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AN ISPA-CAMERA FOR BETA-RADIOGRAPHY

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Abstract

We have developed a new type of beta-camera based on an Imaging Silicon Pixel Array (ISPA)-tube combined with planar plastic scintillators or with $\text{SiY}_2\text{O}_5(\text{Ce})$ -scintillating powder. The ISPA-tube consists of a photocathode viewed at 3 cm distance by a silicon anode divided into 1024 rectangular ($75\text{ }\mu\text{m} \times 500\text{ }\mu\text{m}$) detector pixels, each bump-bonded to its equally-sized electronic pixel. Depending on the beta-detector thickness we achieved spatial resolutions (FWHM) between $105\text{ }\mu\text{m}$ (^{63}Ni source and $30\text{ }\mu\text{m}$ thick plastic scintillator) and $240\text{ }\mu\text{m}$ (^{90}Sr - ^{90}Y source and $120\text{ }\mu\text{m}$ thick plastic scintillator) by covering the detectors with brass templates. With their four $60\text{ }\mu\text{m}$ wide slits oriented parallel to the long pixel edges we simulated small sized beta-strips. The impact of detector thickness is explained by multiple scattering, angular aperture of the template slits and scintillating light distribution at the ISPA-photocathode. Beta detection sensitivities were measured with calibrated ^3H (tritium)- and ^{14}C -Amersham microscale sources. They amount to 0.1 Bq (^3H) with 150 min counting time and to 0.025 Bq (^{14}C) with 180 min counting time.

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1. INTRODUCTION

Beta radiography is employed in medical, chemical and micro-biological investigations to image human or animal tissues and chemical compounds labelled with beta-emitting radionuclides, mainly ^3H , ^{14}C , ^{32}P and ^{35}S . Until now, mostly autoradiography is applied by exposing photographic film or emulsion to the samples in question. The excellent spatial resolution of finely grained film is, however, counterbalanced by its restricted detection efficiency, its limited dynamic range and corresponding long exposure times (days to weeks).

To obtain prompt and in situ results, beta imagers were conceived, based on different beta-detectors and on fast electronic readout. With multi-wire proportional chambers (MWPC) Yu. V. Zanevsky et al. [1] obtained spatial localizations of chromatographic zones labelled with ^3H , ^{14}C and ^{32}P . With a one-dimensional MWPC a spatial resolution of 3 mm (FWHM) with a ^{14}C source of 10 nCi activity was achieved by C. W. E. Van Eijk et al. [2]. A more sophisticated approach has been realized by G. Charpak et al. [3], who coupled a parallel-plate avalanche chamber to an image intensifier via the light emission of the chamber's gas molecules excited by the electron avalanche process. With a CCD-readout they obtained 0.5 mm (FWHM) spatial resolution. Meanwhile, this method is commercially available^{#1} with further improved resolution.

Results with a radio-imager have also been reported by P. Lanière et al. [4]. They detected beta particles with 10 μm thick layers of $\text{SiY}_2\text{O}_5(\text{Ce})$ -scintillating powder of 3.2 μm granularity. Its light emission was amplified with an image intensifier containing a double micro channel plate (MCP) readout by a CCD-chip. By imaging a 10 μm diameter tungsten wire labelled with ^{35}S they estimated a spatial resolution of 17 μm (FWHM). This resolution was evaluated by calculating the centroids of event signatures distributed over several CCD-pixels, each of them with 23 μm x 23 μm edges.

A beta-camera with low noise level (1 Bq sensitivity with ^{14}C) has been published by K. Ljunggren and S. E. Strand [5]. Their position-sensitive light detector consists of a 0.3 mm thick NE102A rectangular plastic scintillator sheet, a photocathode (evaporated on a fibre optic window), three MCP and a resistive anode. The low background is due to event coincidences

^{#1} Biospace Instruments, F-01710 Thoiry, France.

between the camera and a photomultiplier connected via a special light guide [6] to one edge of the rectangular NE102A sheet. The spatial resolution amounts to 0.5 mm (FWHM).

Preliminary studies with silicon strip detectors were reported by B. Sanghera and R. J. Ott [7]. They used one-dimensional strips and achieved two-dimensional pictures by successive rotations of a slit collimator. The average spatial resolution obtained with a strip pitch of 0.25 mm was 1 mm (FWHM). With a cooled (-55°C) CCD of $31 \times 31 \text{ mm}^2$ area and 0.015 mm pixel edge A. Karellas et al. [8] subtended with an optical lens system a 0.1 mm thick $\text{Gd}_2\text{O}_2\text{S(Tb)}$ -scintillator of $9 \times 9 \text{ cm}^2$ size. They showed that their signal-to-noise ratio is sufficient to perform autoradiography.

In addition to these published research results, there exist already a number of commercially available radio-imaging systems. They are based on storage phosphors readout by laser scanners^{#2} and on multi-wire proportional chambers^{#3}. According to their specifications the spatial resolutions range from 0.05 to 0.4 mm (storage phosphors) and from 0.4 to 1 mm (MWPC).

The following article describes a new concept for a beta-camera. It is based on an imaging silicon pixel array (ISPA)-tube^{#4}, already applied for particle tracking with scintillating fibres [9, 10], for position-sensitive photon-counting [11] and for a gamma-camera [12]. We report on spatial resolutions obtained with beta-imaging of ^{63}Ni , ^{14}C , ^{90}Sr - ^{90}Y sources and on counting sensitivities achieved with Amersham microscopes of ^3H and ^{14}C .

2. EXPERIMENTAL ARRANGEMENT

Several types of planar beta detectors were applied : discs of NE102A^{#5} or BC400^{#6} polystyrene scintillators doped with an additional wavelength shifter (2-components). Their thicknesses varied between 30 μm and 120 μm . Also a 40 μm thick PMP420 [13] doped (1-component) planar disc was applied to compare its spatial resolution with the 2-component system (NE- and Bicron-discs). Some beta-detectors were aluminized at their particle entrance

^{#2} Fuji, Molecular Dynamics, Biorad

^{#3} Ambis, Aloka, Bioscan, EG&G-Berthold, Packard

^{#4} The first prototype was assembled at DEP, NL-9300 AB Roden, The Netherlands

^{#5} NE Technology Ltd, Edinburgh, Scotland

^{#6} Bicron, Newbury, Ohio, USA

faces forming a reflecting mirror in order to increase the light fraction reaching the photocathode. In addition, 2.6 mg/cm² thick SiY₂O₅-scintillating powder was used for comparison with the polystyrene discs.

All beta detectors were covered (fig. 1) with brass templates of 1.5 mm (⁹⁰Sr - ⁹⁰Y) and 0.15 mm (¹⁴C, ⁶³Ni) thickness. Their slit pattern is drawn at the insert in fig. 1 and serves to determine the spatial resolution of the beta camera. All slits are 60 µm wide.

The scintillating light of all beta detectors was read-out with an ISPA-tube. As shown in fig. 1, it consists of a multialkali (S20)-photocathode, evaporated on the optic fibre entrance window of a vacuum-sealed tube. The photocathode is confronted at 30 mm distance by a 8 mm x 4.8 mm silicon chip^{#7} containing 1024 pixels of 75 µm x 500 µm edges. Each pixel is bonded via Pb-Sn solder bumps to its proper front-end electronics, including preamplifier, comparator with adjustable threshold, delay line, coincidence logic and memory element. The 64 columns of 16 pixels each are binary readout at 5 to 10 MHz in a line-parallel mode, resulting in readout times of 6 to 12 µs. Nearly all electronic connections are thus inside the ISPA-tube and only a few wires (2% of the total number of channels) for setting the detector bias voltage, the comparator thresholds, their delay and the strobe length as well as their readout lines are leading through the tube's envelope for outside access. The pixel delay lines allow external or internal triggering of the ISPA-tube and the gating is provided by the strobed output. For the beta camera we installed an internal triggering mode : each absorbed photoelectron provides a signal on the back-electrode of the pixel chip via the bias voltage line. These signals were amplified and transmitted to a low- and to a high-level discriminator. Their window activates within 400ns the strobed output of the ISPA-tube and triggers its data acquisition. All signals falling outside this window are discarded [12].

^{#7} In front of the chip a diaphragm limits its active surface to 7 mm x 4 mm. This first ISPA-prototype contains a small silicon chip. Its area will be enlarged in future four times within the same tube

3. MEASUREMENTS AND RESULTS

3.1 Spatial resolution

The β -sources used are listed in table 1 together with the two often employed β -nuclides ^{35}S and ^{32}P of relatively short half-lives but of β -spectra similar to those of ^{14}C and ^{90}Sr - ^{90}Y , respectively. It shows their maximum and their average [14] kinetic β -energies together with their respective β -ranges. The spatial resolutions of the ^{63}Ni , ^{14}C and ^{90}Sr - ^{90}Y β -emissions were determined with the four 60 μm wide slits of the templates (insert of fig. 1) which covered the planar detector discs. These slits were oriented more or less parallel to the 500 μm edges of the rectangular ISPA-anode pixels.

An example of the raw accumulated data is displayed in figs. 2a and 3a which show the four hit pixel lines of the ISPA-tube frame corresponding to the four template slits. The respective spatial resolutions (FWHM) are indicated on the histogrammes of figs. 2b and 3b which show the intensity profiles of figs. 2a and 3a. The FWHM-values can be attributed to the contributions of the slit widths (60 μm), the pixel widths (75 μm) and the share X of the planar detector disc :

$$\text{FWHM}(\mu\text{m}) \approx (X^2 + 75^2 + 60^2)^{1/2} \quad (1)$$

The error ΔX on X amounts to :

$$\Delta X(\mu\text{m}) = \frac{\text{FWHM}}{X} \Delta(\text{FWHM}) \quad (2)$$

The contributions X and their errors ΔX are listed in table 2 together with the measured total FWHM-values of the different detectors discs applied. Their relative errors range between 12% and 65%, decreasing with increasing detector contributions.

3.2 Photoelectron sensitivities

The number of photoelectrons produced by the energy losses of β -particles along their paths in the planar detector discs results in different spectral distributions depending on the β -detectors employed. These distributions were measured with a ^{14}C source and a Silena multi-

channel analyser (mod. 7423 VHS)^{#8}. The analyser was connected via an amplifier and the bias voltage line to the ISPA-anode chip, where each absorbed photoelectron provides a signal corresponding to about 7000 electron-hole pairs.

Fig. 4 shows two examples obtained with (curve 1) and without (curve 2) evaporated aluminium mirror at the β -incident surface of the 100 μm thick detector discs. The photoelectron peaks corresponding to the number of absorbed photoelectrons can easily be recognized on top of the β -continuum. The abscissa can therefore be scaled in number of produced photoelectrons, with the first three peaks, which contain also noise and dark counts, cut by the low-level discriminator. The maximum energy loss within the applied 100 μm thick polystyrene amounts to 80 keV which indicates the endpoint energies of the spectral distributions in fig. 4. From these values we estimated the photoelectron sensitivities (number of photoelectrons per keV energy loss) listed in table 3 for the ^{14}C isotope and different β -detectors. It is again worth noting that these spectra are obtained with the same ISPA-camera during an acquisition and they are the base of the energy-window self-triggering system.

3.3 Beta detection sensitivities

The detection sensitivities for ^3H (tritium)- and ^{14}C -sources have been evaluated with activity-calibrated autoradiographic microscales^{#9}. These are methacrylate polymers of $21 \times 3.5 \text{ mm}^2$ area and 50 μm (^3H) or 120 μm (^{14}C) thickness. Each microscale contains eight ^3H - or ^{14}C -labelled polymer strips, produced from the relevant monomers containing the isotopes in question. These radioactive strips are sandwiched between inactive polymer strips. Each β -active polymer strip is about 1.1 mm wide and separated by a 1.4 mm wide inactive strip from the next one. Therefore, two or three active strips of 3.5 mm length each fit to the ISPA-anode frame of $7 \times 4 \text{ mm}^2$ area.

Fig. 5 shows the histogram of three ^3H -active microscale layers (activity levels 1, 2 and 3 according to the Amersham notation). Their tritium contents are graduated in activities of 1 : 0.62 : 0.36. According to the small range of tritium betas, electrostatic charging of the

^{#8} SILENA, Cernusco, Italy

^{#9} Amersham International, Little Chalfont, England

plastic strips and the restricted solid angle for their detection probability, only an extremely small fraction of them finally reaches the detector disc.

Fig. 6 shows a similar histogram of two ^{14}C -active microscale layers (activity levels 4 and 5). Their activity ratio amounts to 1 : 0.63. Again, a small fraction only of the emitted betas reaches the detector surface.

4. DISCUSSION

4.1 Spatial resolution

The spatial resolution is composed of the template slit widths ($60\text{ }\mu\text{m}$), the dimension of the small pixel edges ($75\text{ }\mu\text{m}$) and the contribution X of the planar beta detectors (table 2). The contribution X is mainly due to the intensity distribution of the scintillating light emitted along the β -paths in the detectors. Only light photons hitting the ISPA-photocathode close to normal incidence provide enough energy density to release a meaningful quantity of photoelectrons. This provides a spatial detector resolution without any further optical segmentation of its detection area.

The (FWHM)-values evaluated from slit a (insert of fig. 1) of the brass templates and their detector contributions are compared with theoretical estimations for raw accumulated images and analysed images in fig. 7 (^{63}Ni -source), fig. 8 (^{14}C -source) and fig. 9 (^{90}Sr - ^{90}Y -source). The difference between accumulated images and analysed ones is the following: the accumulated images are the sum of all the events without performing any operation on the raw pixels data (figs. 2 and 3). The analysed pictures instead consist in the accumulation of the centre-of-gravity points, calculated for each beta-event.

For the theoretical estimations we suppose that the contributions to the resolutions X of the β -detectors (relation 1) are multiple scattering (ms), angular aperture of the template slits (ap) and the scintillating light distribution from the β -detector on the photocathode (sl) :

$$X^2 = X_{\text{ms}}^2 + X_{\text{ap}}^2 + X_{\text{sl}}^2 \quad (3)$$

For the multiple scattering contribution we obtain :

$$X_{\text{ms}} \approx \frac{6.1}{\langle E \rangle} t^{3/2} \quad (4a)$$

if the β -range R of $\langle E \rangle$ exceeds the detector thickness t , where $\langle E \rangle$ denotes the expectation value of the average β -energy for the β -spectrum of the source in question.

If the betas are stopped within the detector, the multiple scattering contribution becomes :

$$X_{ms} \approx \frac{R}{\sqrt{2}} \quad (4b)$$

The angular apertures of the template slits contribute for both range cases in the following way :

$$X_{ap} \approx 0.4t \quad (R > t) \quad \text{or} \quad X_{ap} \approx 0.4R \quad (R \leq t) \quad (5)$$

Finally, the scintillating light distributions on the photocathode contribute, again for the two range cases^{#10} :

$$X_{sl} \approx \sqrt{3}t \quad (R > t) \quad \text{or} \quad X_{sl} \approx 2t \quad (R \leq t) \quad (6)$$

These theoretical estimations are indicated for the (FWHM)-values (relation (1)) as full (accumulated data) and dashed (analysed data) curves in figs. 7 to 9.

For ^{63}Ni -irradiations (17 keV average energy) we suppose that the vast majority of betas (6 μm average range) are stopped in all detectors. For the ^{90}Sr - ^{90}Y -spectra nearly no betas are stopped in any of the employed detectors. ^{14}C involves both cases and the theoretical curves of fig. 8 are therefore calculated for 100 μm and 120 μm detector thickness t (assuming stopping betas) and for all smaller thicknesses t (assuming $R > t$).

The difference between the solid (accumulated data) and dashed (analysed data) curves is only in the term X_{sl} . To obtain a rough estimation of the analysed data, the accumulated data should be scaled by $1/\sqrt{(N-1)}$, where N is the average number of pixels firing per event. This number depends on the average light cluster size on the photocathode ($\sim X_{sl}$) and on the average number of photoelectrons, which in turn depends on the average energy lost by the betas in the detectors. Table 3 shows photoelectron sensitivities of betas emitted by ^{14}C for the different

^{#10} These distributions were calculated first by assuming either uniform energy distribution along the particle path inside the scintillator (particle not stopped), or by assuming all energy being released at the point equivalent to the range in the plastic.

detectors employed. These sensitivities were calculated from measured photoelectron spectra as shown in fig. 4 for the example of two 100 μm thick plastic scintillators. For the 100 μm thick aluminized detector they amount to 0.31 photoelectrons per keV. Therefore the average number of photoelectrons becomes : $\sim 0.31 \frac{\text{phel}}{\text{keV}} \times 45 \text{ keV}^{\#11} = 14$ photoelectrons, when this detector is irradiated with the ^{14}C source. With about 150 μm cluster diameter, only two or three pixels fire per β -event. Taking the 14 photoelectrons of the mentioned example, this means between 7 and 5 photoelectrons per pixel. But since the pixel readout is binary [9], this high number of photoelectrons per pixel is not quantified and therefore does not improve the spatial resolution. On the contrary an analog readout indicating the number of photoelectrons per pixel would narrow the centre-of-gravity error considerably. Already a two bits range per pixel would improve the spatial resolution.

The total spatial resolutions achieved with our ISPA-camera (columns 4 to 6 in table 2) are certainly better than those reported in ref. [2, 3, 5, 7]. They cannot directly be compared with the results of Lanière et al [4], since they imaged a 10 μm diameter wire. With the same detector (SiY_2O_5 -powder) we could not achieve their resolution (17 μm with ^{35}S -source), even if we consider the detector contribution only (71 μm with ^{14}C -source).

Finally, analysed pictures show better resolutions compared to accumulated ones (see figs. 7 to 9), especially when the event cluster size (roughly equal to the detector thickness) is bigger than the pixel size (75 μm), and show signal-to-noise ratios improved of a factor 2 to 10.

^{90}Sr - ^{90}Y is a special case (fig 9): the average range of the electrons is much bigger than the detector thicknesses (see table 1); consequently the average kinetic energy left in the plastic detector amounts to $\sim 0.2 \text{ keV}/\mu\text{m}$ (all electrons are minimum ionizing) multiplied by the detector thickness, resulting in only 1.2 photoelectrons detected for the 30 μm detector (for ^{14}C this number is $\sim 5^{\#11}$). On the contrary, these same electrons produce large noise signals on the detector due to multiple scattering in the template, backscattering on the photocathode window, etc. This explains the poorer resolutions obtained with thin detectors and the fact that

^{#11} 45 keV means the average energy loss of ^{14}C -betas in 100 μm thick polystyrene. This average energy loss drops to $\sim 25 \text{ keV}$ for 30 μm thick polystyrene.

analysing the data does not improve them (see table 2 and fig. 9); except for the thin SiY_2O_5 -powder foil, where its higher sensitivity and energy loss factor provide excellent results.

4.2 Photoelectron sensitivities

The photoelectron sensitivities listed in table 3 show clearly higher values of photoelectrons per energy loss for the SiY_2O_5 -powder and for those polystyrene discs which were evaporated on their β -entrance surface with aluminium mirrors. In the first case this is due to the higher light yield and in the second case more of the produced light reaches the photocathode according to the scintillations reflected from the surface of particle incidence. However, sometime the advantage of a mirrored reflection is counter-balanced by the worsening of the spatial resolution (table 2) since the reflections cause a broadening of the light distribution.

4.3 Beta detection sensitivities

The detection sensitivities for the tritium (^3H) had to be evaluated by carefully arranging the ^3H -microscale strips on the detector surface. Even small air gaps between ^3H -source and detector must be avoided since the β -range in air of its average kinetic energy (5.72 keV) amounts to 0.7 mm only. Similar considerations hold for the ^3H -betas escaping from their 50 μm thick microscale confinement. To roughly estimate the effective activity on the plastic detector, we proceed as following: The range of 5.72 keV betas amounts to 1 μm polymer layer of the ^3H -microscale. This must be further reduced by the ratio of the subtended emission cone (45°) to the total solid angle, which amounts to about 14%. Therefore the total activity of each microscale layer in fig. 5 (1195 Bq, 741 Bq, 431 Bq) must be reduced to about 0.25%. Taking the lowest microscale activity (1 Bq in fig. 5) reaching our plastic detector, we can certainly detect about 0.1 Bq within 150 min counting time.

Evaluating the counting activities for ^{14}C -betas was not as difficult. Its average kinetic β -energy is 49.5 keV (table 1) with a range of 40 μm within the ^{14}C -microscale polymer which is 120 μm thick. Taking the same subtended emission cone (45°) as for ^3H we estimated that 4% of the ^{14}C -activity (level 4 : 9 Bq, level 5 : 5.9 Bq) reaches our plastic detector. Taking the numbers in fig. 6, we can certainly detect 0.25 Bq of ^{14}C within 180 min counting time.

This β -detection sensitivity can be compared with the reported 1 Bq for ^{14}C by Ljunggren and Strand [5]. These authors assume that only 3% of the micro-scale β -activity reach their detector.

Conclusions

We developed a new type of beta-camera, based on planar plastic scintillators or $\text{SiY}_2\text{O}_5(\text{Ce})$ -scintillating powder coupled to an ISPA-tube. We have demonstrated resolutions (FWHM) between 100 and 240 μm , varying according to the thickness of the scintillator and the source type. The measured data fit well to a simple analytical estimation. The contrast is always better than 0.8, being after analysis close to one, even for activities lower than 1 Bq. With this beta-camera we have performed measurements of "in situ hybridization" with ^{35}S as a marker^{#12}, the results of which will be discussed in a forthcoming paper.

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^{#12} In collaboration with M. Dubois-Dauphin, Centre Medical Universitaire, Geneve, Switzerland

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Table 1 : β -emitters with their end-point and average [14] kinetic energies and their corresponding ranges in polystyrene (PS) and copper (Cu).

* The often employed but short lived nuclides ^{35}S and ^{32}P are replaced in this paper by ^{14}C and ^{90}Sr - ^{90}Y , respectively.

** Daughter from ^{90}Sr .

Nuclide	half life	E _{max} keV	Range		E _{average} keV	Range	
			in PS mm	in Cu mm		in PS mm	in Cu mm
^3H	12.3 y	18	0.0075	-	5.72	0.0009	-
^{63}Ni	~100 y	65	0.07	0.012	17.2	0.006	-
^{14}C	3568 y	156	0.30	0.05	49.5	0.04	0.007
$^{35}\text{S}^*$	87 d	168	0.35	0.06	48.8	0.04	0.007
^{90}Sr	28 y	545	2.0	0.33	196	0.4	0.075
$^{90}\text{Y}^{**}$	64.5 h	2225	11.0	1.7	934	4.0	0.62
$^{32}\text{P}^*$	14 d	1710	8.0	1.3	695	2.8	0.45

Table 2 : Spatial resolutions of planar detector samples employed for the measurements. They were covered with brass templates (see insert of fig. 1) of 150 μm (^{63}Ni , ^{14}C) and 1.5 mm thickness and with 60 μm slit widths. The detector contributions were calculated with relation (1). The upper line of each row shows the direct results from accumulated data, the lower one after analysis. The errors for the scintillator contributions are calculated from relation (2), assuming $\pm 10\%$ error for the measured FWHM-values and are all comprised between 20 and 30 μm .

* Irradiated detector surface evaporated with an 80 nm thick aluminium mirror.

Sample	Thickness		Total FWHM (μm)			Detector FWHM, X (μm)		
	μm	mg/cm^2	^{63}Ni	^{14}C	^{90}Sr - ^{90}Y	^{63}Ni	^{14}C	^{90}Sr - ^{90}Y
SiY_2O_5	10	2.6	124	142	151	78	105	117
			116	120	151	64	71	117
BC-400	30	3.1	105	112	191	41	57	165
			116	138	285	65	98	268
BC-400*	30	3.1	107	129	250	47	85	231
			120	138	267	72	98	249
PS+PMP*	40	4.12	138	151	165	98	116	133
			124	129	200	78	85	175
BC-400	50	5.15	142	147	156	105	111	122
			133	133	169	92	92	139
BC-400*	50	5.15	183	165	191	155	134	165
			138	124	200	98	78	175
BC-400	100	10.3	-	240	230	-	220	209
			-	187	210	-	160	187
BC-400*	100	10.3	-	240	230	-	220	209
			-	142	175	-	105	146
NE-102A*	120	12.4	222	249	240	200	230	220
			160	178	175	128	150	148

Table 3 : Estimated photoelectron sensitivities (number of photoelectrons per keV energy loss) measured with the ^{14}C -source and the multi channel analyser connected via the bias voltage line to the back-electrode of the ISPA-chip. An example of the sensitivity evaluation is shown in fig. 4.

* Irradiated detector surface evaporated with an 80 nm thick aluminium mirror.

Sample	Thickness (mg/cm ²)	Sensitivity (pe/keV)
SiY ₂ O ₅	2.6	0.69
BC-400	3.1	0.21
BC-400*	3.1	0.26
PS+PMP*	4.1	0.31
BC-400	5.15	0.18
BC-400*	5.15	0.38
BC-400	10.3	0.18
BC-400*	10.3	0.31

Figure Captions

Fig. 1 Arrangement of the beta-camera. The insert shows the magnified brass template with its four 60 μm wide slits.

Fig. 2 a) Picture taken with the beta camera (equipped with a 30 μm thick BC-400-detector) and a ^{63}Ni -source. The four template slits a, b, c and d (insert of fig. 1) are clearly separated. They are not exactly parallel to the pixel rows of the ISPA-anode.

b) Intensity distribution of the projected picture showing its 15:1 signal-to-noise ratio and its (FWHM)-values.

Fig. 3 a) Picture taken with the beta camera (equipped with 10 μm thick SiY_2O_5 -powder) and a ^{63}Ni -source.

b) Intensity distribution of the projected picture showing its 30:1 signal-to-noise ratio and its (FWHM)-values.

Fig. 4 Photoelectron spectra produced by the energy loss of ^{14}C β -particles in a 100 μm thick planar BC-400-detector with (curve 1) and without (curve 2) evaporated aluminium mirror. The maximum energy loss within the 100 μm range corresponds to the photoelectron numbers indicated by the two arrows. Both curves are normalized at 4 photoelectrons.

Fig. 5 Intensity distribution from three ^3H -Amersham microscales (total activity levels : 1195 Bq, 741 Bq and 431 Bq) resulting from 150 min irradiation of the NE-102A planar disc. The activities effectively reaching the detector surface are indicated, whereas most of the activity is absorbed inside the microscales.

Fig. 6 Intensity distribution from two ^{14}C -Amersham microscales (total activity levels : 9 Bq and 5.9 Bq) resulting from 180 min irradiation of the NE-102A planar disc with evaporated aluminium mirror. The activities effectively reaching the detector surface are indicated, whereas most of the activity is absorbed inside the microscales.

Fig. 7 Comparison of total resolution (FWHM) experimental results (points) with theoretical estimations (curves) according to relations (1) and (3) for ^{63}Ni -source versus the detector thickness in mg/cm^2 .

Fig. 8 Comparison of total resolution (FWHM) experimental results (points) with theoretical estimations (curves) according to relations (1) and (3) for ^{14}C -source versus the detector thickness in mg/cm^2 .

Fig. 9 Comparison of total resolution (FWHM) experimental results (points) with theoretical estimations (curves) according to relations (1) and (3) for ^{90}Sr - ^{90}Y -source versus the detector thickness in mg/cm^2 .

The ionization loss of the ^{90}Sr - ^{90}Y -betas produces only small numbers of photoelectrons and therefore the spatial resolutions of thin ($<50\ \mu\text{m}$) plastic detectors are worse. However, this is not the case for the $\text{SiY}_2\text{O}_5(\text{Ce})$ -powder because of its higher light output.

Fig. 1

Fig. 2a

from accumulated data

Fig. 2b

Fig. 3a

from accumulated data

Fig. 3b

Number of photoelectrons

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9