The GPICsIT Monte Carlo simulation program of the PICsIT detector

- PICsIT Qualification Model -

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Abstract

GPICsIT is a Monte Carlo program developed to simulate the PICsIT high energy detection plane of the IBIS telescope using the GEANT package. The simulation studies allow the optimisation of the detector design and functional parameters setting, the developement of the reconstruction and analysis programs and the interpretation of the experimental data. Final aim of the simulation is the production of the instrument response matrices. The structure of the program, which comprise the implemented detector geometry, the event generation, the "tracking" and the event recording and analysis, is described in details. Preliminary simulation results obtained in parallel to the PICsIT ML/QM test campaign are presented and compared with the experimental data.

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1 Introduction

The PICsIT (Pixellated Imaging CsI Telescope) instrument is the high energy detection plane (150 keV - 10 MeV) of the IBIS (Imager on-Board the INTEGRAL Satellite) imaging telescope onboard the ESA satellite INTEGRAL (INTErnational Gamma-Ray Astrophysics Laboratory). PICsIT comprises 8 independent rectangular modules, arranged in a 2×4 pattern. Each module consists of a 16×32 CsI(Tl) pixels array for a total assembly of a 4096 element matrix. The detection units, physically and optically independent from each other, have dimensions $8.55 \times 8.55 \times 30$ mm^3.

The response of the gamma-ray detector is expressed as a matrix (the *response matrix*) which allows to interpret the data obtained during in-orbit observations to reconstruct the incoming gamma-ray spectrum, intensity and sources position. The building of the response matrices, which depend upon a number of variables as the incident photon energy, the incoming direction, the interaction vertex and so on, is therefore the primary object. The response of PICsIT to γ rays is first measured in the calibration campaign by irradiating the detector with a number of radioactive sources with known emission lines. The results are next coupled to a Monte Carlo simulation program which allows to produce the instrument response at all energies. The response matrix is then "updated" during the subsequent calibration campaign at system (IBIS) and payload level and finally verified in orbit during commissioning phase.

The GPICsIT program has been developed to simulate the PICsIT detector using the CERN GEANT package. The structure of the program is described in detail and preliminary results relevant to the Qualification Model (QM) are presented. PICsIT QM consist of a 16×32 pixels module electronically divided in two 16×16 semimodules.

2 The PICsIT detector

2.1 PICsIT Laboratory Model and Qualification Model

PICsIT Laboratory Model (PLM) is an intermediate state between the Engeneering Model (EM) and the Qualification Model (QM), representative in terms of scientific performances of the PICsIT detector. PLM consist of:

- one flight representative eggcrate;
- 256 CsI pixel (16x16) inserted in one semimodule;
- one complete flight representative DFEE;
- flight representative detector harness;
- 16 ASICs MPW2 (flight version).

PICsIT ML has been "upgrated" to QM adding:

- 256 CsI pixel (16x16) inserted in a semimodule electronically independent from the other one;
- 16 ASICs MPW2 (flight version).

The QM integration and the campaign for performances verification and test have take place on March-April 2000.

3.2 To build GPICsIT

The GEANT program contains *dummy* and *default* user subroutines called whenever application-dependent actions are expected. It is responsability of the user to:

- code the relevant user subroutines providing the data describing the experimental environment;
- assemble the appropriate program segments and utilities into an executable program;
- compose the appropriate data records which control the execution of the program.

A main program provided by the user allocates the dynamic memory for ZEBRA [?] and HBOOK [?] and passes control to the three phases of the run: initialisation, event processing, termination.

The initialisation is controlled by the user who has the responsability to call the appropriate routines. It consist of the following steps, most of them performed through calls to GEANT subroutines:

GEANT initialise the GEANT common blocks with default values;

GEANT read data records either to modify the default options or to provide information on the current run;

GEANT initialise the memory manager, the link areas and the run header bank;

GEANT initialise the drawing package;

GEANT fill the data structure with particle properties and with the characteristics of the materials used;

USER define the geometry of the different components of the setup stored in the data structure;

USER define materials and tracking medium parameters stored in the data structure;

USER specify which elements of the geometrical setup should be *sensitive detectors* giving a response when hit by a particle;

GEANT process all the geometrical information provided by the user and prepare for particle transport;

USER book GEANT histograms required by the user;

GEANT compute energy-loss and cross-section tables and store them in the data structure.

The event processing consist on the following steps:

GEANT initialise event processing and create the event header bank;

GEANT process one event;

GEANT clean up the portion of memory used by the event;

USER generates or reads the kinematics of the event and stores it in the data structure;

USER controls the propagation of each particle through the setup;

USER follow the secondary particles generated;

USER fill the data structure during tracking;

USER simulate the detector response for the event using the information recorded during particle transport and store the results in the data structure;

Material	Magnetic field [Kgauss]	Maximum step permitted [cm]	Maximum fractional energy lost in one step	Boundary crossing precision [cm]	Minimum value for the maximum step imposed by physical processes
Hydrogen	0.00	0.100E+11	0.243	0.001	0.032
Deuterium	0.00	0.100E+11	0.243	0.001	0.029
Helium	0.00	0.100E+11	0.243	0.001	0.041
Lithium	0.00	0.100E+11	0.234	0.001	0.025
Berillium	0.00	0.100E+11	0.216	0.001	0.015
Carbon	0.00	0.100E+11	0.204	0.001	0.016
Nitrogen	0.00	0.100E+11	0.220	0.001	0.030
Neon	0.00	0.100E+11	0.209	0.001	0.028
Aluminium	0.00	0.100E+11	0.183	0.001	0.022
Iron	0.00	0.100E+11	0.250	0.001	0.019
Copper	0.00	0.100E+11	0.250	0.001	0.020
Tungsten	0.00	0.100E+11	0.250	0.001	0.024
Lead	0.00	0.100E+11	0.250	0.001	0.033
Uranium	0.00	0.100E+11	0.250	0.001	0.027
Air	0.00	0.100E+11	0.249	0.001	0.765
Vacuum	0.00	0.100E+11	0.000	0.001	0.000
CsI	0.00	0.100E+11	0.250	0.001	0.041
Silicon	0.00	0.100E+11	0.185	0.001	0.024
Cellulose	0.00	0.100E+11	0.218	0.001	0.024
Fiberglass	0.00	0.100E+11	0.193	0.001	0.022
Silicone	0.00	0.100E+11	0.207	0.001	0.027
Peraluman	0.00	0.100E+11	0.190	0.001	0.025
Ceramics	0.00	0.100E+11	0.181	0.001	0.021

Table 2: Tracking medium parameters definition of materials implemented in the geometrical routine of GPICsIT.

terial which fills the volume and by the tracking medium parameters, a set of attributes in connection with the drawing package and the detector response package.

The transport of particles through a setup requires access to data which describe:

- the geometry of the setup;
- the *material* and *tracking medium* parameters;
- the particle properties.

The material (basic materials, mixture or compounds) constants and the tracking medium parameters are stored in the data structure. All particle properties as particle constants, branching ratios and decays modes, are defined and stored in the data structure. Quantities such as energy loss and cross-section tables are computed iduring the initialisation and stored in the data structure.

The geometry package has two main functions: define, during the initialisation, the geometry in which the particle will be tracked and communicate, during the event processing, to the tracking

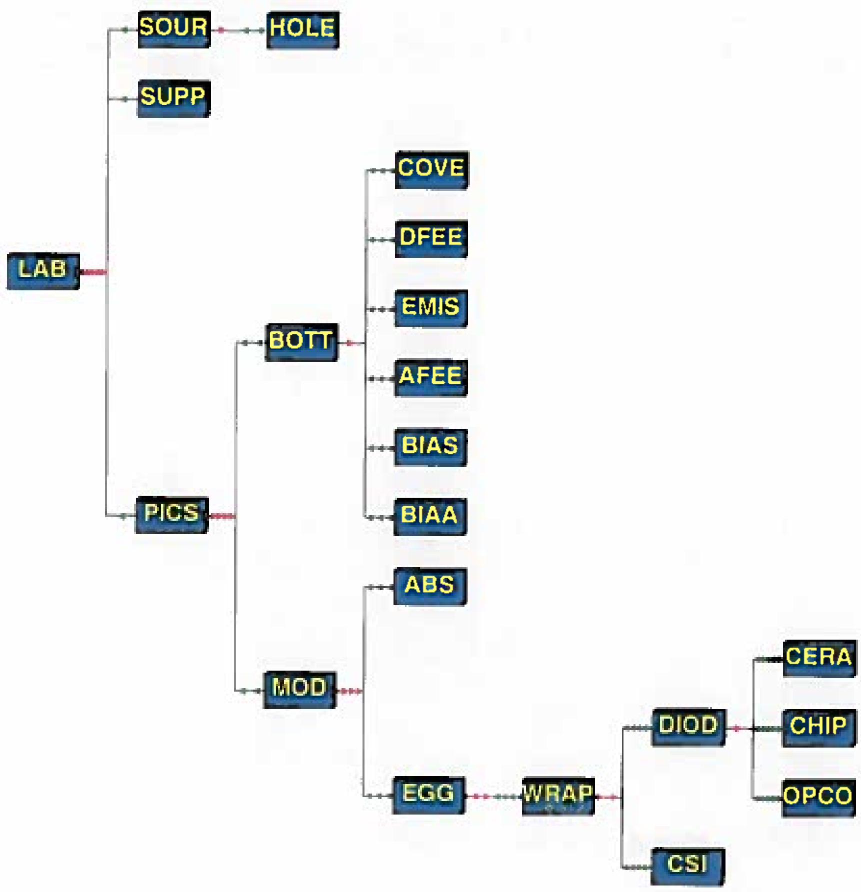


Figure 1: Geometrical tree structure of PICsIT implemented in GPICsIT.

GEANT are always referred to the MARS. Tracking is performed in the MARS.

Fig. 1 show a hierarchical representation of the geometrical structure of PICsIT implemented on the GPICsIT simulation program.

Fig. 2 shows the PICsIT QM detector inserted in an air mother volume (MARS) in the adopted coordinates reference system. The photon source, contoured from a Pb housing is on the origin of the frame on the axis normal to the surface of PICsIT passing from the center of the detector at the distance of 40 cm. The backscattering of the particles due to the PICsIT QM laboratory support is simulated by a 1.2 mm thick sheet of iron with a surface double with respect the area of PICsIT appliyed on the detector bottom.

3.2.3 Storing and retrieving vertex and track parameters

Each event is defined by a particle emitted in a primary vertex. Generation (or input) of event initial kinematics is implemented in the kinetical routine of GEANT. The kinetic vector consist in a seven dimension vector : energy, vertex coordinates, three particles momenta . The GEANT tarcks one vertex at time, therefore all particles of one vertex and secondaries generated must be transported before the particles of the next vertex are considered.

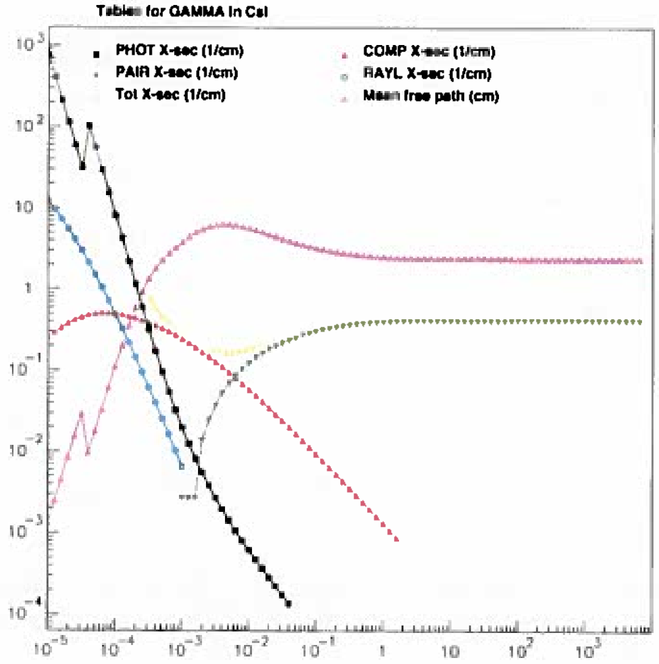


Figure 4: Table of physical processes cross-section for gamma in CsI.

3.2.4 Event generation

Photons are emitted isotropically on 4π by the laboratory radioactive sources. For this pourpose, according to angles definition of the GEANT spherical-polar coordinates system, events are generated in the vertex of origin of the frame randomly with $-1 \leq cos\theta \leq 1$ and $0 \leq \phi < 2\pi$. Momenta are calculated from GEANT by the initial energy and angles and particle type.

For sources emitting different energy photon the decays branching ratios are taken into account.

In Fig. 3 is represented a cross-section of the experimental setup and trajectories of particle emitted from a radioactive source of ^{137}Cs visualized with the GEANT drawing package. The blue dotted lines are gamma tracks while the red solid lines are charged particles (electrons and positrons).

3.2.5 The particle tracking

Particle are transported through the experimental setup in the tracking routine of GEANT. The particle tracking consists in calculating a set of points in a seven-dimensional space (x,y,z,t,p_x,p_y,p_z) which is called the trajectory of the particle. This is achieved by integrating the equations of motion over successive *steps* from one trajectory point to the next and applying corrections to account for the presence of matter. The tracking package perform the tracking for all particles in the current event included secondary products which they generate and store the space point coordinates computed along the corresponding trajectories. The estimation of the step size is performed automatically by the program. For a particle with a given energy the step size depends on the intrinsic properties of the particle (mass, charge, lifetime, etc.) and on the characteristics of the current medium.

Using the interactive package of GEANT is possible visualize for each particle type in a defined material the cross-section of the interaction processes-mechanism and the mean free path, as represented, as an example, in Fig. 4 for gammas in CsI.

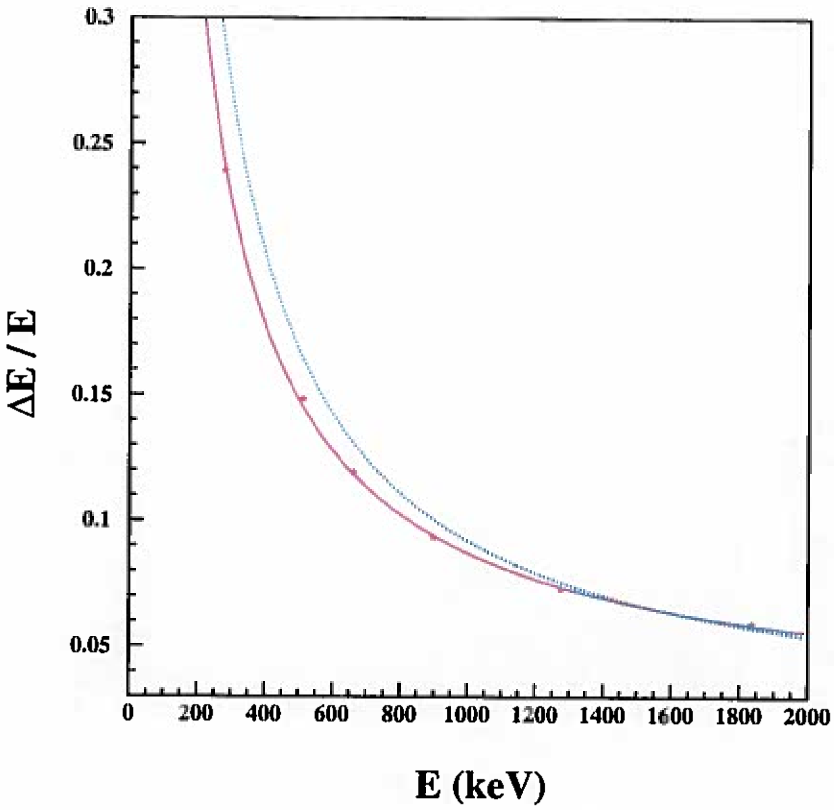


Figure 5: The energy resolution curve (solid line) implemented in GPICsIT with superimposed the expected physical energy resolution curve (dotted line).

The resolution curves 1 and 2 are showed in Fig.5 with the experimental average energy resolutions point. The figures shows that the two equations are in a good agreement.

After convolution, a threshlod is applied to the detection of energy deposit. The lower threshold is 145 keV while the upper is 10000 keV. In Fig. 6 is shown the distribution of total energy deposit in event before and after the convolution of energy for detector resolution.

Events are independently treated according to their multiplicity which is defined to be the number of pixels triggered by one primary incoming photon.

The electronical separation of the semimodules arouse the splitting of a multiple event triggered by both semimodules in two events.

Events that deposit all energy in the detector are denominated photopeak events. They are defined with the relation:

$$|E_{detected} - E_{incident}| \leq 2\Delta E \quad (3)$$

3.3 Simplified GPICsIT program flow chart

In the following a simplified GPICsIT flow chart to visualize the program level.

- generate or read kinematics of the event and store it in the data structure
- follow secondaries generated
- loop over *step* and *tracks* including secondaries particles generated
  * retrive and store information from data strucure
  * retrive vector of incidence on PICsIT {particle type, energy, momenta, vertex coordinates}
  * retrive vector of any energy deposit in the detector {particle type, energy lost, mechanism, vertex coordinates}
- simulate detector reponse for the event
- perform all processing at the end of the event and output the relevant data structure
- store information for current event filling histos and n-tuple
- perform analysis required by the user for current event {event selection (by implementation of finite detector resolution and thresholds, different detector semimodules separation, multiplicity) , distribution of energy, counts map, adjacency, incidence pixel reconstruction and so on}

* compute and store information for current run filling histos and n-tuple
* perform analysis required by the user for current run {counters, computation of efficiencies and so on}

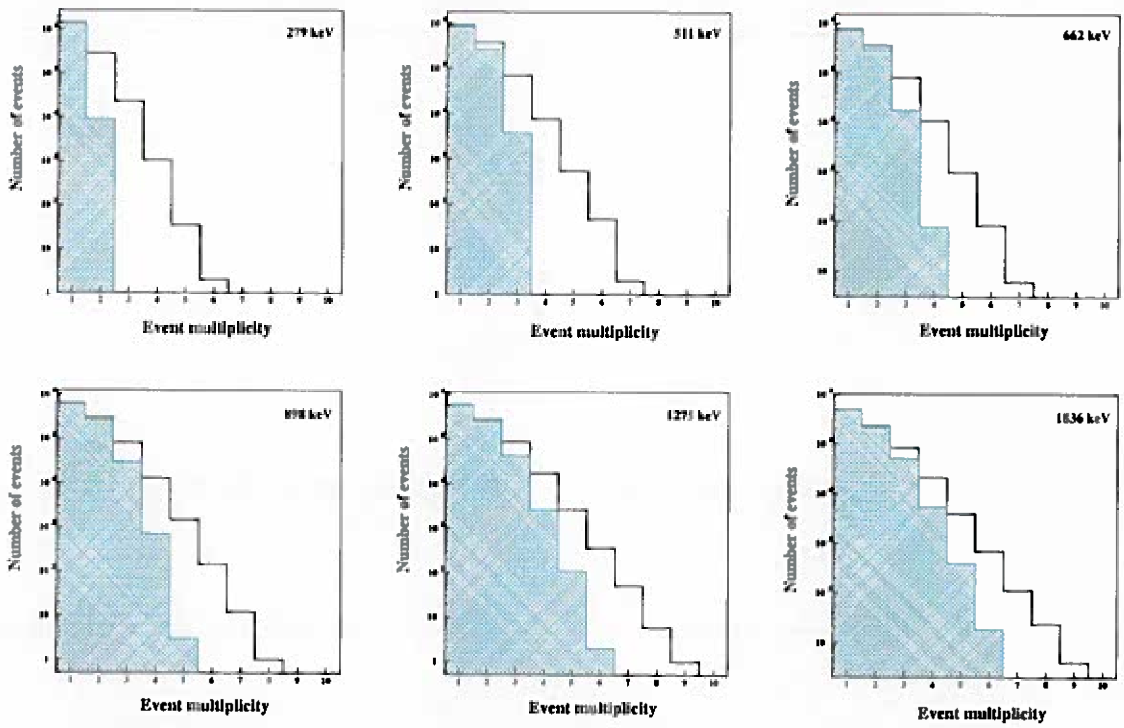


Figure 7: Event multiplicity distributions for gamma sources of ^{203}Hg, ^{137}Cs, ^{22}Na and ^{88}Y. Multiplicity distributions before (solid line) and after (filled histo) the application of detector resolution and thresholds.

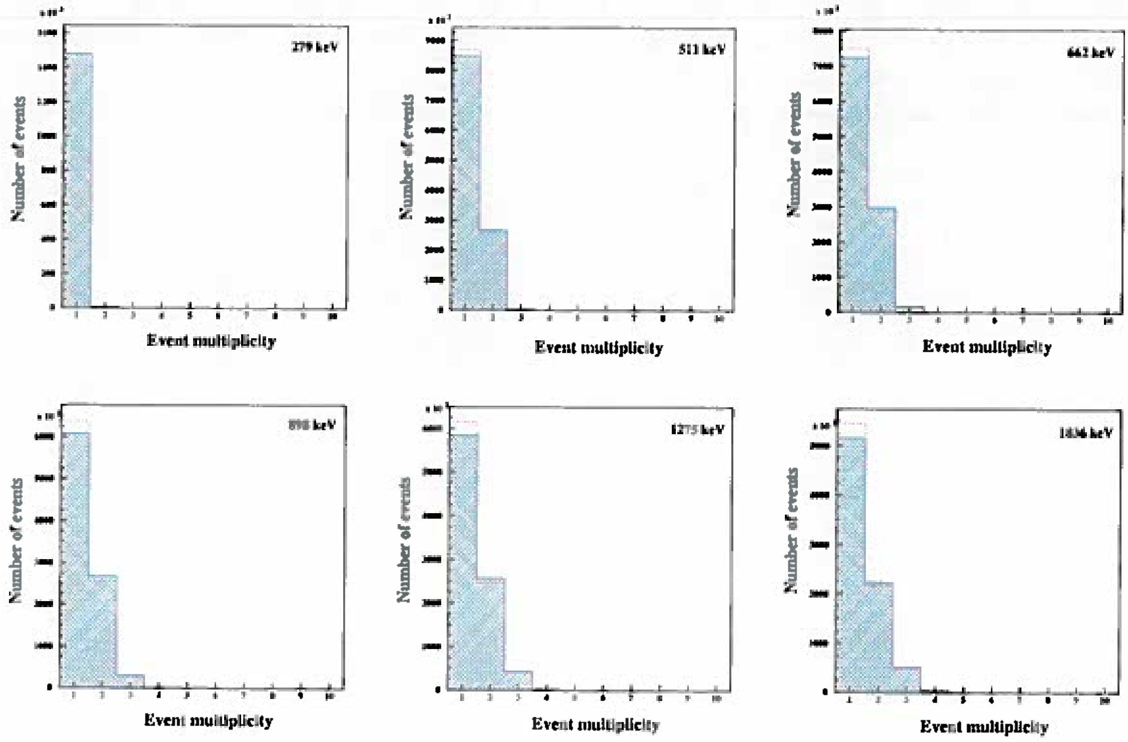


Figure 8: The same distribution in a linear scale (filled histo) with superimposed (dashed line) the finel event multiplicity obtained after event rejection and semimodule electronical separation.

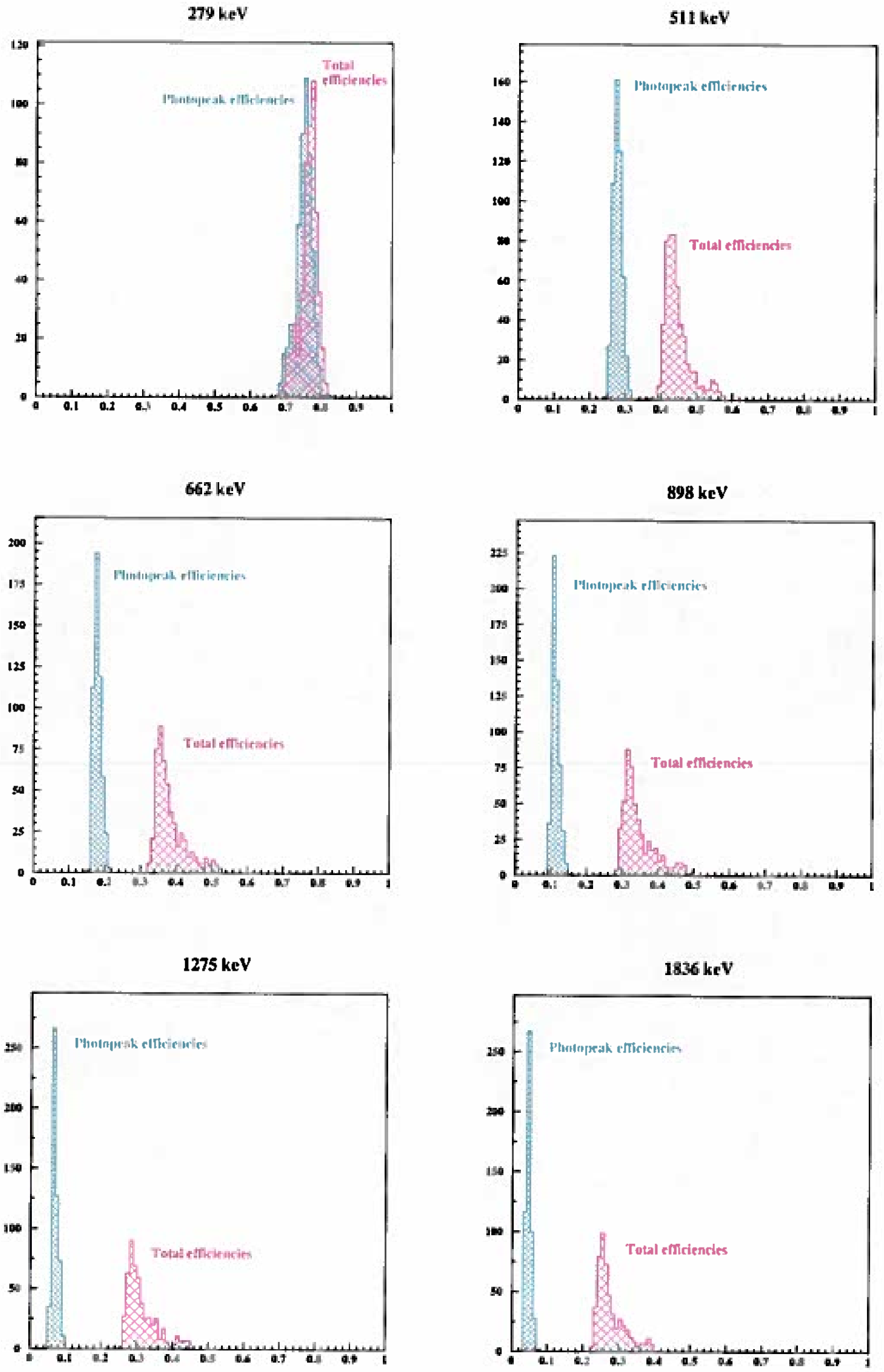


Figure 10: Distributions of pixel total detection efficiencies and photopeak efficiencies.

4.3 Distribution of energies-Spectroscopic results

Distribution of energies obtained from Monte Carlo analysis after the implementation of detector threshold and resolution are showed in Fig. 13 where single events are selected. A peak is evident on the incident energy value while the second peak at low values (around 200 keV) is due to the Compton backscattering. The single pixel spectra are showed in Figures 14 and 15. To notice the backscattering peak more evident in the external pixels, which have a higher probability of interaction with source photons scattered off the surrounding material. This behaviour is better explained in Fig. 12 in which the spectra are obtained by summing respectively the peripheral, the intermediate and the central pixels.

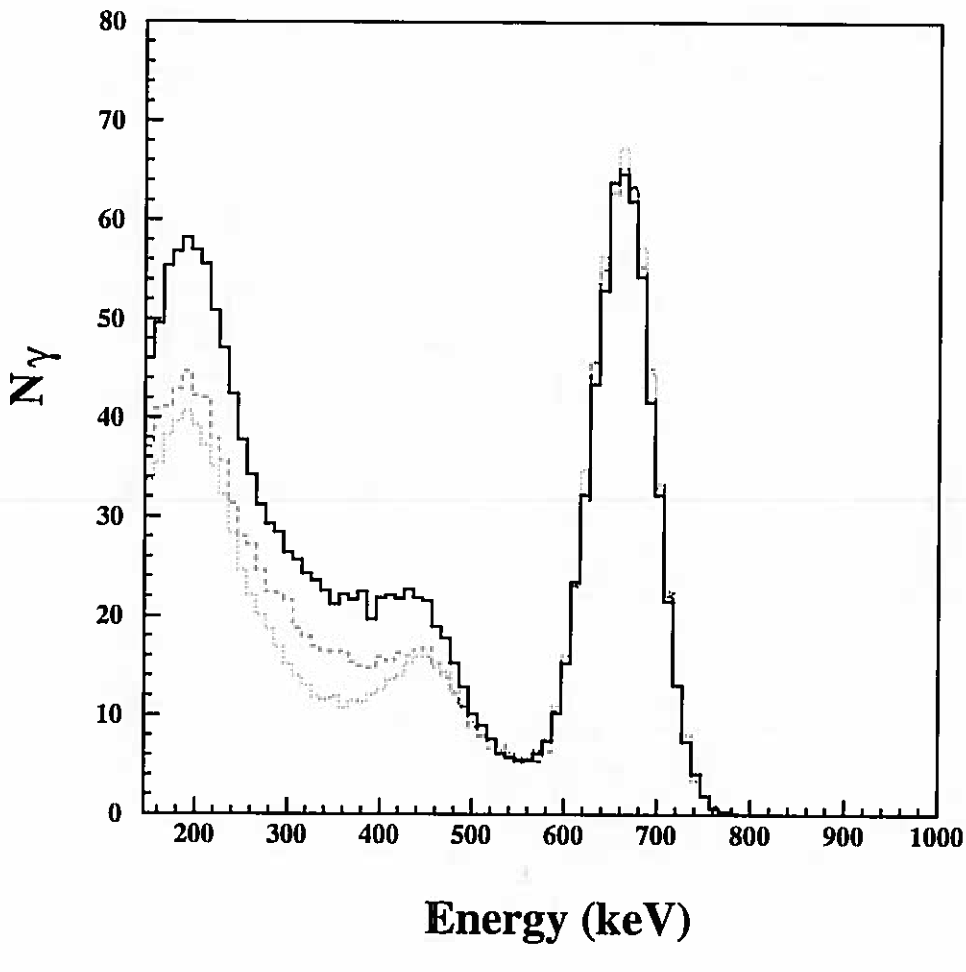
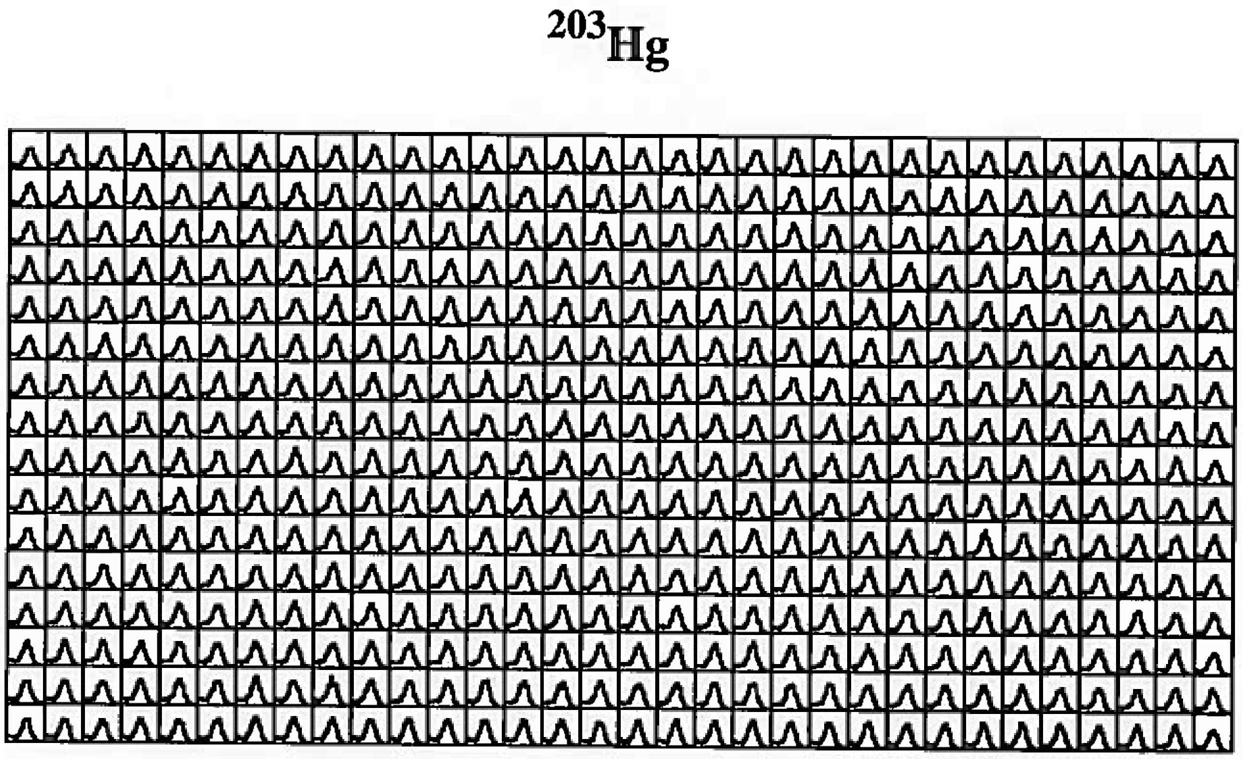


Figure 12: The single spectra relative to the peripheral (black), intermediate (cyan) and central (magenta) regions of PICsIT detector.



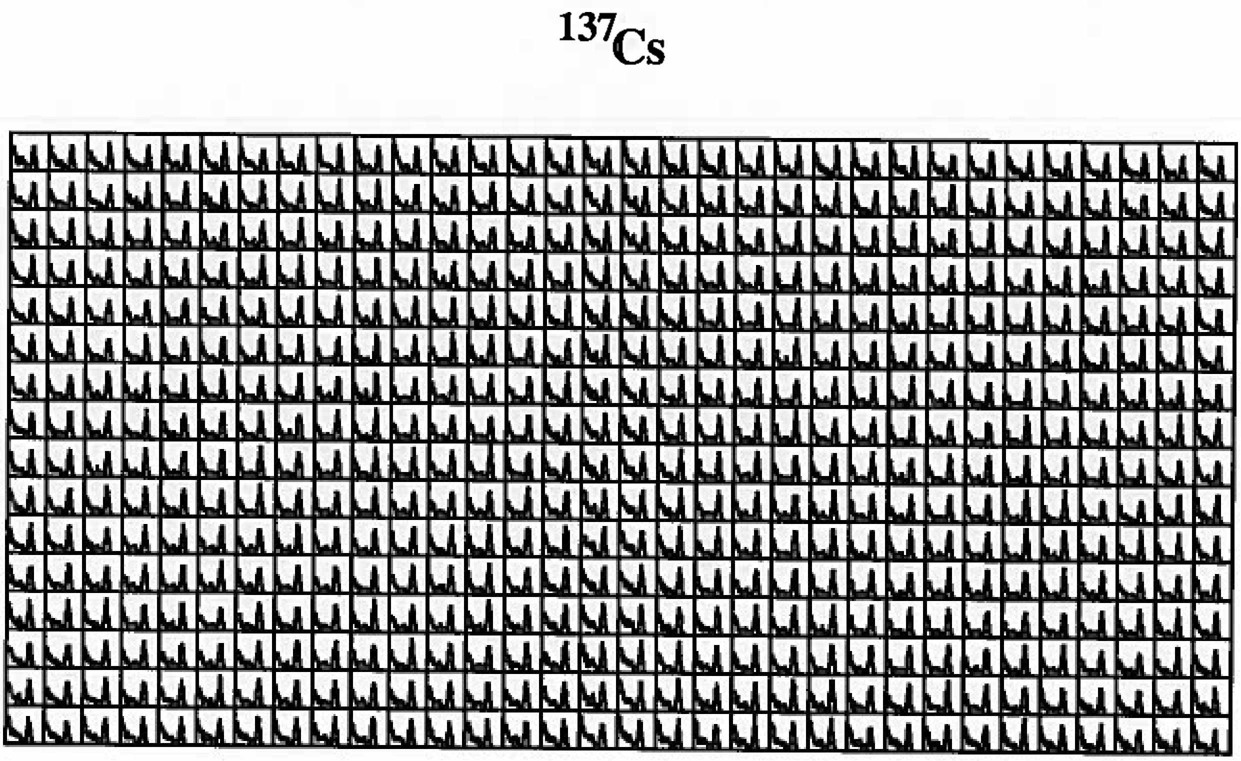


Figure 14: Distribution of single pixel spectra obtained for sources of ^{203}Hg and ^{137}Cs.

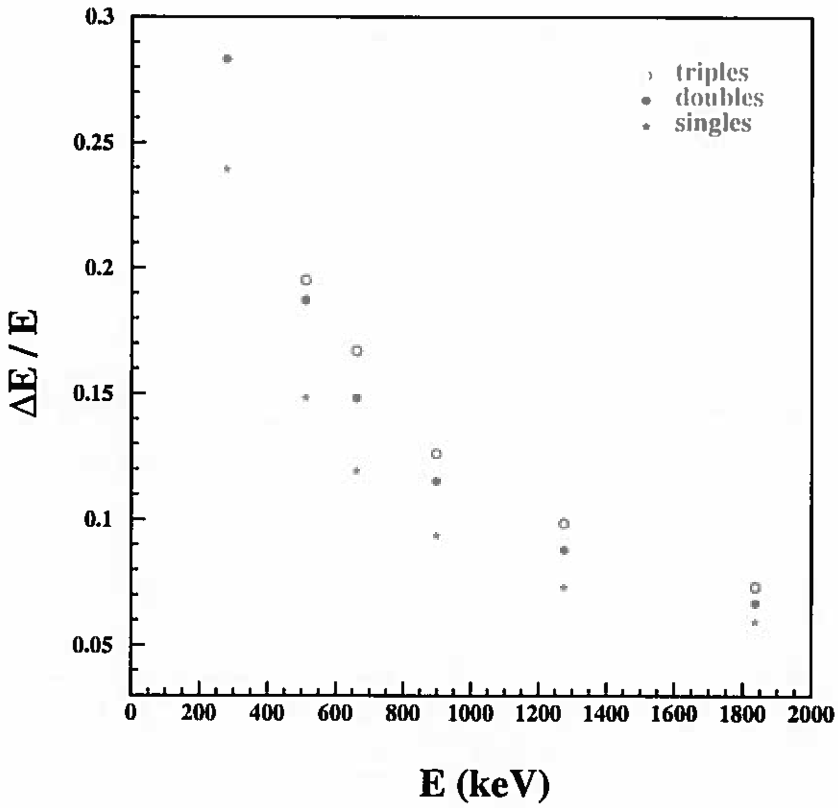


Figure 16: Energy resolution obtained for single (star), double (filled circles) and triple (open circles) events.

4.4 Energy resolutions

Starting from the implementation of equation 2 relevant to experimental single events resolution, the resolutions for double and triple events are obtained from the simulation. Fig. 16 shows the resolutions obtained for single, double and triple events.

Fig. 17 shows the distribution of energy for double and triple events. Resolutions are obtainded by fitting the spectra with a gaussian function.

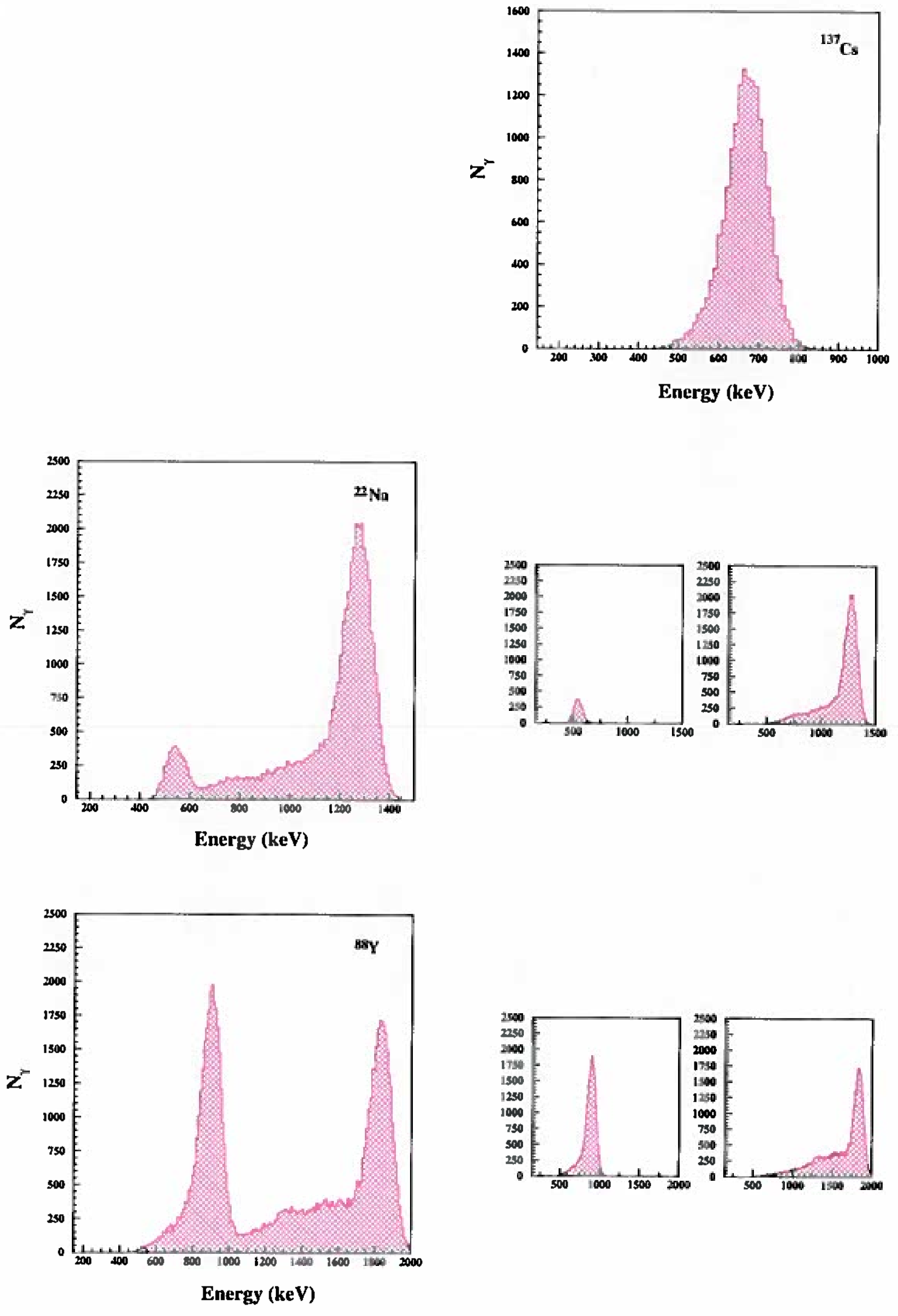


Figure 18: Triple events energy distribution for sources of ^{203}Hg, ^{137}Cs, ^{22}Na and ^{88}Y. The two pairs of smaller spectra are relative to the two different emission lines of radioactive source.

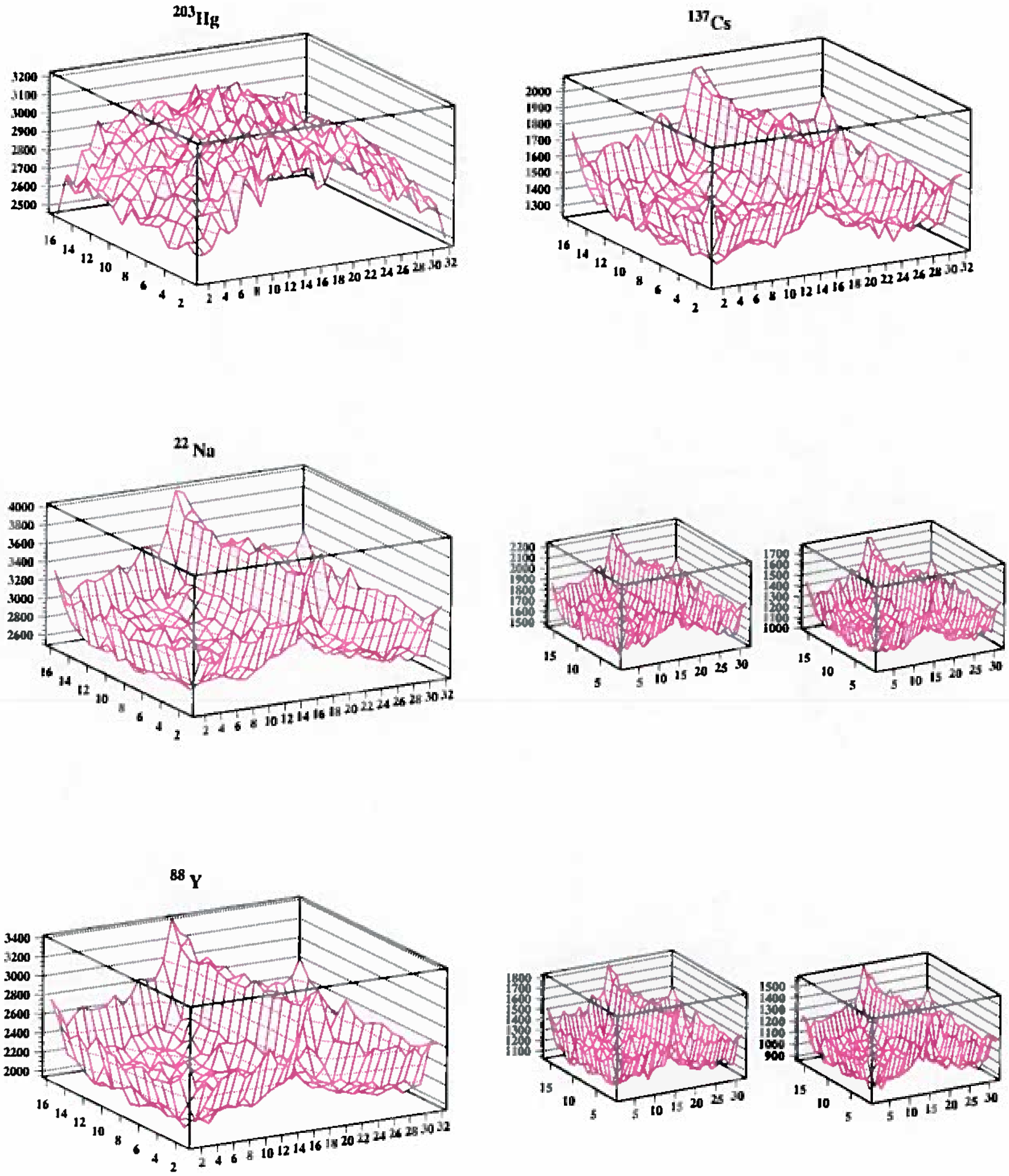


Figure 19: Distribution of detecting singles events from sources of Hg, Cs, Na and Y.

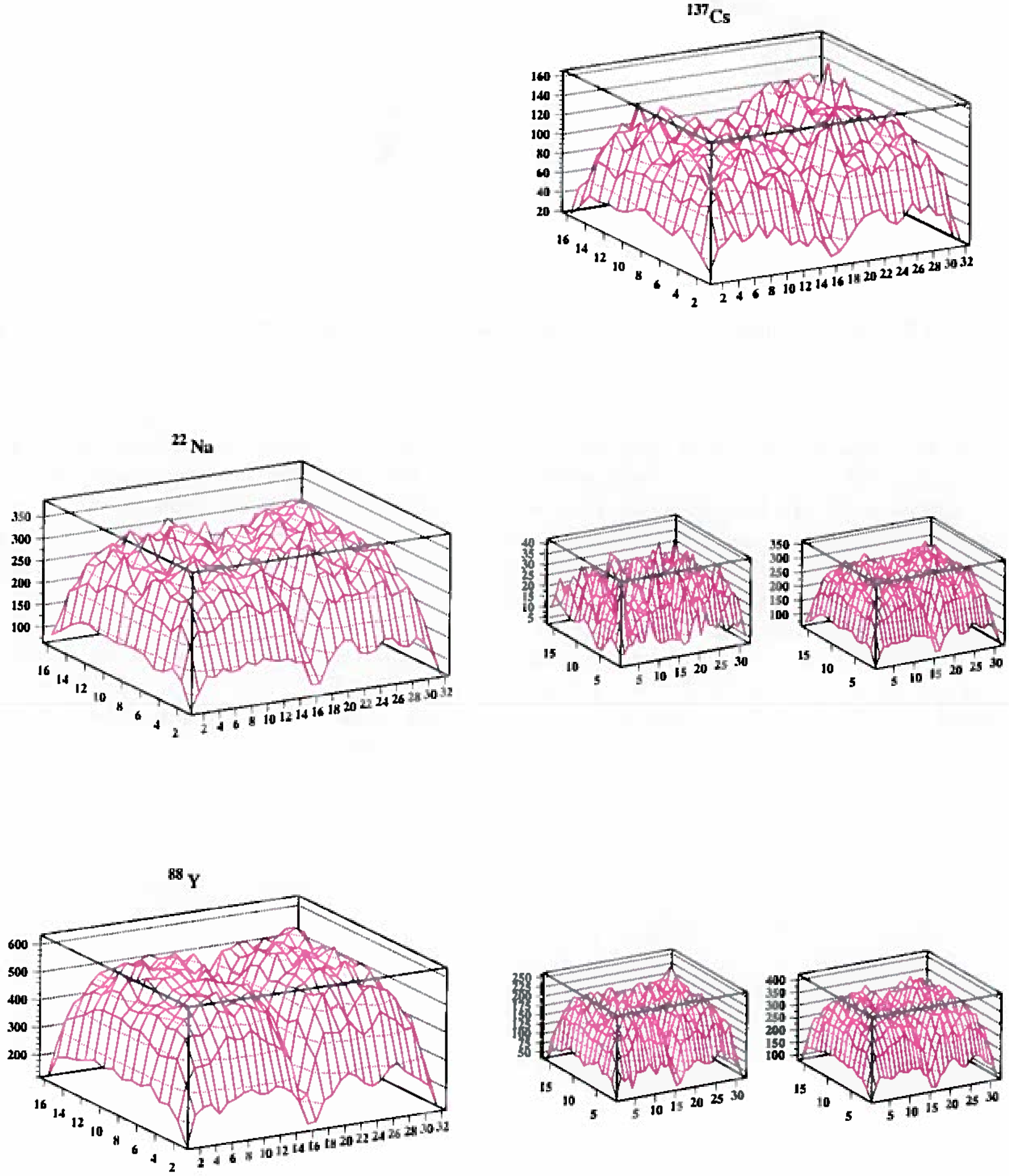


Figure 21: Distribution of detecting triples events from sources of Hg, Cs, Na and Y.

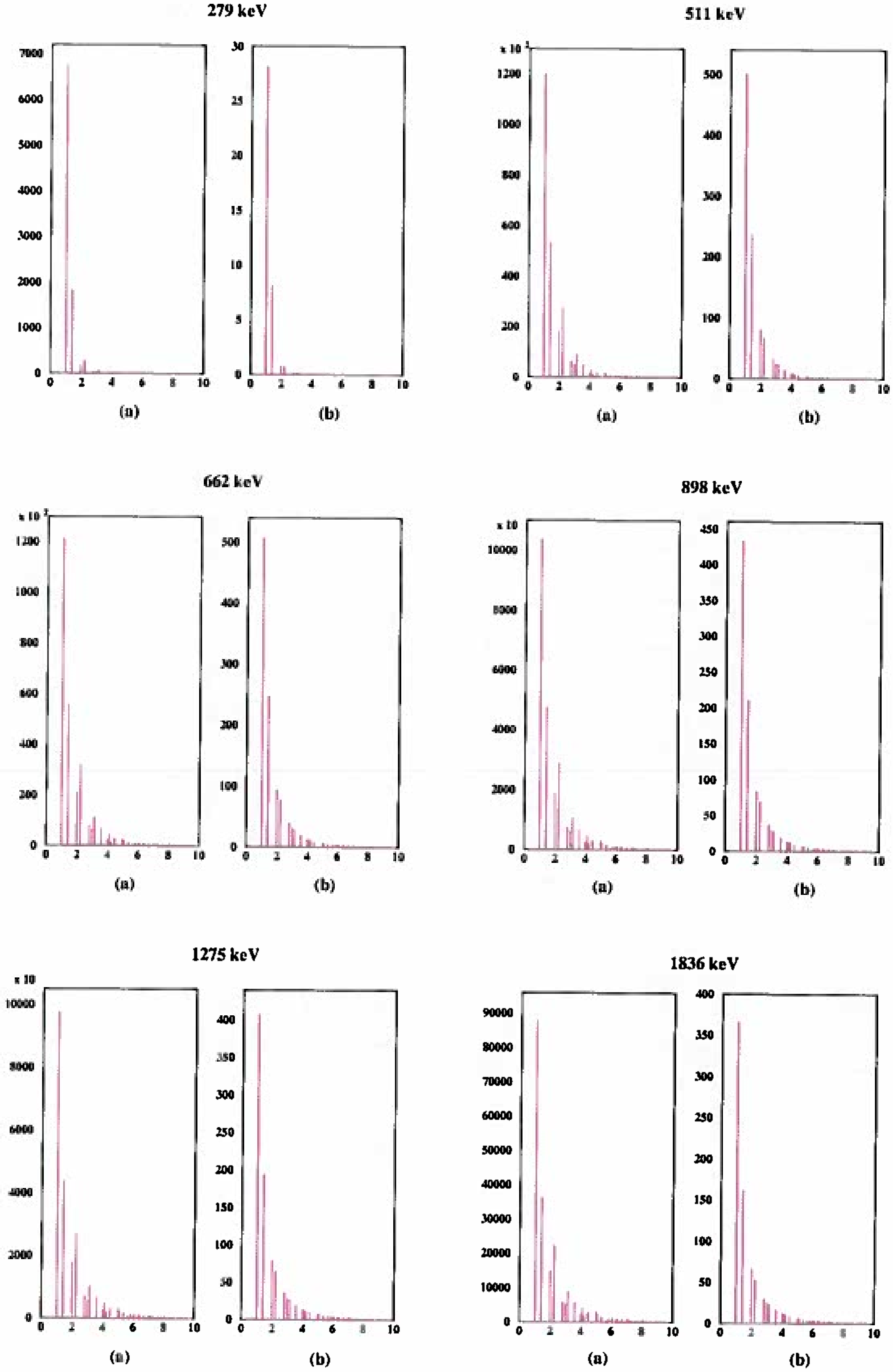


Figure 23: The distributions of the distances between two energy deposits in double events samples before (a) and after (b) the normalization.

4.7 Incidence pixel reconstruction

Multiple events are processed onboard and "transformed" into single events using an incidence pixel reconstruction algorithm. The method envisaged for the onboard incidence pixel reconstruction in the case of multiple events is based on the consecutive energy deposit quantities in the event. For this pourpose the distributions of consecutives energy deposits in the triggered pixels in the case of double and triple events have been investigated.

In Table 5 are represented the fractions of double events in which the minimum and the maximum energy deposit is realised in the incidence pixel, in Table 6 the fractions of triple events in which the minimum, the medium and the maximum energy deposit is realised in the incidence pixel. The same

Incident energy [keV]	Fraction of minimum energy deposit in incidence pixel	Fraction of maximum energy deposit in incidence pixel	Fraction of no energy deposit in incidence pixel
279	0.524	0.314	0.162
511	0.398	0.379	0.223
662	0.294	0.480	0.226
898	0.202	0.570	0.228
1275	0.151	0.615	0.233
1836	0.124	0.641	0.235

Table 5: Fraction of double events in which the minimum and the maximum energy deposit occur in the incidence pixel. The missing fraction is due to events in which no detecting pixel correspond to the incidence pixel.

Incident energy [keV]	Fraction of minimum energy deposit in incidence pixel	Fraction of medium energy deposit in incidence pixel	Fraction of maximum energy deposit in incidence pixel	Fraction of no energy deposit in incidence pixel
279	0	0	0	0
511	0.308	0.270	0.311	0.111
662	0.242	0.243	0.394	0.121
898	0.155	0.200	0.516	0.129
1275	0.095	0.166	0.592	0.147
1836	0.067	0.133	0.636	0.164

Table 6: Fraction of triple events in which the minimum, the medium and the maximum energy deposit occur in the incidence pixel. The missing fraction is due to events in which no detecting pixel correspond to the incidence pixel.

values are shown in Fig. 25 as a function of the incident energy.

The missing fraction correspond to events for which no energy deposit pixel is the incidence pixel. Analyses performed to investigate the origin and the topology of this events, show that this fraction is due mainly to the backscattering photons coming from the surrounding material, to the passive

4.8 PICsIT QM images

The imaging capability of PICsIT detection plane has been checked for the QM applying a mask which consist of a 3 mm thick sheet of Pb with hole pattern in the shape of the word "PICsIT" onto the detector during the acquisition of a ^{203}Hg beam. Figures 26 and 27 show respectively the distribution of single pixel spectra and the detected pixel count map, obtained from the simulation selecting single events.

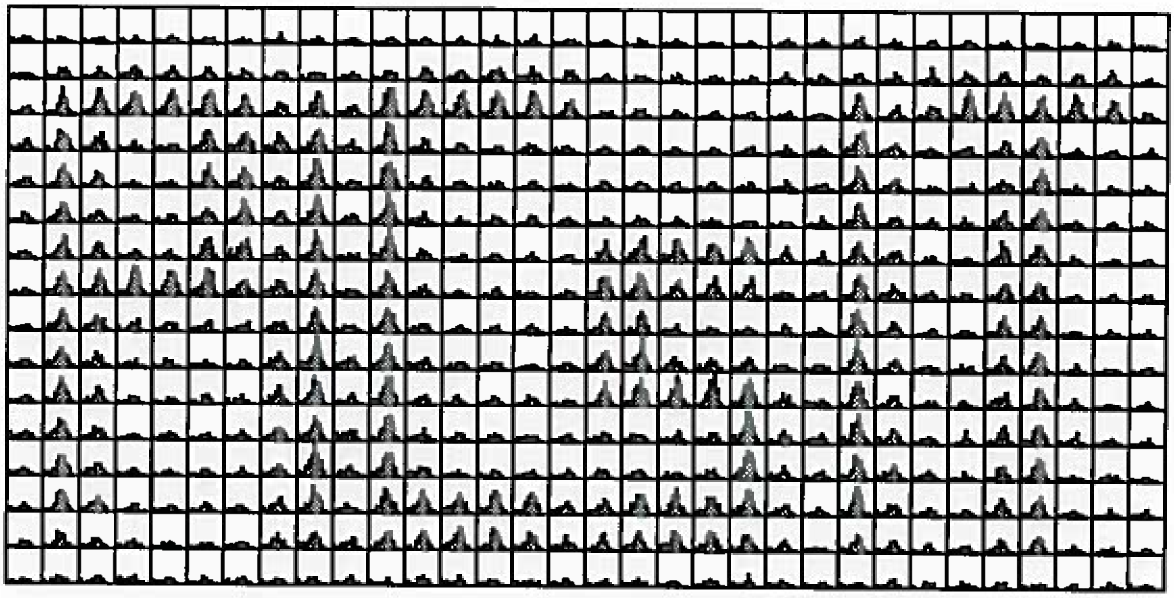


Figure 26: The distribution of the 16 × 32 pixel spectra computed for single events.

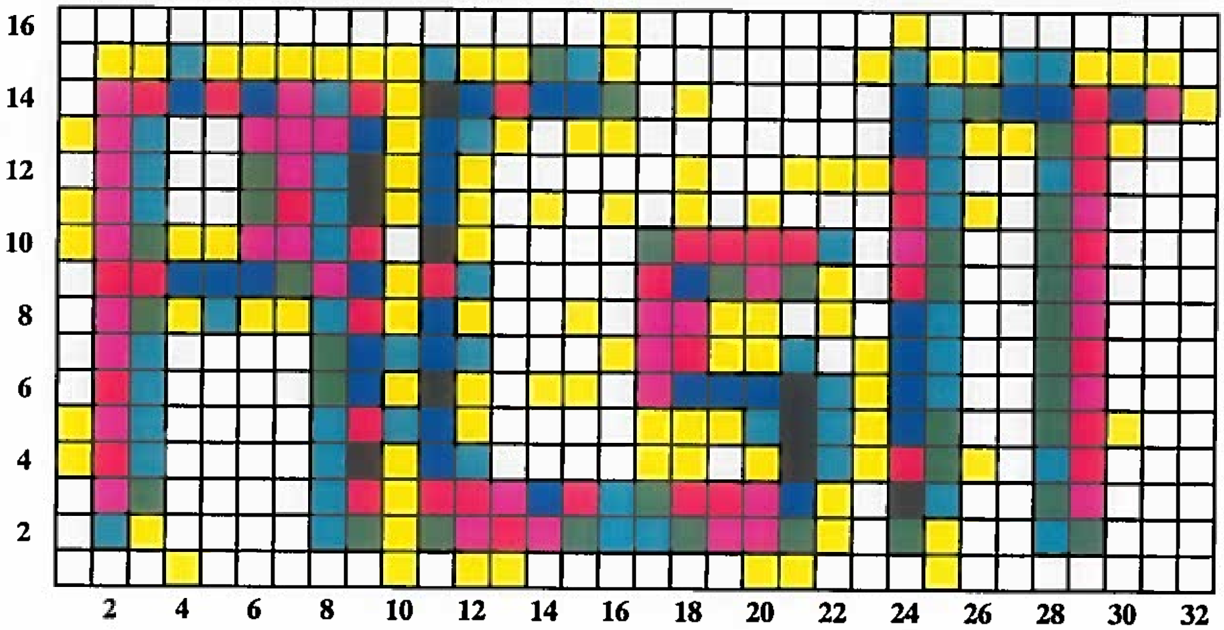


Figure 27: The image obtained with single events count map.