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METHOD OF ENERGY CALIBRATION OF THE TANSY NEUTRON DETECTORS

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Abstract

A method to calibrate an array of scintillation neutron detectors, using a γ source, is presented. The count rate is measured as a function of high voltage at a given discrimination level. The obtained distribution is differentiated and a maximum value is determined which corresponds to the voltage at which the gamma peak passes through the discrimination level. By repeating the measurement at different discrimination levels the experimental dependence between the discrimination level and the high voltage is found as a straight line in a log–log diagram. Two calibration parameters for each detector are determined from a fit of these straight lines. A recalculation from the energy of the used γ source to any other energy is then possible and the obtained relation can be used to calculate discrimination levels and high voltages for each detector. Verification procedures are described.

Contents

1. Introduction

In experiments using detector arrays, efficient methods for calibrating and checking detector performance are essential. A method for calibrating an array of neutron detectors of scintillator type has been developed in order to calibrate two arrays of 16 neutron detectors that form a part of a neutron spectrometer built for thermonuclear fusion diagnostics. The neutron spectrometer, TANSY, is based on neutron time–of–flight and recoiled proton energy measurement. The coincidence of the recoiled proton and the scattered neutron are measured and from this the original neutron energy can be calculated. The complete spectrometer is described in references 1, 2 and 3. The principle is sketched in Fig.1. Each neutron detector consists of a fast plastic Bicron 420 scintillator (of 145 mm diameter and

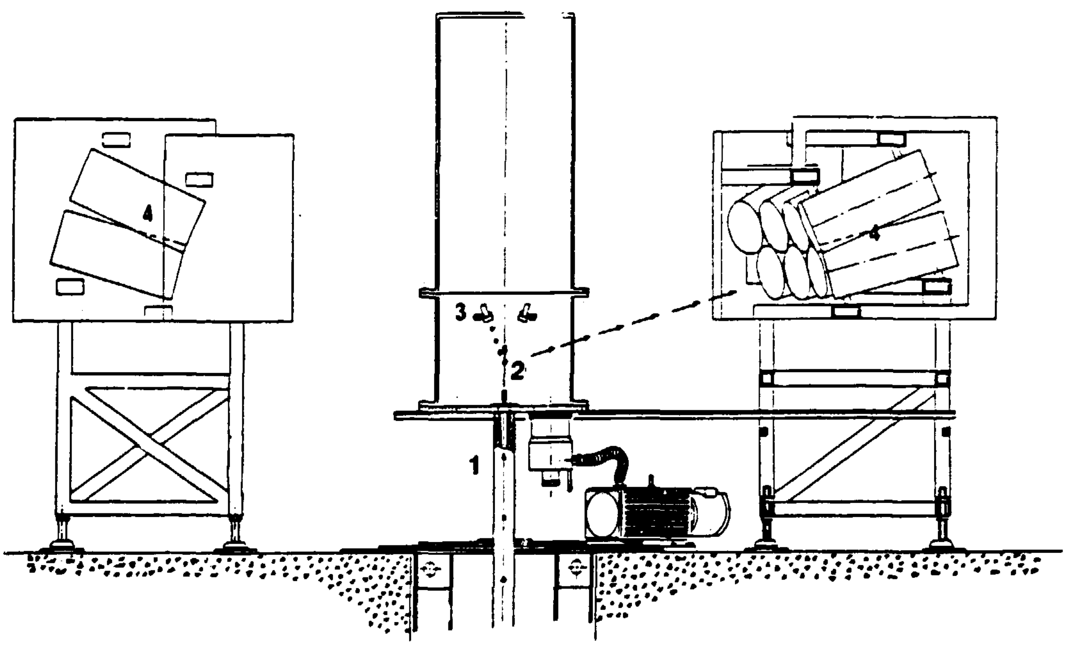

Fig 1. The principle of TANSY.

A thin beam of neutrons is shaped by the collimator (1). Neutrons are scattered in the foil (2) and the recoil protons are detected in the proton detectors (3). The scattered neutrons are detected in the neutron detectors (4).

20 mm thickness) which is coupled via a light guide to a photomultiplier tube. The TANSY neutron detectors will be exposed to neutrons of energies in the range of 0.5–3 MeV.

A diagram of the electronics used in the neutron detection system is shown in Fig.2. The high voltage supply for the photomultiplier is computer controlled via a CAMAC module.

The base of the photomultiplier has two built-in preamplifiers, one fast and one slow. The fast NIM signal from the photomultiplier is fed into the constant fraction discriminator. Each discriminator NIM module contains eight channels. The incoming signal for each channel is also available at half the amplitude through a jack on the rear of the module. The attenuated signal from the lower level discriminator is fed to the input of the upper level discriminator, a module of the same model as for the lower level discriminator, only modified for the range of the discrimination setting. The output from each of the two units is fed to the coincidence unit which produces output for signals that have amplitudes higher than the lower discrimination level but not above the upper discrimination level. Conversion to ECL signals is done within the discriminators and the signal chain thereafter is ECL electronics. From the coincidence unit the net output is fed through a fan-out to the CAMAC latching scaler. Data taking is handled by computer controlled CAMAC electronics.

It is essential that the settings of the upper and lower level discriminators are as correct as possible in order to cut away background without losing any useful signal. The settings are related to the high voltage of the photomultiplier tubes. Thus one must determine for each detector three parameters: the two discriminator settings and the high voltage.

This report describes the simultaneous calibration of all detectors in an array using successive adjustments of the high voltages applied to the photomultiplier tubes. The existing NIM– and CAMAC–electronics are used together with a radioactive source. The behaviour of each detector is determined by two parameters and from these parameters the high voltages and the discrimination levels for the wanted calibration can be calculated.

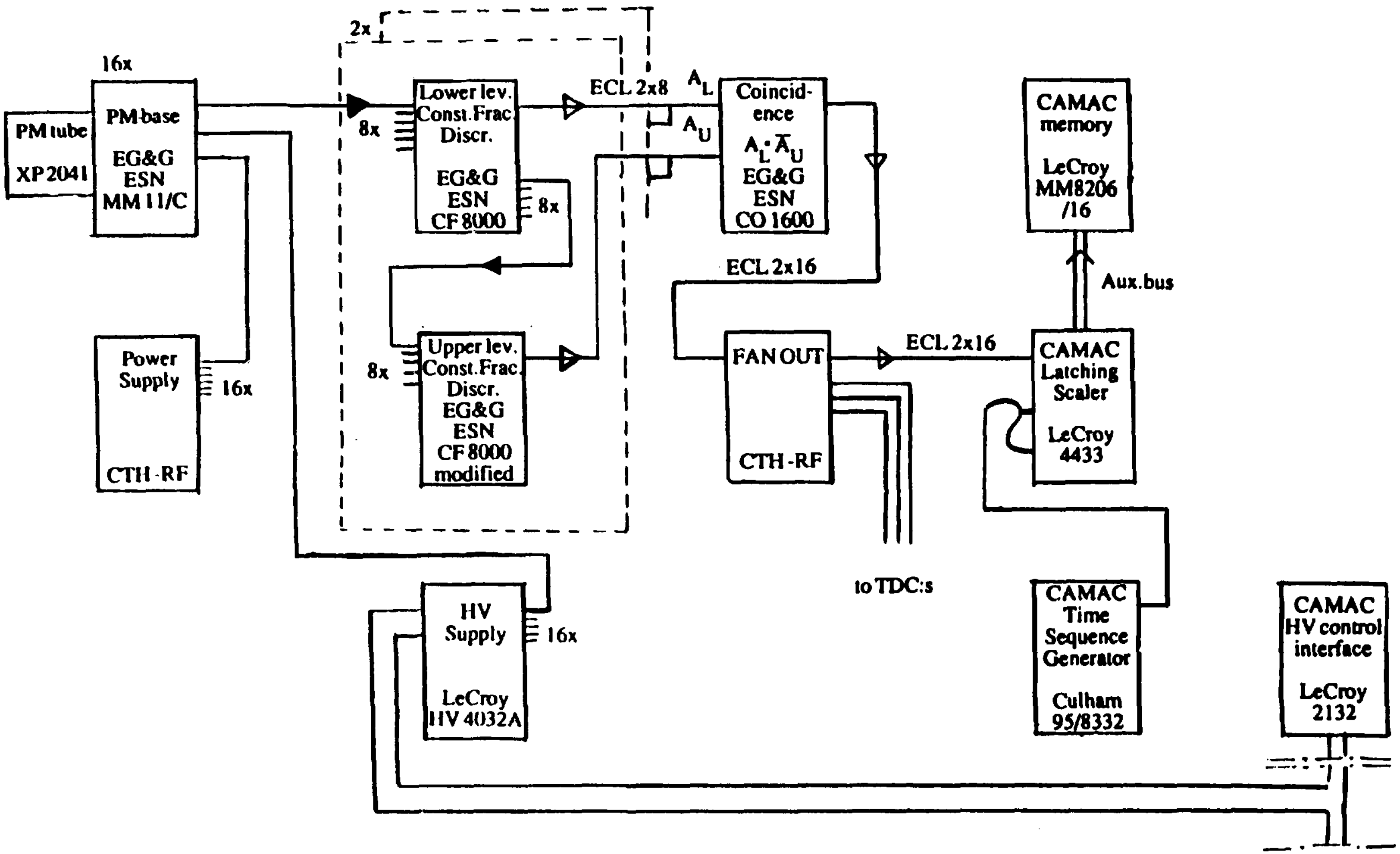

Fig.2. Principle diagram of the electronics used in the neutron detection system.

(The diagram shows components of one array. Instruments marked RF-CTH are made for the purpose at the department in Gothenburg.)

2. Basic relations

The amplitude of the output signal from a photomultiplier (PM) is described by

$$A = L \cdot M \tag{1}$$

where

L is the light signal from the scintillator and

M is the amplification of the tube.

The amplification of the PM–tube is described by [4] as

$$M = k \cdot V^n \tag{2}$$

where

k is a coefficient,

V is the high voltage applied to the PM–tube, and

n is a constant proportional to the number of dynods in the PM–tube.

The light signal from the scintillator is proportional to the energy, E, of the radiation :

$$L = \varepsilon \cdot E \quad . \tag{3}$$

The amplitude A is then

$$A = \varepsilon \cdot E \cdot k \cdot V^n \quad . \tag{4}$$

The constants ε, k, and n are individual for each scintillator, PM–tube and PM–base combination. The wide spread of these constants gives a substantial difference in amplitudes from different detectors at the same high voltage and exposed to the same radiative energy. The relation Eq.(4) can be transformed to the form

$$\ln(A) = \ln(\varepsilon \cdot E \cdot k) + n \cdot \ln(V) \quad . \tag{5}$$

As long as we consider the same energy we have a constant

$$C = \varepsilon \cdot E \cdot k \tag{6}$$

and the dependence Eq.(5) is a straight line in a log–log diagram

$$\ln(A) = K + n \cdot \ln(V) \tag{7}$$

with

$$K = \ln(C) \quad . \tag{8}$$

3. Relative Calibration

The parameters ε, k and n, *cf* Eq.(4), are different for each detector in a set. The idea of the relative calibration is to find, for all detectors, such values of the high voltages, V_i, that the same energy gives the same amplitude signal, A_i, from each detector.

3.1. Calibration Parameters of Detectors

The relative calibration of the neutron detectors is done by the use of a γ source. The energy of the source does not have to be known but a clearly defined amplitude distribution should be present.

If the calibration energy is E_0 then the constant C (*cf* Eq.(6)) for the i^{th} detector is

$$C_{0i} = E_0 \cdot \varepsilon_i \cdot k_i \qquad (9)$$

and

$$K_{0i} = \ln(C_{0i}) \quad , \qquad (10)$$

and the straight line

$$\ln(A_i) = K_{0i} + n_i \cdot \ln(V) \qquad (11)$$

describes the dependence of amplitude, A_i, of the i^{th} detector on the high voltage. The constants K_{0i} and n_i are the calibration parameters of the i^{th} neutron detector.

3.2. Method of Relative Calibration

When the set of calibration parameters $\{K_{0i}, n_i\}$ is known it is possible to find a set of high voltages, $\{V_i\}$, giving the same amplitude, A, from all detectors for the same incoming energy.

Let us assume that the amplitude is chosen as A_0 for all detectors. Thus from Eq.(4) and Eq.(9), for each detector we can calculate the high voltage that fulfils the above requirement

$$V_{0i} = (A_0/C_{0i})^{1/n_i} \tag{12}$$

or from Eq.(8)

$$\ln(V_{0i}) = \frac{1}{n_i} \cdot [\ \ln(A_0) - K_{0i}\ ]\ \ . \tag{12a}$$

The last formula, Eq.(12a), is more suitable for use in a computation because the direct calibration parameter, K_{0i}, is used and any computer problems of limits of exponents are avoided during the calculation of the value of C_{0i}=exp(K_{0i}). (K_{0i} is of the order of −100). The procedure is shown in Fig.3.

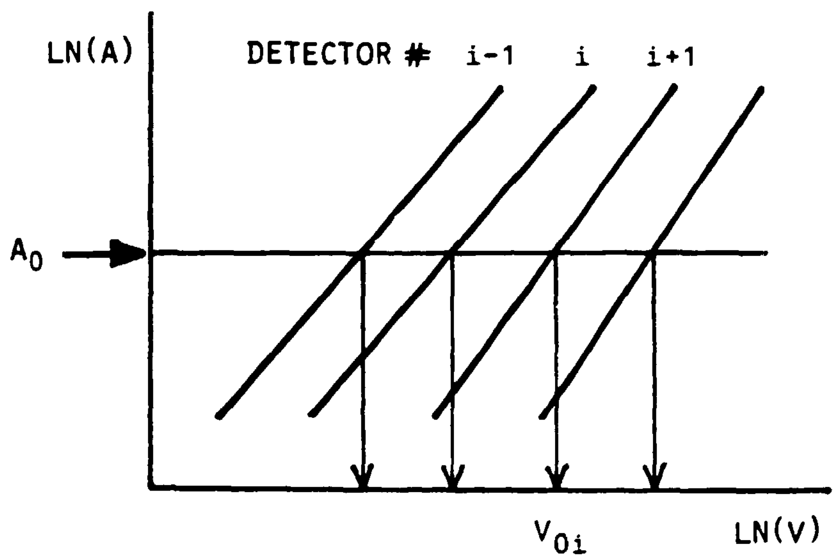

Fig.3. Determination of the set of the individual V_{0i} high voltages giving the same amplitude, A_0.

Using the obtained voltages, the same amplitude A_0 for each detector corresponds to the energy E_0 (which is not necessary to know). This is still described by Eq.(4) as

$$A_0 = E_0 q_i \tag{13}$$

where

$$q_i = \varepsilon_i \cdot k_i \cdot (V_{0i})^{n_i} \tag{14}$$

is a variable which is now equal for all detectors.

3.3. Experimental Determination of Calibration Parameters

When a γ source of any energy, E_0, is used an amplitude distribution as in Fig.4 is obtained. The count rate as a function of high voltage is measured using a certain

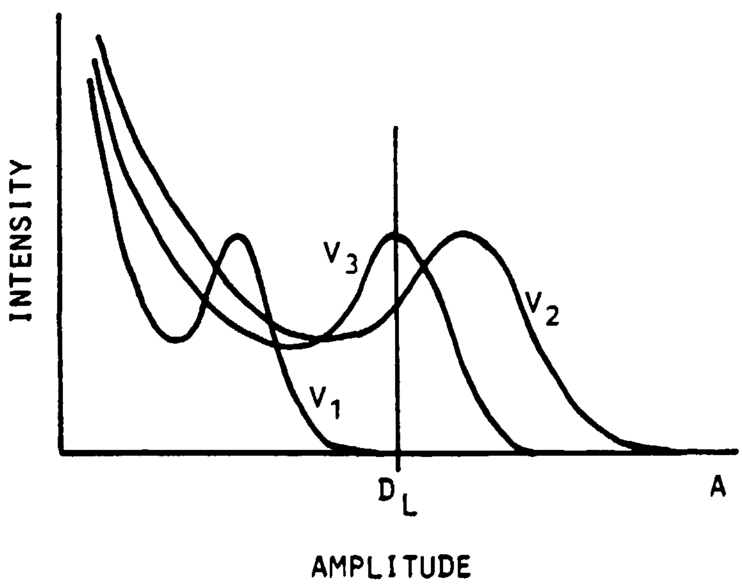

Fig.4. Amplitude distributions at three different high voltages.

discrimination level, D_L. At the high voltage equal to V_1 there are no pulses with amplitudes $A > D_L$ (no counts) but at the higher high voltage, V_2, counts are observed. From the measured distribution we detect that high voltage, V_3, at which the position of the peak of the amplitude distribution corresponds to the D_L level. It is observed as a maximum slope of the obtained count rate distribution, or better, as a peak in the differentiated distribution.

In the experimental procedure, the count rate, P, for each detector is observed at the fixed discrimination level, D_j, as a function of the high voltage which is changed in steps of ΔV (*eg* 5 volts), which is illustrated in Fig.5.

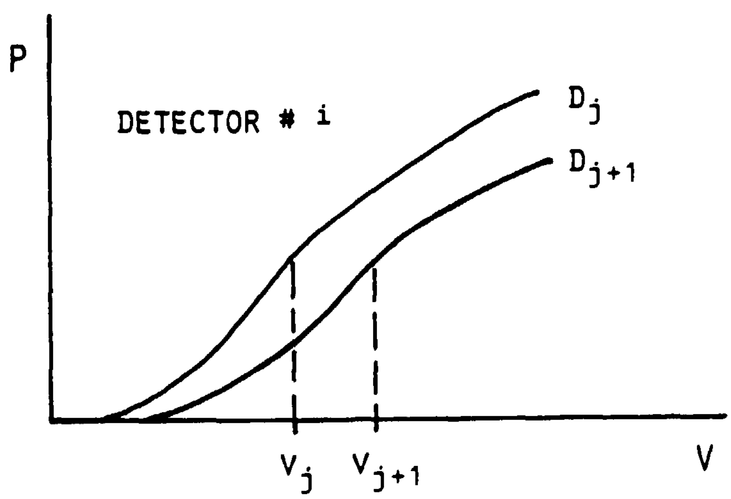

Fig.5. Number of counts, P, as a function of high voltage, V, in the count rate measurement at two different amplitude discrimination levels, D_j and D_{j+1}.

The maximum change in count rate per voltage step is observed when a peak of the amplitude distribution passes through the amplitude level of the lower discriminator. The differentiated P(V) curve immediately gives the high voltage level, V_j, as the position of the maximum of the dP/dV function (Fig.6).

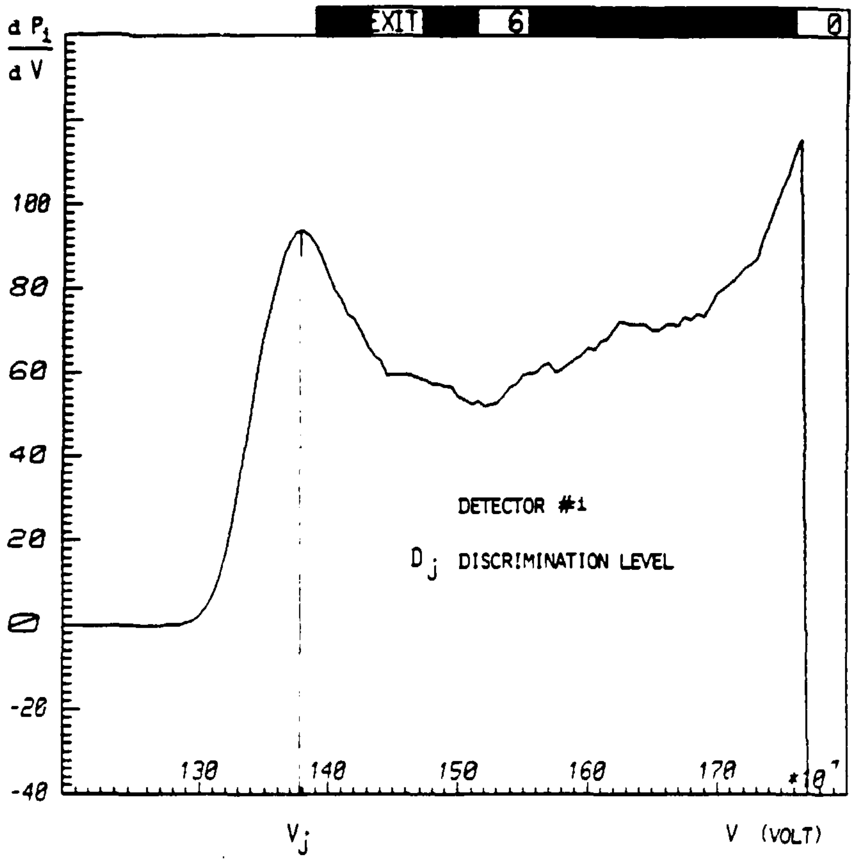

Fig.6. Peak position, V_j, in the differential distribution dP/dV = f(V) for the i^{th} detector at the discrimination level D_j .

By repeating the experiment at different discrimination levels, D_j, the experimental dependence D = f(V) is obtained for the i^{th} detector. This is given by pairs of the $(D_j,V_j)_i$ values where V_j is the high voltage at which the amplitude peak overcomes the lower discrimination level, D_j (*cf* Fig.7). The parameters K_{0i} and n_i are determined from a fit of the straight line, Eq.(11), to the experimental data, $(D_j, V_j)_i$.

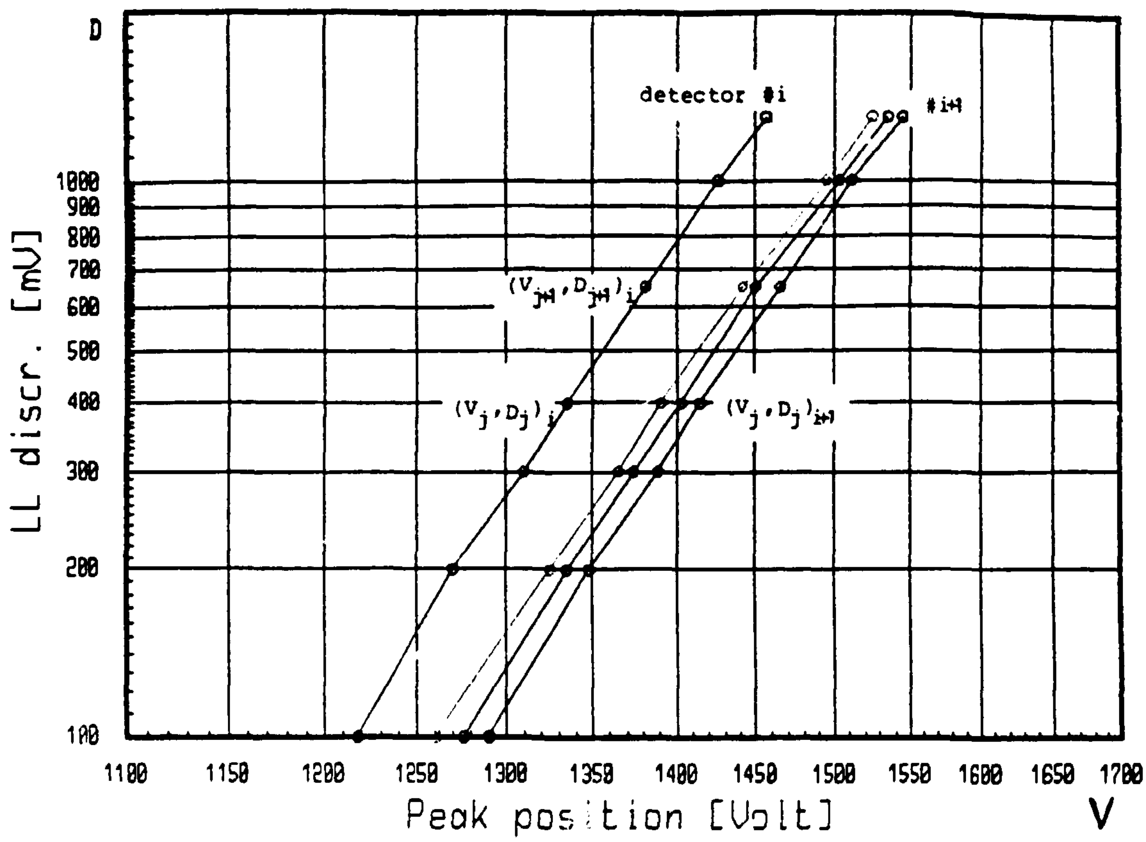

Fig.7. Experimental dependence between the discrimination level (mV) and the differential distribution peak position (high voltage, V) from the count rate measurement (four detectors).

If the upper level discriminator is connected in the system this will give a negative contribution to the distribution at higher voltages when a part of the amplitude distribution starts to fall above the upper level. To avoid any complications the measurements have been done without any upper level discrimination.

Calibration parameters for the neutron detectors should be the same while using the upper level discriminator. But in this particular set of detectors there is a problem with the upper level discrimination, D_U, because the signal after crossing the lower level (LL) discriminator, *cf* Fig.2, is attenuated by approximately a factor of two (different between channels). This relative change in amplification (which is not well–known) means a difference between calibration parameters from LL and UL. As a consequence, each detector will be described by two pairs of two calibration parameters, one pair for the lower level discriminator and one pair for the upper.

Therefore, the procedure is repeated in a separate measurement to get the calibration parameters from the upper level discriminator. Thus an independent set of parameters is obtained for the UL discriminators.

3.4. Verification of the Obtained Calibration Parameters

3.4.1. Test of the Method

A certain high voltage, $V = V_t$, is chosen. Then for each detector the amplitude of the discrimination level, D_i, can be calculated and preset. The positions of the differential distribution peaks will appear at the same voltage, V_t, in the count rate measurement for all detectors. From Eq.(4)

$$D_i = C_{0i} \cdot V_t^{n_i} \tag{16}$$

or

$$\ln(D_i) = K_{0i} + n_i \cdot \ln(V_t) \tag{16a}$$

which is shown in Fig.8.

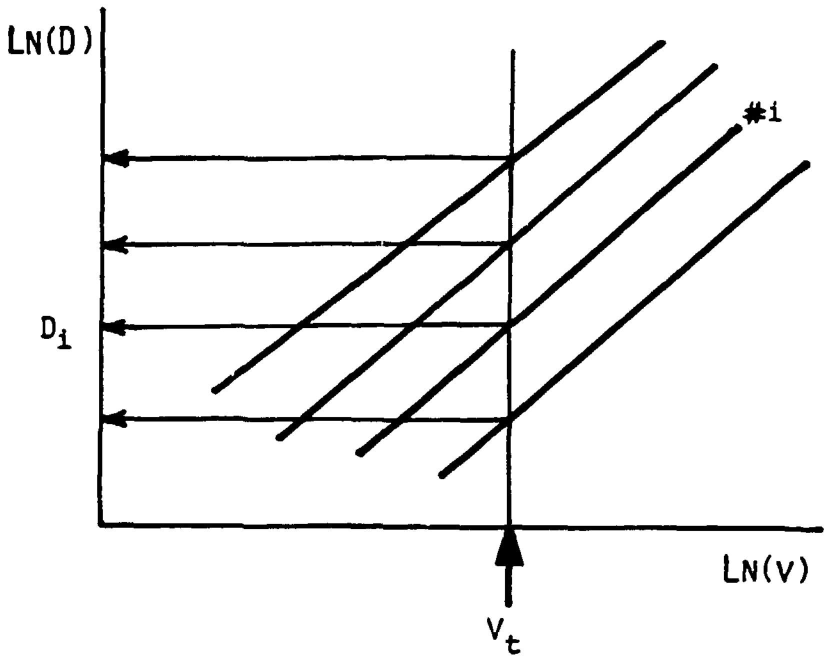

Fig.8. Determination of the set of the individual discrimination levels, D_i, corresponding to the chosen high voltage value, V_t, the same for all detectors.

Then the count rate measurement, using the same calibration source as during the determination of the calibration parameters, gives the result shown in Fig.9. This test is not always possible because the calibration parameters of different detectors may be too far apart. This is due to large differences in amplification between different photomultiplier tubes and bases.

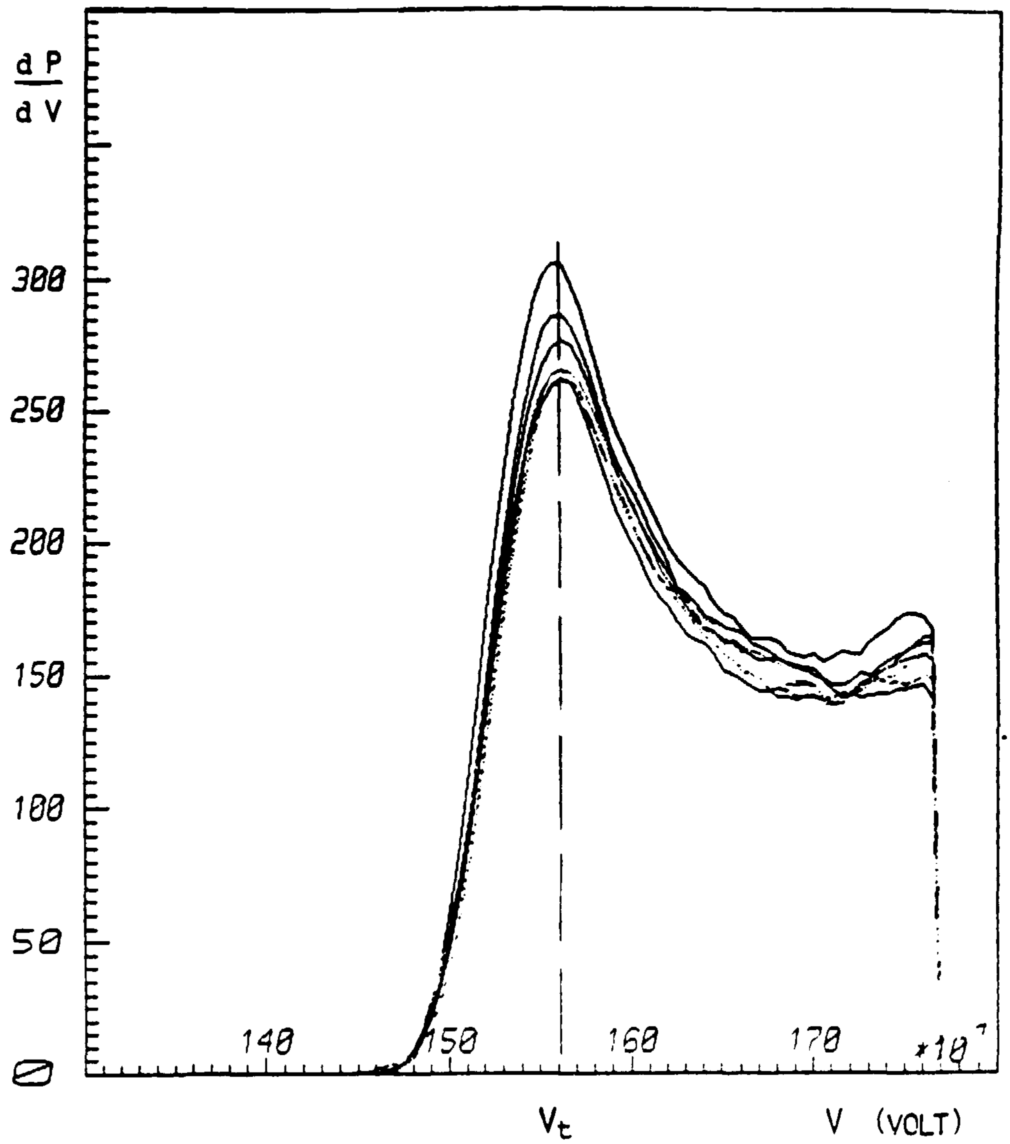

Fig.9. Result of the test count rate measurement (differentiated curves) for several neutron detectors at the calculated individual discrimination levels.

3.4.2. Test Closer to Operation Conditions

A certain LL discrimination $D = D_L$ is chosen, the same for all detectors. Individual high voltages, V_i, are calculated from Eq.(12) or Eq.(12a). The count rate

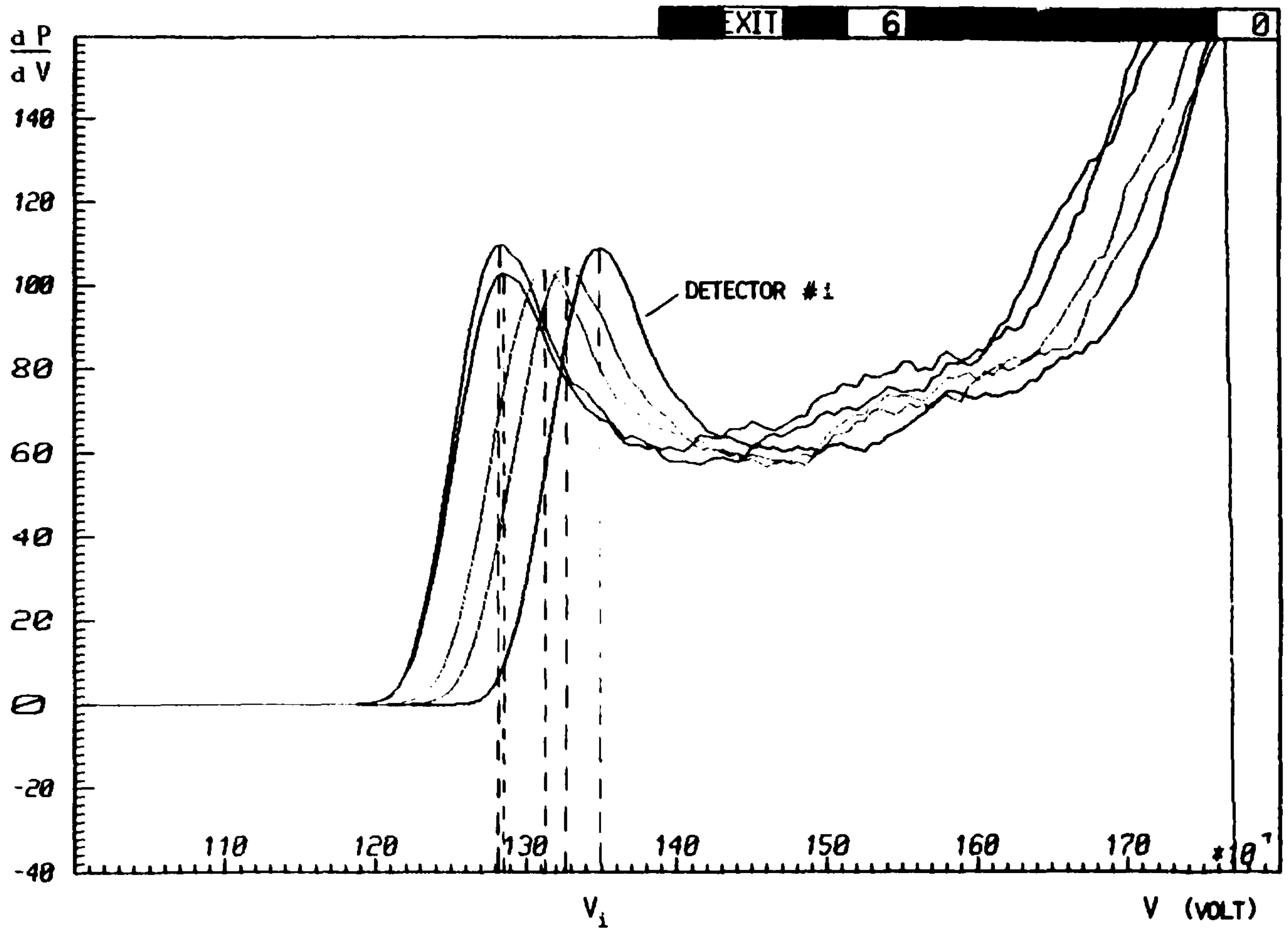

Fig.10. Result of the test count rate measurement for several neutron detectors at the same chosen discrimination level, D_L . The different positions of the differential distribution $(dP/dV)_i$ maxima, V_i , should be compared with the calculated V_i values.

measurement is then performed for all detectors and the peak positions of the $(dP/dV)_i$ functions are compared to the calculated V_i values (*cf* Fig.10). In our experiments we found agreement between calculated and measured values within 5 volts.

4. Absolute Calibration

By the absolute energy calibration is meant that high voltages and discrimination levels are preset so that the signal from each detector corresponds to the same required energy interval.

4.1. Determination of the Correspondence between Amplitude Signal and Energy

The main goal of the absolute energy calibration is to select the proper window of amplitude signals. We may write this as

$$V_i \Leftrightarrow [(D_{Li} < A_i < D_{Ui}) \Leftrightarrow (E_L < E < E_U)] \qquad (17)$$

where

- i is the detector number,
- V_i is the operation high voltage,
- A is the amplitude of the signal,
- D_L is the lower discrimination level corresponding to the lower energy limit, E_L.
- D_U is the upper discrimination level corresponding to the upper energy limit, E_U.

For the TANSY spectrometer, the neutron energy window is $0.5 - 3$ MeV. Compared to the γ interaction these neutron energies correspond to an electron energy window of

0.15–0.90 MeV [5]. This is due to the fact that the interaction mechanism in the scintillator differs for different types of radiation. When neutrons are measured, the energy is transferred in neutron–proton–electron interactions and when γ radiation is measured γ–electron interactions (*eg* Compton effect) take place. Thus, when the neutron detectors are calibrated by a γ source, the energy has to be referred to the electron energy.

The maximum energy transferred to an electron from a γ quantum, the Compton edge energy E_C, is:

$$E_C = h\nu \cdot \frac{2h\nu \ / \ (m_0 c^2)}{1 \ + \ 2h\nu \ / (m_0 c^2)} \tag{18}$$

where

$h\nu$ is the γ energy and

m_0c^2 is the electron rest mass energy.

The Compton edge from this kind of scintillator gives a wide distribution. Where the Compton energy E_C is depends on several detector parameters and can not easily be calculated. Several researchers have worked in this field, *eg* Cherubini *et al* [6]. Here we have chosen to define E_C as the value which corresponds to the position of the half–maximum value of the amplitude distribution (Fig.11).

The energy scale calibration should be carefully performed on γ sources of well–known energies, *eg* ^{22}Na, ^{137}Cs or ^{207}Bi, see Table 1. In an amplitude distribution measurement the energy E_0 of the source, used for the determination of the calibration parameters, can be found on the energy scale as seen by the scintillator. ^{60}Co emits γ quanta of two energies (E_γ = 1173 and 1332 keV, giving E_C = 963 and 1118 keV, respectively). However, due to the limited resolution of the scintillator, these energies are not resolved and appear as if there was only one energy. The observed single peak energy, E_0, is taken as reference in the neutron detector calibration procedure.

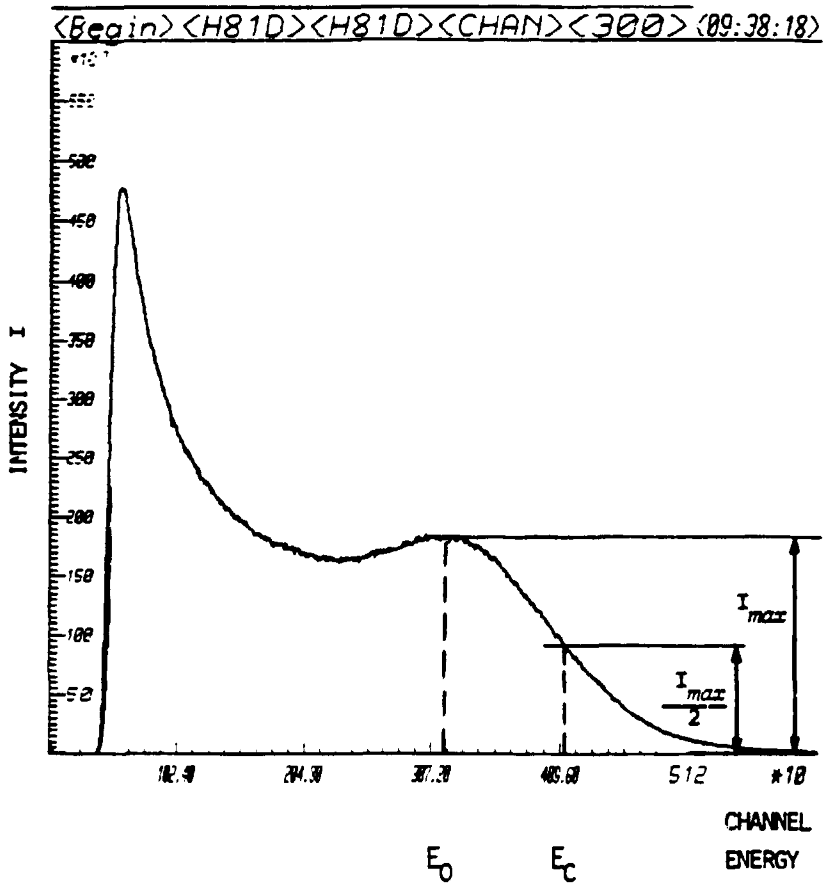

Fig.11. Definition of the E_0 and E_C energies in the amplitude distribution.

Table 1. The energies of the different γ-sources used for the absolute energy calibration.

Source	E_γ (keV)	E_c (keV)
^{22}Na	1274.5	1062
	511.0	341
^{137}Cs	661.6	477
^{207}Bi	1063.6	858
	569.7	393

4.2. Method of Absolute Calibration

From the count rate measurements the sets of calibration parameters are known, *ie*:

$$\{ K_{0Li}, n_{Li}, K_{0Ui}, n_{Ui} \} \quad .$$

Theoretically, it should be $n_{Li} = n_{Ui}$ but $K_{0Li} \neq K_{0Ui}$, because of the attenuation of the signal for the UL discriminator. Any deviation which is observed, is a result of statistical uncertainties, non–linearities, saturation, and fluctuations of DC levels.

The K_0 constants were obtained for a certain E_0 energy of the source used (*eg* ^{60}Co). The dependence, Eq.(4), of the amplitude on the energy can be rewritten as:

$$A_i = \frac{E}{E_0} \cdot C_{0i} \cdot V^{n_i} \tag{19}$$

where C_{0i} was defined in Eq.(9), or

$$\ln(A_i) = \ln(E/E_0) + K_{0i} + n_i \cdot \ln(V) \quad . \tag{19a}$$

If the E_0 value is known, the amplitude A_i for the i^{th} detector can be calculated to correspond to the required energy E at the high voltage V. This is an absolute reference for the amplitude signal to the energy E, and the proper individual discrimination levels $D_i = A_i$ can be determined from Eq.(19a).

An alternative is to select any discrimination level, D_i, corresponding to a chosen energy, E, and calculate the high voltage for each detector:

$$V_i = \sqrt[n_i]{D_i/C_{0i} \cdot E_0/E} \tag{20}$$

or

$$\ln(V_i) = \frac{1}{n_i} [\ln(D_i) - K_{0i} - \ln(E/E_0)] \quad . \tag{20a}$$

Because of the difference in the signals for LL and UL discriminators, the following procedure is used:

1) A choice of a lower limit energy, E_L, and a lower limit discrimination amplitude, D_L, *ie*

$$E_{Li} = E_L \text{ and } D_{Li} = D_L.$$

2) For each detector, the high voltage fulfilling the above is calculated (using the LL calibration parameters) from

$$\ln(V_i) = \frac{1}{n_{Li}} \cdot [\ \ln(D_L) - K_{0Li} - \ln(E_L/E_0)\ ] \tag{20b}$$

3) A choice of an upper limit energy, E_U, which is the same for all detectors.

4) The upper level discrimination amplitudes, D_{Ui}, based on the UL calibration parameters, are calculated using Eq.(19a) for each detector from:

$$\ln(D_{Ui}) = \ln(E_U/E_0) + K_{0Ui} + n_{Ui} \cdot \ln(V_i) \tag{21}$$

where V_i comes from step (2).

The method is illustrated in Fig.12. The following set of data is then obtained:

E_L	– lower energy level
E_U	– upper energy level
D_L	– lower discrimination level which is the same for all detectors
$\{D_{Ui}\}$	– set of upper discrimination levels
$\{V_i\}$	– set of operation high voltages for the PM–tubes.

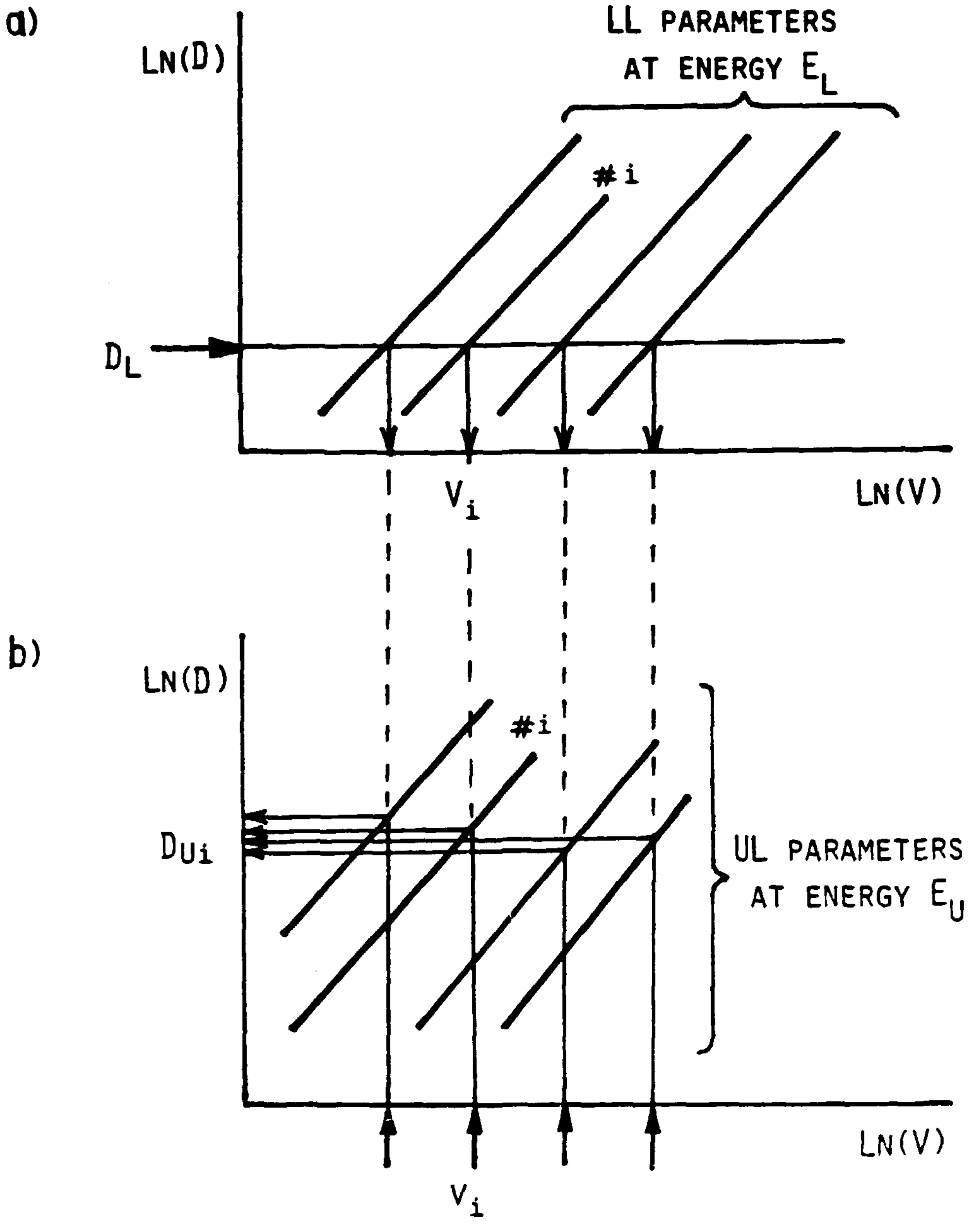

Fig.12. (a) Determination of the operation high voltages, V_i , for the detectors at the chosen lower discrimination amplitude, D_L, and lower energy limit, E_L (steps 1 and 2 of the procedure).

(b) Determination of the upper discrimination levels, D_{Ui}, corresponding to the chosen upper limit energy, E_U, at the earlier found high voltages, V_i (steps 3 and 4 of the procedure).

4.3. Verification of Absolute Calibration

The PM–base has two kinds of output, one fast timing output and one linear signal output. For the time–of–flight spectrometry the fast timing signal is used and it is used also in the count rate measurement. Connecting the output signal to an Analog to Digital Converter, ADC, would be a straightforward way to check the absolute calibration. However, the ADC accepts only pulses of a few μs width while the timing signal has a pulse width of a few ns. To make the ADC measurement possible we have chosen to connect the linear output signal, B, as the input to the ADC and the fast timing signal, A (which is discriminated), triggers a gating signal for the ADC (Fig.13). The coincidence unit opens the gate only if the A signal is between the lower and upper discrimination levels

$$D_L < A < D_U$$

which allows only the pulses

$$B_1 < B < B_2$$

to be transmitted to the ADC, see Fig.14. The cut values B_1 and B_2 correspond to the lower and upper discrimination levels, D_L and D_U, of the signal A. When the B amplitude scale is energy calibrated, the energies E_1 and E_2 are found which correspond to the D_L and D_U amplitudes of the A signal. The energies E_1 and E_2 should be equal to the lower and upper energy levels, E_L and E_U, which were assumed for the calibration.

The linearity of the system can also easily be investigated (*cf* Appendix, paragraph A2) by changing the lower level discrimination D_L and repeating the B amplitude distribution measurement. An experimental $D = D(E)$ function is then found (through $B = B(E)$).

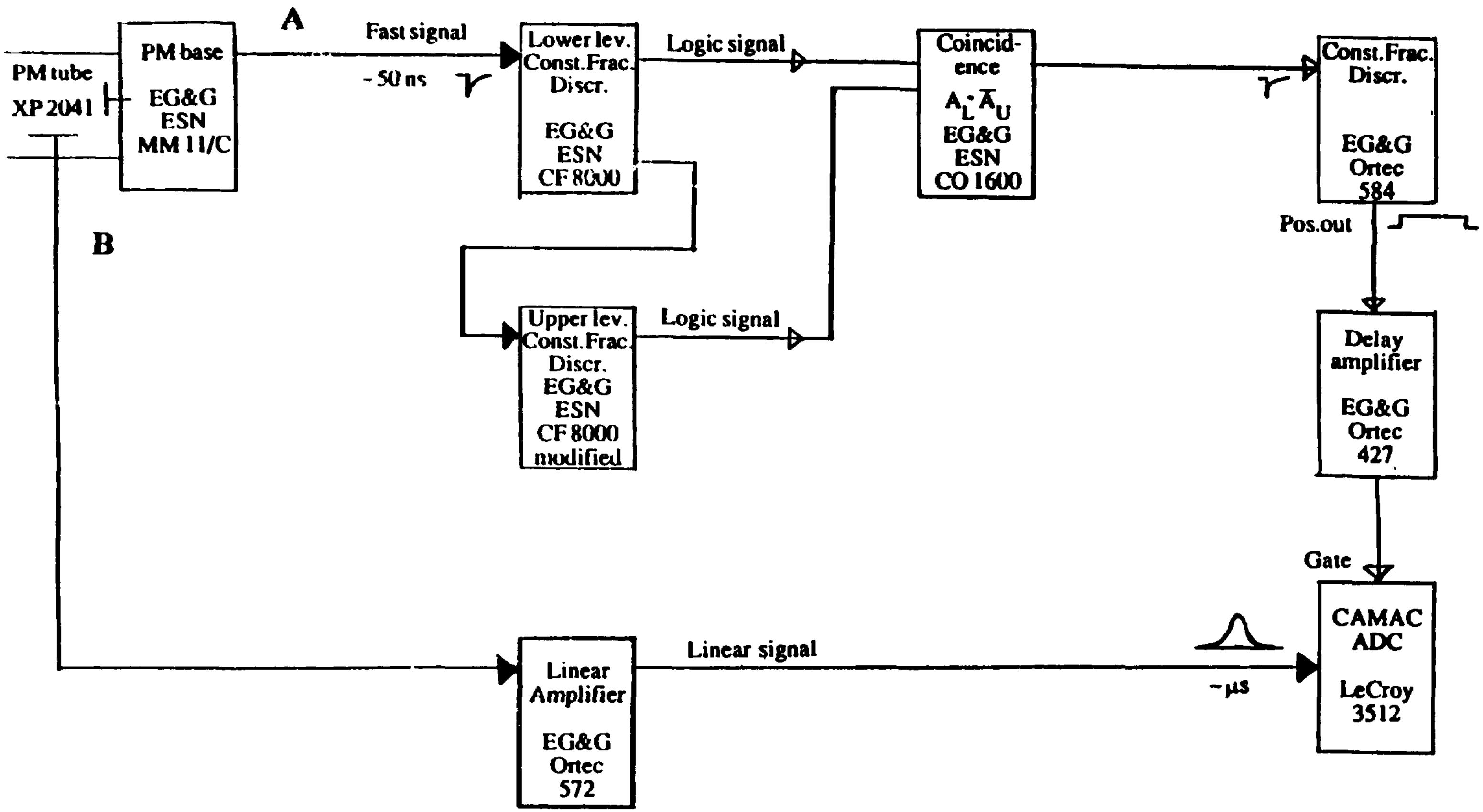

Fig.13. Block diagram of the setup for the measurement of the amplitude distribution of the linear signal, B, gated by the discriminated fast signal, A.

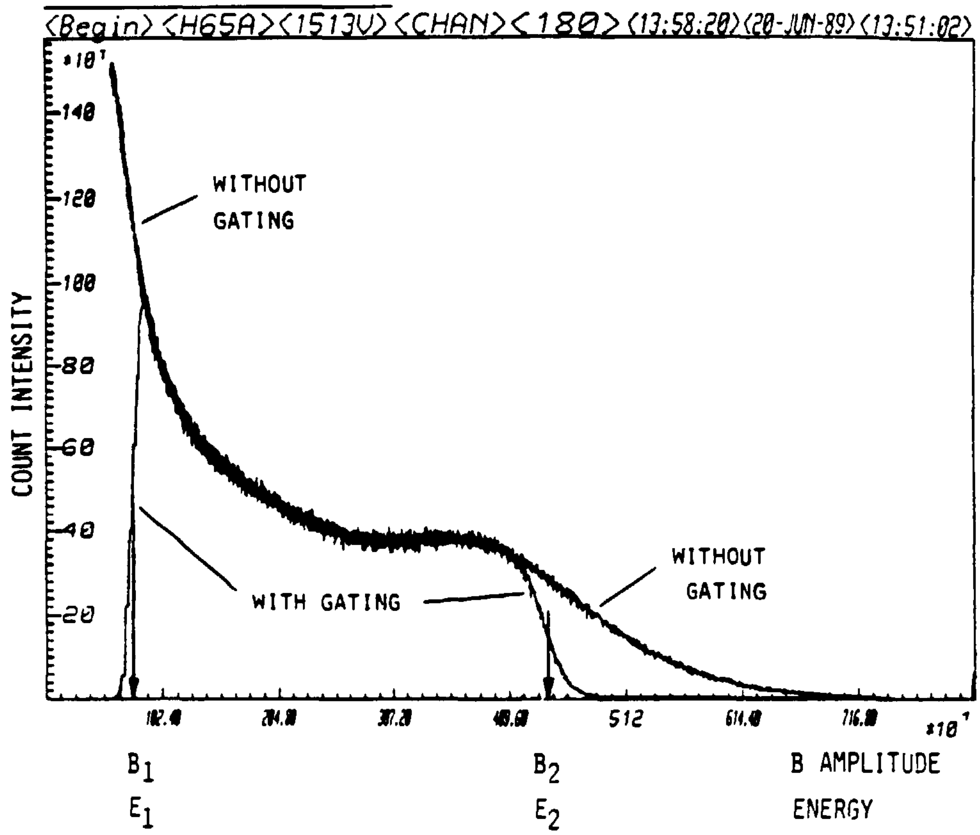

Fig.14. Result of the measurement of the linear signal amplitude distribution in the system shown in Fig.13.

5. Accuracy of Calibration

The accuracy of the calibration is dependent on many factors. The following items are the most important.

1) DC levels of the fast timing output signal from the PM–base:

a) a deviation of 2 mV means 2% inaccuracy of the LL discriminator (LL amplitude is *ca* 100 mV);

b) an uncertainty of the origin of the energy amplitude scale is introduced if DC $\neq 0$ (it is assumed (0,0) in the D(E) dependence).

2) Discrimination levels (particularly LL):

a) the best possible precision is *ca* 2 mV due to the precision of potentiometers and permanent small rapid fluctuations;

b) long time fluctuations (instabilities) on the order of several mV, which is several percent of the amplitude of the LL discriminator, can occur; these fluctuations are seldom observed but are possible due to instability of supplying voltages for discriminators, fluctuations in temperature, humidity, etc.

3) The precision of the amplitude–to–energy scaling of the linear B signal:

a) the precision is affected by the DC level of the linear output, and by

b) the resolution of the scintillator and statistical errors in the amplitude distribution measurements; inaccuracies, in our experiments, finally gave a precision of *ca* 20 keV which is only 2% of 1 MeV, but this inaccuracy has a stronger influence at lower energies,

c) the geometry of the measurement is important because a change in the source position introduces a change of the observed amplitude (corresponding in certain cases to 20 keV).

4) The precision of the determination of the calibration energy E_0 :

a) the precision is not only affected by the counting statistics but also by other fluctuations during the E_0–measurements;

b) the precision of the determin tion of the E_0 energy is affected by the precision of the energy scale (see i. m 3a).

5) Saturation of the A amplitude signal concerning the UL discriminators:

The saturation process is individual for different PM–tubes and PM–bases and may cause the amplitude signal as a function of the HV to become non–linear in a log–log diagram at higher voltages.

6) HV precision:

a) the precision of the HV–unit is declared to be 1.5 V;

b) the time–stability of the HV is acceptable inside the precision interval;

c) the time of stabilization after a change in HV may be several seconds.

7) The precision of the calibration parameters (K_{0i}, n_i) is affected by:

a) the discrimination level values (see item 2) during the count rate measurements and the verification procedure;

b) HV values (see item 6);

c) non–linearities due to fluctuations of the DC–levels and discrimination levels (see items 1 and 2) and saturation (see item 5).

6. Discussion and Conclusions

Many measurements were performed during elaboration of the presented method of energy calibration for the TANSY neutron detectors. We include some results in the Appendix although the obtained data are preliminary. However, general conclusions can be drawn on that basis. Full results of the calibration measurements for two arrays of the TANSY neutron detectors will be reported later.

The suggested method for calibrating an array of detectors is time–consuming. However, once the calibration parameters are obtained the procedure for checking the performance and function of the detector array is rapid and simple.

The most time–consuming procedure is the experimental measurement of the calibration parameters n_i and K_{0i}. To obtain these parameters the method is as follows:

1) Choose a fixed value $D = (D_j)_i$ for the i^{th} LL discriminator and run the count rate measurement. As a result the number of counts, $P_i(V)$, as a function of high voltage of the PM–tube for the used calibration source (*eg* ^{60}Co) is obtained.

2) Calculate the differentiated number of counts versus high voltage $\{dP/dV = f(V)\}_i$ to obtain the voltage, $(V_j)_i$, corresponding to the maximum of the dP/dV curve.

3) Change the value of the LL discrimination, $D = (D_{j+1})_i$, and repeat steps 1) and 2) until a sufficient amount of the $(D_j,V_j)_i$ data is collected. The accuracy of the calibration parameters is dependent on the amount of collected data. In our measurement 5–6 points have been chosen.

4) The calibration parameters, n_i and K_{0i}, are now given by the slope and the intersection with the ln(V) axis in a ln(D) = f(ln(V)) diagram.

5) If the signal from the LL for the UL discriminator input is different from the original one then it is necessary to repeat from step 1) to 4) using the UL discriminator in the role of LL discriminator.

When the calibration parameters n_{Li}, n_{Ui}, K_{0Li} and K_{0Ui} for each detector are known the procedure of calculating the high voltages and discrimination levels using the energy E_0 to obtain an absolute energy calibration of the detectors is possible. Finally, by adjusting the high voltage, V, and the discriminations, D_1 and D_2, the required energy interval, $[E_1, E_2]$, is obtained.

To increase the accuracy of the calibration parameters it is important to adjust carefully the DC levels of the PM–bases to zero. Then the precision of the discrimination levels (as an independent variable during the count rate measurement, and as a final setting) is better. Uncertain DC levels strongly influence the relation between the energy E_1 through the signal B_1 to the signal $A = D_1$ in the verification experiments. The uncertainty of DC levels gives a false D(E) dependence, especially in the important region of the lower discrimination.

The precision and stability of the high voltage are significant due to the n–power dependence in the amplification of the signal. A relative standard deviation, $\sigma(V)/V$, of only 0.1 % (*ie* the lowest possible at 1500 V) gives the standard deviation for the n_i parameters of $n_i \cdot \sigma(V)/V \simeq 1.5\%$. Therefore, it is important to wait some time after each change of the voltage in the count rate measurements to let the module stabilize (*eg* 5 s).

To conclude, the measurements gave as results:

1) deviations of 15 keV (electron energy) for the signals from different detectors;

2) the lowest LL discrimination (D_1) of *ca* 150 mV;

3) the highest UL discrimination (D_2, attenuated signal) of about 1000–1100 mV, *ie* *ca* 2300 mV of the original signal.

This should enable the adjustment of the discriminator levels to correspond to 100–1500 keV (electron) which corresponds to 500–4000 keV neutron energy window. By a very careful determination of the calibration parameters better results are expected which means a wider energy interval with a possible accuracy of 10 keV. That is the best accuracy that can be achieved with the present apparatus.

APPENDIX

Preliminary results from the energy calibration of the TANSY neutron detectors

A1. Calibration Parameters for the Neutron Detectors

The calibration parameters have been determined for each neutron detector in the way described in paragraph 3.3 (using separately the LL and UL discriminators). The set of parameters $\{ K_{0L}, n_L, K_{0U}, n_U \}_i$ has been calculated from a fit of the straight line to the collected $(D_j, V_j)_i$ data for the i^{th} detector. An example of the results for one branch of the TANSY spectrometer is given in Fig.A1. It contains a print of the output of a computer program which calculates the settings for the neutron detectors. The settings have been calculated using the obtained calibration parameters (also listed, as ln(C) and n) when the following conditions were required:

Energy window: 100 keV < E < 1400 keV (electron),

Lower discrimination level: 150 mV.

The E_0 energy for ^{60}Co (which corresponds to the amplitude distribution maximum position when the E_C energy is adjusted to a half–maximum, *cf* paragraph 4.1 and Fig.11) was an approximated value.

One can notice big differences in amplification of individual PM–tube – PM–base sets, which is reflected by a wide interval of the operation high voltages (from 1397 to 1623 V). The slopes n_i (a value proportional to the number of dynods) for different detectors are close to each other. The mean value $\bar{n}_L = 14.08$ (when the LL discriminators are used) with an average standard deviation for the individual n_i values $s = 0.25$. When the UL discriminators were used the $\bar{n}_U = 13.50$ was obtained with $s = 0.30$. A difference between the $\bar{n}_L$ and $\bar{n}_U$ values is due to various inaccuracies in the system during elaboration of the method, which is mentioned in paragraph 5 ('Accuracy of Calibration'). The precision of the calibration will be improved in a further step of the work.

SETTINGS for energy-calibrated NEUTRON DETECTORS - branch A.

Input data:

LL Energy = 100.0 [keV] LL Discrim. = 150.0 [mV]
UL Energy = 1400.0 [keV]

Calibration parameters:

E0 = 822.4 [keV] - Co-60 Energy

Neutron detector parameters: VERSION 0 of 22-JUL-89

det#A	LL LN(C)	LL n	UL LN(C)	UL n
00	-98.00778	14.2398	-98.81548	14.2419
01	-96.88528	14.1798	-93.60132	13.621[illegible]
02	-95.83118	14.0359	-91.80809	13.3[illegible]
03	-97.59722	14.2820	-94.32255	13.7279
04	-99.64397	14.5162	-91.30981	13.2709
05	-96.48675	14.0628	-93.74849	13.5832
06	-96.62009	14.0335	-90.68847	13.1221
07	-98.44909	14.2824	-94.13954	13.5940
08	-92.44746	13.7479	-87.70313	12.9824
09	-95.34250	14.0641	-91.69955	13.4513
10	-95.17468	13.9876	-92.69332	13.5355
11	-96.34103	14.1434	-91.33918	13.3488
12	-94.46368	13.8599	-93.11914	13.5679
13	-96.73176	14.2705	-92.65548	13.6006
14	-97.19422	14.2190	-95.27670	13.8496
15	-91.27195	13.4339	-90.32767	13.1970

SETTINGS FOR NEUTRON DETECTORS - BRANCH A.
==

det#A	LL discr. [mV]	UL discr. [mV]	HV [V]
00	150.	951.	1608.
01	150.	930.	1532.
02	150.	913.	1533.
03	150.	955.	1528.
04	150.	921.	1563.
05	150.	948.	1583.
06	150.	938.	1623.
07	150.	964.	1622.
08	150.	944.	1397.
09	150.	924.	1459.
10	150.	920.	1500.
11	150.	934.	1503.
12	150.	948.	1524.
13	150.	945.	1447.
14	150.	951.	1535.
15	150.	952.	1516.

Fig.A1. Example of the settings for the TANSY neutron detectors obtained from the energy calibration procedure.

(Note: the pulse amplitude for the UL discriminator is attenuated, $A_U \approx 0.5\ A_L$).

A2. Verification of the Absolute Calibration

The elaborated method of the absolute energy calibration of the TANSY neutron detectors has been verified as described in paragraph 4.3. The amplitude distribution of the signal B gated by signal A (*cf* Fig.13) has been measured for several detectors. The operation voltage, V_i, for the i^{th} detector was used, which was found from the method for ; chosen lower levels of the discrimination and the energy.

First the B pulse amplitude scale (for the i^{th} detector at the V_i voltage) was calibrated to the energy by the amplitude distribution measurements using the γ sources listed in Table 1. Then the ^{60}Co source was used to get a series of the amplitude distributions of signal B gated by signal A crossing different lower discrimination levels, D_{Lk} (*cf* Fig.14). The cut values B_k (corresponding to different positions of the B_l value in the figure) were found from the distributions giving the energies E_k, which corresponded to the discrimination levels D_{Lk} for pulse A. In this way an experimental dependence of the discrimination level, D_L, on the energy was found. The same dependence was obtained from Eq.(19) (for the pulse amplitude A equal to the discrimination level D_L). The measured and calculated dependences are plotted in Fig.A2. An observed discrepancy is about 15 keV. One should remember that the 'experimental' results are indirect (the signal of interest, A, only controls the measured one, B) and are also given with a certain error resulting from calibration of the energy scale. However, the authors hope to obtain a better agreement in the final procedure of calibration of the neutron detectors when the conclusions from the present work (see paragraph 6) will be taken into account and the E_0 value which is used in calculation will be improved.

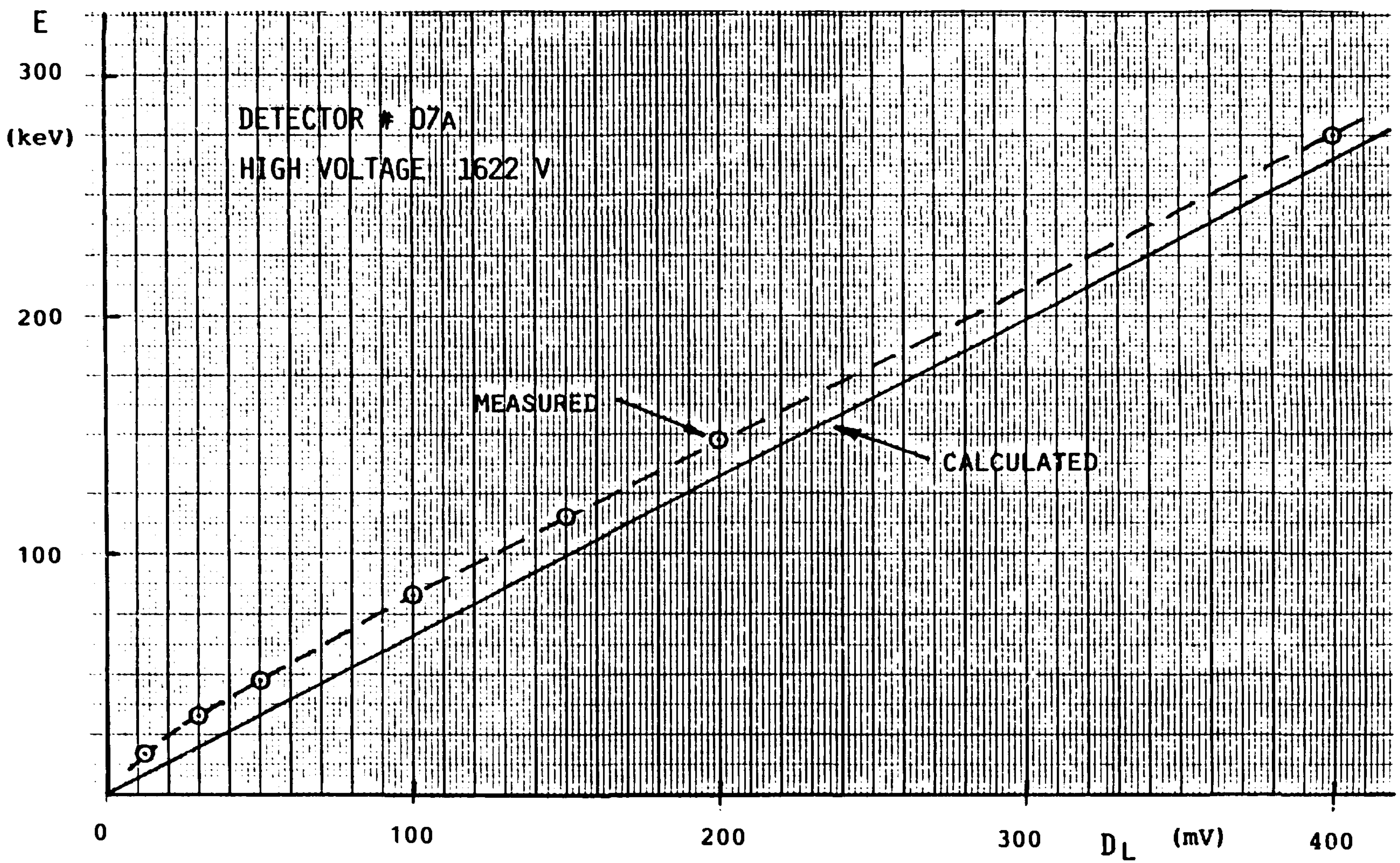

Fig A2. Correspondence of the energy E to the lower discrimination level D_L.
A dependence obtained for signal A from the used method of the energy calibration is compared with the results deduced for that signal from the measurements of the B signal amplitude distribution.

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