The Fazia initiative: more powerful detectors for a more detailed investigation on the origin and the decay of charged fragments

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Abstract

The main results of the R&D program of the FAZIA collaboration are described. The objective was to improve particle identification capabilities from solid-state telescopes made of Silicon detectors and CsI(Tl) scintillators in view of a new large acceptance apparatus to be used for heavy-ion physics. Important progresses have been made on silicon detectors thanks to a careful control of the material, of its doping uniformity and of the crystal orientation. Moreover, the use of appropriate fast digital electronics allowed to extract maximum information via Pulse Shape Analysis and to propose new configurations of CsI(Tl) readout. Some of the recent results of the telescopes are discussed here, together with some perspective and preliminary data on the physics program at intermediate bombarding energies

1 Introduction

In recent years, heavy-ion physics put the focus on the isospin degree of freedom which can be particularly stressed when using radioactive beams to perform experiments. With their employment, important steps can be done both in nuclear structure and in reaction mechanisms because one can explore ground state properties and excited states of nuclei which are far from the beta stability. Fundamental aspects of nuclear science like the evolution of shell closures and of the level lifetimes, the modification of basic reaction processes like fusion or fission, the finding of exotic decay modes and correlation phenomena related to unusual shapes, all these subjects can be investigated in the scarcely explored region towards the nuclear drip lines.

Let's focus on reaction processes: it is particularly interesting to study how the reaction cross section varies, at the different energy and mass scales, with changing isospin. There are, for example, specific effects related to loosely bound neutrons which have been investigated in light n-rich halo-nuclei [1] but which have been so far poorly known for heavier systems in relation with neutron skin or surface [2]. A big subject is the symmetry energy term, which favours the same number of protons and neutrons in nuclei. This term is not well known for systems at densities far from the saturation value and at high excitation energies; indeed, several behaviors have been theoretically proposed [3,4]. In heavy-ion reactions, as a function of the energy and of the impact parameter, the interacting system heats up and experiences density variations (compression and expansion); thus, isospin dynamics can suitably investigated and the effects are obviously enhanced in nuclei far from the β-stability.

Coming to the decay modes, it is well known that "hot" and rapidly spinning systems are formed in ion collisions. Therefore, also the description of the decay of these systems, possibly with unusual isospin values, can be an other interesting field, where the interplay between structure and dynamics for exotic species is strong. In this context, we just cite results on (alpha-)cluster phenomena observed in weakly excited N=Z systems [6] or in fusion-like reactions between very light systems [7]. Moreover, we mention the ongoing developments of theory, in the different sectors of collective [8], stochastic [9] or TDHF [5] models to better describe the trend of the reaction cross section from low to intermediate energies (5 to 50 MeV/u).

As the isospin is a crucial variable, it is important that the reaction products be identified both in charge and in mass. This can be reached using powerful spectrometers which offer so far the best mass and charge resolution up to the heaviest ions. A limitation of these devices is their acceptance, which is typically poor and doesn't allow for a (almost) complete event reconstruction, as recommended in collisions with production of many fragments (in particular at the Fermi energy regime).

All above considered, the european FAZIA collaboration [10] was born some years ago in order to improve the operation of silicon and scintillation detectors and to push at the limits their particle identification capabilities also by means of fast-sampling digital electronics. The technological research has led to excellent results and to the definition of a powerful three layer telescope Si-Si-CsI(Tl), a typical choice of modern set-up (see e.g. Reff. [11,12]). Some recent results [13–18]) are discussed here together with some preliminary data which show the FAZIA capabilities for isospin studies at intermediate energies, as planned for our first future experimental campaign. Indeed, a modular array of about 200 telescopes is under construction and should be commissioned in 2014.

2 The FAZIA activities and the Telescope concept

FAZIA is an european collaboration of France, Italy, Poland, Romania and Spain. As said, the driving idea of the initiative, also pushed by the development of Radioactive Ion Beams (RIB) facilities at GANIL and at Legnaro, was to improve the performance of detectors to identify ions, also through the Pulse Shape Analysis (PSA), this latter hugely benefiting of the versatile digital treatment of signals. PSA is important, because one of the main efforts is to keep identification energy thresholds low, in order to recognize also slow ions which stop in thin silicon junctions.

FAZIA adopted a three-layer Silicon-Silicon-CsI(Tl) telescope as the basis module for a future large acceptance array. Many aspects of the telescope operation have been investigated along the years and special solutions have been proposed to improve the results. In 2011 a Memomrandum of Understanding was signed by the five countries in order to rule the construction of a demonstrator. This ongoing phase will last till 2015 and foresees the construction of an array of 192 telescopes with optimum performances. The detectors have an active area 20x20 mm^2, thicknesses 300 and 500 μm for the silicon stages and 100 mm for the slightly tapered CsI(Tl). The silicon resistivity is around 3-4 kOhm*cm while the Tl doping of the CsI is from 1500 to 2000 ppm. In the demonstrator, the modules will be mounted in 16 blocks, each one consisting of four 2x2 matrices with 4 telescopes. They will be mounted at 100 cm from the target, each block covering 0.64 msr solid angle.

2.1 PSA and fast sampling electronics

In certain detectors the signals formed by the passage of ions have a time-development which depends also on the ion nature itself. In silicon junctions, this dependence is due to a combined effect of electric field profile, ion penetration, different mobility of charge carriers (electrons and holes) and, last but not least, to the time delay before that the opposite charged carriers feel the electric field and drift towards electrodes (plasma erosion time) [19]. For different ions of the same energy, the penetration depth

inside the bulk changes depending on the specific energy losses. Charge carriers are therefore differently distributed and sample variable electric field values, so that the study of the signal shapes allows for their identification.
In inorganic crystals, fluorescence presents several decay constants whose relative weight depends on the particle. In typical CsI(Tl) crystals, widely employed as stop detectors in heavy-ion experiments, the two components have decay constants of around 1 to 4-6 μs [17], respectively. In general, the fast contribution increases with the Z of the adsorbed ion; therefore, different ions with fixed energy can be separated by means of an analysis based on these fast-slow components.

FAZIA activity started from these detection bases trying to improve their application by means of sampling electronics. Digital signal processing, indeed, is very versatile and the availability of commercial fast sampling ADC permits its use also in case of the rapid signals (wide bandwidths) produced in nuclear detectors. The processing can be done, shape by shape, in real time by using front-end computation units (DSP or FPGA) to extract the relevant parameters or, as chosen by FAZIA, via off-line analysis applied to the whole waveforms, stored on disk. Off-line analysis is more powerful since it allows to singularly study each waveform, to upgrade identification algorithms whenever available, to implement special analysis types (e.g. related to radiation damage or to border effects). During its R&D phases, FAZIA strongly benefited of this "off-line" approach in particular for silicon detectors [13,20].
Since digital PSA relies on the sampling of intrinsic waveforms produced by the ions, the preamplification stage is an issue, in particular for silicons where PSA applications are mor crucial. Special low-noise preamplifiers [21] have been developed within the collaboration, with both current and charge ouputs. For silicon detectors, two gains have been adopted for the charge outputs in order to better exploit the dynamics: 250 MeV@Si-eq and 3/4 GeV@Si-eq. For CsI(Tl) the only charge output is exploited with a sensitivity of $\approx$ 300 MeV@Si-eq.
The sampling stages are 14bit-ADC with clock at 250 MS/s and 100 MS/s for silicons and CsI, respectively. Indeed, the bandwidth of scintillators is less extended than in silicon, where transient times down to 20 ns should be measured. Preamplifiers and ADC circuits, together to other stages (e.g., the programmable logic arrays, the slow controls, the pulser generation, the bias voltage supply and tuning), are all hosted in "custom" boards, each hosting 6 channels (2 complete telescopes). Also noise contributions should be kept low enough in order not to spoil the information brought by the waveforms. In other words, the effective number of bits (ENOB) of the channels must be as highest as possible, possibly not too far from the NOB of the chosen ADC in order to save its resolution typical FAZIA values are ENOB$\approx$11-12, overall.

2.2 Silicon detectors

The two silicon stages (Si1 and Si2) of the FAZIA telescope are the core of the module and thus they have been the objective of careful investigation. The silicon chips have a twofold purpose: i) ion identification and ii) energy measurement. Particles which punch-through the first Si1 and stop in Si2 are recognized, in charge and mass via the usual $\Delta E - E$ method, while the kinetic energy is given by the sum of the two contributions $\Delta E + E$. This method cannot be used with ions stopping in Si1 and thus it presents a energy threshold that can be severe: for instance, for a 300 μm thickness, the threshold is 6 MeV/u for protons and alphas and it increases to about 22 MeV/u for Z=30. For ions adsorbed in Si1, an estimate of the particle mass can be obtained from the energy and the time-of-flight (tof) variables. It is thus important to preserve good timing properties for silicons and this fact would suggest to mount silicons in "front" configuration, where particles hit the high electric field (junction) side and produce faster signals. However, PSA applications demand to reconsider this aspect. As a matter of fact, FAZIA chose the rear mounting configuration, in which particles enter the ohmic side of the junction (for both silicon layers) where the electric field is at the minimum. This choice, as discussed in the literature [22, 23], is preferable to improve PSA because this way signal shape differences are enhanced with respect to the front mounting. This is shown, as an example, in Figure 1, where experimental charge signals for

Ti ions of two initial energies are shown for rear (red) and direct (blu) configuration. The two energies correspond to ions stopping at the end of the thickness (910 MeV) or with a range of about 2/3 of it (i.e. 190 μm). Clearly, signal shapes appear to differ more in the rear mounting and this reflects in a greater sensitivity of any signal-related parameter for PSA. Attempts to microscopically describe the (charge or current) signals produced by heavy-ions in silicon detectors are on progress within FAZIA and recently they gave promising results [19]. Besides the optimisation of the electronics, FAZIA devoted

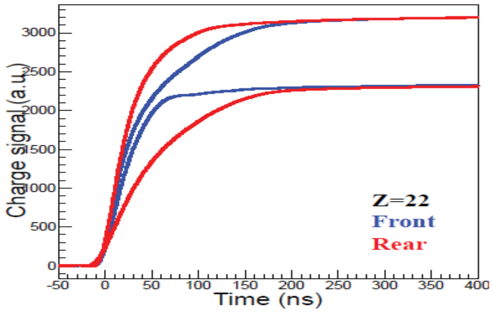


Fig. 1: Charge signals for Titanium ions of two energies as measured for a 300 μm silicon detector in front (blu) or rear (red) configurations. From Ref [18].

many efforts in studying and reducing the effects which intrinsecally degrade the PSA. They are related both to the silicon structure (like crystalline nature and doping homogeneity) and to the detector use (like radiation damage). For the latter we refer to Ref. [24]. Here we briefly discuss the structural aspects which affect PSA in silicon detectors. Good PSA performances need that signal shape variations are only due to different ion/range combinations with negligible fluctuations introduced by spurious sources. Channeling effects of heavy-ions in silicon detectors have been observed since many years, showing up as a spoiling of the energy resolution with humped energy distributions even for monochromatic ions [25]. When ion beams with narrow emittance impinge on silicon junctions with directions close to crystallographic axes and/or planes, the ion-electron interactions along the tracks are strongly position dependent; the effective charge of the slowing ions fluctuates as function of the track details and this produces the humps in the spectra. The powerful sampling techniques allow to better evidence the signal shape fluctuations due to channeling, as FAZIA demonstrated with specific experiments [13]. It was shown that these spurious shape variations can be strongly reduced with almost random irradiation, corresponding to incident angles far from crystallographic directions. In this case the crystalline structure is almost hidden to impinging ions and a smooth behavior is obtained with reduced fluctuations.

The doping homogeneity is an other crucial aspect for PSA with silicon detectors. In fact, dis-homogeneities of dopants create local changes of the electric field inside the device which, again, produce spurious signal smearing. This is known since the pioneering works on PSA which suggested the use of neutron trasmutation doped (nTD) detectors, having better doping uniformity with respect to FZ-implanted ones. FAZIA clearly evidenced the effect of doping inhomogeneities on PSA [15]; therefore, only nTD wafers were adopted, with resistivity which should be constant, for each detector, within 6-7%. To check this figure in the final ready-to-mount pads, FAZIA implemented a tool to probe the homogeneity of the silicon detectors without need of beam tests. The method, based on very fast UV-laser flashes [14], leads to a resistivity map for each pad over its active area; only the pads with the flattest resistivities are retained. Best homogeneities are less than 1% but typical values are 4 to 6%. Recently, a method has been proposed to compensate for the residual doping inhomogeneity, by further thermal neutron irradiation of the wafer with purposely shaped Cadmium masks [26]. The method, still at its concept phase, needs the previous knowledge of the resistivity map in order to shape the mask for each wafer.

2.3 CsI(Tl) scintillators

The selected CsI(Tl) are slightly tapered piramidal crystals; their front square face (20.3x20.$3mm^2$) contains the silicon dimensions. Tipically, the luminescence is read by a photodiode (PD) glued with soft

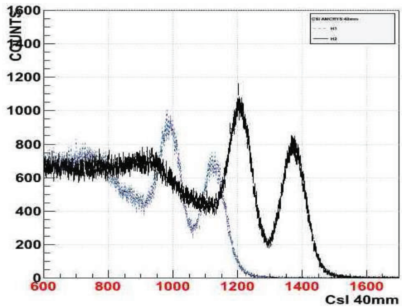


Fig. 2: ^{60}Co gamma ray spectrum for a 40 mm long CsI crystal wrapped with a diffusive paper (blu) or with the 3M-Vikuiti (black) reflector

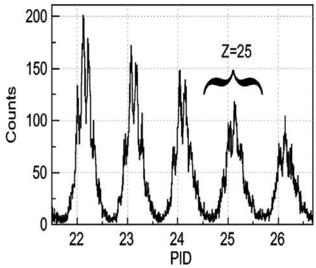
optical epoxy to the crystal. The square PD are specifically produced for FAZIA; they are 300 μm thick single pads with ρ=6000 ohm*cm, whose main feature is the very narrow lateral dead zone (active area 19.6x19.6 mm^2, 81% of the total area); commercial devices couldn't be used except loosing a relevant fraction of light sensitive area. The crystal length (10 cm) allows to stop even the most energetic light particles in reactions at intermediate energies. Particular care has been devoted in selecting the surface type and the wrapping materials. The front and rear faces are polished while the lateral ones are slightly roughed after polishing. The wrapping material was chosen after laboratory tests with gamma and alpha sources on several crystals. The use of a new high-reflecting polymer [27] gave an enhancement of light output of about 18-20% with respect to previously used white diffusive papers (see Figure 2). Tests under vacuum were done to verify the good operation also in typical experimental conditions and to exclude major de-gassing effects of this polymer.

3 In beam performances

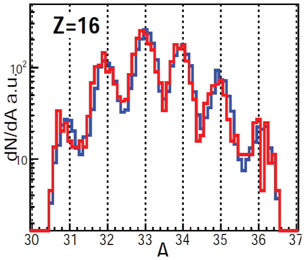
We now discuss a few examples of the under-beam performances of the FAZIA telescopes, prepared as described above. The results refer to experiments done at Laboratori Nazionali del Sud (Catania, Italy). Pulsed beams of ^{84}Kr and ^{129}Xe at 35 MeV/u were sent on thin (0.2-2.0 mg/cm^2) foils made of various enriched isotopes of tin and nickel. The telescopes were positioned at distances 100 to 250 cm from the targets.

3.1 ion identification via ΔE-E

Ions with enough energy punch-through the first stage of a telescope and can be identified via $\Delta E - E$ technique. We can use the Si1 or the Si1+Si2 as the first lens of the telescope, for particles stopping in Si2 or CsI(Tl), respectively. A rich set of the FAZIA results is reported in Ref [16, 18]; here, we stress that unprecedented mass separation is reached by our telescopes. For example, isotopes are resolved up to Z≈24-25 for both Si1 vs. Si2 and (Si1+Si2) vs. CsI as shown in Figure 3.1 a). This opens the door to more complete isospin studies at Fermi energies because one can afford isospin reconstruction of the very fast quasi-projectiles (at least for medium-heavy mass) produced in semi-peripheral collisions and



(a)



(b)

Fig. 3: a): Isotopic distribution in the iron region for ions stopped in CsI(Tl). The identification is obtained with the $\Delta E - E$ technique applyied to one FAZIA telescope (from [16]). b): Comparison of the isotopic distributions for Sulphur as measured via the $\Delta E - E$ method for a given pair of Si1-Si2, mounted in reverse (red) or direct (blu) configuration (from [18]).

not only of the lighter fragments as done so far.
An important conclusion has been drawn by FAZIA on a debated subject, namely the quality of the $\Delta E - E$ technique with silicon detectors in front or reverse geometry. In a specific beam-test, we compared the the method with front and reverse mounting by flipping the Si1 and Si2 stages in two phases of the same experiment. This way, the comparison is strictly conclusive. No difference was found as demonstrated in Figure 3.1 b), which shown the sulphur isotopic yield obtained in the two silicon configurations [18].

3.2 Ion identification via digital PSA

The strong interest in the identification of less energetic ions which stop in the first layer is due to the fact that they represent a large fraction of the population of the ejectiles at moderate bombarding energies, as those of the next exotic beam facilities. Also, fragments emitted by the rather slow big sources formed in central collisions or by quasi-target nuclei at larg impact parameters typically demand low thresholds. The good quality of the FAZIA silicon material allowed to reach promising results. About charge identification, the limit has been amply extended: in our reverse mounted silicon pads the elements have been separated up to the maximum values of the test reactions (Z=54). Concerning isotopic separation the situation is more critical because it depends quite sensitively on the various parameters (doping homogeneity, channeling suppression, radiation damaging, overall operation stability). So far, we verified that, PSA permits a safe separation up to carbon ions with energies greater than MeV/u [15].

3.3 The single chip configuration

The use of fast sampling electronics pushed the FAZIA collaboration to better investigate the Single Chip Telescope (SCT) configuration, proposed years ago [28]. The idea is to use the second silicon Si2 as the photodiode for the following CsI(Tl) crystal. The SCT solution can be useful to spare electronic channels (and money) in large apparatus. In a SCT, the Si2 acts both as an ionization detector and as a photosensor: thus, the signal waveforms for ions stopping in the CsI(Tl) are given by different contributions, extending on different timescales, from many nanoseconds to microseconds. From the sampled recorded shapes one can first recognize the signals of ions stopped in Si2 (no scintillation component) and those for ions stopped in the CsI(Tl). Then, for these latter, one can perform an appropriate analysis (e.g. based on various shaping times) and disentangle the fast silicon contribution from the slow one(s) of the scintillator. The behaviour of a SCT has been accurately compared with that of a reference standard Telescope and the results are described in Ref. [17]. We show in Figure 4 the $\Delta E - E$ identification plot of the reconstructed SCT signals. The quality is very good and in particular the hydrogen isotopes (in the zoomed inset) are well distinguishable. As a matter of fact, the SCT is almost equivalent to the standard read-out for Z=1,2 ions while for Z$\geq$ 2 it is worse for energies below 20 MeV/u, although the isotopic separation is preserved. Therefore, the SCT concept appears to be appealing and also other groups adopted this solution [**?**].

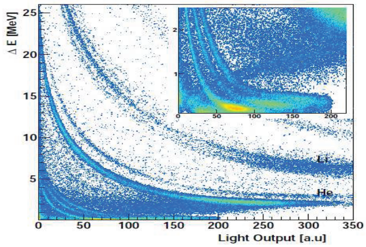
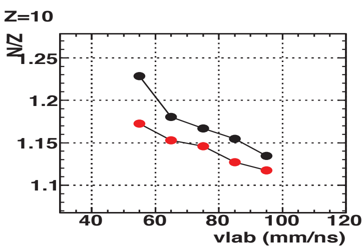


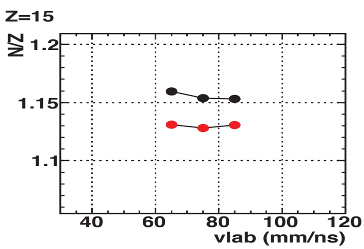
Fig. 4: $\Delta E - E$ identification plot obtained from a Single Chip Telescope. Lithium isotopes are separated. In the inset, hydrogen isotopes are shown (from Ref. [17]).

4 Towards the demonstrator phase

During the last test under beam at the INFN-LNS (Catania), we measured reactions induced by a ^{84}Kr beam with 35 MeV/u on targets of enriched tin isotopes. The idea was to prove that the perfomance of the FAZIA telescopes permits to measure isospin variables with unprecedented quality at the Fermi regime. First, we wanted to investigate the role of the isospin diffusion and drift [3,4] occuring in the transient systems formed in semi-peripheral binary reactions which finally lead to excited quasi-projectile (QP) and quasi-target (QT) fragments. Secondly, we aimed at studying odd-even staggering effects which are ruled both by reaction mechanisms and nuclear structure. In the experiment, only QP were detected and identified in charge up to the maximum Z=36 (Kr); isotopes were separated up to about Chromium as described above (Figure 3.1 a)). The use of ^{124}Sn and ^{112}Sn targets permits to verify the effect on QP characteristics due to changes of the isospin content of the target; indeed, the N/Z of Kr (1.33) is in between those of the n-rich ^{124}Sn (N/Z=1.48) and of the n-deficient ^{112}Sn (N/Z=1.24). Event types



(a)



(b)

Fig. 5: Preliminary results of average isospin N/Z of fragments Ne (a) and P (b) as function of their lab velocity. Red dots for ^{112}Sn, black dots for ^{124}Sn

were selected on the basis of the $Z - v$ correlation where v is the laboratory velocity of the detected ions. This correlation has been widely used in the past to characterize different event types [29]. The analysis of these data is on progress and it will be reported in the future [30]. Here we just anticipate some preliminary results which allow to appreciate the goodness of the data and give some hints of the physics cases. This is done in Figure 5 where the average N/Z ratio is presented versus v for neon and phosphor isotopes. Red (black) points refer to the ^{112}Sn (^{124}Sn). The following observations can be done. The detected (cold) fragments show a memory of the different isospin target content, although they are mainly associated with QP. Then, lighter fragments with v compatible with the intermediate QP-QT region (midvelocity region) appear to be more neutron rich than those having v close to the QP. This trend is quite in agreement with results, among others, of a very recent study [31]. Finally, we observe that the region above Z=9-10 was unaccessible for this kind of variable by modern multidectors, so far. The example of Z=15 isotopes (Figure 5, right) is, in this sense, new and give an idea on how isospin related quantities can be extended by the next experiments with the FAZIA demonstrator.

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