NA62

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1 The NA62 Experiment

The branching ratio (BR) for the decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ can be related to the value of the CKM matrix element $V_{td}$ with minimal theoretical uncertainty, providing a sensitive probe of the flavor sector of the Standard Model. The measured value of the BR is $1.73^{+1.15}_{-1.05} \times 10^{-10}$ on the basis of seven detected events [1]. NA62, an experiment at the CERN SPS, was originally proposed as P326 with the goal of detecting $\sim 100$ $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decays with a S/B ratio of 10:1 [2]. The experimental layout is illustrated in Fig. 1.

The experiment will make use of a 75 GeV unseparated positive secondary beam. The total beam rate is 800 MHz, providing $\sim 50$ MHz of $K^+$'s. The decay volume begins 102 m downstream of the production target. 10 MHz of kaon decays are observed in the 120-m long vacuum decay region. Ring-shaped large-angle photon vetoes are placed at 12 stations along the decay region and provide full coverage for decay photons with $8.5 \text{ mrad} < \theta < 50 \text{ mrad}$. The last 35 m of the decay region hosts a dipole spectrometer with four straw-tracker stations operated in vacuum. The NA48 liquid krypton calorimeter [3] is used to veto high-energy photons at small angle. Additional detectors further downstream extend the coverage of the photon veto system (e.g. for particles traveling in the beam pipe).

The experiment must be able to reject background from, e.g., $K^+ \rightarrow \pi^+ \pi^0$ decays at the level of $10^{12}$. Kinematic cuts on the $K^+$ and $\pi^+$ tracks provide a factor of $10^4$ and ensure 40 GeV of
electromagnetic energy in the photon vetoes; this energy must then be detected with an inefficiency of $\leq 10^{-8}$. For the large-angle photon vetoes, the maximum tolerable detection inefficiency for photons with energies as low as 200 MeV is $10^{-4}$. In addition, the large-angle vetoes (LAV) must have good energy and time resolution and must be compatible with operation in vacuum.

The principal involvement of the LNF NA62 group is in the design and construction of the LAV system. In 2009, the main responsibilities of the LNF NA62 group were:

- Development of tools and procedures for assembly of the ANTI-A1 station;
- Assembly of the ANTI-A1 prototype station;
- Vacuum testing and outgassing measurements for ANTI-A1;
- In-beam testing of the ANTI-A1 prototype;
- Development and testing of the front-end electronics for the large-angle veto system.

In addition the group continues to collaborate in the analysis of NA62 data on $R_K \equiv \Gamma(K_{e2})/\Gamma(K_{\mu2})$.

2 Large-Angle Photon Veto

The 3800 modules from the central part of the OPAL electromagnetic calorimeter barrel [4] that became available for use in NA62 consist of blocks of SF57 lead glass with an asymmetric, truncated square-pyramid shape. The front and rear faces of the blocks measure about $10 \times 10$ cm$^2$ and $11 \times 11$ cm$^2$, respectively; the blocks are 37 cm long. The modules are read out at the back side by Hamamatsu R2238 76-mm PMTs, coupled via 4-cm cylindrical light guides of SF57. The current
design of the LAV system calls for the construction of 12 cylindrical stations made of lead-glass blocks. The diameter of the stations increases with distance from the target, as does the number of blocks in each, from 160 to 256, for a total of about 2500 blocks. Each station consists of four or five rings of blocks, with the blocks staggered in azimuth in successive rings. The total depth of a five-layer station is 27 radiation lengths; this structure guarantees high efficiency, hermeticity, and uniformity of response. The overall design for the first prototype of such a station is illustrated in Fig. 2, left.

2.1 ANTI-A1 construction
The vessel is made of steel, is 192 cm in diameter, and includes five flanges for HV and signal feedthroughs and for vacuum pumping, a large flange for access, and a mesh for cable routing. The prototype vessel was constructed in early 2009 at Fantini SpA (Anagni (FR)), under the supervision of the LNF SPAS. The vessel was shipped to LNF in April 2009 for the installation of the lead-glass detectors.

The support brackets for the mounting of the lead-glass modules, also knowns as “bananas,” were designed at Pisa. The ANTI-A1 consists of a 40-bracket setup in five rings for a total of 160 blocks.

ANTI-A1 was constructed in many different steps. The original gluing of the lead-glass block on the aluminum support by the OPAL experiment was considered too old to be reliable by the CERN safety authorities, so a new gluing procedure has been established. The original bond was reinforced by thin steel plates glued to the side of the block (see fig Fig. 3, top left).

The blocks were tested with a LED pulser and cosmic rays to measure light yield and PMT gain and to equalize the detector response. A common working point at 4.5 pC for MIP generated signals was selected. The test infrastructure, which was developed by INFN Naples, allows us to automatically test 12 block per day.

Four tested lead-glass modules are arranged on a support bracket (“banana”) for installation in the vacuum vessel as shown in Fig. 3, left. During assembly, the fibers for the monitoring system and the signal and HV cables were also routed and fixed inside the bracket structure.

After the mounting of each single ring, composed of eight bananas as shown in Fig. 3, the cables were fastened to a stainless steel mesh, routed to the vacuum flanges, and connected to the feedthroughs. Each block was then tested for HV and signal connection integrity. A photo of the the fully assembled ANTI-A1 is shown in Fig. 2, right.

2.2 Vacuum tests and outgassing measurements
In the NA62 experiment, the interaction of the beam with residual gas in the decay region can produce a significant level of photon-free background to $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ if the vacuum in the decay region is worse than a few $10^{-6}$ mbar.

During 2008, a comprehensive series of measurements of outgassing rates of different components of the LAV system were made in close collaboration with the Servizio di Vuoto of the LNF Accelerator Division. Measurements were performed on components such as the wrapping materials for the lead-glass blocks, the PMT and mu-metal assemblies, fully wrapped blocks, and bare blocks. A complete vacuum test of the prototype vessel was also performed at the Fantini SpA facility. The measurement technique, the setup and the outgassing results are described in
Table 1. After the construction a measurement of the outgassing rate of the entire ANTI-A1 was also performed to verify the extrapolation in Table 1. The measured leak/outgassing rate after two weeks of pumping was $(0.9 \pm 0.15) \cdot 10^{-3} \text{mbar} \cdot \text{1} \cdot \text{s}^{-1}$, which is in perfect agreement with the quoted extrapolation.

2.3 Front-end electronics

Monte Carlo simulations have shown that photons from $K^+ \rightarrow \pi^+\pi^0$ decay with a wide range of energies, from a few tens of MeV to several GeV, reach the veto stations. To be able to reject photons from $\pi^+\pi^0$ events with a maximum inefficiency of $10^{-4}$, the detectors must simultaneously furnish time and energy measurements. The time resolution is dominated by the intrinsic contribution from the detectors. For the energy measurement, the biggest challenge in the design of the readout electronics is the need to accept signals over an extended dynamic range, from a few
Table 1: Outgassing measurement results Ref. 5.

<table>
<thead>
<tr>
<th></th>
<th>( Q_S ) (mbar ( \cdot s^{-1} ))</th>
<th>Pumping time (days)</th>
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</thead>
<tbody>
<tr>
<td>PbGl detectors (worst case)</td>
<td>((2.9 \pm 2.0) \cdot 10^{-4})</td>
<td>15</td>
</tr>
<tr>
<td>PbGl detectors (average)</td>
<td>((1.5 \pm 1.0) \cdot 10^{-3})</td>
<td>15</td>
</tr>
<tr>
<td>Monitoring system fibers</td>
<td>((1.0 \pm 0.2) \cdot 10^{-5})</td>
<td>15</td>
</tr>
<tr>
<td>Tyvek wrapping</td>
<td>((3.1 \pm 0.6) \cdot 10^{-5})</td>
<td>5</td>
</tr>
<tr>
<td>ANTI-A1 vessel</td>
<td>((1.1 \pm 0.2) \cdot 10^{-5})</td>
<td>4</td>
</tr>
<tr>
<td>Total ANTI-A1 (extrapolation)</td>
<td>((1.5 \pm 1.0) \cdot 10^{-3})</td>
<td>15</td>
</tr>
</tbody>
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millivolts to tens of volts, and to provide charge measurements with a precision better than 10%. During 2009, the LNF group was responsible for the design and construction of prototypes of the

![Figure 4: Layout of a single channel of prototype time-over-threshold board.](image)

front-end electronics for the large-angle veto system. The basic idea is to exploit the time-over-threshold technique to measure the signal charge over a broad interval. A new board designed by the LNF Servizio di Elettronica converts the analog signals from the PMTs into an LVDS logic signal of the same width. The width will be measured by a TDC and its value used to reconstruct the charge. The energy can thus be measured via TDC time measurements only.

A first prototype of the front-end electronics was designed and tested during 2009. The system consists of three main stages, as shown in the single-channel layout of Fig. 4:
• **Clamping:** Protects the amplifier from PMT signals as high as 10V. The clamp stage preserves the time duration of the input analog signal to allow the measurement of time over threshold (ToT).

• **Amplifier:** Amplifies the input signal by a factor 5 to reduce the slewing in crossing the threshold at the comparator stage.

• **Comparator and LVDS driver:** Compares the amplified signals with an adjustable threshold (0-50 mV) and produces an LVDS output signal. The LVDS signal has a duration equal to the time the analog signal is greater than the threshold.

Six prototype boards for a total of 96 channels were produced and tested with cosmic rays at LNF and with muons and electrons during the ANTI-A1 beam test at CERN. In both cases a good correlation between ToT and charge was observed. Fig. 5 shows the correlation obtained with 2 GeV electrons during the ANTI-A1 beam test.

![Figure 5: Charge vs time over threshold (ToT).](image_url)

We expect to conduct a test of the final front-end electronics scheme and its integration with the data-acquisition system at CERN in 2010.

### 2.3.1 ANTI-A1 test beam

After the assembly of ANTI-A1 was completed at LNF in July 2009, the module was transported to CERN. It was installed in the existing NA48 vacuum vessel (the so-called “blue tube”) in October 2009.

The five prototype front-end boards were also used to fully equip one half of the ring (80 crystals), so that we were able to perform extensive tests with muons and electrons using the SPS beam line.
The boards include an amplification stage with dual output: one copy of the signal is fed to the discriminator, which produces LVDS digital signals with time-over-threshold duration, while a second copy is available for routing to a different readout. The second copy was used for direct charge measurements for the purposes of comparison.

For the charge measurement, we used commercial 12-bit charge QDCs (CAEN V792), while for the time measurements we used commercial TDCs (CAEN V1190B). In order to provide a gate for QDC integration, a trigger signal was provided by the fast-OR of the 16 digital signals in the upstream ring of lead-glass detectors. A stand-alone DAQ system was also prepared, capable of gating the acquisition with SPS status signals and sustaining a trigger rate of about 1 kHz.

We collected large samples of data both with a diffuse halo of muons, thus illuminating all the counters in the ring, and with electron beams of energy 2, 4, and 6 GeV.

The muon data were used first for checking the equalization of the PMT gains, which had been performed before installation with the cosmic-ray test stand at LNF. The average MIP response for all crystals is $\sim 4$ pC, as expected for a gain of about $10^6$, with a RMS at the level of 10% using nominal HV settings.

Using muon data we also performed a calibration of the time-over-threshold discriminator threshold. We collected data at 7, 10, 15, and 25 mV/50Ω for the input signal, corresponding to a range from 0.3 to $\sim 1$ MIP.

Using electron data we were able to check the performance of the time-over-threshold technique, by comparing the time-width of the LVDS output of the discriminator measured by the TDC with the charge measured by the ADC (Fig. 5). The correlation is excellent, except for a fraction of events (in the top part of the figure) for which the time-over-threshold measurement is lengthened: this is due to the ringing of the analog signal, caused by a small dynode dispersive inductance in the PMTs, which has since been fixed in the HV divider circuit.

3 NA62 and the Measurement of $R_K$

Despite poor knowledge of the meson decay constants, ratios of leptonic decay rates of pseudoscalar mesons such as $R_K \equiv \Gamma(K_{e2})/\Gamma(K_{\mu2})$ can be predicted with high accuracy within a given model, and have been considered to be stringent tests of the $V-A$ structure of the weak interaction and of lepton universality. By convention, the definition of $R_K$ includes the contribution of inner bremsstrahlung (IB) to the radiative $K_{e2}$ width, while the structure-dependent (DE) processes are considered as background. The Standard-Model prediction is [6]:

$$R_{K}^{SM} = \left( \frac{m_e}{m_{\mu}} \right)^2 \left( \frac{M_{K}}{M_{K}^2 - m_{e}^2} \right)^2 (1 + \delta R_{QED}) = (2.477 \pm 0.001) \cdot 10^{-5}$$

where $\delta R_{QED} = -3.6\%$ is a correction due to the contributions to the $K_{e2}$ width from IB and virtual photon processes. Theoretical studies point out that lepton-flavor violating effects arising in supersymmetric extensions of the Standard Model can induce sizable violations of $\mu-e$ universality, shifting the value of $R_K$ by as much as a few percent, without contradicting any other presently known experimental constraints [7]. The $K_{e2}$ decay rate is particularly sensitive to new physics because the Standard Model contribution is helicity suppressed.

The 2006 world average [8] is determined by experiments performed in the 1970s; the relative error on this average is $\delta R_K/R_K = 4.5\%$. Inclusion in the average of the recent results from the
KLOE collaboration (final result [9]) and from NA48/2 (preliminary result) leads to a new value of $R_K^{2007} = (2.468 \pm 0.025) \cdot 10^{-5}$, with a precision of $\delta R_K / R_K = 1\%$.

During a dedicated run in 2007, NA62 collected more than 110,000 $K_{e2}$ events, together with various smaller data samples to allow detailed systematic studies. The Frascati group contributed significantly to the success of this run. Group members participated in data taking for a significant fraction of the running period and provided on-call support for the hodoscope readout electronics. As run coordinators for five weeks of the 18-week run, LNF group members were directly responsible for the operational aspects of the experiment. The running period coordinated by LNF group members included $K_{e2}$ data collection, the collection of samples for systematic studies, and the entire straw tracker beam test.

LNF group members are currently playing a central role in the analysis of the 2007 data. At the collaboration level, the analysis effort is being conducted by two independent groups to ensure redundancy and tighter systematic control. Frascati group members form the core of one of these two analysis groups. Some of the $K_{e2}$ selection criteria have been first implemented by the LNF group and have been then accepted as standards. In particular, the treatment of radiative corrections has been completely revised. Since the DE component is not suppressed by helicity, it constitutes an order-unity background to IB. Therefore, the criteria for vetoing additional photons detected by the liquid krypton calorimeter have been defined, so as to retain as much as possible $K \rightarrow e\nu(\gamma)$ IB events, while rejecting radiative $K \rightarrow e\nu\gamma$ from the DE process, as well as other backgrounds. Moreover, $K \rightarrow e\nu(\gamma)$ events from IB are selected by kinematics by requiring the missing mass squared at the $K$ decay vertex to be below $\sim 0.001$ GeV$^2$. The efficiency for this condition increases inversely with the energy of the emitted photon, so that the implementation of an accurate simulation of the $K \rightarrow e\nu\gamma$ IB component is crucial for an evaluation of the related acceptance with an accuracy better than the percent. The LNF group provided a new simulation of the IB signal, with an exponentiated photon energy spectrum and no photon energy cutoff. A preliminary result for $R_K$ was released during the 2009 winter conferences, with a total error of about 0.6\%.

References