**SEARCH FOR A NEUTRAL HIGGS PARTICLE
IN THE DECAY SEQUENCE $K_L^0 \rightarrow \pi^0 H^0$ AND $H^0 \rightarrow e^+ e^-$**

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ABSTRACT

We have searched for the sequence of decays $K_L^0 \rightarrow \pi^0 H^0$ and $H^0 \rightarrow e^+ e^-$ at the CERN Super Proton Synchrotron (SPS), and have allowed for a non-zero H^0 lifetime. Three candidates have been seen, consistent with an expected background of 3.3. Limits on the branching ratio product in the range 10^{-8} to 10^{-7} are presented as a function of the mass and lifetime of the H^0 . These can be used to restrict the neutral Higgs of the minimal Standard Model.

1. INTRODUCTION

Fundamental particles of spin 0 have been proposed over the past decades as a means of solving a number of physical puzzles. The final state $\pi^0 e^+ e^-$ resulting from K_L^0 decay affords an opportunity to search for scalar particles that couple to electrons, light quarks, virtual heavy quarks, and massive gauge bosons. In experiments conducted with high-energy K^0 beams, a non-zero lifetime of the scalar particle H^0 may lead to a significant displacement between the point of origin of the π^0 and that of the electron pair resulting from the sequence of decays $K_L^0 \rightarrow \pi^0 H^0$ and $H^0 \rightarrow e^+ e^-$. In this letter, we present a search for this decay sequence. This is an extension of an earlier search [1] for the direct decay $K_L^0 \rightarrow \pi^0 e^+ e^-$. We have formulated a new analysis, which allows for a non-zero separation between the π^0 and $e^+ e^-$ points of origin. In addition, we have analysed data collected in 1988, thus increasing our sensitivity by almost a factor of 2 over the earlier search.

There is at present a particularly interesting class of spin-0 particles—the Higgs bosons [2]. A neutral scalar Higgs arises in the minimal Standard Model, and is intimately related to maintaining local gauge invariance in the presence of massive gauge bosons, as well as to avoiding cross-sections that violate unitarity at high energy [3]. The coupling constant of the Higgs to quarks, leptons, and massive gauge bosons is specified, but the mass of the Higgs, m_{H^0} , is essentially unconstrained. If one accepts the precise shape of the minimal Standard Model Higgs' potential, then lower limits of $m_{H^0} > 7\text{--}10\text{ GeV}$ are obtained [4]. These limits can be obviated if the mass of the t-quark is $\geq 80\text{ GeV}$, or if one rejects considerations of the evolution of the very early Universe. These lower bounds may also cease to hold if there is a more complex Higgs structure.

The Standard Higgs should decay predominantly to the heaviest fermions or gauge bosons accessible by kinematics, namely electrons, if $1\text{ MeV} = 2m_e \leq m_{H^0} < 2m_\mu = 211\text{ MeV}$ [5]. The decay to two photons proceeds via loops of charged particles, and the rate depends on the number of fermion generations [6]. In this m_{H^0} range, the amplitude for $H^0 \rightarrow \gamma\gamma$ is dependent on assumptions made about the masses of light quarks. We find that the branching ratio for $H^0 \rightarrow \gamma\gamma$ is less than 32%, and that $\tau_{H^0} \approx [35\text{--}40\text{ ps}] \cdot (100/m_{H^0}\text{ MeV})$, for $m_{H^0} \gg 2m_e$ *).

Estimates for the branching ratio $K_L^0 \rightarrow \pi^0 H^0$ vary from $\sim 10^{-7}$ to $\sim 10^{-4}$ [3, 10, 11] **). This large variation appears to be caused by interference between long-distance and quark-level amplitudes, which may be either constructive or destructive. The quark-level amplitude contains one term that is extremely sensitive to the mass of the t-quark. The branching ratio can be made less than 10^{-7} if the interference is destructive and the t-quark mass is fine-tuned.

There exist strong limits on Higgs bosons with masses less than 11 MeV [12]. Between 11 and 211 MeV, most limits have been derived from studies of $K \rightarrow \pi e^+ e^-$. In many cases these limits depend on extensive *a posteriori* analyses of experiments that were not designed to observe non-zero

*) The branching ratio for $H^0 \rightarrow \gamma\gamma$ is negligible at $m_{H^0} = 2m_e$, and increases until $m_{H^0} = 2m_\mu$. We assume that there are three fermion generations. The largest $H^0 \rightarrow \gamma\gamma$ branching ratio results from the use of constituent light-quark masses; those from N. Isgur [7] ($m_u = m_d = 330\text{ MeV}$, $m_s = 550\text{ MeV}$) yield a branching ratio, for $H^0 \rightarrow \gamma\gamma$, of 18% at $m_{H^0} = 200\text{ MeV}$, whilst those recommended by J. Gunion [8] ($m_u = m_d = 68\text{ MeV}$, $m_s = 450\text{ MeV}$) give 32% at $m_{H^0} = 200\text{ MeV}$. Current quark masses at a mass scale of 1 GeV [9] ($m_u = 5.6\text{ MeV}$, $m_d = 9.9\text{ MeV}$, and $m_s = 199\text{ MeV}$) give a branching ratio of 1.3% at $m_{H^0} = 200\text{ MeV}$, but these running masses should be evaluated at m_{H^0} , which leads to some ambiguity.

**) Estimates for the branching ratio $K^+ \rightarrow \pi^+ H^0$ should probably be multiplied by a factor of 4.2 to account for the longer K_L^0 lifetime.

H^0 lifetimes [1, 11, 13]. However, several experiments [14] allowed this possibility for the decay $K^+ \rightarrow \pi^+ H^0$ *).

2. EXPERIMENTAL SET-UP AND DATA-TAKING

The data were collected in 1986 and 1988 while performing a measurement of the CP-violation parameter ϵ'/ϵ by comparing the rate of decay of K_S^0 and K_L^0 into $\pi^0\pi^0$ and $\pi^+\pi^-$ final states [22]. Final states containing one π^0 and two electrons appear similar to the $\pi^0\pi^0$ final state in electromagnetic and hadronic calorimeters. In addition, π^0ee final states should contain, in the drift chambers, two tracks that point towards two showers in the electromagnetic calorimeter. Effects due to these tracks are taken into account by studying samples of $K^0 \rightarrow \pi^0\pi^0$, followed by a subsequent Dalitz decay, $\pi^0 \rightarrow ee\gamma$ (we refer to this decay sequence as $\pi^0\pi^0_D$). Branching-ratio results are obtained from a comparison of the number of π^0ee candidates and $\pi^0\pi^0_D$ events observed, with acceptance corrections as a function of the electron-pair mass m_{ee} and of the flight distance.

The beam layout and the experimental set-up of the detector have been described elsewhere [23]. Protons of 450 GeV impinge on a target 217 m in front of the first wire chamber in the detector. The secondary particles proceed through sweeping magnets and collimators of 120 m, resulting in a neutral beam of ± 0.2 mrad opening angle. Typically 10^{11} incident protons per 2.8 s SPS spill yield 10^6 neutral kaons of mean energy 100 GeV. The 50 m after the final collimator are chosen as a fiducial region for the K^0 decay, but we accept H^0 decays anywhere in the 95 m region downstream from this collimator.

The detector employs track measurement and calorimetry, and is designed for good stability, high efficiency, large acceptance, and fast data acquisition. It consists of

- four ring-shaped anticounters placed between 60 and 120 m from the final collimator;
- two wire chambers, spaced 24.5 m apart in 1986 and 23 m apart in 1988, containing four planes with 6 mm wire spacing and ± 0.5 mm resolution in each projection;
- scintillator hodoscopes for trigger purposes;
- a liquid-argon/lead sandwich calorimeter with strip readout to measure photons and electrons with ± 0.5 mm position and $\pm 7.5\%/\sqrt{E}$ (GeV) energy resolution;
- an iron/scintillator sandwich calorimeter to measure the energy of charged pions;
- two planes of scintillators (four planes in 1988), shielded by 3 m iron equivalent, to reject muons;
- for the data taken in 1988, a transition radiation detector [24] inserted between the second wire chamber and the first scintillator hodoscope.

The wire chambers are used to measure the direction of the electrons and the position of their vertex. The liquid-argon calorimeter is used to measure the energies and positions of both the electrons and the photons. The iron/scintillator calorimeter is used to reject events containing charged pions.

3. DATA REDUCTION

The relevant trigger for this analysis is based on the total energy and the number of clusters in the liquid-argon calorimeter. The π^0ee final states fulfil the same conditions as events from $K^0 \rightarrow$

*) During the preparation of this manuscript, a new search for a light Higgs in $\pi^+ \rightarrow e^+ \nu_e e^+ e^-$ has been performed [15], and an *a posteriori* search for a light Higgs in the same channel has appeared [16]. These are subject to some uncertainty [17]. A new search for bremsstrahlung of a light Higgs by electrons has been published [18] and one for a light Higgs in B decay has also been performed [19]; both may be comparatively free from theoretical uncertainty. An *a posteriori* analysis of a beam dump experiment [20] is subject to some uncertainty in the Higgs–nucleon coupling [21].

$\pi^0\pi^0$ [22]. There is a small loss of acceptance for events with both large m_{ee} and long H^0 flight distance. This is due to an on-line cut on the spatial moments of energy distributions, which corresponds, for $m_{ee} = 0$ and zero flight distance, to a cut on the distance from the calorimeter to the point of K^0 decay. This loss of acceptance is modelled by a Monte Carlo simulation. Events of the $\pi^0\pi^0$ type usually fail to meet the $\pi^0\pi^0$ trigger conditions, because they contain five electromagnetic clusters; however they are retained by a dedicated trigger condition.

The data sample of 2×10^8 triggers committed to tape is reduced by two orders of magnitude by the following conditions:

- less than 6 GeV of energy in the iron/scintillator calorimeter;
- two reconstructed space points in the first wire chamber;
- at least two reconstructed space points in the second wire chamber, located 2 m upstream of the liquid-argon calorimeter (3.5 m upstream in 1988).

The remaining events are processed by a revised version of the reconstruction program [1] used in the $K^0 \rightarrow \pi^0\pi^0 \rightarrow 4\gamma$ analysis for ϵ'/ϵ . The algorithm that associates space points in the wire chamber so as to reconstruct the ee decay, has been modified to incorporate information from the liquid-argon calorimeter in order to improve the efficiency at low ee mass. The candidates satisfy the following requirements:

- i) They have four electromagnetic clusters of energy between 3 and 100 GeV, all separated by at least 5 cm, and away from boundaries and support rods in the calorimeter.
- ii) Their total energy is between 50 and 190 GeV.
- iii) The K^0 decay point is between 0 and 50 m from the final collimator.
- iv) Their decay ‘centre of energy’ as measured in the liquid-argon calorimeter, is within the beam. More precisely, the centre of energy $(\bar{x}, \bar{y})$ is computed from $\bar{x}(\bar{y}) = \sum_{i=1}^4 x_i(y_i)E_i / \sum_{i=1}^4 E_i$, where the sum is over the four clusters, (x_i, y_i) are their positions and E_i their energies. We require that $\sqrt{\bar{x}^2 + \bar{y}^2} \leq 5$ cm.
- v) They have two tracks in the drift chambers, with the two space points associated with the tracks in either wire chamber separated by at least 3 cm.
- vi) The vertex of the two charged tracks is more than 2 m upstream of the first wire chamber.
- vii) There is an electromagnetic cluster within 2.0 cm of the extrapolated impact point of each track in the liquid-argon calorimeter.
- viii) For track-linked clusters, there is less than 4 GeV deposited in the front layers of the iron scintillator calorimeter.
- ix) Also for track-linked clusters, the ratio of energy deposition in the first half of the liquid-argon calorimeter (12.5 radiation lengths) to the total energy deposition must be > 0.65 .

A total of 3742 candidates remain after these requirements have been fulfilled. These consist primarily of $K_L^0 \rightarrow \pi^+\pi^-\pi^0$ decays, where both charged pions have produced showers of a largely electromagnetic nature in the liquid-argon calorimeter.

A sample of the $\pi^0\pi^0$ final states is written out for control studies and for normalization. Five electromagnetic clusters are required for this sample; the one γ from $\pi^0 \rightarrow ee\gamma$ is the fifth one. The first four clusters are subject to requirement (i) above, but the fifth is only subject to cuts due to boundaries and support rods. Requirements (ii) and (iv) apply to all five clusters.

4. ANALYSIS

For candidate events, the two electromagnetic showers correlated with the tracks are assumed to be electrons, and the remaining two showers are assumed to be photons from the π^0 decay. The distance $|z_{LAC} - z_{\pi^0}|$ from the liquid-argon calorimeter to the π^0 (and K^0) decay point is computed from $z_{LAC} - z_{\pi^0} = d_{12}\sqrt{E_{\gamma 1}E_{\gamma 2}}/m_{\pi^0}$, where $E_{\gamma 1}$ and $E_{\gamma 2}$ are the two photon energies, and d_{12} is the distance between them. The coordinates of the π^0 (and K^0) transverse to the beam direction (x_{π^0}, y_{π^0})

are obtained by assuming that the decay occurred on a line joining the target and the liquid-argon calorimeter centre of energy $(\bar{x}, \bar{y}, z_{\text{LAC}})$. The flight path of the ee system is reconstructed from the centre of energy of the two electron showers, $\bar{x}_{ee}(\bar{y}_{ee}) = [x_{e1}(y_{e1})E_{e1} + x_{e2}(y_{e2})E_{e2}]/[E_{e1} + E_{e2}]$, where (x_{ei}, y_{ei}) are the electron shower coordinates and E_{ei} are the energies in the electromagnetic calorimeter and the vertex of the electron tracks. The flight path should extrapolate to the π^0 decay point $(x_{\pi^0}, y_{\pi^0}, z_{\pi^0})$, and the vertex of the electron tracks should be between this point and the wire chambers, within experimental resolutions.

The reconstruction of the $\pi^0\pi_D^0$ decays is intended to follow closely that of the candidate sample. There is a threefold ambiguity in the assignment of one photon to $\pi^0 \rightarrow ee\gamma$. We make the assignment by minimizing $\chi_z^2 = (z_{\pi^0} - z_{\pi_D^0})^2/(\sigma_{z_{\pi^0}}^2 + \sigma_{z_{\pi_D^0}}^2)$, where $z_{\pi_D^0}$ is computed from the three showers in a manner similar to that for z_{π^0} . The errors are computed from the energy and position resolutions of the electromagnetic calorimeter.

The resolutions in the distance d of the line of flight of the ee system to the π^0 decay point, and in the H^0 flight path length s , have been studied with the sample of $\pi^0\pi_D^0$ decays. Both are dominated by the tracking error, which itself receives contributions from drift chamber resolution and multiple Coulomb scattering. Typically, σ_d is 8 mm, with variation from 5 to 10 mm, depending on electron energies, opening angle, and distance of the vertex from the drift chambers. We compute σ_d for each candidate, and require $d < 2.5\sigma_d$. Values for σ_s vary strongly with the opening angle, but are typically 3.5 m for $m_{ee} = 50$ MeV. In a manner similar to that used for the cut in d , we require $s > -2\sigma_s$; that is, candidates must have a non-negative ee flight path. A total of 1684 candidates remains after these cuts, which we estimate are $> 86\%$ efficient, based on studies of K_S^0 decay samples.

The mass M of the decaying system is computed for these remaining candidates, with allowance for the non-zero value of s . The mass distribution for the 28 candidates within 50 MeV of the K^0 mass is shown in fig. 1. Monte Carlo studies indicate a mass resolution of 6 MeV for the signal from K^0 decay, with slight variation with s and m_{ee} . The Monte Carlo reproduces the measured mass resolution in $\pi^0\pi_D^0$ events quite well. The expected background near the K^0 mass comes from $\pi^0\pi_D^0$ events where one photon has been lost, and yields $M < m_{K^0}$, but with a tail up to m_{K^0} . Most events in fig. 1 are from this background. We determine a lower cut of 485 MeV on M by optimizing the sensitivity in the Monte Carlo, and in addition require $M < 518$ MeV. Three candidates satisfy these mass requirements^{*)}. The ee mass and flight paths of these three candidates are shown in fig. 2. Two have m_{ee} near the mass of the π^0 , and one is somewhat lower. All proper lifetimes are consistent with zero.

The normalization has been determined by the control sample of $K_L^0 \rightarrow \pi^0\pi_D^0$ events. There are 535 ± 38 such events after 86 events from $K_L^0 \rightarrow \pi^0\pi^0\pi^0$ background are subtracted. The acceptance for the control sample, computed from our Monte Carlo, is 2.5%. From these numbers we estimate that the background, to Higgs candidates, of $\pi^0\pi_D^0$ events with a lost photon surviving all cuts, is 0.7 ± 0.3 events. Another known source of background occurs when both photons from a single π^0 convert to electron pairs in the 0.004 radiation length of material upstream from the first wire chamber. Each electron pair appears as one track in the drift chambers. The 2.6 background events expected from this process should have m_{ee} near m_{π^0} . We conclude that the three events observed are consistent with these two background sources, and compute upper limits on the occurrence of the decay sequence $K_L^0 \rightarrow \pi^0 H^0$ and $H^0 \rightarrow e^+ e^-$.

*) One candidate is that described in ref. [1]; one failed the tighter photon energy cuts of ref. [1]; and one failed the tighter overlap criteria of ref. [1]. These three candidates are all in the data from 1986.

5. INTERPRETATION AND CONCLUSIONS

The acceptance within the cuts has been estimated by Monte Carlo simulation as a function of ee mass and lifetime, and is exhibited in fig. 3 for $\tau_{H^0} = 0$. The loss of acceptance at low mass is due to the cuts on shower and space-point separation. The Monte Carlo reproduces the distribution of ee masses from $\pi^0\pi_D^0$ events, as shown in fig. 4. Acceptance is lost for long lifetime as well, primarily through the escape of the H^0 from the detector. Acceptances are calculated for non-zero lifetimes assuming an exponential distribution of proper lifetimes.

The 90% confidence levels are computed as a function of the ee mass and the H^0 mean lifetime. The numbers of expected background events and observed events in a $\pm 2\sigma$ bin around a given ee mass are then used to obtain the 90% confidence level upper limit on the number of events from $K_L^0 \rightarrow \pi^0 H^0$ and $H^0 \rightarrow e^+ e^-$ in that bin. Then the normalization and acceptance as a function of lifetime are used to obtain 90% confidence level upper limits on the product of the branching ratios $BR(K_L^0 \rightarrow \pi^0 H^0) \times BR(H^0 \rightarrow e^+ e^-)$ as a function of lifetime. A contour plot of the lines of the constant branching-ratio product limit is shown in fig. 5. This plot can be used to restrict the existence of any H^0 that might appear in the sequence of decays and have mass and lifetime within our acceptance. For the particular case of the Higgs, the relationship between mass and lifetime, as discussed in the Introduction, is shown also in fig. 5. One sees that for $m_{H^0} \gtrsim 50$ MeV, the limit is approximately 2×10^{-8} , and it is $\approx 1 \times 10^{-7}$ at $m_{H^0} \approx 15$ MeV. These limits severely constrain the neutral Higgs of the minimal Standard Model in this mass region.

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Figure captions

- Fig. 1 Mass M of the decaying system. There are 28 events from K_L^0 within 50 MeV of the K^0 mass. The background at a mass below that of the K^0 is primarily from $\pi^0\pi_D^0$ decays where one photon is lost. The search region from 485 to 518 MeV is indicated.
- Fig. 2 Electron-pair mass m_{ee} versus flight path for the three candidate events. The event with $m_{ee} = 130$ MeV and negative flight path was the one found in the earlier study [1].
- Fig. 3 Acceptance as a function of H^0 mass for $\tau_{H^0} = 0$.
- Fig. 4 Distribution of ee mass for events of the type $\pi^0\pi_D^0$, for data and Monte Carlo simulation. In addition to the 621 events from K_L^0 decays, 3761 events from K_S^0 decays have been included.
- Fig. 5 The 90% confidence limits on the product of the branching ratios $BR(K_L^0 \rightarrow \pi^0 H^0) \times BR(H^0 \rightarrow ee)$ as a function of the H^0 mass interval and lifetime interval. Contour lines of equal limit, as a function of mean lifetime and m_{ee} , are shown. Also shown (dot-dashed line) are values for the lifetime as a function of mass for the single neutral Standard Model Higgs.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5