The NA62 rare Kaon decay experiment Photon Veto System

V. Palladino for the NA62 Photon Veto Working Group. *

July 15, 2008

Abstract

The NA62 experiment at CERN SPS has been proposed with the purpose to measure the Branching Ratio for the ultrarare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$. The photon veto system will have to provide a rejection better than $10^{-8}$ for $\pi^0$ decays. The system is composed by several detectors. The larger ones constitute the Large Angle Veto (LAV) system, and will cover an angular region up to 50 mrad with respect to the incident beam. In order to optimize the cost/performance ratio we have tested three different technologies for the LAV system using a low energy electron beam at the LNF Beam Test Facility. A lead-scintillating fibers prototype has been built on purpose; a lead-scintillating tiles prototype was on loan by former CKM collaboration; a set of lead glass blocks from the OPAL barrel calorimeter have also been tested. We present preliminary results on detector performances and compare the three solutions.

1 The NA62 experiment

The Branching Ratio (BR) $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ can be related to the CKM element $V_{td}$ (the less well known one), the precise theoretical estimation in the Standard Model (SM) and SUper SYmmetry (SUSY) will allow us to have a probe of the flavour sector or the evidence of physics beyond the Standard Model, if deviation from the predicted SM value will be observed.

The SM prediction is $(8.22 \pm 0.84) \times 10^{-11}$. Until now only three events have been collected and the experimental value is $1.47^{+1.30}_{-0.89} \times 10^{-10}$[1]. The NA62 experiment (a.k.a. P326) has been proposed to detect 100 events of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ with a $S/B$ ratio of 10 : 1 [2].

---

* A. Antonelli, E. Capitolo, P.S. Cooper, L. Iannotti, M. Moulson, M. Raggi and T. Spadaro, from Laboratori Nazionali di Frascati dell’INFN, Frascati, Italy; P.S. Cooper is a visitor from Fermi National Laboratory, Batavia IL, USA; F. Ambrosino, M. Napolitano, V. Palladino, A. Romano and G. Saracino, from Dipartimento di Scienze Fisiche and Sezione INFN, Napoli, Italy; R. Fantechi, G. Lamanna, L. Mannelli and S. Venditti, from Dipartimento di Fisica and Sezione INFN, Pisa, Italy; E. Leonardi, F. Perfetto, M. Serra and P. Valente, from Dipartimento di Fisica dell’Università “la Sapienza” and Sezione INFN, Roma, Italy; Speaker e-mail: vito.palladino@na.infn.it.
The experimental layout is proposed in 1.

![Figure 1: NA62 experimental setup.](image)

The experiment will make use of a 75 GeV unseparate positive secondary beam. The total beam rate is 800 MHz providing 50 MHz of $K^+$'s. The fiducial decay volume (in vacuum) begins 102 m from the production target position. The $K^+$ decay rate in the 120 m long fiducial decay will be about 10 MHz.

The success of the experiment depends crucially in obtaining the required level of background rejection. To provide this, many different detectors have been proposed for both kinematic based and particle identification based rejection.

The decay fiducial volume is surrounded by 12 LAV (Large Angle Veto) stations ring shaped, that cover the angular range from 8.5 to 50 mrad. The last 35 m of the decay region host a dipole spectrometer with four straw-tracker stations operated in vacuum. The spectrometer, together with the RICH system and the dedicated muon detector downstream, will provide the required level of $\pi/\mu$ separation.

The NA48 Liquid Krypton calorimeter (LKr) and some other small detectors are used to veto small angle (high energy) photons.

The apparatus must be able to reject background from, e.g. $K^+ \to \pi^+\pi^0$ decays at level $10^{-12}$. Kinematical cuts on the $K^+$ and $\pi^+$ tracks will provide a factor $10^{-4}$ and ensure 40 GeV of electromagnetic energy in the photon veto; this energy must be detected with an inefficiency better than $10^{-8}$. The LAV system will be able to detect photons as low as 200 MeV with inefficiency better than $10^{-4}$. In addition, the LAV system must have a good energy and time resolution in order to define a precise energy threshold and to use the system in the trigger logic. In order to minimize the amount of material crossed by photons
produced in $\pi^0$ decays and reach such a high efficiency, the LAV system will be operated in vacuum.

2 LAV system

The LAV system will be made by 12 ring shaped subdetectors. The detectors at the first five stations have inner radii of 60 cm and outer radii of 96 cm. The other stations have inner and outer radii which match the shape of the vacuum chamber. The largest covers the range from 90 cm → 140 cm.

The LAV requirements are:

- **Photon Inefficiency** at $10^{-4}$ level or better in the energy range 200 MeV → 1 GeV;
- **Mechanical design** optimized in order not to spoil the vacuum inside the decay volume;
- **Time Resolution** better than 1 ns in order to use the system in the trigger logic;
- **Energy Resolution** at level 10% or better for 1 GeV photons, in order to define a precise energy threshold.

The overall front surface is about 30 $m^2$. We now describe the three prototypes we have tested at the Frascati Beam Test Facility (BTF).

2.1 Scintillating Fiber Prototype

This prototype is based on scintillating fibers [4]: the structure consists of 1 mm diameter scintillating fibers sandwiched between 0.5 mm thick lead foils. The fibers are arranged orthogonal to the incident particle and are read out at both ends. Two U-shaped modules form a station. We have built one U-shaped module from scratch. The prototype, built in Frascati, has the inner radius of 60 cm and the outer of 72.5 cm. These dimensions are 35% of the dimensions for an upstream module, this thickness was chosen in order to reduce the prototype costs; it should be sufficient for the transverse shower containment of low-energy electrons incident half-way between inner and outer edge along the radial direction. In order to reduce the costs the fiber density is not uniform in the beam direction, this of course slightly spoils the energy resolution which however is not a crucial feature for a veto system. The read out is provided by a PMTs matrix coupled with the fibers by Winston-cones light concentrators.

2.2 Scintillating Tiles Prototype

The second possible technology choice is based on a sandwich of scintillating tiles (5 mm thick) and lead foils (1 mm thick) with wavelength shifter (WLS)
fibers read out [?]. An assembly of wedge-shaped modules forms the veto station. A partial prototype had been built by CKM collaboration at Fermilab. The prototype was tested with 1.2 GeV electrons at Jefferson Lab, the tests confirmed that the detector inefficiency was at most $3 \times 10^{-6}$. We have obtained CKM prototype on loan for further test at lower energies, and comparison. The structure is fully described in the reference [?].

2.3 Lead glass blocks

The last possible choice is an original reuse of the leadglass blocks from the OPAL barrel calorimeter. Blocks will be arranged in five staggered sub-rings, this disposition is able to ensure at least three layers (corresponding to about 20 radiation lengths) involved in the particle detection.

3 BTF setup and test

The Frascati Beam Test Facility (BTF) [5] allows tests with low multiplicity beams of electrons with energies ranging from 100 MeV to 750 MeV. The beam pulse width is 10 ns with a repetition rate of 50 Hz. The BTF beam is generated using electrons and positrons coming from DAΦNE LINAC, which after impacting on a target are converted in electrons in a wide energy spectrum. The energy selection is then provided using a 45° dipole. The target with double twin slit reduces the beam multiplicity from $10^{9}$ to < 1. The beam direction may be tuned using another 45° dipole and two quadrupoles.

4 The BTF tagging System

The selection used to tag single electrons is shown in Figure 2. The trigger counters are all made with 10 mm thick plastic scintillator:

- F1 is a paddle of area $60 \times 85 mm^2$, it is positioned few centimeters from the end of the vacuum beam pipe,
- H1 is a paddle of area $200 \times 130 mm^2$ with a 14 mm diameter hole in the center, it is positioned 10 mm downstream of F1,
- H2 is a paddle of area $330 \times 100 mm^2$ with a 14mm diameter hole in the center, it is positioned 90 cm downstream of H1,
- F2 is a paddle of area $60 \times 85 mm^2$, it is positioned as little as 10 mm upstream of the prototype to be tested.

The trigger logic for one electron events selection can be summarized as $F1 \overline{H1} \overline{H2} F2$, where F1 and F2 refer to the presence of charged signal on the paddles consistent with the passage of a single electron, and $\overline{H1}$ and $\overline{H2}$ refer to no signal in the hole paddles.
The thickness of the paddles has been chosen to allow efficient identification of events with exactly one electron in the paddle within a 10 ns linac pulse. The hole dimension has been chosen in order to help rejecting events with straight beam particles present.

The mistag probability has been monitored and correspond to a false rate of $< 2 \times 10^{-6}$ at 90% CL.

## 5 Technology choice

During 25-day run in June-July 2007 we testes all three technologies [4] described above. For the lead glass block test we used four blocks positioned orthogonally wrt the beam axis, hit approximately in their center by the beam.

The inefficiency results are shown in the Table 5.

| Beam Energy[MeV] | Tagged Events | Event Below 50MeV | Inefficiency |
|------------------|---------------|-------------------|-------------|
| **Scintillating Fiber** |               |                   |             |
| 203              | 68 829        | 5                 | $7.3^{+4.1}_{-3.3} \times 10^{-5}$ |
| 350              | 207 385       | 3                 | $1.4^{+1.1}_{-0.9} \times 10^{-5}$ |
| 483              | 371 633       | 1                 | $2.7^{+4.7}_{-1.7} \times 10^{-6}$ |
| **Scintillating Tiles - Preliminary** |               |                   |             |
| 203              | 651 65        | 2                 | $3.1^{+3.5}_{-1.0} \times 10^{-5}$ |
| 350              | 221 162       | 3                 | $1.4^{+1.0}_{-0.9} \times 10^{-5}$ |
| 483              | 192 412       | 1                 | $5.2^{+2.1}_{-3.3} \times 10^{-6}$ |
| **Leadglass - Preliminary** |               |                   |             |
| 203              | 25 069        | 3                 | $1.2^{+0.9}_{-0.8} \times 10^{-4}$ |
| 483              | 91 511        | 1                 | $1.1^{+0.7}_{-0.9} \times 10^{-5}$ |

We can see that the efficiency is above the requirements for all solutions. The availability of a large amount of OPAL leadglass blocks has driven our choice in favour of this technology.
6 Cosmic test and LG characterization

After the definitive choice of the LGs as the baseline technology, we started a systematic characterization of them. With this aim in Naples we arranged a test station composed by a darkbox and a tower tracker. The procedure consists in measuring, for each LG, the gain and the Photoelectron Yield (PeY).

6.1 PMT Gain

PMT gain is obtained for each High Voltage (HV) applied to the PMT, by a linear fit of the observed variance of the response versus the response itself, when the block is exposed to different intensity LED pulses inside a dark box. The values are corrected for the contribution of the gain fluctuations. The gain curve is then obtained by fitting the measured gain versus the HV value, and the PMTs are all equalized to a HV such to get a gain $G = 10^6$.

6.2 Photoelectron yield

Photoelectron Yield (PeY) is the number of photoelectrons produced per 1 MeV deposited energy by muons travelling transversally in a leadglass block. The measurement of PeY has been made in Naples with a tracker tower that enable us to track cosmic muons and select those traversing the blocks with the desired inclination. The PeY is then defined as:

$$PEY = \frac{Q}{Ge77MeV}$$

where $Q$ is the collected charge, $G$ is the PMT gain, $e$ is the elementary charge and 77 MeV is the mean energy released by a muon traversing a 10 cm block. The observed PeY for 40 blocks chosen at random among the available OPAL blocks, is about 0.4 pe/MeV, and the distributions shows a spread in PeY values at level 10.

7 Lead glass prototype studies

After the single block characterization we have assembled in Naples, using 25 blocks, a small prototype mounted in a linear shape 3. The geometrical staggered disposition is the same of the final one, in order to study edge effects and measure a more realistic inefficiency value.

7.1 Data set

The data referred to in this section were collected during a two week test at the BTF in February 2008. Data were taken at various energies and hitting the detector in different geometrical configurations. In this paper we report a preliminary analysis of part of the data collected at energy 471 MeV using some different beam impact positions. We will focus our attention on comparing beam
impacting on the center of one block (Central Beam), and beam impacting on the lateral (longer) edge of one block (Edge Beam).

7.2 Intercalibration and Energy Calibration

Response of each block is characterized by its PeY as measured with cosmic rays. One of them was chosen as reference \( (PeY_{ref}) \) and the intercalibration constants were found dividing each PeY to \( PeY_{ref} \). In order to set an absolute energy scale we defined a clustering algorithm. Given the energy of incident electrons and the intercalibration constants we can measure the energy scale as the ratio between the number of ADC counts and the electrons energy. Clustering has been made using a variable threshold channel by channel, optimized on the background level observed in each cell of the prototype. The background was dominated by soft photons in the BTF hall; the integral of this background on all 25 cells was monitored during data taking and was typically at level of about 7 MeV. The energy scale on runs with the same energy was stable at level of 3%, this effect is still to be investigated; it could be related to hysteresis effects in the BTF magnets used to drive the beam to the experimental hall.

7.3 Cluster shape and Energy Resolution

For central beam events the average number of cells for a cluster is 5 while it gets to 6 for edge beam events. In the longitudinal (along the beam) direction, on average a central beam cluster hits 3 planes of the prototype, and less than 10% of events hits the last plane, while a edge beam cluster hits the fifth plane in about 30% of the cases. In both cases 80% of the energy is released in the first plane. The energy resolution observed is about 9.5 % at 471 MeV for central beam events and about 11 % for edge beam events.

7.4 Time Resolution

The time response, measured with a 12 bit TDC, has been corrected for each block for the time walk by means of the appropriate slewing corrections, evalu-
ated as described in [4]. For a block in the most upstream plane, which is hit always in the same position by the beam, the typical time resolution is at level 200 ps. Resolution is instead of about 1 ns for a block in the second plane, dominated thus by the distribution of the impact points on the block. We also defined an energy weighted time average for a cluster; its resolution is about 560 ps.

### 7.5 Inefficiency

A preliminary analysis of part of our data set gives the following results for the LG prototype:

|          | Tagged Events | Event Below 50MeV | Inefficiency          |
|----------|---------------|-------------------|-----------------------|
| Central  | 47 252        | 2                 | $4.2^{+3.8}_{-2.6} \times 10^{-5}$ |
| Edge     | 9 711         | 1                 | $1.0^{+2.8}_{-0.7} \times 10^{-4}$ |

### 8 Conclusions and future plans

An intensive R&D program has been carried out to assess the technology and evaluate the performances of a Large Angle Veto system for the NA62 experiment. The lead glass blocks formerly used for the OPAL barrel calorimeter are our baseline choice. A prototype with a geometry very similar to the one foreseen for the final ring shaped detectors has been tested and its performances meet the requirements for the LAV system. Further tests will be made, in vacuum, on a secondary beam extracted from the SPS in October 2008. The design of a complete ring is almost completed; construction of the first complete ring will likely start in year 2009.

### References

[1] E949 Collaboration, V. Anisimovsky et al., CERN, Geneva, Tech. Resp. CERN/SPSC 2005-013, 2005.

[2] G. Anelli et al., CERN, Geneva, Tech. Resp. CERN/SPSC 2005-013, 2005.

[3] E. Ramberg, P. Cooper and R. Tschirhart, IEEE Trans. Nucl. Sci., vol. 51, p2201, 2004.

[4] M. Moulson et al., Presented at 2007 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS MIC 2007), Honolulu, Hawaii, 28 Oct - 3 Nov 2007.

[5] G. Mazzitelli et al., Nucl. Instrum. Meth. A, vol. 515, p. 524, 2003.