An overview of OSCAR: a new hodoscope of silicon detectors for low energy charged particles

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Abstract. Modern nuclear physics experiments demand for new high-resolution and high-versatility detectors for the reconstruction of collision events. In this framework, we have developed a new hodoscope of silicon detectors for charged particles called OSCAR. This new device consists of individual modules with partially embedded electronics capable to identify low energy particles down to about 1 MeV/u. OSCAR is a particularly suitable detector to be used as a standalone detector or as ancillary system for large acceptance devices. This paper presents an overview of the layout and capabilities of the detector.

1. Introduction

Silicon detectors offer a number of advantages such as limited costs, good linearity in broad ranges of deposited energies and excellent energy resolutions. In the last decades, silicon detectors became increasingly popular also thanks to the development of reduced size semiconducting detection units such as pads, strips or pixels. Additionally, their reduced stopping power makes them particularly suitable for the detection of low energy charged particles. In this framework, several modular detection systems based on silicon detectors or hybrid configurations of silicons and scintillator materials, such as FAZIA [1, 2], MUST2 [3], LASSA [4], FARCOS [5, 6, 7] and HiRA10 [8], have been recently developed to account for the requirements for high versatility, high angular segmentation and high resolution of modern nuclear physics experiments. Moreover, new low energy facilities for radioactive ion beams (RIBs) currently in development (like for example SPES@INFN-LNL [9], SPIRAL2@GANIL [10] and ISOLDE@CERN [11]) demand for new generation devices capable to detect and identify low energy charged particles with high versatility.

To account for the above mentioned requirements, we have recently designed and developed a new hodoscope of silicon detectors: OSCAR (Hodoscope of Silicon for Correlations and Analysis of Reactions). The OSCAR device is constituted by two silicon-based detection layers (a 20 μm Single-Sided Silicon Strip Detector (SSSSD) followed by 300 μm silicon pads). The major strengths of this detector are the excellent energy resolution, the identification capabilities, the good angular segmentation and the high versatility. In addition, OSCAR consists of independent self-consistent modules, making it suitable to be easily used as ancillary system for large acceptance devices.

In this paper we provide a short overview of the layout of the OSCAR detector and its capabilities as probed by a commissioning experiment carried out at the INFN-Laboratori
Figure 1. A photo of an OSCAR module assembled during the INFN-LNS commissioning experiment. The pre-amplifier box used to serve the SSSSD is placed below the detector mounting and is therefore not visible in the photo, while the 16 individual pre-amplifiers for the second detection stage are connected on the rear side of the connection board, and thermally coupled to a customized copper heat sink.

Nazionali del Sud (LNS) of Catania, Italy. During this experiment, OSCAR was placed at large detection angles to detect fragments and light charged particles in Ca+Ca collisions at 35MeV/nucleon, while the main goal of the experiment was to investigate isospin transport phenomena with the FAZIA multidetector [12]. A more extended overview of the OSCAR project can be found in Ref. [13]. Finally, it is worth mentioning that, beside the commissioning experiment mentioned in this paper, the OSCAR device was also successfully used in a number of other recent experiments [14, 15, 16].

2. Detector's layout
OSCAR is a modular device for the detection and identification of low energy charged particles emitted in nuclear collisions. It consists of two detection stages. The first stage is a SSSSD (≈ 50 × 50 mm² nominal active area, having a nominal thickness of 20µm) type 2M detector manufactured by Micron Semiconductor. This detector operates at a depletion voltage of 2.5V. An aluminium metallization segmented into vertical strips is made in its front surface. In such a way, signals can be collected independently from 16 individual strips, with a pitch of 3.125mm and with an inter-strip of 0.125mm nominal value. As described in Ref. [13], these values were carefully benchmarked through Atomic Force Microscopy (AFM) techniques. A uniform aluminium metallization is instead made in its back surface. A connector collects 16 electric lines from the front side of the detector. These lines are displaced in the ceramic frame to minimize the cross-talk with levels lower than 1%. A bond for each individual strip ensures the electric connection between the pre-amplifiers and the front strips, while the rear side is simply grounded by means of two bondings. In order to minimize the electronic noise, the strip detector is connected, by means of a short flat cable, with a charge sensitive pre-amplifier model.
Figure 2. A schematic of the geometry of OSCAR. Red squares delimit the active area of pads while blue rectangles that of strips. Couples of indexes \((n_s, n_p)\) are used to indicate the strip and pad number forming each individual pseudo-telescope. Because of the presence of the ceramic frame surrounding the active area of each pad, different pseudo-telescopes are characterized by different active areas.

NPA-16FE, manufactured by the *Net Instruments* and installed inside the vacuum chamber. This pre-amplifier has a sensitivity of 45mV/MeV and has a special design to operate in high-vacuum. This compact pre-amplifier works with GND and ±6V service voltages given via a 5+5 pin service connector together with a common bias for the 16 silicon strips. During our commissioning experiment, we slightly over-depleted the SSSSD by using a bias voltage of 3.0V. We observed leakage currents not exceeding 10nA with all the strips simultaneously biased. 16 individual repetitions of a NIM front-end electronics with a spectroscopy amplifier are used to process the 16 signals coming from the strips. The connections between the pre-amplifier and the electronics are made with two groups of high-quality SCI coaxial cables in order to minimize the noise.
The second detection stage characterizing OSCAR consists of 16 independent silicon pad detectors manufactured by Hamamatsu. Each of those has a nominal active area of $1 \times 1 \text{cm}^2$ and a ceramic frame. The latter has a width of 1.4mm except for the bottom side, for which a larger 3.2mm frame is required to host the connection pins. The silicon pads are welded on a printed circuits board, manufactured by the INFN-Sezione di Napoli, containing the electronic lines required for the 16 pads. An independent ground line for each of the pads is made to minimize the noise. The SSSSD is anchored to the board containing the silicon pads as shown Fig 1. The board where all the pads are welded is connected, by means of two SMC Type Q connectors, to a second board with embedded pre-amplifiers. Such a module, characterized by plug-and-play connections, is highly portable and easy-to-install, making feasible its use also coupled to other existing high-complexity and large acceptance devices. Two rows of 8 Hamamatsu H4083 charge sensitive pre-amplifiers with 22mV/MeV sensitivity are connected to the rear board by means of 9-pins single line type connectors. 16 SCI connectors are used to collect the signals produced by the silicon pads and delivered them to a 16 channel Mesytec spectroscopic amplifier with integrated logic lines. The latter are typically used to generate the local trigger signals of OSCAR. Finally, pre-amplifiers are thermally connected to a copper heat sink, used as passive cooling system.

Being a two-detection stage system, OSCAR identifies particle tracks by reconstructing coupled signals in its two detection stages. The geometry of such a system is therefore determined by the possible strip/pad correspondences. More in detail, 64 $\Delta E-E$ pseudo-telescopes are identified through the overlap of a strip and a pad, as described in Fig. 2. In the figure, active areas of pads are symbolically represented by red squares, while blue rectangles are the active areas of strips. Additionally, each pseudo-telescope is identified by a couple of indexes $(n_s, n_p)$ representing, respectively, the strip number (from left to right) and the pad number, from left to right and from top to bottom. As visible from the figure, strips and pads are not in exact geometrical match. For example, the upper and lower parts of the second detection stage are not completely covered by the first detection stage. These features affect the efficiency of each pseudo-telescope in the detection of particles emitted in a nuclear reaction. If we look at the experimental efficiency for each pseudo-telescope recorded in our commissioning experiment, Fig. 3 (a), the yield for the first and last rows of pseudo-telescopes is reduced, as expected from the considerations of Fig. 2. By inspecting the recorded yields in each quartet of pseudo-telescopes in Fig. 3 (a), i.e. the pseudo-telescopes corresponding to a certain pad and 4 consecutive strips, one observes a significantly lower statistics for first and last pseudo-telescope of each quartet. This fact is also not surprising if one carefully inspects the geometrical coherence drawing of Fig. 2. As clearly visible, the first and last strip of each quartet have a lower superposition with the corresponding pad if compared to the 2 central strips. This is due to the partial overlap of strips with the ceramic frames of the underlying pads. These features have to be carefully taken into account while extracting the experimental yield of particles detected in each pseudo-telescope. To this end, we implemented a complete geometrical simulation of the OSCAR device. In Fig. 3 (b) we report a lego-plot analogous to that of Fig. 3 (a) but obtained considering a sample of randomly generated particle tracks filtered with our complete simulation of the OSCAR device. We can easily observe that the two plots are in satisfactory agreement, indicating that the relative efficiency differences observed for the various pseudo-telescopes can be attributed exclusively to geometrical effects. Finally, in Fig. 3 (a) one can observe an interesting feature not present in the simulated plot and consisting in the average reduction of the yield for decreasing strip numbers. This can be attributed to the kinematics of the nuclear collisions involved, being the polar detection angle increasingly larger while the the strip number decreases. In the case of Fig. 3 (b) we have instead considered uniformly distributed particle tracks, without accounting for the observed angular distribution.
Figure 3. Efficiency of each pseudo-telescope with the same numbering of those of Fig. 2 respectively for (a) experimental data and (b) simulated ones. Z-axis represents the percentage of the maximum. Patterns in the efficiency observed in the experimental data are correctly reproduced in the geometrical simulation. The simulation accounts also for pads and strips that were not working during the commissioning experiment, namely pad16 and strip06.

3. Detector’s capabilities

The capabilities of OSCAR were tested in a dedicated commissioning experiment performed at the INFN-LNS, where OSCAR was used together with the demonstrator of the FAZIA array. In this paper, we focus exclusively on data obtained with OSCAR, while more information regarding the analysis of FAZIA can be found in Ref. [12].

Before to deliver the beam to the experimental hall, a three peaks $\alpha$-source was used to calibrate the energy of the second detection stage. After inspecting the pulse-shape of signals produced in the silicon pads, we estimated the noise levels. The average noise turns out to be of the order of 0.3% of signal amplitudes (and not exceeding 0.6% level) when the pads were irradiated by 5.48 MeV $\alpha$ particles at a rate of $\approx 300$Hz on the whole pad stage. During the beam time, the cooling system was tested by keeping the detector working under vacuum for a few days. Under these circumstances, we measured temperatures of about $\approx 30^\circ$C and $\approx 40^\circ$C at the pre-amplifiers of, respectively, SSSSD and pads. These values were not exceeded during the whole experimental run.

To test the capabilities of OSCAR in detecting and identifying low energy charged particles we used on beam data. $^{40}$Ca and $^{48}$Ca beams were accelerated by the superconductive cyclotron
Figure 4. An example of $\Delta E$-E plot for a pseudo-telescope of the OSCAR detector. Isotopes are correctly identified up to beryllium (as indicated by labels). An excellent separation is obtained in particular for $Z \leq 2$. Loci corresponding to $Z = 1$ isotopes, $^4$He and $^7$Li show a pronounced punch-through line due to the limited thickness of the silicon stages.

K-800 of INFN-LNS, impinging on $^{40}$Ca and $^{48}$Ca targets. OSCAR was placed at $\theta = 55^\circ$ in the laboratory frame at a distance of 103 cm from the target, while, simultaneously, 4-blocks of the FAZIA demonstrator were used at forward angles. In Fig. 4 we report a typical $\Delta E$-E plot obtained for one of the pseudo-telescopes of OSCAR. In this plot, $E_{\text{res}}$ corresponds to the residual energy measured in the pad, while $\Delta E$ is the energy deposited in the first thin stage (SSSSD).

As it can be clearly seen in the figure, lines corresponding to light nuclei are highly populated, while, essentially due to kinematics, the statistics recorded for heavier ions is significantly lower. Several isotopes can be unambiguously distinguished up to $Z = 4$. The higher energy part of the loci corresponding to $Z = 1$ is partially in overlap with the punch-through line of $Z = 2$ isotopes. An excellent separation is anyway observed, especially for light $Z \leq 2$ nuclei. After correctly reconstructing a track into OSCAR, this plot can be used to correctly identify charge and mass of the detected fragment. Track recognition is achieved by means of a geometrical coherence algorithm, see Ref. [13] for details.

Energy calibrations for each strip and pad were obtained by analyzing punch-through points of various isotopes as observed in the corresponding $\Delta E$-E plots. For a given isotope, the punch-through point energy corresponds to the minimum energy required for the isotope to punch through the second detection stage of OSCAR. In such a condition, the energy released by the particle in first and second detection stages is well determined if one knows the thickness of the two layers. Such points can be extracted via a Fermi function fit of the end-points of each $\Delta E$-E locus. We assumed a thickness for the silicon pads equal to the nominal value (300 $\mu$m), while for each strip covering a certain pseudo-telescope we consider a thickness value as measured from a dedicated experiment [13]. Calibrations of the second detection stage have been complemented also by using a 3-peaks $\alpha$-source with and without SSSSD. When the SSSSD is used, because these particles are close to the punch-through in the SSSSD stage, only a small quantity of energy is usually released in the second stage and we are able to extend the calibration at lower energies. In Fig. 5, we focus exclusively on $^4$He isotopes identified in a given pseudo-telescope of OSCAR. Blue points are obtained from a dedicated run in which OSCAR was irradiated by a 3-peak $\alpha$-source containing a mix of $^{239}$Pu, $^{241}$Am and $^{244}$Cm isotopes ($E_{\alpha} = 5.1$MeV, 5.5MeV...
Figure 5. A \( \Delta E-E \) plot for a pseudo-telescope of OSCAR for well-identified \( ^4 \)He isotopes. Black points are obtained from a Ca+Ca experiment run while blue points are relative to a run in which a 3-peaks \( \alpha \)-particle source was used. The total reconstructed energy for the 3-alpha run is shown in the insert. The shadowed region corresponds to the energy region affected by the identification thresholds.

and 5.8MeV. As expected, \( \alpha \) particles detected in the calibration run occupy three different regions of the \( ^4 \)He line, reflecting the three different energies of the source. In addition, the lower energy peak is partially suppressed as a result of the non-vanishing identification threshold. \( \alpha \)-particles of \( \approx 5 \)MeV are indeed at the limit of the identification capabilities of OSCAR. Only the tracks that strike the surface of the detector approximately perpendicularly are successfully identified. In the insert of Fig. 5, we show the energy spectrum obtained by summing the calibrated energies in the two stages for the \( \alpha \)-source data. The yellow band indicates the region affected by the identification threshold. For the 5.5MeV peak we can estimate a global energy resolution of \( \approx 70 \)keV FWHM. This value is particularly satisfactory considering that the energy is reconstructed as the sum of two independent detection stages.

It is important to stress that one of the most salient features of OSCAR is the low identification threshold. This is implemented by means of the use of ultra-thin (20 \( \mu \)m) silicon detectors as the first identification stage. It is thus meaningful to fully characterize the detection threshold for each identified isotope. To this end, we have analyzed the starting point of the energy spectrum built for several identified isotopes produced in the Ca+Ca commissioning experiment. In Fig. 6, we show the experimental identification thresholds of OSCAR for H, He, Li and Be isotopes; they are affected by the thickness of the SSSD. Ideally, for a given isotope, they should correspond to the punch-through energy in the 20\( \mu \)m first silicon stage. In a real application, they are affected by the silicon thickness non-uniformity of the first stage and by the electronic thresholds. To understand the effect of these two factors on the experimental thresholds, we plot experimental threshold values as a function of the ideal ones, taking only into account the thickness of the first detection stage (as experimentally measured in Ref. [13]). Error bars in the theoretical values of thresholds reflect the measured detector thickness non-uniformities. We obtain errors in the range 3–5% depending on isotope and the selected region of the detector. Detector thickness was carefully measured in several points along the surface of the detector via a dedicated experiment [13] and ranges from 11.5 \( \mu \)m to 25.6 \( \mu \)m. As previously discussed, experimental energy threshold values (y-axis) are determined from the starting points of each reconstructed energy distribution;
Figure 6. Experimental energy thresholds $E_{\text{exp}}$ as a function of the calculated ones $E_{\text{theor}}$ for several identified isotopes (in different colours). The red dashed line corresponds to the ideal $E_{\text{exp}} = E_{\text{theor}}$ line. Error bars are calculated as discussed in the text. The trend of the reconstructed points is compatible with that of the ideal line within the error bars, indicating the non-significant effect of electronic threshold on the identification capabilities of OSCAR.

for these values we assumed a maximum (conservative) indetermination of 3% in agreement with the uncertainties in the energy calibrations and in the assignment of the spectra starting points. Experimental points, in different colours for different isotopes as indicated by labels, do not show any significant systematic divergence from the ideal trend $E_{\text{exp}} = E_{\text{theor}}$ (dashed red line in figure). The small deviations from the ideal line reflect essentially the different SSSD thicknesses for each of the considered pseudo-telescopes.

4. Conclusions

In conclusion, we have designed and developed a new hodoscope of silicon detectors for the detection and identification of low energy particles produced in nuclear collisions. Our detector is based on individual modules with embedded pre-amplifiers. Plug-and-play connections and the reduced size enable to easily couple this device, in the future, to other existing high-complexity and larger acceptance multi-detectors such as CHIMERA [17, 18, 19, 20] or INDRA [21, 22, 23]. This will help, for example, to improve the energy resolution and angular segmentation of large acceptance devices in the regions where it is maximally required by the reaction kinematics.

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