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Abstract

A lithium–drifted silicon detector has been used as spectrometer for fast neutrons, utilising the charged particle reactions in silicon. The neutron yield and neutron energy spread from a low voltage deuterium–tritium neutron generator has been measured. The results from the measurement confirm the calibration measurements done on a neutron spectrometer.

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1. Introduction

The aim of this work has been to determine the neutron flux and the energy spread of neutrons from a neutron generator, using the neutron reactions in lithium–drifted silicon diodes (SiLi). The neutron source is the neutron generator of Gothenburg, which is a low voltage accelerator, using the DT–reaction for neutron production. These measurements have been done in a special test bed used at the neutron generator for calibration of the neutron spectrometer TANSY. For a complete description of TANSY, see references 1, 2 and 12. The test bed and the different system tests and calibrations of TANSY are described in reference 3. To determine the total efficiency and the resolution of the spectrometer it is valuable to have data on the incoming neutrons. In the spectrometer TANSY the diodes are used for measuring the energy of the recoiled protons. As the SiLi–diodes were there, together with all equipment necessary, it was easy to do these measurements.

2. The silicon detector as monitor for fast neutrons

The use of silicon diodes for measuring neutrons is a frequently used method, and it has been described e.g. in references 4–6. The physical background is that when silicon is irradiated with fast neutrons there occur (n,α)- and (n,p)-reactions. The dominating isotope in natural silicon is ^{28}Si (93%), and in the rest of this work only that isotope will be considered. The reaction most easy to analyze is ^{28}Si (n,α_0) ^{25}Mg. The notation α_0 is used to indicate the ground state of the product nuclide (^{25}Mg). Several excited states can be identified for ^{28}Si (n,α) ^{25}Mg as well as ^{28}Si (n,p) ^{28}Al and are usually indexed by α_1, α_2, .. and p_1, p_2, .. etc. For peaks that can not be resolved, such as p_2 and p_3 the notation p_{23} is used.

The Q–values for all reactions are negative. The net outcome of energy from a reaction within the diode is divided between the product particle and the product nucleus. Not all of this energy results in ionization but is dissipated in other ways. In the spectrum recorded this can be seen as a pulse height defect for the respective reactions. The amplitudes of the defects are different for different reactions since the set of particles and energies are different. The absolute pulse height defects reported disagree between different authors. Paić et al. [11] suggested that this may be due to differences in the detectors.

2.1 The silicon charged particle reactions for 14 MeV neutrons

The cross sections for the neutron reactions in silicon have been measured by many authors. Miller and Kavanagh [4] and Mingay et al. [5] give cross section data for a wide energy range in the form of diagrams. The cross section for the different states of the product nuclei are shown in diagrams as function of energy. Curves are given for individual states as well as for combinations of several states. One such diagram is shown in figure 1. The variation with the energy is very strong around 14 MeV, which can be an important source of error in our measurements.

Mingay et al. claim their cross section values to be good within 25 per cent, only.

Klochkova and Kovrigin [7] give the cross section for $^{28}Si(n,\alpha_0)^{25}Mg$ as 14.3 ± 0.7 mb at 14.1 MeV neutron energy. However, they do not explain how the absolute value of the neutron flux density was determined in their experiment to achieve such a good accuracy. In a later paper [8] Klochkova and Kovrigin have calculated the non-weighted average of the cross section values for $^{28}Si(n,\alpha_0)^{25}Mg$ given by several authors at 14.1 MeV neutron energy. The value they conclude is 13.6 ± 0.5 mb. They also demonstrate a way to unfold the pulse height diagram and to analyze the peaks of the other states to get cross section data. From their measurements they calculate the cross sections for other states reached after the (n,α)-reaction relative to that of the ground state. See table 1.

Table 1. Relative intensities of different states of the reaction $^{28}Si(n,\alpha_0)^{25}Mg$. From Klochkova and Kovrigin [8].

Reaction	(n,α_0)	(n,α_1)	(n,α_2)	(n,α_3)	(n,α_4)
Relative intensity	1.00	0.41	0.52	0.74	0.82
Cross section (mb)	13.6 ± 0.5	5.6 ± 0.3	7.1 ± 0.3	10.1 ± 0.5	11.2 ± 0.5

3. Silicon diodes used for determining neutron yield for the TANSY calibration experiments

Two experiments were done to calibrate the neutron spectrometer TANSY. The neutron beam entering TANSY was collimated by a 40 cm long, slot-shaped collimator with the cross section 5 mm x 175 mm. The diode used was an Enertec type LEC 300-2500. This is a partially depleted SiLi-detector with sensitive depth 2 500 μm and area 300 mm^2.

In the first experiment (# 397) the diode was positioned centrally over the collimator with the detector surface perpendicular to the neutron beam, see figure 2a. In the second experiment (# 399) it was positioned with the front surface parallel to the neutron beam, see figure 2b. In the # 397 measurement parts of the diode are shadowed from the source by the collimator and the neutron flux is expected to vary considerably over the detector surface. In the # 399 experiment there is a self shielding effect from the silicon diode itself and from the mounting material surrounding the the silicon slice. The loss of intensity due to self shielding is calculated to circa 10 per cent.

A plastic scintillator was used to monitor the neutron flux for normalizing these measurements relative to the TANSY calibrations. The monitor was positioned 2.4 m from the neutron generator target. However, in the line of sight there are construction materials as well as well as concrete shielding. The structure is complicated and it is difficult to make an accurate shielding calculation. Furthermore, a scintillator is sensitive also to gamma radiation. These problems prevent an absolute calibration to be done only from the monitor measurements.

The electronics used was one of the normal TANSY proton detector signal chains, see figure 3. The pulse height signal was analyzed and saved in the multi–channel spectrum. TANSY was operated in the mode normally used when calibrating the diodes, see reference 9, and the monitor pulses were counted in a separate scaler. A ^{241}Am alpha source was used to calibrate the energy scale of the measurement. For a detailed technical description of TANSY see reference 12.

3.1 Measurement results

The spectra collected in the two cases are shown in figure 4. The alpha peak from the α_0 reaction is at 11.3 MeV. If the Q–value of 2.653 MeV and a pulse-height defect of 0.2 MeV are added, the total energy is 14.1 MeV. This agrees well with the theoretical range of energies 14.036 – 14.147 MeV at 90^0 angle to the beam–line [10]. The front window of the diode gives an error when calibrating with an alpha source compared to measuring particles that were generated inside the diode. The 500 Å front window of gold takes circa 22 keV of the alpha particle energy. The energy scale in the calculations have been compensated for this.

The other peaks of the spectra can readily be identified and agree well with the spectra published by e.g. Miller and Kavanagh [4]. The peaks from the (n,p)-reactions are prominent in this measurement as the detector has a relatively large sensitive volume.

Table 2. Relative intensities of the different states of the reaction ^{28}Si (n,α_0) ^{25}Mg as measured.

Reaction Relative intensity	(n,α_0)	(n,α_1)	(n,α_2)	(n,α_3)	(n,α_4)
Klochkova & Kovr. [8]	1.00	0.41	0.52	0.74	0.82
# 397	1.00	0.36	0.56	0.74	0.87
# 399	1.00	0.35	0.56	0.72	0.82

The sensitive volume of the detector used in this experiment was 0.75 cm^3 but the calculation of this value has some uncertainty. Only data from measurement # 399 will be used as the full volume of the detector was utilized. As the SiLi-detectors have relatively high leakage currents, on the order of several μA, the bias supply must be set to compensate for the loss of voltage over the series resistance in the preamplifier. In our case the leakage current was 4 μA, but at the end of the measurement series it increased a little and there may have been loss of voltage to the detector during these measurement. At worst the voltage drop may have been 10 per cent. Since the detector is overbiased to improve the timing characteristics this voltage loss should not affect the sensitive volume.

The sensitivity of the detector depends also on how many reaction particles that leave the sensitive volume without depositing all their energy. This is related to the relative number of reactions that occur so close to the limits that the charged particles manage to escape from the sensitive volume. Assuming isotropic scattering and isotropic reaction density it is a calculation of geometry. [5]

$$f = \frac{(r+t)R}{2rt}$$

where

r = radius of sensitive volume,

t = thickness of sensitive volume, and

R = average range of the charged particles.

For this detector and 11 MeV alpha radiation ($R = 0.01$ cm) the loss factor $f = 0.025$ and for 10 MeV protons ($R = 0.07$ cm) $f = 0.18$.

4. Efficiency determination of TANSY using silicon diode measurements

Analysis of the spectrum from # 399 gives the data in table 3. The # 397 measurement is not useful as it its uncertain how large part of the diode volume that was in the beam. In the TANSY tests the monitor was used to normalize the different measurements. It was therefore of interest to calculate the neutron flux density relative to the monitor.

Table 3. Results of measurements # 399 and data used for its analysis. The reaction rate per neutron flux density is calculated from $R/\phi = N \cdot \sigma$. The spectra have been used in two different ways, either only the (n,α_0) peak or the full spectrum from α_0 to p_{23}. The calculations have not been compensated for the self–shielding effects described in chapter 3.

Spectrum used in the analysis	α_0	$\alpha_0 - p_{23}$	
Cross section value from reference	8	5	
Time	4 000	4 000	s
Monitor pulses	2 021 502	2 021 502	counts
Counts in diode measurement	137 323	686 303	counts
Cross section	13.5	78	mb
Peak pulses / monitor pulse	$67.9 \cdot 10^{-3}$	0.340	
Reaction rate/neutron flux density	$0.51 \cdot 10^{-3}$	$2.9 \cdot 10^{-3}$	cm^2
Neutron flux density/ monitor pulse	$67 \cdot 10^{3}$	$59 \cdot 10^{3}$	$n \cdot cm^{-2} \cdot s^{-1}$

The flux calculated using the full spectrum from α_0 to p_{23} is lower by 14 per cent compared to the one using only the α_0 data. To some extent this effect can be due to the protons that escape the sensitive volume. An error contributing to this difference may be that it is unclear exactly where to limit the p_{23} peak from the lower energy peaks. The peaks are not well - resolved due to the relatively low resolution of the diode. In this analysis the range of energies from 8.2 to 11.7 MeV has been used. The difference between the two ways of calculation is well within the limits of uncertainty.

The errors in the measurement are dominated by the uncertainty in the cross section. According to Mingay et al. [5] the absolute value of the cross section is known only within 25 per cent. Furthermore, the uncertainty in the energy and of the spread of the energy of the incoming neutrons introduces an uncertainty. As seen from figure 1 the cross section ranges from 19.5 to 10.5 mb over the energy range from 13.8 to 14.3 MeV. As highest it is 45 per cent higher and as lowest it is 22 per cent lower than the value used in the calculation (at 14.1 MeV). The statistical errors in the measurement are small as both the spectrum and the monitor counter show very high numbers of counts.

The ratios from table 3 were used to analyze the TANSY measurements, see table 4. The values for the different TANSY experiments agree well. There is, of course, the difference between the two ways of analysis that is discussed above. The theoretical value of efficiency was calculated to $5 \cdot 10^{-6}$ cm^2/(mg/cm^2) [1, 2]. Against the background of considerable sources of uncertainty described above the measured values agree reasonably well with the theoretically calculated value.

Table 4. Results of some TANSY measurements for different foil thicknesses [3], analyzed with data from this work.

Exp #	Monitor s^{-1}	Count rate s^{-1}	Foil thickness mg/cm^2	Efficiency cm^2/(mg/cm^2) α_0	$\alpha_0 - p_{23}$
387	504	0.368	1.87	$2.9\ 10^{-6}$	$3.4\ 10^{-6}$
388	506	0.554	2.89	$2.9\ 10^{-6}$	$3.3\ 10^{-6}$
389	503	0.579	3.71	$2.3\ 10^{-6}$	$2.7\ 10^{-6}$
390	500	0.166	0.95	$2.6\ 10^{-6}$	$3.0\ 10^{-6}$
Average				$2.7\ 10^{-6}$	$3.1\ 10^{-6}$

4.1 Resolution of the neutron generator determined from silicon diode measurement

The width of the (n,α_0) peak was in measurement # 397 determined to 195 keV FWHM and for # 399 it was 208 keV. Together with literature data this can be used to calculate the energy spread of the source neutrons.

Miller and Kavanagh [4] in their measurements obtained a width of 125 keV for the α_0 - peak. They estimate the intrinsic resolution of a 3 mm thick SiLi-detector to be 110 keV and the spread in the recoil energy of ^{25}Mg to 35 keV. These numbers are added quadratically to the electronic resolution, which is assumed to be 15 keV.

Subtracting these contributions from the total energy spread, using an average of 200 keV, gives a spread of energy of the source neutrons of 163 keV. This value depends a lot on the assumption of intrinsic resolution of the diode. A more conservative assumption of 140 keV intrinsic resolution gives an energy spread in the source of 138 keV.

The spread of the source neutrons has been used to estimate the energy resolution of the neutron spectrometer TANSY. The theoretical resolution for TANSY is 200 keV when using 1 mg/cm^2 polyethylene foil as scatterer [2]. One of the measurements with TANSY for a 0.95 mg/cm^2 foil shows a total resolution of about 250 keV [3]. Subtracting the source contribution of 160 keV from this leads to an instrumental resolution of 192 keV. If the value 140 keV energy spread in source is used the value will instead be 207 keV.

5. Conclusions

In this work a silicon diode has been used for determining the neutron flux and the energy spread of neutrons at the energy 14.1 MeV. The data have been used to confirm that the efficiency and the resolution of the neutron spectrometer TANSY is within the range calculated.

The method is reliable and simple to use. However, there is considerable uncertainty in the cross section values which reduces the accuracy of the method.

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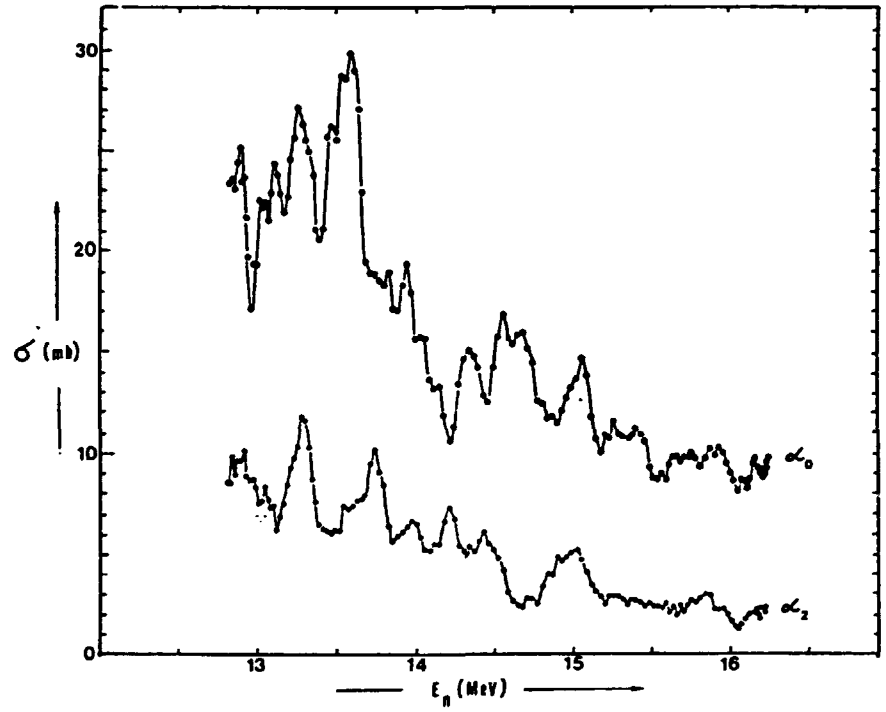


Figure 1. The cross section for the (n,α_0) and the (n,α_2) reactions in ^{28}Si as function of energy for the incoming particle. The cross sections around 14 MeV show strong variations with the energy. Notations p_{01} and p_{23} are used to for peaks that are not possible to separate in the spectrum. From Mingay et al. [5].

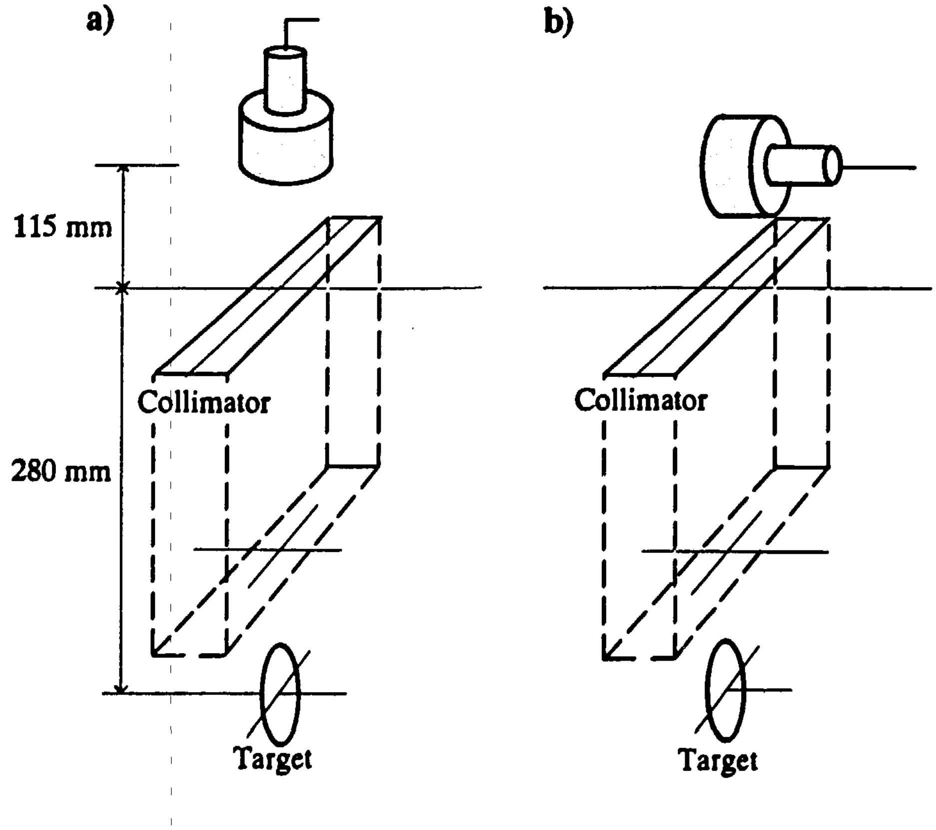


Figure 2. The detector orientation for the two cases measured.

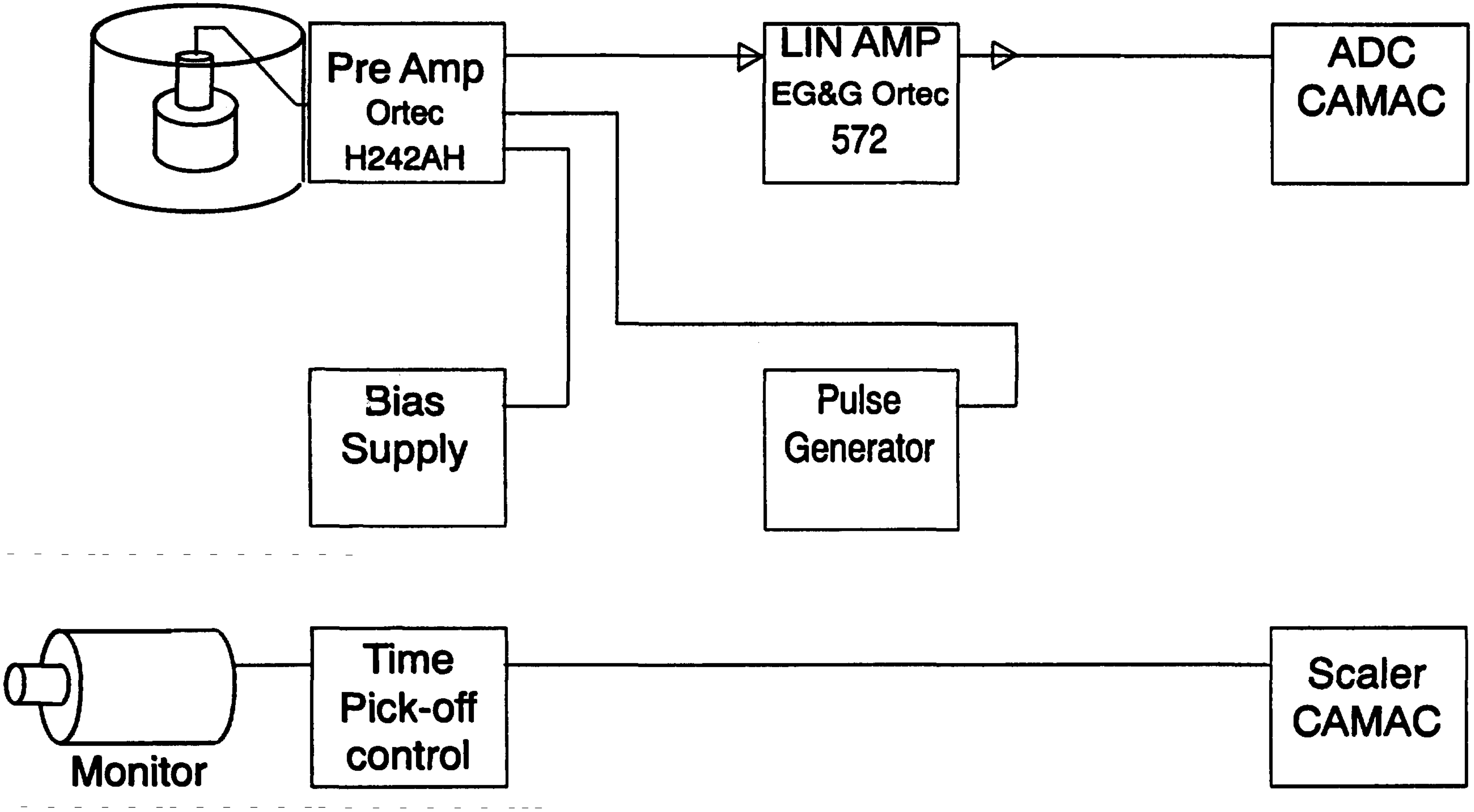
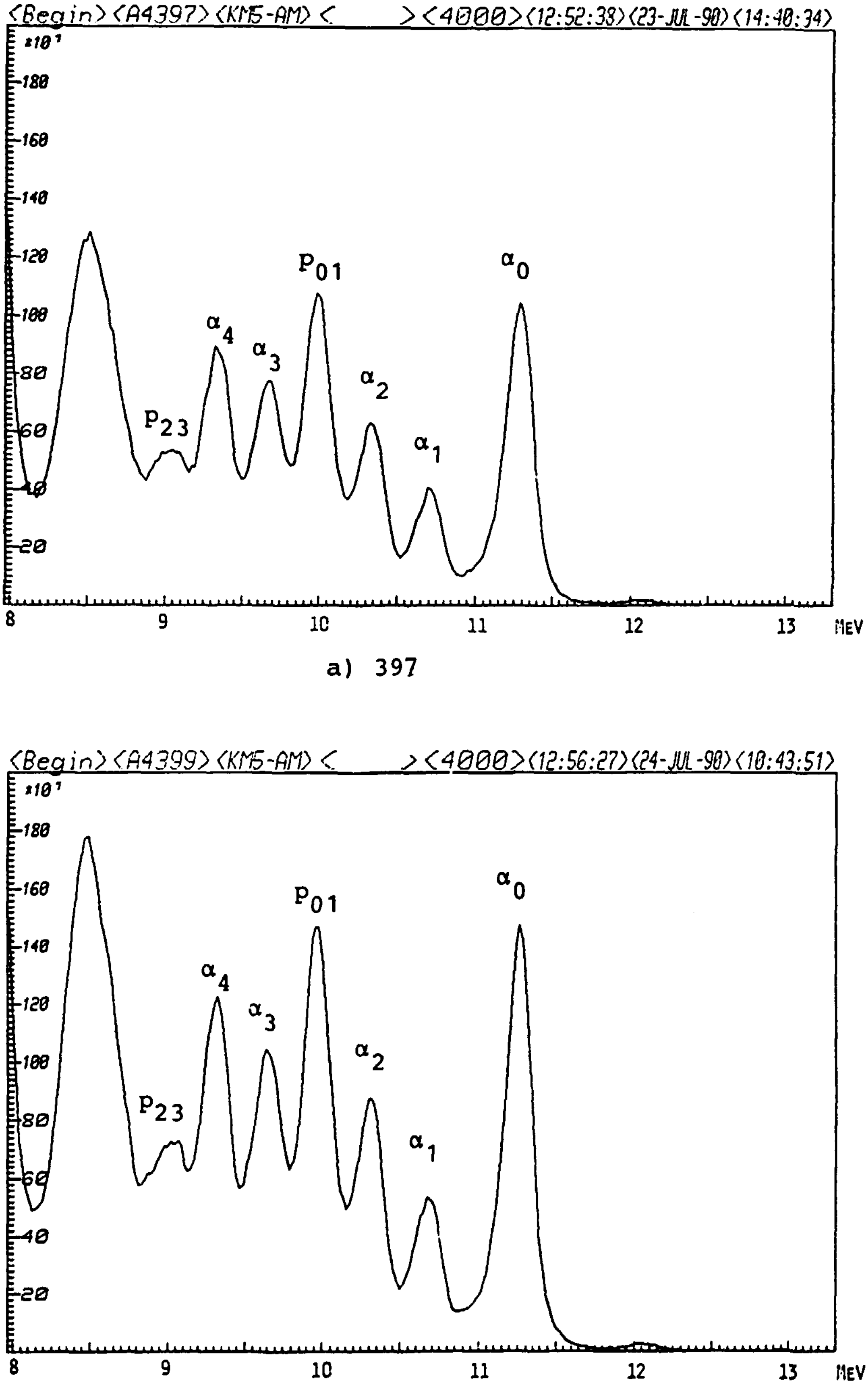


Figure 3. The electronics diagram for the measurements.



a) 397

b) 399

Figure 4. Spectra recorded (a) with the detector surface perpendicular to the beam direction and (b) with the detector surface parallel to the beam direction. The different states of the product nucleus are noted. Notation p_{01} and p_{23} are used to mark the peaks that are not separated in the spectrum.