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 2008, the main responsibilities of the LNF NA62 group were

- Mechanical design of a prototype LAV station
- Design and construction of the vacuum vessel
- Development of tools and procedures for assembly of the station at LNF in 2009
- Vacuum testing and outgassing measurements for lead-glass detectors
- Development of the front-end electronics for the large-angle veto system
- Collaboration in analysis of NA62 data on $R_K \equiv \Gamma(K_{e2})/\Gamma(K_{\mu2})$.

2 Large-Angle Photon Vetoes

2.1 Comparison of technologies

In 2007, the LNF NA62 group led the development and testing of prototype photon veto detectors, in order to guide the choice of technologies to be used in the experiment. Three possible technologies for the LAV system were considered. The first design, originally proposed for use in the (now canceled) CKM experiment at Fermilab, featured a modular structure consisting of alternate layers of 1-mm thick lead and 5-mm thick scintillating tile readout by wavelength-shifting fibers, providing a high sampling fraction and excellent light yield. A second option, adopted for the construction of the electromagnetic calorimeter for the KLOE experiment, featured a structure consisting of 1-mm diameter scintillating fibers embedded between 0.5-mm thick lead foils. The third solution makes use of lead-glass crystals obtained from the dismantled electromagnetic calorimeter of the OPAL experiment [4]. Prototype instruments based on each of the three technologies were obtained or constructed. Experimental tests conducted with the electron beam at the Frascati BTF demonstrated that all three technologies are suitable for use in the experiment [5]. The results obtained for the inefficiency with $E_{\text{th}} = 50$ MeV for all three prototypes are summarized in Fig. 2. The efficiency for detection of low-energy electrons is seen to be similar for all three technologies tested. Since there is a significant practical advantage to basing the NA62 LAV system on existing hardware, we decided to use the OPAL lead-glass modules.

2.2 Mechanical design for the LAV system

The 3800 modules from the central part of the OPAL electromagnetic calorimeter barrel [4] that recently became available for use in NA68 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.
Figure 2: Comparison of detection efficiencies for each of the three prototypes, for 203, 350, and 483 MeV electrons with $E_{\text{thr}} = 50$ MeV. Results obtained with the CKM tile prototype and OPAL lead-glass modules are preliminary.

Figure 3: Left: Design study of the prototype veto station making use of the OPAL lead-glass calorimeter elements. Right: Photograph of the vacuum vessel under construction.
During 2008, our group dedicated significant resources to the development of the mechanics for the incorporation of these modules into a veto station for use in the experiment.

The current design of the LAV system calls for the construction of 12 cylindrical stations 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 250, for a total of about 2500 blocks. Each station consists of 5 rings of blocks, with the blocks staggered in azimuth in successive rings. The total depth of a 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. 3, left.

The principal elements of the mechanical design include the design of the vacuum vessel itself, the hardware associated with the vacuum vessel (i.e., access ports, feedthroughs, and hardware for cable routing, and the support structure for mounting the lead-glass blocks on the internal walls. The LNF NA62 group has collaborated on the design of the vacuum vessel and associated hardware, as has borne the principal responsibility for the construction of the prototype, including the development of the tools and procedures necessary for its assembly.

### 2.2.1 Vacuum vessel

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. Construction on the prototype vessel was started in late 2008 at Fantini SpA (Anagni (FR)), a firm dealing in the manufacture of specialized industrial equipment, under the supervision of the LNF SPAS. A photo of the vessel is shown in Fig. 3, right. The vessel will be shipped to LNF in spring 2009 for the installation of the lead-glass detectors.
<table>
<thead>
<tr>
<th>Example of outgassing measurements</th>
<th>Outgassing rate (mbar·l/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete module</td>
<td>$(2.2 \pm 1.4) \times 10^{-5}$</td>
</tr>
<tr>
<td>Unwrapped module</td>
<td>$(2.0 \pm 1.3) \times 10^{-5}$</td>
</tr>
<tr>
<td>OPAL wrapping</td>
<td>$(1.0 \pm 0.5) \times 10^{-6}$</td>
</tr>
<tr>
<td>PMT &amp; mu-metal</td>
<td>$(2.1 \pm 1.7) \times 10^{-7}$</td>
</tr>
<tr>
<td>Bare crystal</td>
<td>$(2.0 \pm 2.9) \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Figure 5: Setup for leak test and outgassing rate measurements on vacuum vessel.

2.2.2 Module support structures

The support brackets for the mounting of the lead-glass modules were developed at Pisa in 2008 and are now under construction. Four lead-glass modules are arranged on a single mounting bracket for installation in the vacuum vessel, as shown in Fig. 4, left. The LNF group is responsible for the development of procedures and tools for use in the installation of the four-module units and the overall assembly of the station. The tool for the manipulation of the four-module unit shown in Fig. 4, right, was designed by the LNF SPAS in collaboration with the NA62 group members. Procedures for installation and assembly are currently being finalized. A working space for assembly of the station has been set up in the new high bay next to the Gran Sasso building.

2.2.3 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. The measurement of the total outgassing rate of the LAV system and vacuum vessel into the decay volume is an essential parameter for the design of the pumping system of the experiment.

During 2008, a comprehensive series of measurements of outgassing rates of different com-
ponents of the LAV system. The measurements were performed 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. The measurement technique and setup are described in Ref. 6. Examples of outgassing measurements obtained are presented in Table 1. A complete vacuum test of the prototype vessel was performed at the Fantini SpA facility (Fig. 5). The vessel was found to be free of leaks and its outgassing rate was measured to be $1.2 \times 10^{-5}$ mbar·l/s. These results are compatible with the operation of the detector in high vacuum.

2.2.4 Front-end electronics

The readout electronics are currently at a preliminary design stage; the design will have to be finalized over the course of the next two years. Monte Carlo simulations have shown that photons from $K^+ \to \pi^+\pi^0$ 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 millivolts to tens of volts, and to provide charge measurements with a precision better than 10%.

To handle the analog signal from the detectors without saturating the elements of the front-end electronics, a multiscale system has been developed in collaboration with the Servizio di Elettronica. The signal levels correspond to attenuation factors of 1, 10, and 100. Each of these signals will be processed by a different acquisition channel, providing three measurements of the same signal at different amplitude scales. A photograph of the front-end card is shown in Fig. 6, top. A protection circuit after the attenuators will limit the amplitudes of the input signals to the digitizers to acceptable levels without introducing dead time. To measure the charge, a solution is under development based on the correlation between the signal amplitude and the duration during which the signal remains above a discriminator threshold. The energy can thus be measured via TDC time measurements only.

To study the potential of the time-over-threshold technique using cosmic-ray signals from actual detector elements, the group is using the front-end attenuator board described above, together with the NINO chip designed for time-of-flight measurements in the ALICE experiment. The test circuit is illustrated in Fig. 6, bottom. Elements of the readout system will be further tested in situ together with the first LAV ring in the fall of 2009. 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.

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 $R_K \equiv \Gamma(K\mu^2)/\Gamma(K\nu^2)$ 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 $K_{l2}$ width, while the structure-dependent processes are considered as background. The Standard Model prediction is [7]:

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

(1)

where $\delta R_{\text{QED}} = -3.6\%$ is a correction due to the contributions to the $K_{l2}$ width from IB and virtual photon processes. A recent theoretical study [8] points 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. The $K_{e2}$ decay rate is particularly sensitive to new physics because the Standard Model contribution is helicity suppressed. The 2006 world average [9] is determined by experiments performed in the 1970s; the relative error on this average ($\delta R_{K}/R_{K} = 4.5\%$) is too large to allow tests of the Standard Model. Inclusion in the average of the recent preliminary results from the NA48/2 and KLOE collaborations leads to a new value of $R_{K}^{2007} = (2.457 \pm 0.032) \cdot 10^{-5}$ [10], with a precision of $\delta R_{K}/R_{K} = 1.3\%$.

During a 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 $K_{e2}$ 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. A preliminary result for $R_K$ is expected during the first half of 2009.

4 List of Conference Talks

2. T. Spadaro, “$K_{e2}$ and lepton flavor violation searches with kaons,” Ninth International Conference on Heavy Quarks & Leptons, Melbourne, Australia, Crete, June 2008.

References