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STUDY OF $K_S K_L$ COUPLED DECAYS AND K_L-Be INTERACTIONS WITH THE CMD-2 DETECTOR AT VEPP-2M COLLIDER

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НОВОСИБИРСК

Study of K_SK_L coupled decays and K_L-Be interactions with the CMD-2 detector at VEPP-2M collider

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The integrated luminosity $\approx 4000nb^{-1}$ of around ϕ meson mass (5.0×10^6 of ϕ's) has been collected with the CMD-2 detector at the VEPP-2M collider. A latest analysis of the K_SK_L coupled decays based on 30% of available data is presented in this paper.

The K_SK_L pairs from ϕ decays were reconstructed in the drift chamber when both kaons decayed into two charged particles. From a sample of 1423 coupled decays a selection of candidates to the CP violating $K_L \to \pi^+\pi^-$ decay was performed. CP violating decays were not identified because of the domination of events with a K_L regenerating at the Be beam pipe into K_S and a background from K_L semileptonic decays.

The regeneration cross section of 110 MeV/c K_L's was found to be $\sigma_{reg}^{Be} = 53 \pm 17$ mb in agreement with theoretical expectations. The angular distribution of K_S's after regeneration and the total cross section of K_L for Be have been measured.

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1 Introduction

As was realized at the very early steps of the ϕ meson studies at the colliding beam machines, K_SK_L pairs ($\approx 34\%$ of all ϕ decays) can be used as a source for studying CP and CPT violation. These suggestions, including studies of quantum mechanical correlations, were discussed for experiments at the Novosibirsk electron-positron collider VEPP-2M [1-3]. The coupled decays of the K_SK_L pairs will allow demonstration of the quantum mechanical correlations of the two particle decays (Einstein-Podolsky-Rosen paradox) [4].

The ϕ resonance produced in e^+e^- collisions is also a source of low momentum neutral and charged kaon pairs not available from other sources for studies of nuclear interactions. Mesons in each pair are produced with opposite and equal momenta and a detector with good resolution and reconstruction efficiency allows one to use one reconstructed kaon as a tag for another. The most natural way is to use a reconstructed decay of $K_S \to \pi^+\pi^-$ as a tag for K_L. In this case the momentum and direction of K_L are completely determined.

The idea of creating an intensive source of ϕ mesons has been discussed by many authors [5, 6]. The flux of events at these so-called "ϕ-factories" now under construction [7, 8] will make feasible new precise measurements of a possible direct component in the decay

$K_L \to \pi^+\pi^-, \pi^0\pi^0$ (ϵ'/ϵ), as well as an observation of CP-violating three pion decays of the K_S. Studies of the oscillations in the joint decay distributions could provide information about real and imaginary parts of any CP-violating amplitude.

At the VEPP-2M collider at Novosibirsk, which could be considered as a pre ϕ-factory, we have been running with the CMD-2 detector preparing for experiments at the ϕ-factory which is under construction here. Studies of an upgraded detector and accelerator are in progress, including an intermediate $10^{32} cm^{-2} s^{-1}$ luminosity collider for investigating the idea of the round beams, an important ingredient of the Novosibirsk ϕ-factory project[9, 10].

2 The CMD-2 Detector

The CMD-2 detector has been described in more detail elsewhere [2, 11]. The main systems of the detector are shown in Figure 1.

The CsI barrel calorimeter with a 6 x 6 x 15 cm^3 crystal size is placed outside of a 0.4 r.l. superconducting solenoid with a 1 Tesla magnetic field. The endcap calorimeter is made of 2.5 x 2.5 x 15 cm^3 BGO crystals and has not been installed for the data presented here.

The drift chamber(DC) with a 30 cm outer radius and a 44 cm length has about 250 μm resolution transverse to the beam and 0.5 cm longitudinally and is placed inside the solenoid. The vertex reconstruction resolution for the neutral kaon decays into charged particles is about 0.15 cm radially. The muon range system consists of streamer tubes and has 1-3 cm spatial resolution.

A 3.4 cm diameter vacuum beam pipe is made of Be with a 0.077 cm wall thickness and may be considered as a target for studies of the kaon nuclear interaction.

A data sample of the integrated luminosity of 1500 nb^{-1} has been analyzed around the ϕ corresponding to about 1.7×10^6 produced ϕ's. About 300 nb^{-1} were used to measure the ϕ meson parameters and its branching ratios into four major decay modes [12]. The largest part of the integrated luminosity ≈ 1200 nb^{-1} was used for the studies of rare

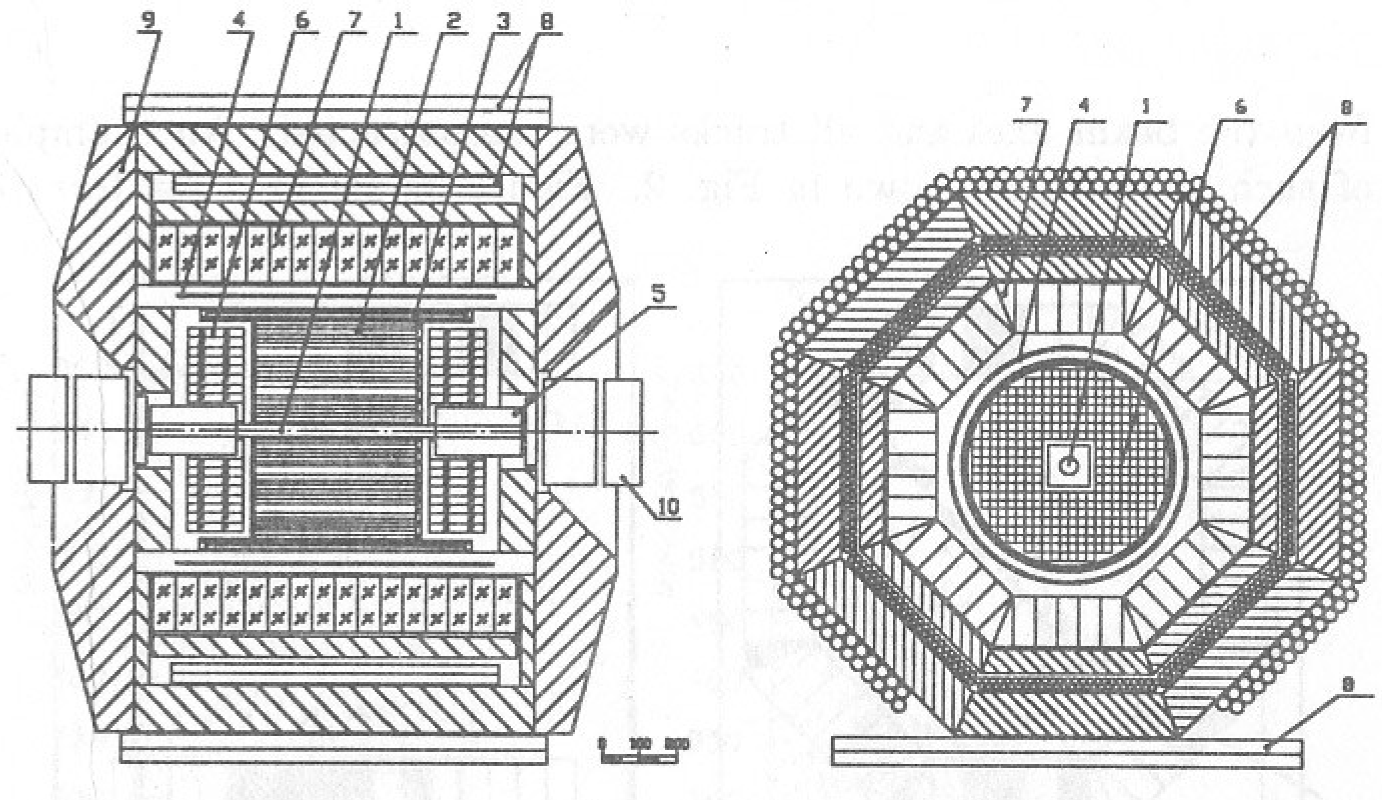

Figure 1: Horizontal and vertical cross sections of the CMD-2 detector. 1 - vacuum chamber; 2 - drift chamber; 3 - Z-chamber; 4 - main solenoid; 5 - compensating solenoid; 6 - BGO endcap calorimeter; 7 - CsI barrel calorimeter; 8 - muon range system; 9 - magnet yoke; 10 - collider lenses.

decay modes of ϕ. Some preliminary results were published in [13].

These data were also intensively used for studies of the detector performance and software development. Several versions of the reconstruction program have been tested and a reconstruction efficiency of about 95-97% per charged track has been achieved with a momentum uncertainty of 4% for 250 MeV/c charged particles. The energy resolution of 8% for photons in the CsI calorimeter has been obtained.

The number of reconstructed $K_S K_L$ coupled decay events is now twice the sample in the preliminary publication [13]. The latest analysis of the $K_S K_L$ coupled decays is presented in this paper.

3 Selection of $K_S K_L$ coupled decays

Candidates were selected from a sample in which two vertices, each with two oppositely charged tracks, were observed within 15 cm from the beam axes and all tracks were reconstructed. An example of such an event is shown in Fig. 2. Figure 3a shows a scatterplot

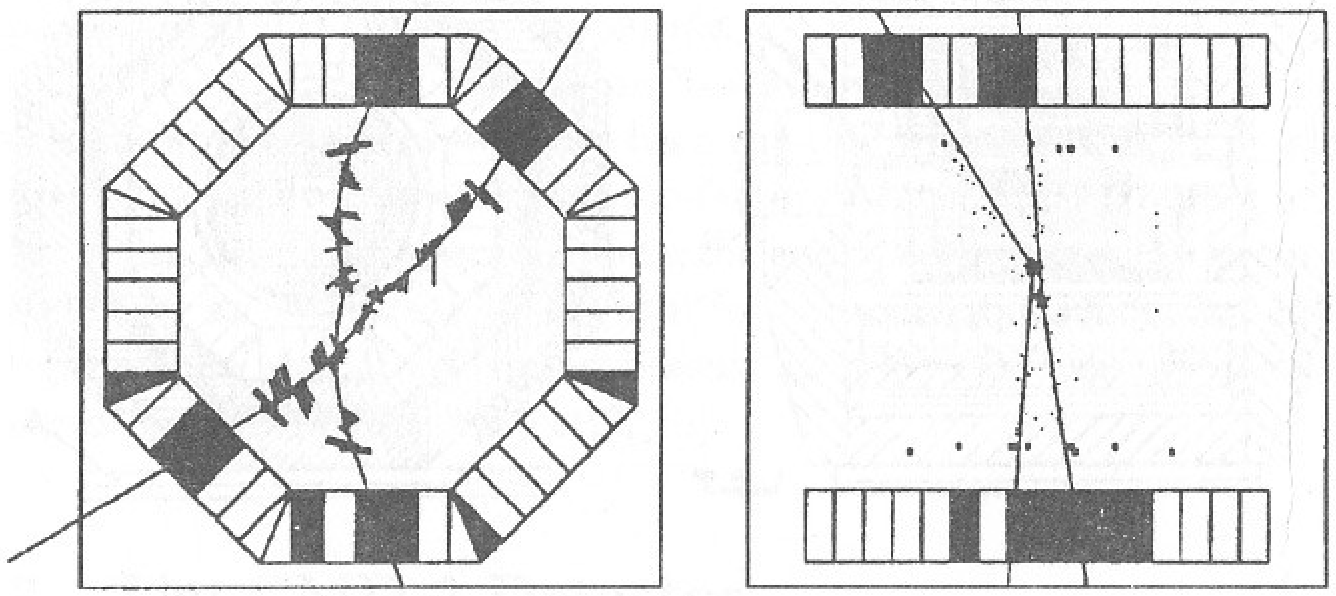

Figure 2: $\phi \to K_S K_L$ event with a coupled decay.

of the invariant mass M_{inv} of two charged tracks assuming they are pions vs. the missing momentum P_{mis} (which is equivalent to kaon momentum P_K in case of two pion decay) for the particle which decays first. Figure 3b shows the same plot for a particle from the second vertex. The concentration corresponding to K_S mesons decaying into a pair of charged pions dominates in the Fig. 3a and is seen in Fig. 3b showing events in which K_S appears in the second vertex. The cuts 470 MeV $< M_{inv} <$ 525 MeV and 80 MeV/c $< P_K <$ 140 MeV/c with an additional requirement to have another reconstructed vertex in the P_{mis} direction select events with K_S in one of the vertices. The K_L is expected to be in the other one. The above cuts represent three standard deviations of the detector resolution.

Figures 3c and 3d show peaked M_{inv} and P_K distributions corresponding to K_S after above cuts (shaded). The M_{inv} and P_K parameters for the other vertex give broad distributions expected for the main 3-body K_L decays (into $\pi\mu\nu$, $\pi e\nu$, $\pi^+\pi^-\pi^0$).

Figure 4a shows the decay length distribution for selected K_S. The exponential decay length is seen with a correct value 0.55±0.02 cm

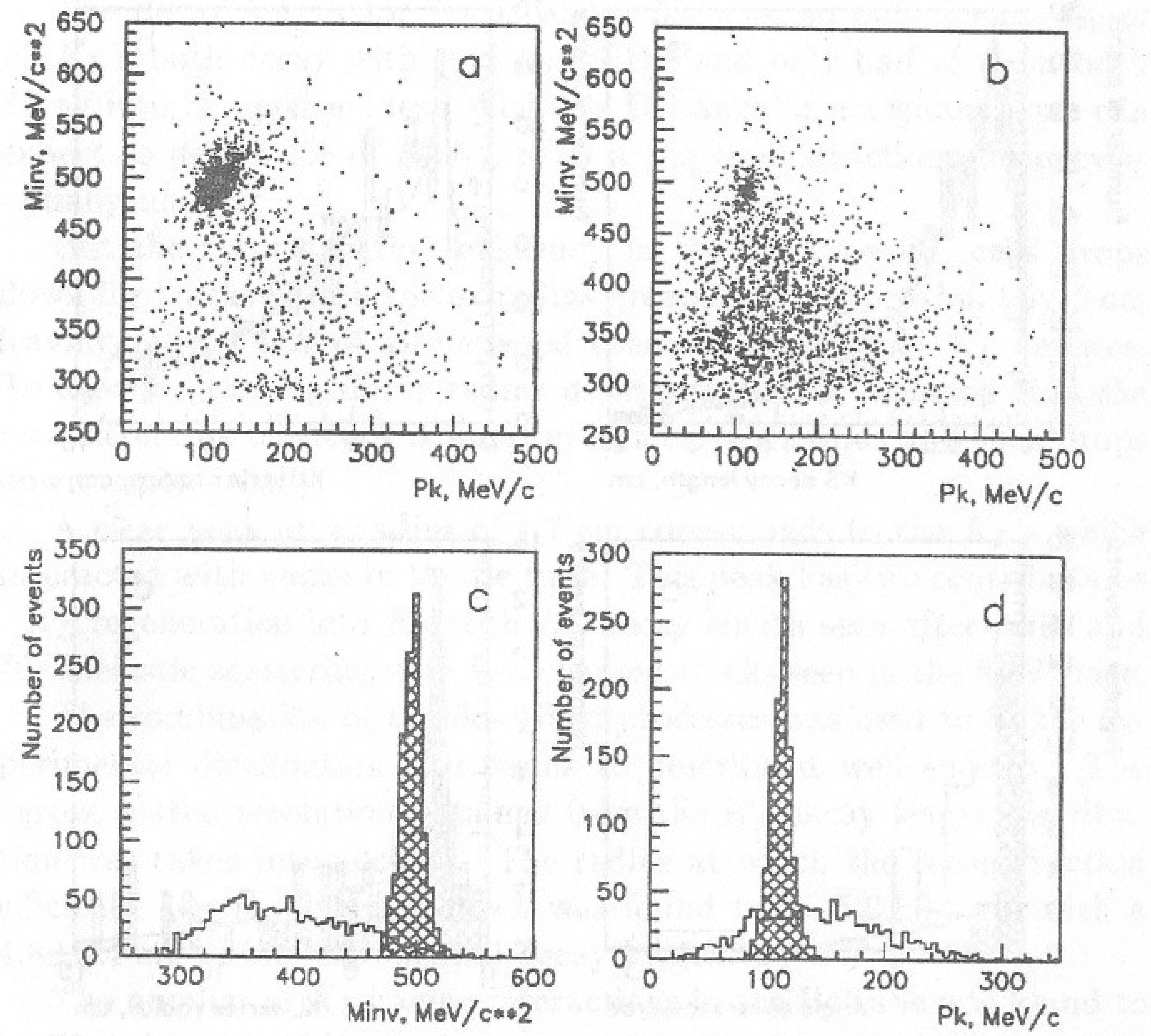

Figure 3: Study of $K_S K_L$ coupled decays: Invariant mass vs. missing momentum for 1-st (a) and 2-nd (b) vertex; c. Invariant mass for K_S (shaded) and K_L after K_S selection; d. Missing momentum for K_S (shaded) and K_L after K_S selection.

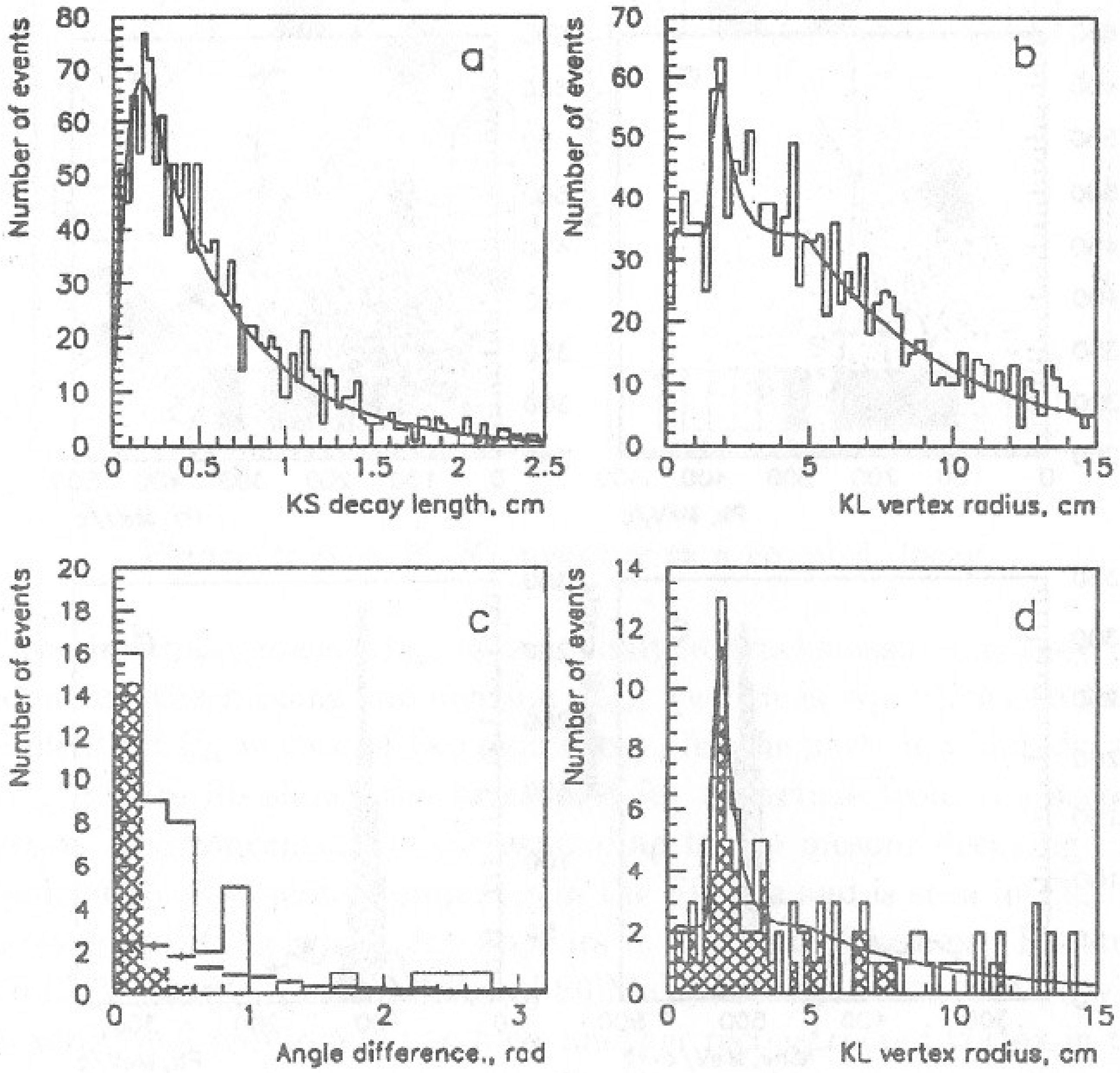

Figure 4: Study of $K_S K_L$ coupled decays: a. Decay length for K_S; b. Decay radius for K_L; c. Difference in the angle of P_{mis} and vertex-beam line for "tube"events (histogram), K_L semileptonic decays (points with errors and K_S two pions decays (shaded); d. Decay radius for K_Ls after M_{inv} cut and after K_S selecting cut (shaded).

and with a vertex position resolution of 0.15±0.03 cm.

The total number of the reconstructed K_L vertices accompanying K_S decays was found to be 1423. The interpretation of the decay radius distribution for the K_L shown in Figure 4b is more complicated.

The decay length for K_L is about 350 cm, so only about 4% of $K_S K_L$'s both decay within 15 cm of DC and only half of them both decay into charged modes. With the DC angular acceptance one can expect to detect 1% of $K_S K_L$ pairs if the reconstruction efficiency is radially uniform.

But the reconstruction efficiency in the jet type DC cells drops down for tracks with a vertex radius greater than approximately 5 cm leaving only 0.64% of all detected events with K_S and K_L vertices. To describe the K_L decay radius distribution, it is assumed that the reconstruction efficiency is uniform to a certain radius and then drops down exponentially.

A clear peak at a radius of 1.7 cm corresponds to the K_L's which interacted with nuclei in the Be tube. This peak has two contributions - K_L regeneration into K_S with K_S decay length seen afterwards and K_L inelastic scattering with two charged tracks seen in the final state.

The combination of the described processes was used to fit the experimental distribution and seems to describe it well enough. The vertex spatial resolution obtained from the K_S decay length distribution was taken into account. The radius at which the reconstruction efficiency begins dropping down was found to be 5.0±0.4 cm with a 4.8±0.4 cm visible exponential decay length.

The number of K_L having interactions in the Be tube was found to be 79 ± 18 with 1355 events representing K_L decaying in flight.

To select candidates to $K_L \to \pi^+\pi^-$ events, an additional cut requiring the invariant mass of two tracks from a K_L vertex to be in the range of 470-525 MeV was applied. The decay radius distribution is presented in Figure 4d together with the fit function where all parameters except the number of events are fixed at the values obtained from the distribution in Figure 4b. The number of events under the peak drops down to 31 ± 7 and 78 remain from decays in flight.

The peak events after the invariant mass cut are interpreted as regeneration of K_L into K_S with its decay into $\pi^+\pi^-$ and are used for the calculation of the regeneration cross section.

For the $K_L \to \pi^+\pi^-$ selection one can apply stronger requirements for these events to satisfy full kinematics within detector resolution, i.e. 80 MeV/c< P_K < 140 MeV/c and K_S vertex in the P_{mis} direction. This selection is shown in Figure 4d by the shaded histogram and demonstrates that the peak at the Be tube survives with 20±5 events and 35 K_L decays in flight remain, still 10 times more than the expected number of CP violating decays.

The DC material (120 μ thick mylar entrance window, 100-150 μ diameter 50%Cu-50%Ti wires, Ar gas) can also contribute to nuclear interaction events. The DC mylar entrance window at 2.1 cm radius adds about 10% to the tail of events peaked at the Be pipe. The biggest concentration of the DC field wires is between 2.5-3.5 cm, where the average thickness of Cu+Ti is estimated as $3 \times 10^{-5} g/cm^2$ and drops down with radius. This amount of material is negligible compared to Be and could produce less than one nuclear interacting event, but a 10% correction from the mylar window is applied to cross section.

A further correction to the K_L cross sections comes from the Λ and Σ hyperon decays which can appear in the kinematic range as $K_L \to 2\pi$. The reactions

$K_L + p \to \Lambda^0 + \pi^+, \Lambda^0 \to p + \pi^-;$

$K_L + p \to \Sigma^0 + \pi^+, \Sigma^0 \to \Lambda^0 + \gamma, \Lambda^0 \to p + \pi^-;$

$K_L + n \to \Sigma^- + \pi^+, \Sigma^- \to n + \pi^-;$

$K_L + n \to \Sigma^+ + \pi^-, \Sigma^+ \to n + \pi^+,$

were studied. In our selection only two charged pions were detected by the requirement of two prong vertex and dE/dX in the DC corresponding to minimum ionizing particles.

As it was shown by simulation, 8% of such events with a final nucleon nearly at rest contribute to the number of regenerated events after the M_{inv} cut with the visible vertex radius distribution similar to that from the K_S decay. These events were removed from the regeneration candidates in the K_L kinematic region and added to $79 - 31 = 48$ K_L interaction candidates.

The following numbers were obtained:

$N_{nucl+reg} = 79 \pm 18,$

$N_{nucl} = 50 \pm 17,$

$N_{reg} = 29 \pm 7.$

Events in the range 1.5–3.5 cm from the distribution in Figure 4d were used to obtain the angular distribution for K_S after regeneration. Figure 4c shows the projected angular distribution of these K_S. Dots with errors show the expected distribution for semileptonic decays of K_L, normalized to the expected number of these background events in the selected range.

The obtained angular distribution is wider than in the case of coherent regeneration which should look like shown shaded distribution for original K_S decaying at the same distance. But with this data sample the coherent contamination is expected to be small and cannot be extracted.

4 Cross sections

For the calculation of the cross sections, the number of the initial K_L passing the Be tube multiplied by the reconstruction efficiency ϵ_{rec} can be found from the distribution of Figure 4b using the expression:

$$N_{K_L} \cdot \epsilon_{rec} = N_0 \cdot L_{K_L} / B_{ch} = 61200 \pm 2500,$$

where N_0 is the visible number of pairs at a zero radius (fit value from the flat region in Figure 4b) and L_{K_L}=350 cm is the decay length for the K_L. The value B_{ch}=0.78 is the probability for a K_L to have a pair of charged particles after decay. Using this expression one can calculate a probability for the K_L to interact at the Be tube as

$$P_{nucl} = N_{nucl} / (N_{K_L} \cdot \epsilon_{rec}) = (0.82 \pm 0.28) \cdot 10^{-3},$$

$$P_{reg} = N_{reg} / (N_{K_L} \cdot \epsilon_{rec} \cdot B_{\pi\pi}) = (0.61 \pm 0.16) \cdot 10^{-3},$$

where $B_{\pi\pi}$=0.686 is a branching ratio of K_S decays into a pair of charged pions. A ratio (1.12±0.16) for the reconstruction efficiencies of K_L decaying into two pions (after regeneration) and into three particles was obtained by simulation and was taken into account.

Using the above probabilities the cross sections can be calculated from the equation

$$\sigma = \frac{P \cdot A}{N_A \cdot \rho \cdot t},$$

where A and N_A are the atomic number and the Avogadro constant, ρ and t are the density and the thickness of the material. After correction for the mylar window interactions the following cross section for Be has been obtained:

$$\sigma_{reg}^{Be} = 53 \pm 17 \quad \text{mb}.$$

For the nuclear cross section (excluding regeneration) one can obtain the inelastic cross section into a two particle final state, arising from the Λ and Σ production discussed earlier:

$$\sigma_{inel}^{vis} = 70 \pm 26\text{mb}.$$

To estimate the total cross section, the relative weight of these reactions was found to be 0.21 from the NUCRIN package [16]. Using the CMD-2 experimental σ_{inel}^{vis} value and a ratio $\sigma_{inel}/\sigma_{tot} = 0.52$ [15], one can estimate $\sigma_{tot}^{Be} = 641 \pm 238$ mb. A systematic error of this estimation is about 30% and comes from uncertainties in the event selection and in the ratio above.

5 Discussion

The selection of candidates for $K_L \to \pi^+\pi^-$ events faced two problems.

First is a background from the dominant K_L decays. Simulation gives a rejection factor of only 0.03 for the given DC resolution, and the ratio of the number of events within our cuts (away from the beam pipe) to the total number of K_L decays, 35/1355, is consistent with this result. However, the expected rate of $K_L \to 2\pi$ decays is $2 \cdot 10^{-3}$, so that only 3 true $K_L \to 2\pi$ events could be expected in

the sample. The observed events are mainly from the semileptonic decays of $K_L \to \pi\mu\nu$, and to improve the achieved rejection and select $K_L \to \pi^+\pi^-$ events better angular and momentum resolution in the DC is needed.

The effect of tightening resolution may be illustrated by selecting events within 1.5 standard deviations of the detector resolution.

In this case 9.5±3.4 of the original events remain under the peak at the pipe and only 5 K_L decays in flight remain (2 of them should be real $K_L \to \pi^+\pi^-$ events). DC resolution better by a factor of 2 expected for the rest of our data, could give a signal/background ratio about 1 or better.

A second problem is the relatively high background from nuclear interactions of K_L and the regeneration effect. The obtained cross sections can be compared to the data available at higher momenta and with theoretical expectations. There are no data for the regeneration cross section for Be and for slow kaons.

In Figure 5a the experimental regeneration cross section is plotted together with the theoretical calculations performed in [15]. The obtained cross section is consistent with calculations. The calculated regeneration cross section for Cu is also presented in the Figure. The comparison of the calculated regeneration cross sections for these two different materials shows that at momenta below 200 MeV/c one cannot scale them by a simple $A^{2/3}$ dependence. To verify these theoretical calculations one needs experimental measurements for different materials.

The experimental angular distribution of the regenerated K_S after background subtraction is presented in Figure 5b together with the fit function and the theoretical prediction [15] and seems to be a little narrower than the expectation.

This result for the total nuclear cross section in Be for 110 MeV/c kaons can be compared to the experimental data at higher momenta [17] and theoretical calculations [15]. Such comparison is presented in Figure 6. The cross sections extracted from GHEISHA and FLUKA simulation codes are also shown. It is seen that the FLUKA code, as well as the calculations from [15] give cross sections in good agreement

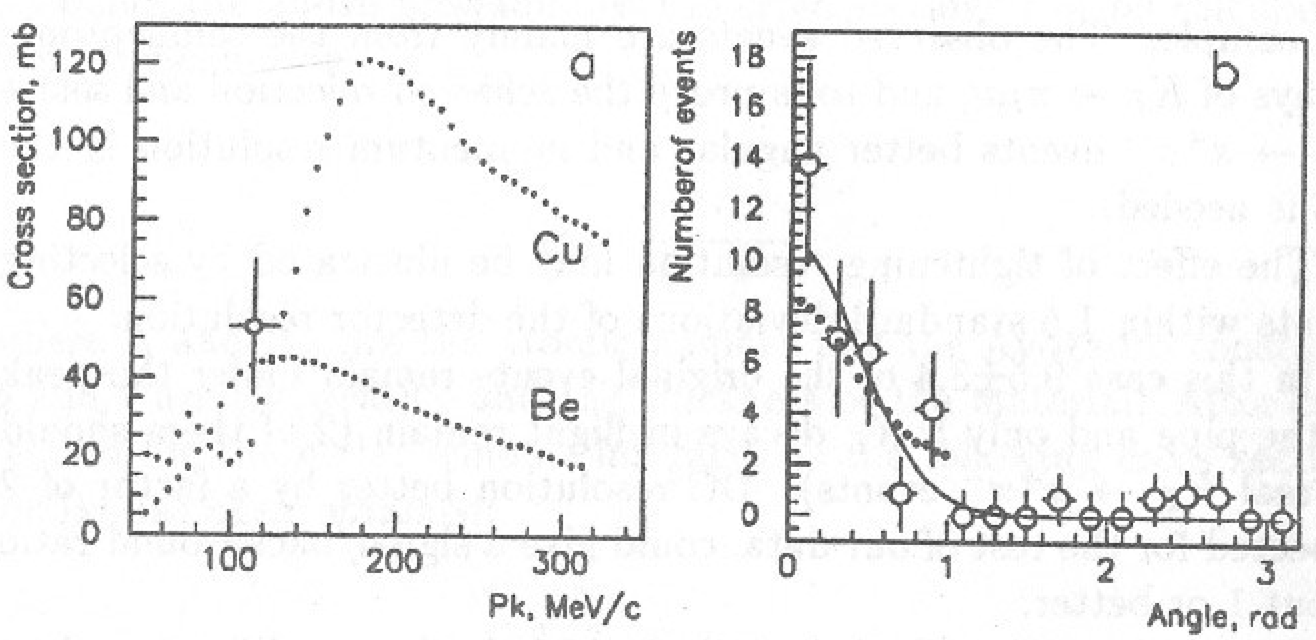

Figure 5: a. Experimental regeneration cross section and theoretical calculations for Be and Cu; b. Angular distribution of the regenerated K_S with the best fit function (solid line) and theoretical prediction (dots);

with experimental data. The GHEISHA code gives completely wrong absolute values as well as momentum dependence.

After publishing our preliminary results [13], the regeneration influence was discussed for the ϵ'/ϵ measurement planned in KLOE detector[15]. A possible way to remove regeneration events is to require that the final state particles lie in a plane (since for regeneration events, recoil nucleons will carry a momentum). It was shown that the total regeneration probability in the KLOE drift chamber after an acoplanarity cut (factor of 4 rejection) was 10^{-4} that should be compared with 2×10^{-3} probability for the "normal" CP violating $K_L \to \pi\pi$ decay and $\approx 10^{-6}$ probability for the expected direct CP violation decay.

The regeneration itself does not give any decay asymmetry expected for the direct CP violating K_L decay, but the acoplanarity cut as well as other selection cuts applied separately to $\pi^+\pi^-$ and $\pi^0\pi^0$ final states with a different resolution (DC for the first and calorimeter for the

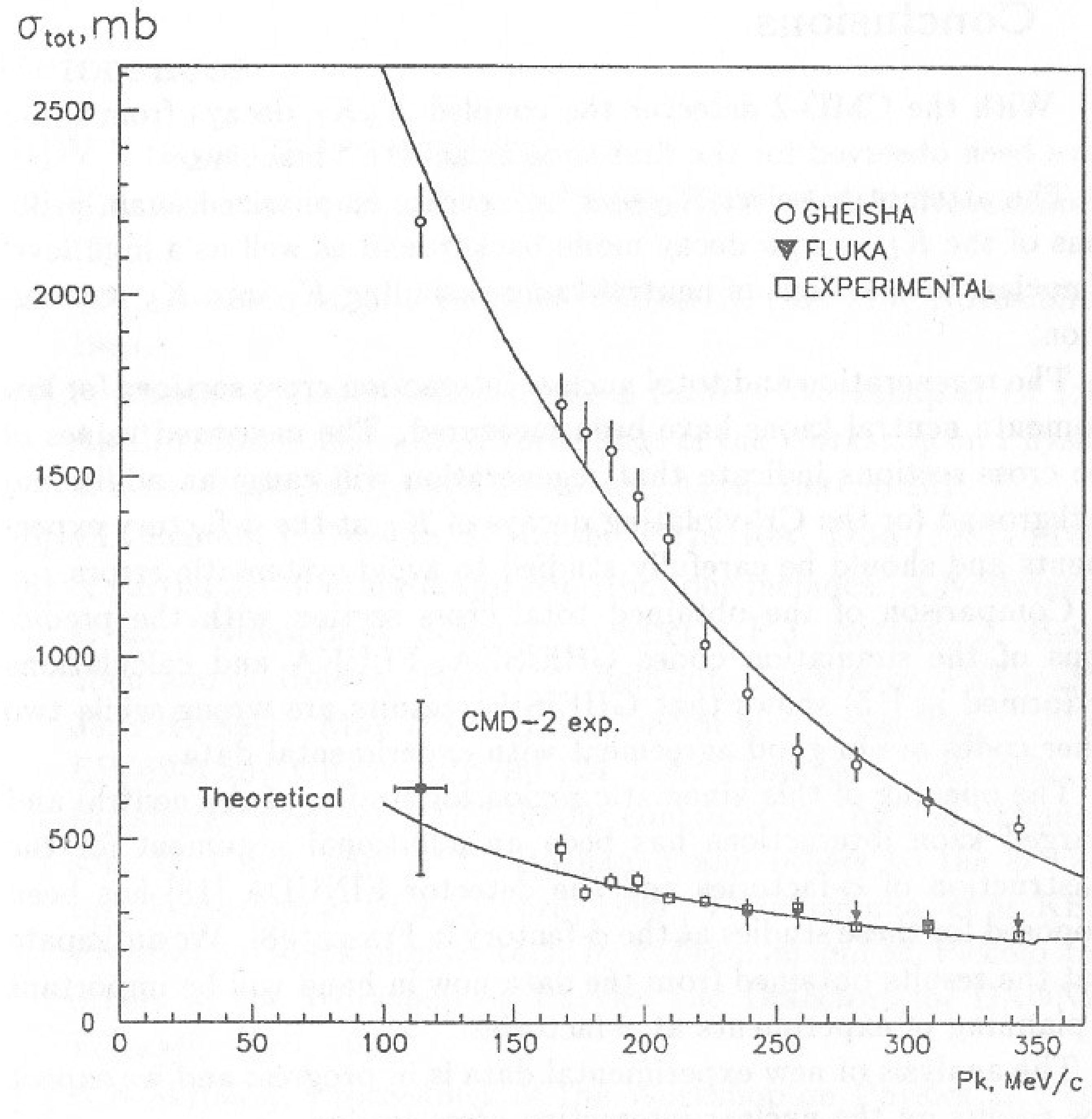

Figure 6: Comparison of the total experimental K_L nuclear interaction cross section in Be with the theoretical calculations and simulation by different codes.

second) can cause a systematic asymmetry due to the broad angular distribution of the regenerated events.

6 Conclusions

With the CMD-2 detector the coupled $K_S K_L$ decays from the ϕ have been observed for the first time at an e^+e^- machine.

The attempt to select $K_L \to \pi^+\pi^-$ events emphasized again problems of the $K_L \to \pi\mu\nu$ decay mode background as well as a high level of nuclear interactions of neutral kaons including K_L into K_S regeneration.

The regeneration and total nuclear interaction cross sections for low momenta neutral kaons have been measured. The measured values of the cross sections indicate that regeneration will cause an additional background for the CP-violating decays of K_L at the ϕ-factory experiments and should be carefully studied to avoid systematic errors.

Comparison of the obtained total cross section with the predictions of the simulation codes GHEISHA, FLUKA and calculations performed in [15] shows that GHEISHA results are wrong while two other codes are in good agreement with experimental data.

The opening of this kinematic region for studies of the neutral and charged kaon interactions has been an additional argument for the construction of ϕ-factories and the detector FINUDA [18] has been proposed for these studies at the ϕ-factory in Frascati[8]. We anticipate that the results obtained from the data now in hand will be important in planning of experiments at ϕ-factories.

The analysis of new experimental data is in progress and we expect new results on the nuclear interaction cross section.

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Study of K_SK_L coupled decays and K_L-Be interactions with the CMD-2 detector at VEPP-2M collider

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Изучение парных распадов K_SK_L и взаимодействие K_L-Be с детектором КМД-2 на накопителе ВЭПП-2М

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