-\pi^+\pi^-\pi^0)$ events. Events with two positive and two negative tracks and two unassociated showers in the electromagnetic calorimeter were selected. The effective mass of the two photon pair was requested in the range $(0.105, 0.165)\ GeV/c^2$. Accepted pairs were subjected to $1C$ kinematic fit to the π^0 mass, and fitted π^0 parameters were used in the analysis. The total event energy was required to be greater that 25 GeV or greater than 34 GeV at beam momenta of 27 and 36.6 GeV/c, respectively. Events with identified e^+/e^- were excluded. Both K^+ and K^- were identified in Cherenkov detector. The invariant mass of (K^+K^-) pair is shown in Fig. 5a, clear $\phi(1018)$ signal is seen. Two remaining charged tracks were considered as pions and taken together with

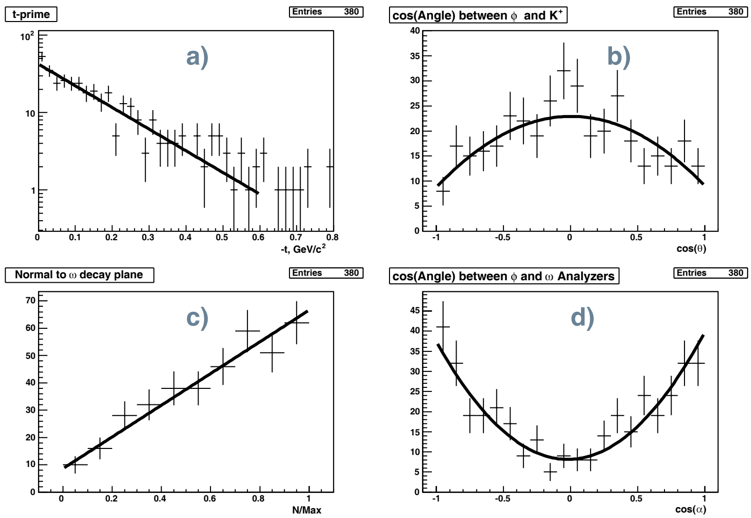

Fig. 6. Distributions for the $(\omega\phi)$ system at $m(\omega\phi) < 1.975\ GeV/c^2$ (a) $|t|$ distribution; (b) $cos(\theta)$, θ is angle between direction of ϕ and the K^+ momentum in the ϕ rest frame; (c) vector product of $p(\pi^+)$ of $p(\pi^-)$ in ω rest frame, normalized to the maximum value; (d) $cos(\alpha)$, α is angle between K^+ direction in ϕ rest frame and the normal to ω decay plane in the ω rest frame.

the π^0. Invariant mass of the $(\pi^+\pi^-\pi^0)$ system is shown in Fig. 5b, clear $\omega(782)$ signal seen, it becomes more clean if the $m(K^+K^-)$ close to the $m(\phi)$ is requested (Fig. 5c). If requirements on both $m(K^+K^-)$ and $m(\pi^+\pi^-\pi^0)$ are imposed, then accumulation of events near the $(\omega\phi)$ threshold is observed(Fig. 5d).

Properties of the $(\omega\phi)$ system are demonstrated in Fig. 6. Events at $m(\omega\phi) < 1.975\ GeV/c^2$ were selected. The t-distribution is shown in Fig. 6a. The t-slope was estimated from an exponential fit, it is $-6.45 \pm 0.50\ GeV^{-2}$. This value is close to the expectation for the pion exchange.

Angular distributions, which are shown in Fig. 6b and 6c, show that the expected angular dependencies for decays of vector resonances are observed. The *cosine* of the angle between the ω and ϕ analysers is shown in Fig. 6d. It clearly demonstrates, that two vector resonances are produced from decay of a scalar system.

With higher statistics and in another production process we confirm the observation of a resonance-like bump with scalar quantum numbers near the $(\omega\phi)$ threshold.

5. Detector Upgrade

Main direction of the ongoing upgrade have the objectives to increase the resolution and identification capability of the spectrometer and to improve its performance during the data taking. It is planned to have a gain in “exclusivity”, kinematics accuracy, backgrounds suppression, and also a gain in statistics (dead time decrease from 100 mksec to 15-20 mksec).

Major steps:

- improvement of multichannel Cherenkov counter for pion-kaon discrimination: new mirrors with better focusing, more stable amplifiers for Photomultipliers. Commissioned.
- construction of beam spectrometer with momentum resolution of 0.8% at 30 GeV/c. Commissioned, still a room to improve.
- modernization of electromagnetic calorimeter: fine layers "shashlyk" against lead glass for better (almost factor 2) energy resolution. In progress, years 2008-2009.
- replacement of large (2.5 by 2 m) drift chambers in self-quenching regime of gas amplification with new ones in proportional mode. Straws in consideration.
- All these is supplemented with ReadOut electronics, Data Aquisition, Slow Control and software improvements.

In conclusion we should stress that all values given in this talk are preliminary. We continue cross-checks of the stability of measured $BR(f_1 \to \pi^+\pi^-\pi^0)$ with respect to variations of background functions and the signal shape. Possible contribution of the "universal" mixing to this process is also under investigation.

Acknowledgments

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