G. Pausch, W. Bohne, D. Hilscher,

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Particle Identification in a Wide Dynamic Range Based on Pulse-Shape Analysis with Solid-State Detectors

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G. Pausch[a], W. Bohne[b], D. Hilscher[b], H.-G. Ortlepp[c], and D. Polster[b]

[a] *Freie Universität Berlin, Fachbereich Physik, Arnimallee 14, D–14195 Berlin
(present address: Forschungszentrum Rossendorf e.V., Institut für Kern-
und Hadronenphysik, Postfach 51 01 19, D–01314 Dresden)*

[b] *Hahn-Meitner-Institut Berlin GmbH, Glienicker Str. 100, D–14109 Berlin*

[c] *Forschungszentrum Rossendorf e.V., Institut für Kern- und Hadronenphysik,
Postfach 51 01 19, D–01314 Dresden*

Heavy ions detected in a planar silicon detector were identified by exploiting a recently proposed combination of the pulse-shape and the time-of-flight techniques. We were able to resolve charge numbers up to $Z=16$ within a wide dynamic range of $\approx$ 1:5, and to identify even isotopes for the elements up to Magnesium. The simple scheme of signal processing is based on conventional electronics and cheap enough to be exploited in large multidetector arrays.

The analysis of pulse shapes has proved to be a promising method to identify heavy ions in solid-state detectors without exploiting $\Delta E - E$ telescopes (see e.g. [1,2,3] and refs. therein). This technique is of special interest for 4π charged-particle detectors which shall be operated inside large gamma-ray detector arrays or 4π neutron counters. Shells or spheres consisting of single silicon detectors on thin backings, e.g. the Berlin Silicon Ball [4], are distinguished by a very compact design, low mass (which is favourable to reduce the scattering of neutrons or gamma rays), a large effective solid angle, simple operation, and relatively low costs – which can hardly be achieved with detector arrays based on $\Delta E - E$ particle identification. However, a disadvantage of the simple and cheap pulse-shape discrimination schemes proposed in reference [3] is the relatively high energy threshold and the small dynamic range for particle identification.

Recent simulations suggested to operate silicon detectors with the low-field side (normally the rear side of the detector!) facing the target, and to exploit a parameter t_Q – the time difference between a time-of-flight start signal and the first moment (centre of gravity) of the current pulse from the detector – as a particle-sensitive parameter, thus combining the time-of-flight (TOF) and the pulse-shape techniques [5]. This method was succesfully tested in an experiment at the VICKSI cyclotron in Berlin. We irradiated a totally depleted silicon detector of 500 μm thickness (Intertechnique IPH 450–500–20 TM with an active area of 450 mm^2, transmission mount) with heavy ions produced in reactions of a 698 MeV ^{32}S beam in a mixed {Au + Ni + C} target. The detector was placed at a distance of 16.5 cm from the target, with the rear contact facing the target. An aperture of 22 mm diameter was used to shield the outer border of the detector from charged reaction products, thus reducing the irradiated area to 380 mm^2.

In contrary to the suggestion of reference [5] we renounced the scanning of the current signal with flash ADC's, but exploited a very simple and cheap method to measure t_Q. The underlying idea is sketched in figure 1: The bipolar output of a spectroscopic amplifier (SPA) reacts on a delta-like current pulse $i(t) = q_0 \cdot \delta(t)$ in the detector (corresponding to a step-like charge signal) with an output pulse $U_0(t)$ crossing the zero level at a fixed time $t = t_0$. In a certain region τ around t_0, the shape of $U_0(t)$ can be approximated by a linear function

$$U_0(t) \approx a\, q_0 \cdot (t - t_0) \qquad (|t - t_0| < \tau)$$

where a denotes a gain factor. If the current flow $i(t)$ in the detector has a finite duration Δt, and if this Δt is smaller than τ – which is approximately given by the shaping time constant of the SPA – the resulting bipolar signal near the zero crossing can be approximated by

$$U(t) = \int_0^{\Delta t} \frac{i(t')}{q_0}\, U_0(t - t')\, dt' \approx a \int_0^{\Delta t} i(t') \cdot (t - t_0 - t')\, dt' =$$

$$= a \cdot (t - t_0) \int_0^{\Delta t} i(t')\, dt' \; - \; a \int_0^{\Delta t} i(t')\, t'\, dt'.$$

The zero level, $U(t) = 0$, is then reached at $t = t_0 + t_q$ with

$$t_q = \frac{\int_0^{\Delta t} i(t')\, t'\, dt'}{\int_0^{\Delta t} i(t')\, dt'} \;.$$

For a detector current of a finite duration, the zero crossing of the bipolar signal $U(t)$ is therefore shifted relative to t_0 by the time t_q which is just given by the first moment (centre of gravity) of the current signal $i(t)$. Consequently, the particle-sensitive parameter $t_Q = t_q + $TOF can be obtained by taking the time difference between this zero crossing and the RF signal of the cyclotron which gives the TOF-start reference.

The used block scheme of signal processing is based on conventional electronics (figure 2). We derived the energy information as usual by means of a charge-sensitive preamplifier (IV69C, Hahn-Meitner-Institut Berlin) combined with a spectroscopic amplifier SPA 1 (shaping time $\tau_1 = 1\mu$s). A second spectroscopic amplifier SPA 2

with a shaping time of $\tau_2 = 0.25\mu s$ generated the bipolar signal which was fed into a zero-cross trigger (ZCT) developed in the electronics department of the Hahn-Meitner-Institut. The ZCT consists of a level discriminator (LD) with an adjustable threshold, and a zero-cross detector (ZD) which is activated by the LD. To measure t_Q, the ZD and cyclotron RF signals were used to start and to stop a time-to-amplitude converter (TAC), respectively, whereas the LD output activated the data-acquisition system based on CAMAC ADC's. No "fast" timing signal must be derived from the detector. The disadvantage of injecting ions into the low-field region (rear contact) of the detector – huge rise-time differences of the current signals which cause considerable problems e.g. for a constant-fraction timing [5] – is therefore insignificant.

The results of our measurement are illustrated in the figures 3–4. A two-dimensional plot of the count rate versus t_Q and the energy deposition E in the detector (figure 3) shows clearly separated element branches. The charge numbers of the detected ions up to $Z = 16$ can be identified within a dynamic range of $\approx$ 1:5 (e.g. 3...14 AMeV for carbon, 5...23 AMeV for silicon ions) where the upper energy limit of the Z identification is given by the maximum energy deposition in a silicon detector of 500 μm thickness. For energies near the punch-through point we were even able to resolve isotope lines up to magnesium.

To obtain a sufficient range for the t_Q measurement, the accelerator was operated with a pulse suppression rate of 1:8. Due to the not perfect bunch suppression, the helium branch and the region of (quasi-)elastically scattered projectiles and projectile fragments occur in figure 3 once again – with a count rate reduced by the bunch-suppression factor and shifted by $\Delta t_Q = 58.53$ ns corresponding to the RF frequency of the cyclotron. For absolute calibration of the time scale we fixed the t_Q of ^{12}C ions at the punch-through point to the value which was calculated with the simulation code described in reference [5]. For the simulation we used the actual bias voltage, $U_D = 145$ V, and a depletion voltage (i.e. the bias voltage necessary just for total depletion of the detector) of 140 V which corresponds to the experimental value.

The two-dimensional plot (figure 3) clearly shows a deterioration of the particle resolution with decreasing energy. This effect can be explained by means of our simulation code. We calculated the $t_Q(E)$ correlation for selected ions, assuming two different depletion voltages of $U_{dep} = 135$ V or 140 V. Figure 5 demonstrates that the sensitivity of the calculated t_Q on U_{dep}, i.e. on the resistivity of the detector material, increases strongly with decreasing particle energies. Small local variations of the resistivity are therefore of minor importance for energies near the punch-through point, but may considerably influence the particle resolution at lower energies. To estimate the resolution of the t_Q measurement resulting from electronics and bunch width of the ^{32}S beam, we projected a small region of the $Z = 6$ branch (carbon ions of $\approx$ 160 MeV) onto the t_Q axis and found for the ^{12}C peak a half width of $\approx$ 1 ns. However, the lower threshold for Z identification in our experiment was – at least for the lighter ions – determined by the large bump of slow and heavy particles, fission fragments and heavy residues produced in complete or incomplete fusion reactions. Such particles are stopped in the low-field region of the detector, thus generating current signals of very long duration. With an oscilloscope and a current-sensitive preamplifier we observed pulse lengths up to $\approx$ 600 ns, which is

too long for a correct t_Q measurement using a shaping time of $\tau_2 = 0.25\mu s$ for the bipolar signal. It is therefore evident that the parameters determining the pulse shapes – thickness, resistivity, and bias voltage of the detector – as well as the time constants must be adapted to the mass, charge, and energy range of interest.

In summary, our test experiment showed that the dynamic range for particle identification based on pulse-shape analysis in solid-state detectors can be drastically extended by the technique proposed in [5]. We obtained charge identification up to $Z = 16$ for energies larger than 3–5 AMeV, and even isotope resolution up to magnesium. Up to now, a comparable charge and mass resolution has been achieved only with the $\Delta E - E$ method or sophisticated and expensive detectors, e.g. Bragg ionization chambers. The described scheme of signal processing is well suited and cheap enough to be exploited even in large multidetector arrays. It is evident that the presented technique is a powerful tool to extend the experimental range of applications for 4π silicon-detector shells. Furthermore it is obvious to exploit the pulse-shape discrimination method for particles stopped in thin ΔE counters, thus reducing the lower energy threshold for particle identification in telescopes or arrays with ΔE silicon detectors considerably.

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Figure Captions

Figure 1:
Principle of the t_Q measurement: A delta-like current signal at $t = 0$ results in a zero crossing of the bipolar output signal $U_0(t)$ of a spectroscopic amplifier (SPA) at t_0. A second delta current after Δt shifts the zero crossing of the sum signal, $U(t) = U_0(t) + U_0(t - \Delta t)$, to $t'_0 = t_0 + t_q$ where t_q is the centre of gravity of both current pulses, if Δt is smaller than the linear range of the bipolar signal. Since any current signal can be described as a superposition of delta functions, the same holds for signals of a finite duration (see text). The time difference between the zero crossing and a time-of-flight (TOF) start signal (e.g. cyclotron RF) yields the parameter $t_Q = t_q + \text{TOF}$ which has proved to be well suited for particle identification.

Figure 2:
Block diagram of our measurement: qPA – charge-sensitive preamplifier; SPA – spectroscopic amplifier; ZCT – zero-cross trigger (LD: level discriminator output; ZD: zero-cross detector output); DGG – delay and gate generator; TAC – time-to-amplitude converter; ADC – analog-to-digital converter.

Figure 3:
Two-dimensional plot of the count rate versus energy deposition E and the particle-sensitive parameter t_Q, which represents a combination of time-of-flight and pulse-shape information. The resolved lines are due to ions with different charge numbers Z. The bump of fission fragments (FF) and heavy residues (HR) determines the lower energy threshold for Z identification, the upper limit is given by the maximum energy deposition of the corresponding ion in a silicon detector of 500 μm thickness (see text).
The zoomed detail of the spectrum shows that isotope lines can be resolved in the element branches.

Figure 4:
Isotope separation obtained for selected elements: The element branches shown in figure 3 were linearized within the specified energy range, and projected onto an arbitrary mass scale.

Figure 5:
Sensitivity of the correlation $t_Q(E)$ on the depletion voltage, i.e. the resistivity of the detector material: The $t_Q(E)$ curves for ^{12}C and ^{32}S were calculated with a simulation code [5], assuming two different depletion voltages of $U_{dep} = 135$ V (solid lines) and 140 V (dotted lines). It is evident that small local variations of the resistivity broaden the particle branches and determine the lower energy threshold for charge and mass identification (see text).
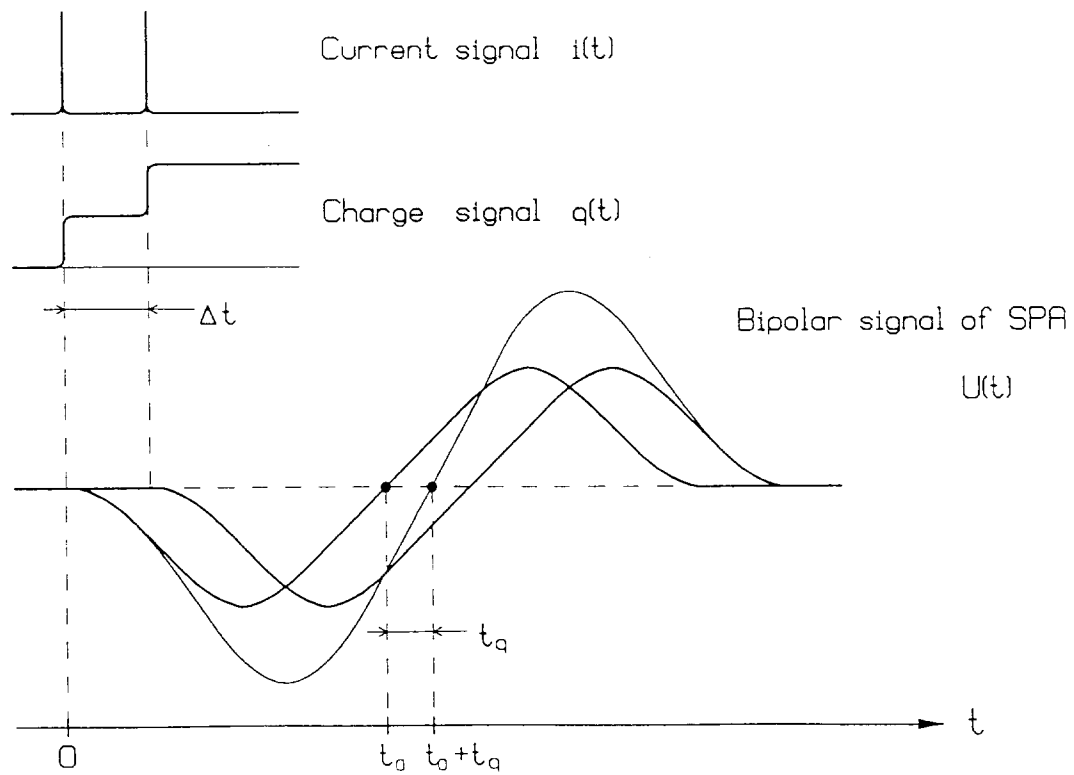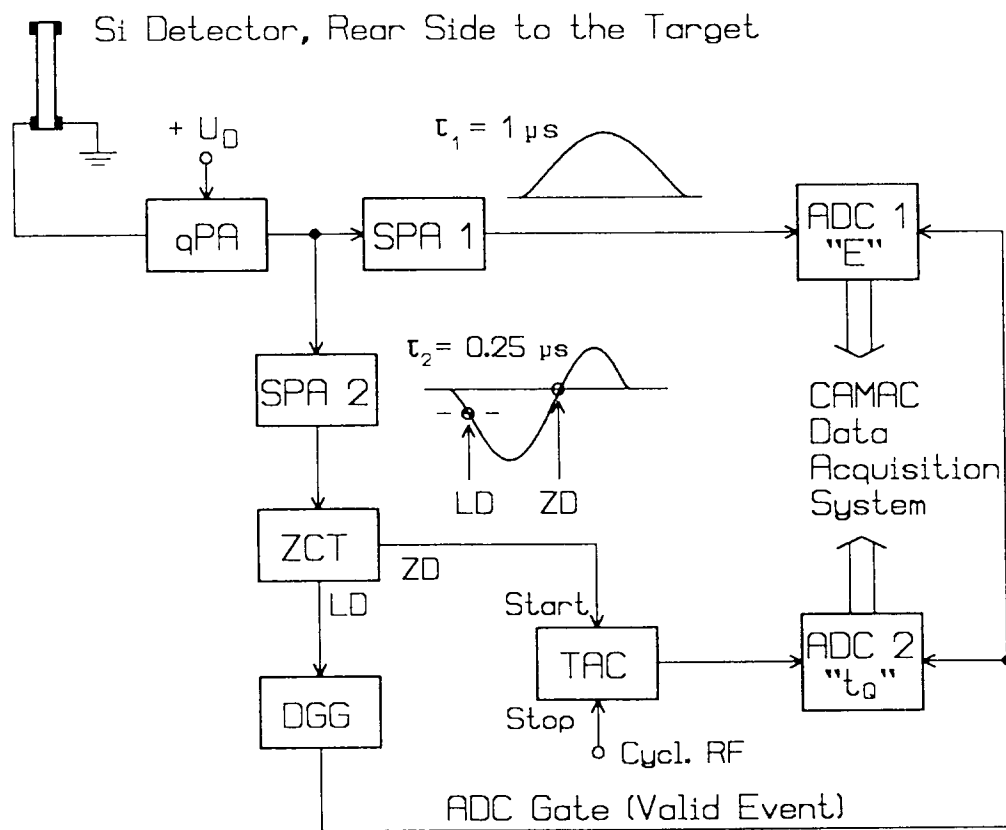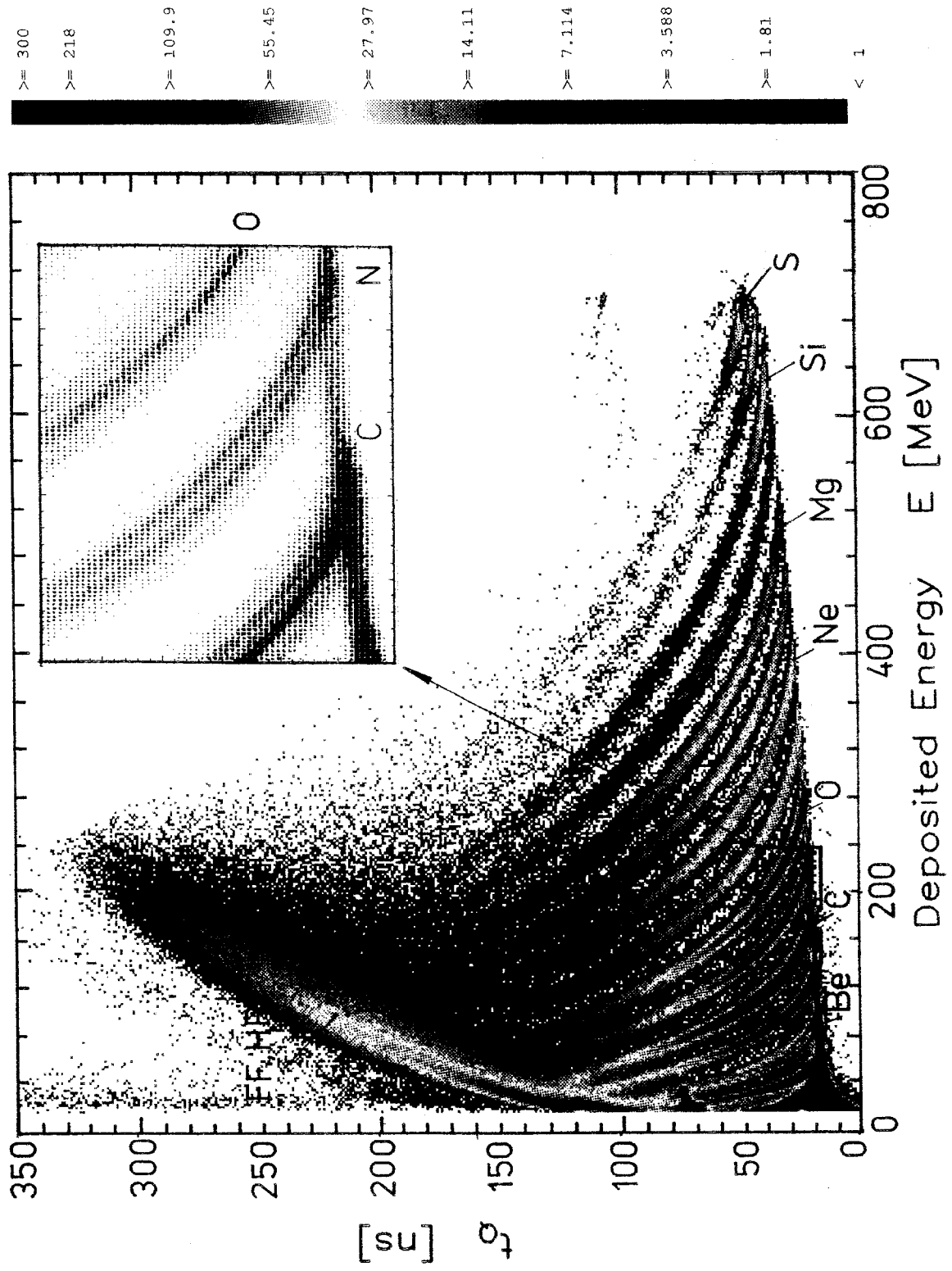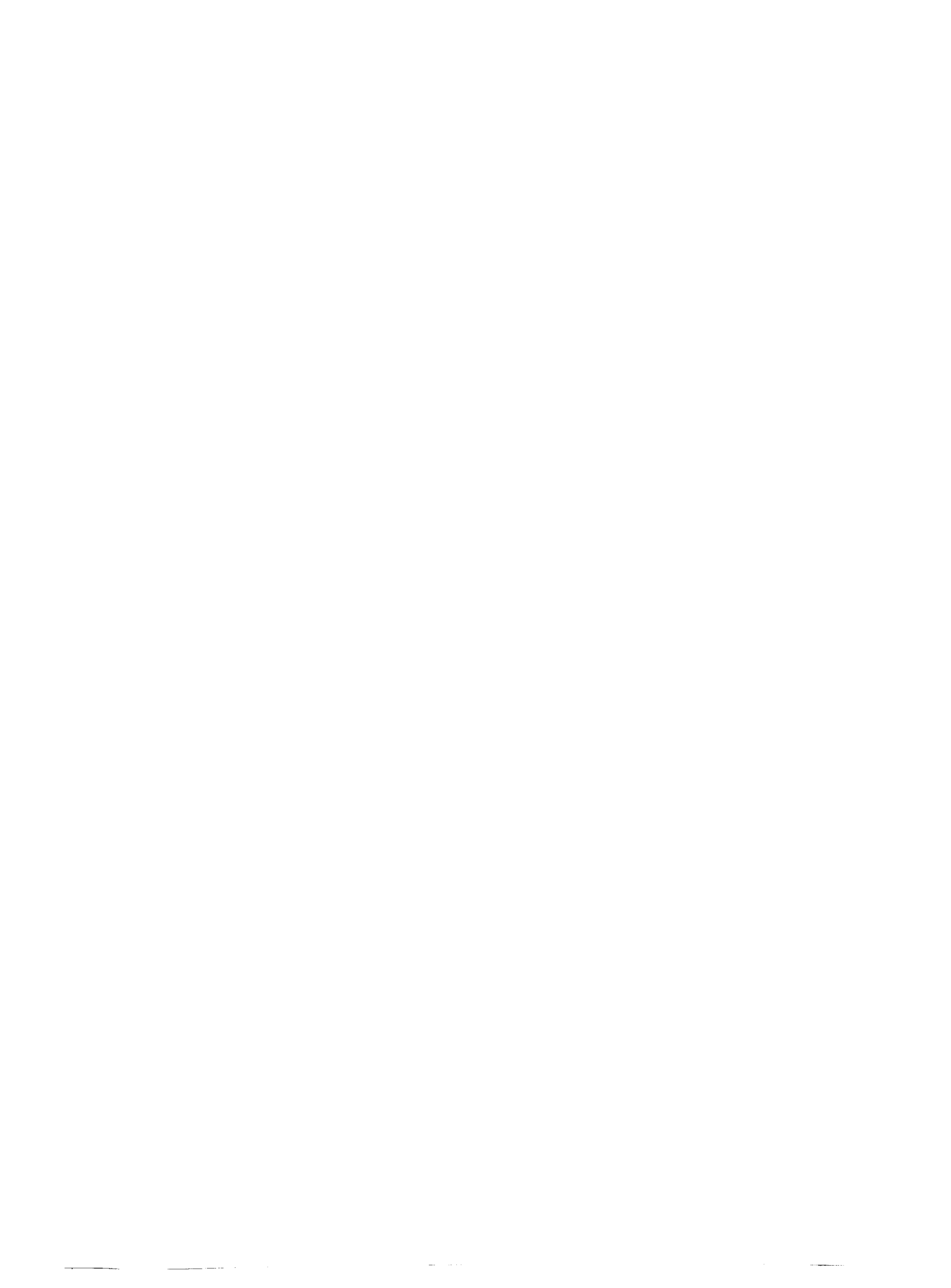
Figure 1.

Figure 2.

Figure 3.

Figure 5.

Figure 4.