Search for light pseudoscalar sgoldstino in $K^-$ decays

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Abstract

A search for the light pseudoscalar sgoldstino production in three-body $K^-$ decay $K^- \rightarrow \pi^- \pi^0 P$ has been performed with the “ISTRA+” detector exposed to the 25 GeV negative secondary beam of the U-70 proton synchrotron. No signal is seen. Upper limit for the branching ratio $Br(K^- \rightarrow \pi^- \pi^0 P)$ at 90% confidence level is found to be $\sim 8 \cdot 10^{-6}$ in the effective mass $m_P$ range 0 ÷ 200 MeV, excluding the region near $m_{\pi^0}$ where it degrades to $\sim 3 \cdot 10^{-5}$. 
1 Introduction

In supersymmetric models with spontaneous supersymmetry breaking superpartners of a Goldstone fermion — goldstino, pseudoscalar $P$ and scalar $S$, should exist. In various versions of gravity mediated and gauge mediated theories one or both of these weakly interacting bosons (sgoldstinos) are light and therefore can be observed in kaon decays. Moreover, if sgoldstino interactions with quarks conserve parity, (as in left-right extensions of MSSM), and $P$ is lighter than $S$, so that $m_S > (m_K - m_\pi)$ and $m_P < (m_K - 2m_\pi)$, sgoldstinos show up in the decay $K \rightarrow \pi\pi P$(see Fig.1), rather than in a much better constrained $K \rightarrow \pi S$. The phenomenology of light sgoldstinos in this scenario is considered in detail in [1]. Under assumption that sgoldstino interactions with quarks and gluons violate quark flavor and conserve parity, low energy interactions of pseudoscalar sgoldstino $P$ with quarks are described by the Lagrangian:

$$L = -P \cdot (h_D^{ij} \cdot \bar{d}_i \gamma^5 d_j + h_U^{ij} \cdot \bar{u}_i \gamma^5 u_j)$$

with

$$h_D^{ij} = \frac{m_{D,ij}^{(LR)}}{\sqrt{2}F}, \quad h_U^{ij} = \frac{m_{U,ij}^{(LR)}}{\sqrt{2}F},$$

here the scale of supersymmetry breaking is denoted as $\sqrt{F}$. The constraints on the flavor-violating coupling of sgoldstino to quarks is evaluated using the $K_L^0 - K_S^0$ mass difference and $CP$ violating parameter $\epsilon$ in the neutral kaon system: $|h_{12}^D| \leq 7 \cdot 10^{-8}, |Reh_{12}^D \cdot Imh_{12}^D| < 1.5 \cdot 10^{-17}$. It has been shown in [1] that, depending on the phase of sgoldstino-quark coupling, these constraints result in the following limits on the branching ratio: $Br(K^- \rightarrow \pi^-\pi^0 P) \leq 1.5 \times 10^{-6} \div 4 \times 10^{-4}$. A search for P in charged kaon decays is of particular interest for the case $Reh_{12}^D \sim 0$, when the corresponding branching ratio of $K_L$ is small.

Light sgoldstino decays into two photons or into a pair of charged leptons, two photon decay dominating almost everywhere in the parameter space. Depending on the parameter $g_\gamma = \frac{1}{2\sqrt{2}} \frac{M_\gamma}{F}$, where $M_\gamma$ is the photino mass, sgoldstino decays either inside or outside the detector. In the present search we assume that sgoldstino decays outside the detector, i.e. is invisible. The existing limits on the branching $Br(K^- \rightarrow \pi^-\pi^0 P)$ are at the level of $4 \cdot 10^{-5}$ [2], whereas the limits for the scalar sgoldstino $S$ can be estimated from the studies of the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ at the level of $4.7 \cdot 10^{-9}$, see [3] for a recent review.

The aim of our present study is to search for invisible pseudoscalar sgoldstino in the decay of $K^-$. Experimental setup and event selection are described in Section 2, the results of the analysis are
The preliminary results of this study have been presented in [4].

2 Experimental setup and event selection

The experiment is performed at the IHEP 70 GeV proton synchrotron U-70. The ISTRA+ spectrometer has been described in some detail in our recent papers on $K_{e3}$ [5], $K_{µ3}$ [6] and $π^{-}π^{0}π^{0}$ decays [7], here we briefly recall characteristics relevant to our analysis. The ISTRA+ setup is located in the negative unseparated secondary beam line 4A of U-70. The beam momentum is $\sim 25$ GeV with $\Delta p/p \sim 1.5\%$. The admixture of $K^{-}$ in the beam is $\sim 3\%$, the beam intensity is $\sim 3 \cdot 10^{6}$ per 1.9 sec U-70 spill. A schematic view of the ISTRA+ setup is shown in Fig. 2. The beam particles deflected by the magnet $M_1$ are measured by four proportional chambers $BPC_1$—$BPC_4$ with 1 mm wire step, the kaon identification is done by three threshold Cerenkov counters $\hat{C}_0$—$\hat{C}_2$. The 9 meter long vacuumed decay volume is surrounded by eight lead glass rings used to veto low energy photons. The same role is played by 72-cell lead glass calorimeter $SP_2$. The decay products deflected in the magnet $M_2$ with 1 Tm field integral are measured with 2 mm step proportional chambers $PC_1$—$PC_3$, with 1 cm cell drift chambers $DC_1$—$DC_3$ and finally with 2 cm diameter drift tubes $DT_1$—$DT_4$. A wide aperture threshold Cerenkov counters $\hat{C}_3, \hat{C}_4$, filled with He, serve to trigger electrons and are not used in the present measurement. $SP_1$ is a 576-cell lead glass calorimeter, followed by $HC$ — a scintillator-iron sampling hadron calorimeter. $MH$ is a 11x11 cell scintillating hodoscope, used to improve the time resolution of the tracking system, $MuH$ is a 7x7 cell muon hodoscope.

The trigger is provided by scintillation counters $S_1$—$S_5$, beam Cerenkov counters and by the analog sum of amplitudes from last dinodes of the $SP_1$: $T=S_1 \cdot S_2 \cdot S_3 \cdot \hat{C}_4 \cdot \hat{C}_2 \cdot \hat{C}_3 \cdot \hat{C}_5 \cdot \Sigma(SP_1)$, here $S_4$ is a scintillation counter with a hole to suppress beam halo, $S_5$ is a counter downstream of the setup at the beam focus, $\Sigma(SP_1)$ - a requirement for the analog sum to be larger than a MIP signal.

During first run in March-April 2001, 363 million of trigger events were logged on DLT’s. During second physics run in November-December 2001 350 million trigger events were collected with higher beam intensity and stronger trigger requirements. This information is supported by about 300M MC events generated using Geant3 [8] for dominant $K^{-}$ decay modes. Signal efficiency for possible sgoldstino production has been estimated using one million generated events for the first run configuration and 0.5 million events for the second run configuration, for each effective mass $m_P$ point in the mass interval from 0 to 200 MeV with a step of 10 MeV. These signal events were

![Figure 2: The elevation view of the ISTRA+ setup.](image)
Data collected in two runs, Spring 2001, first run, and Winter 2001, second run, are used. Some information on the data processing and reconstruction procedures is given in [5, 6, 7]. Here we briefly mention the details, relevant for \( \pi^-\pi^0 + \) missing energy event selection. Part of technical distributions, omitted in the present paper, has been shown in [4].

The muon identification (see [6]) is based on the information from the SP\(_1\) — a 576-cell lead glass calorimeter and the HC — a scintillation-iron sampling calorimeter. The electron identification (see [5]) is done using \( E/p \) ratio — of the energy of the shower associated with charged track and charged track momentum.

A set of cuts is designed in order to suppress various backgrounds to possible sgoldstino production:

0) Events with one reconstructed charged track and with two electromagnetic showers in the electromagnetic calorimeter SP\(_1\) are selected. We require the effective mass \( m(\gamma\gamma) \) to be within \( \pm 50 \) MeV from \( m_{\pi^0} \). Events with vertex inside interval \( 400 < z < 1650 \) cm are selected.

1) “Soft” charged pion identification is applied, tracks having electron or muon flag (as described in [5, 6]) are rejected.

2) Events with missing energy \( E_{\text{beam}} - E_{\pi^-} - E_{\pi^0} \) above 3 GeV are selected. This cut serves to reduce the \( K_{\pi2} \) contamination. In Fig. 3 missing energy spectra for the second run data, MC background and MC signal with \( m_P = 90 \) MeV are compared.

3) To reduce the charged particles background in the photon sample, the MH information is used. The distance \( r \) between SP1 shower and the nearest MH hit in the plane transverse to the beam is shown in Fig. 4. The events are selected where at least one shower has this distance above 10 cm.

4) The events where one of the photons is suspected to be irradiated by the charged particle in a detector material upstream/inside M2-magnet are rejected.

Such photons have nearly the same \( x \) coordinate (in the direction of the magnetic field) as the charged track on the SP\(_1\) face, i.e. an event is rejected if for one or both showers \( \Delta x = |x_{ch} - x_{y}| < 7 \) cm and \( \Delta y = |y_{ch} - y_{y}| < 30 \) cm.

5) Events having good \( K_{e3} \) 2C-fit are removed.

6) To suppress the tails from the \( K_{\pi2} \) decay a cut on the charged pion momentum \( p^* \) in the kaon rest frame \( p^*(\pi^-) < 180 \) MeV is applied.
7) The pion identification, mainly based on the HC information is required. The efficiency and muon suppression of this selection has been determined using $K\mu_2$ and $K\pi_2$ decays. The efficiency is found to be 70% and 80% for the first and second run data respectively. The remaining muon admixture is equal to 3% and 2%.

8) To suppress $\pi^-\pi^0\gamma$ background only the events with missing momentum pointing to SP1 transverse plane within SP1 working aperture are selected.

9) The “Veto” cut uses information from the Guard System GS and the guard electromagnetic calorimeter SP2: absence of signals above noise threshold is required.

The data reduction information for the second run is given in Table 1 and is compared there with MC-background statistics and with MC-signal statistics for the sgoldstino mass of $m_P = 90$ MeV. The cut suppression factors $w_{i-1}/w_i$ for the MC data are calculated using the corresponding matrix elements.

The influence of the last cuts on the missing mass squared spectra $(P_K - P_{\pi^-} - P_{\pi^0})^2$, which is used as the signal “estimator”, is shown in Fig. 5. The left wide bump in Fig. 5 is due to $K\mu_3$ decays, the shift to negative missing mass squared is caused by the use of the pion mass in its calculations. Second peak is caused by $\pi^-\pi^0(\pi^0)$ decay with gammas from second $\pi^0$ escaping detection. No evidence for additional sgoldstino signal is seen.

| Cut | real data | $N_{i-1}/N_i$ | BG MC | $w_{i-1}/w_i$ | MC $m_P=90$ MeV | $w_{i-1}/w_i$ |
|-----|-----------|---------------|-------|--------------|-----------------|--------------|
| (0) $\pi^-$, $m(\gamma\gamma)$ near $m(\pi^0)$ | 9943046 | 5512890 | 98289 | 1.05 |
| (1) no (e, $\mu$) | 7771606 | 1.28 | 4545059 | 1.19 | 93470 | 1.05 |
| (2) $E_{\text{mis}} > 3.0$ GeV | 1123220 | 6.92 | 588735 | 7.78 | 82602 | 1.17 |
| (3) MH filter | 939052 | 1.20 | 516922 | 1.19 | 747/44 | 1.09 |
| (4) conv. gammas | 722622 | 1.30 | 426286 | 1.22 | 56513 | 1.25 |
| (5) no $K_{\text{e3}}$ fit | 458338 | 1.58 | 201580 | 2.27 | 35906 | 1.69 |
| (6) $p^*(\pi^-) < 180$ MeV | 326935 | 1.40 | 134706 | 1.28 | 35698 | 1.01 |
| (7) $\pi^-$ identification | 122804 | 2.66 | 68380 | 2.06 | 33401 | 1.06 |
| (8) $10 < r < 60$ cm | 108992 | 1.13 | 60698 | 1.12 | 31451 | 1.06 |
| (9) Veto | 31451 | 3.47 | 18674 | 3.58 | 31104 | 1.01 |

As a result of the previous cuts, especially the last ”Veto” cut, $\pi^0$-signal practically disappears.
Figure 5: Missing mass squared distributions after cuts 6, 7 and 9, left column — second run data, right column — MC for dominant $K^-$ decay modes. The bin size is equal to 0.0005 (GeV/c)^2.
Figure 6: $m(\gamma\gamma)$ spectrum for events with $E_{\text{miss}} > 3.0$ GeV with the results of the fit by the sum of the Gaussian and third degree polynomial (left part); $m(\gamma\gamma)$ spectra after the "Veto" cut for the missing mass $m_P$ intervals 120-130, 130-140, 140-150 and 150-160 MeV (right part), run 1 plus run 2 data.

3 Analysis and results

In order to calculate the upper limits the "filtered" missing mass distribution has been fitted by the sum of the signal Gaussian with a fixed width of $\sigma = 11.1$ MeV, as determined from the signal MC and a background. The background has been described by two components: the Gaussian for the $\pi^-\pi^0(\pi^0)$ peak and a constant background. Fig. 7 shows an example of such a fit for the signal at $m_P = 5$ MeV. The events upper limits at the 90% confidence level are calculated as

$$N_{UL} = \max(N_{sig}, 0) + 1.28 \cdot \sigma ,$$

(3)
where $N_{sig}$ is the number of events in the signal Gaussian and $\sigma$ is the error estimate for $N_{sig}$. The signal upper limit $UL$ is calculated as

$$UL = \frac{N_{UL} \cdot 0.2116 \cdot \varepsilon(K_{\pi2})}{N(K_{\pi2}) \cdot \varepsilon} \quad (4)$$

with 0.2116 equal to the branching ratio $Br(K_{\pi2})$, and $N(K_{\pi2})$ equal to the number of reconstructed $K^- \rightarrow \pi^- \pi^0$ decays found to be $\sim 1.5$ M events for the first run and $\sim 4.5$ M events for the second run. The values $\varepsilon$ and $\varepsilon(K_{\pi2})$ are respective efficiencies for $K^- \rightarrow \pi^- \pi^0 P$ and $K_{\pi2}$ decays, which include both the reconstruction efficiency and geometrical acceptance. The signal efficiency $\varepsilon$ rises monotonically from $\sim 3.3\%$ to $\sim 11.3\%$ in the mass interval from 0 to 170 MeV and then drops slightly to the value $\sim 10.3\%$ at 200 MeV. The values for two runs are practically the same. The $K_{\pi2}$ efficiency $\varepsilon(K_{\pi2})$ is equal to 17.49 $\%$ for the first run and 24.92 $\%$ for the second run.

The weighted average ratio $\varepsilon/\varepsilon(K_{\pi2})$ with the weights proportional to the runs statistics has been used for the combined data sample.

The final results obtained using combined statistics of two runs are given in Fig. 8. Left part of this figure shows a comparison of our result with that published by the E787 collaboration [2].

Systematic uncertainty in the obtained upper limits have been determined by variation of the selection criteria, changing the bin size of the missing mass intervals, etc. It is found to be $\sim 25 — 30 \%$.

The obtained upper limits can be transformed into the limits on the value of the modulus $|h_{12}^D|$ (see equation 2). The corresponding limits are compared in Fig. 8 (right part) with the theoretical limit evaluated using $K_L - K_S$ mass difference.

4 Summary and conclusions

A search for a possible pseudoscalar sgoldstino production in the decay $K^- \rightarrow \pi^- \pi^0 P$ has been performed. It was assumed that sgoldstino decays outside the setup, i.e. is invisible. No signal is seen in the $m_P$ mass interval between 0 and 200 MeV. The obtained 90% confidence upper limits are $\sim 8.0 \cdot 10^{-6}$ for the sgoldstino mass range of 0 ÷ 200 MeV, excluding the interval near $m(\pi^0)$, where the limit is $\sim 3.0 \cdot 10^{-5}$. These results improve the confidence limits published by the E787 collaboration.
Collaboration. Our limits improve also the theoretical constraints on $|h_{12}^D|$ evaluated using $K_L - K_S$ mass difference.

In future, we plan to extend our search for a sgoldstino signal in the scenario when the decay $P \rightarrow \gamma\gamma$ happens inside the setup.

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