Investigation of the Pulse Height Distribution of Boron Trifluoride Proportional Counters

I. Ö. Andersson and S. Malmskog
INVESTIGATION OF THE PULSE HEIGHT DISTRIBUTION OF BORON TRIFLUORIDE PROPORTIONAL COUNTERS

by

I Ö Andersson  S Malmskog

Summary:

The report describes a theoretical and experimental investigation of the factors that determine the pulse height distribution of BF$_3$ proportional counters irradiated by thermal neutrons.

The branching ratio of the B$^{10}$(n,$\alpha$)Li$^7$ reaction for thermal neutrons has been measured.

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1. Introduction

Boron trifluoride proportional counters are used as detectors for thermal neutrons. They are characterized by high neutron sensitivity and good gamma discriminating properties. The neutron recording is performed by the reaction $^{10}\text{B} (n,\alpha) ^7\text{Li}$, which has a cross section for thermal neutrons of 4017 barns (1). The Q-value of the reaction is $+2.78\text{ MeV}$. In about 6.5% of all cases the reaction goes to the ground state of $^7\text{Li}$ and the remaining part goes to its first excited level, which is at $0.48\text{ MeV}$. The disintegration energy is distributed between the $^7\text{Li}$ and $\alpha$ particles. They ionize the gas in the counter and an electric pulse arises. Under ideal conditions two sharp peaks would arise in the pulse height spectrum, one corresponding to the energy $2.78\text{ MeV}$ and one to $2.30\text{ MeV}$. Experiments show often great deviations from this result. The reasons may be (1) fluctuation of the number of initial ion pairs and (2) fluctuation of the gas amplification. The fluctuation of the number of initial ion pairs can arise due to wall effects, that is the ionizing particles reach the walls of the counter before all the energy is emitted. The fluctuation of the gas amplification can be due to electron capture by the impurities in the counter gas or to saturation effects because of the space charge at the anode wire, particularly at high gas amplification.

The purpose of this investigation was to measure the pulse height distributions from $\text{BF}_3$ proportional counters and to study the important factors. The result of a measurement of the branching ratio for the $^{10}\text{B} (n,\alpha) ^7\text{Li}$ reaction is also reported.

2. Apparatus

The construction of the counters used in the experiments is shown in Fig. 1.
The material is high conductivity oxygen-free copper. The diameter of the tube is 30 mm and the sensitive length 200 mm. The anode wire is made of tungsten, $\phi$ 0.03 mm. It is screened at both ends by canula tubes, $\phi$ 0.7 mm. Before being filled with gas the counters are carefully outgased in vacuum at about 400°C. The counters were filled with $^{10}$B$_3$F$_3$ (95% $^{10}$B) and argon in different proportions.

A schematic of the electronic equipment is shown in Fig. 2. The electrical pulses from the detector are amplified in a low noise amplifier of the cascade type. The pulse height distributions are measured by a 256-channel analyzer of type Nuclear Data ND 120.

1 c Po-Be, placed in a paraffin block, was used as neutron source.

3. Purification of the boron trifluoride gas

The gas in a proportional counter must not contain substances which absorb free electrons. If the primary electrons are absorbed before they reach the anode for gas multiplication, the pulse height will not be proportional to the primary ionization. For example the contents of oxygen gas or water vapour, which both have a high electron affinity, have to be kept in the region 1-100 ppm (3, 4) - the value depends on the counter gas - if their influence is to be negligible.

Boron trifluoride, as usually prepared, has to be carefully purified before it can be used in a counter. In our case the boron trifluoride is generated from a boron trifluoride/calcium fluoride complex (CaF$_2$BF$_3$). The complex is heated in vacuum up to 250°C at which BF$_3$ escapes. The gas passes a cold trap with solid carbon dioxide and acetone to separate water vapour etc., and is then collected in a trap which is cooled by liquid air. The gas obtained in this way contains small quantities of electron absorbing gases, including about 1% SiF$_4$, which has to be removed to yield an ideal counter gas. We therefore make a second purification, which is done in a vacuum system with three cold traps (No. 1, 2, 3) connected in series. Cold trap No. 1 is kept at a constant temperature of -124°C by a thermostat (5), No. 2 at -166°C, also by a thermostat, and No. 3 is cooled by liquid air. The thermostats keep the temperatures constant to within $\pm$ 0.2°C. The BF$_3$ gas is
transferred to cold trap No. 1 by cooling with liquid air (-193°C).
Between No. 1 and No. 2 there is a needle valve. At -124°C the pressure
of the BF₃ gas is about 100 mm Hg and the needle valve is adjusted to
pass a gas stream of 15 ml/min (NTP) from cold trap No. 1 to cold trap No. 2.
BF₃ is condensed in cold trap No. 2, while the impurities, especially SiF₄,
proceed to cold trap No. 3. During the whole procedure a high vacuum pump
is connected to cold trap No. 3.

The purified BF₃ gas from cold trap No. 2 is used to fill the counters.
First, however, the gas is tested in a pulse ionization chamber connected to
the vacuum system. A neutron source is placed close to the ionization
chamber and a discriminator curve is recorded. Information of the
electrical pulse height distribution is then obtained, which reveals the
quality of the gas.

4. Pulse spectrum from BF₃ proportional counters

When a counter, containing BF₃ gas, is irradiated with thermal
neutrons, the following two nuclear reactions are obtained:

\[
\begin{align*}
\text{Li}^7 + \text{He}^4 & \rightarrow \text{Li}^7 + \text{He}^4 + Q_1 \quad (2.78 \text{ MeV}) \\
\text{Li}^7* + \text{He}^4 & \rightarrow \text{Li}^7* + \text{He}^4 + Q_2 \quad (2.30 \text{ MeV})
\end{align*}
\]

Li⁷ is formed in the ground state and in its first excited level. The released
energy, Q₁ and Q₂, respectively, is emitted as kinetic energy of the reaction
products Li⁷ and He⁴. They ionize the gas in the counter. The number
of ion pairs formed is proportional to the kinetic energy of the particles.
A proportional counter delivers an electrical pulse directly proportional to
the primary ionization. From a BF₃-filled proportional counter an ideal
pulse height distribution would consequently be composed of two sharp
peaks corresponding to the two energies Q₁ and Q₂.

In Fig. 3 an experimental recording of the pulse height spectrum
from a BF₃ counter is shown. Besides the two peaks expected, continuous
distributions on the low energy sides of the two peaks have arisen. They
are due to the fact that some of the reaction products reach the walls of
the counter before they have dissipated all their kinetic energy. The phenomenon is usually called wall effect and is quantitatively given as the fraction of all the nuclear reactions of the same kind whose fragments hit the wall. A theoretical and experimental investigation of the wall effect is described in section 6 of this paper.

It appears from the pulse height spectrum in Fig. 3 that the peak at 2.30 MeV is much larger than the one at 2.78 MeV. This means that the dominant reaction is that in which Li⁷ is formed in the excited level. The ratio between the probabilities of the two reactions taking place is indicated by the branching ratio.

It is defined as

$$\frac{\sigma \left[ B^{10 \text{(n,\alpha)}} \text{Li}^7 \right]}{\sigma \left[ B^{10 \text{(n,\alpha)}} \text{Li}^7* \right]}$$

A determination of the branching ratio is reported in section 5.

In Fig. 3 two edges in the continuous distribution appear. They are caused by boron reactions which occur close to the walls of the counter. In order to preserve the momentum, the He⁴ and Li⁷ fragments in a nuclear reaction with thermal neutrons are emitted in opposite direction. The He⁴ and Li⁷ fragments obtain energies of 7/11 and 4/11 respectively of the disintegration energy 2.30 MeV, which gives the values of 1.46 MeV and 0.84 MeV. Consequently, when a reaction takes place on or close to the wall, only one of the He⁴ or Li⁷ particles contributes to the ionization, the result being that edges in the pulse height distribution are obtained at 0.84 MeV and 1.46 MeV. The edges in the distribution at 1.01 MeV and 1.77 MeV, which are to be expected from the reaction direct to the ground state of Li⁷ with the total energy of 2.78 MeV, are too small to be discerned. The peak at 1.95 MeV is caused by some wall effect and disappears when the pressure in the counter is increased.

The energy resolution of a proportional counter is given by $\Delta E$, where $\Delta E$ is the width of the peak in pulse height distribution at half the $E$ height of the peak and $E$ is the energy of the peak. Even if a fixed quantity of energy is emitted in a proportional counter there are variations in the pulse height.
The factors that determine the resolution in the energy range over 200 keV are variations in the gas amplification because of irregularity of the anode wire, electron absorption in the impurities in the counter gas and drift in the electronics. The electron absorbing gases are particularly troublesome in connection with BF$_3$ and careful gas cleaning is necessary in order to obtain a useful energy resolution.

5. Measurement of the branching ratio

The pulse height distribution of a boron counter shows that most of the B$^{10}$ (n,$\alpha$) Li$^7$ reactions go via the first excited level of Li$^7$ (Fig. 5). Published measurements of the branching ratio have shown values between 8.6% and 4%. However, the most recent measurements indicate that the correct value is close to 6.5%.

In most determinations made up to now, the energy resolution has been rather unsatisfactory. This causes inaccuracies in separation of the actual peaks, particularly when estimating the number of impulses or tracks from the high energy branch.

Proportional counters filled with a mixture of B$^{10}$F$_3$ and argon have provided favourable conditions for an accurate determination of the branching ratio. By having a low partial pressure of B$^{10}$F$_3$, about 10 mm Hg, a high energy resolution has been obtained, about 2.5%. The addition of argon, 1–3 atm, has caused a reduction of the wall effect, so that the continuous pulse distribution at the low energy sides of the peaks is kept low. This gives an improved precision in the determination of the number of pulses in the peaks and makes it unnecessary to correct for pulses from 2.78 MeV disintegrations which appear at 2.30 MeV. The branching ratio is obtained from the quotient between the sums of the number of pulses in the 2.78 MeV peak and in the 2.30 MeV peak. The measurements have been performed with different gas mixtures and with different gas amplification factors in order to avoid systematical errors. The results are given in Table I, and Fig. 5, 6 and 10 show examples of measured pulse height distributions. The standard deviation of the average value is $\pm$ 0.05%. In all the recordings of pulse spectra it was arranged that the number of pulses in the smallest peak exceeded 10,000 in order to give
a statistical accuracy of better than 1%. Systematical errors are estimated to $\pm 0.05\%$. The result of the measurement of the branching ratio of the $^{10}\text{B}(n,\alpha)^7\text{Li}$ reaction with thermal neutrons is thus $6.47 \pm 0.07\%$.

Table II contains a review of earlier measurements of the branching ratio. It appears that our value is in excellent agreement with the results of de Juren and Rosenwasser and of Brinkmann and Greber.

<table>
<thead>
<tr>
<th>Gas filling</th>
<th>Gas amplification</th>
<th>Branching ratio %</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 mm Hg $^{10}\text{B}_3$ + 3 atm argon</td>
<td>2</td>
<td>6.45</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6.52</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>6.49</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>6.36</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>6.27</td>
</tr>
<tr>
<td>70 mm Hg $^{10}\text{B}_3$ + 3 atm argon</td>
<td>5</td>
<td>6.75</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>6.48</td>
</tr>
<tr>
<td>100 mm Hg $^{10}\text{B}_3$ + 1 atm argon</td>
<td>3</td>
<td>6.22</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>6.50</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>6.54</td>
</tr>
</tbody>
</table>

Average value $6.47 \pm 0.05\%$
**TABLE II**

Earlier measurements of the branching ratio.

<table>
<thead>
<tr>
<th>Year</th>
<th>Method</th>
<th>Branching ratio %</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1945</td>
<td>Cloud chamber (400 tracks)</td>
<td>6.7</td>
<td>Bøggild (6)</td>
</tr>
<tr>
<td>1948</td>
<td>Cloud chamber with ( \text{B(OCH}_3\text{)}_3 \text{ gas} )</td>
<td>8.6</td>
<td>Gilbert (7)</td>
</tr>
<tr>
<td>1949</td>
<td>Ion-chamber with ( \text{BF}_3 \text{ gas} )</td>
<td>8.0</td>
<td>Stebler, Huber and Bichsel (8)</td>
</tr>
<tr>
<td>1950</td>
<td>Ion-chamber with thin boron layer</td>
<td>5.8 ± 0.1</td>
<td>Hanna (9)</td>
</tr>
<tr>
<td>1951</td>
<td>30,000 tracks in nuclear emulsions</td>
<td>4.27 ± 0.15</td>
<td>Ciller and Lonchamp (10)</td>
</tr>
<tr>
<td>1952</td>
<td>Ion-chamber with thin boron layer</td>
<td>6.3 ± 0.9</td>
<td>Rhodes, Franzén and Stephens (11)</td>
</tr>
<tr>
<td>1952</td>
<td>Ion-chamber with ( \text{BF}_3 \text{ gas} )</td>
<td>7.0 ± 0.7</td>
<td>Bichsel, Hälg, Hüber and Stebler (12)</td>
</tr>
<tr>
<td>1954</td>
<td>Ion-chamber with thin boron layer</td>
<td>6.52 ± 0.05</td>
<td>de Juren and Rosenwasser (13)</td>
</tr>
<tr>
<td>1957</td>
<td>Prop. counter with ( \text{BF}_3 \text{ gas} )</td>
<td>4.0 ± 0.15</td>
<td>Sehgal (14)</td>
</tr>
<tr>
<td>1958</td>
<td>Boron in nuclear emulsions</td>
<td>8.6 ± 0.9</td>
<td>Bujdosó (15)</td>
</tr>
<tr>
<td>1960</td>
<td>Prop. counter with ( \text{BF}_3 \text{ gas} )</td>
<td>6.51 ± 0.05</td>
<td>Brinkmann and Greber (16)</td>
</tr>
<tr>
<td>1962</td>
<td>Prop. counter with ( \text{BF}_3 \text{ gas} )</td>
<td>6.47 ± 0.07</td>
<td>This investigation</td>
</tr>
</tbody>
</table>
6. **Investigation of the wall effect**

When the $^7\text{Li}(n,\alpha)^4\text{He}$ reaction takes place near the walls of the counter, one of the reaction fragments is likely to reach the wall without all its energy being dissipated into ionization in the gas. This so-called wall effect gives rise to the continuous distribution on the low energy sides of the peaks in the pulse height spectrum. The wall effect is directly related to the range of the reaction fragments. The wall effect may thus be lowered by increasing the gas pressure in the counter. In Fig. 3-5 a trial series is shown in which the argon pressure has been varied while the $^4\text{He}$ pressure and the gas amplification have been kept constant. It can clearly be seen that the continuous distribution in relation to the number of pulses in the peak decreases with an increased pressure in the counter.

With certain simplifying assumptions it is relatively easy to calculate the size of the wall effect. M. Yamane has shown such a calculation (17). He made use of the circumstances that 1) the nuclear reactions take place uniformly throughout the counter volume, 2) the tracks of the reaction fragments occur in random direction, 3) the $^7\text{Li}$ fragments have a much shorter range than the $\alpha$-particles so that the wall effect will be mainly due to the $\alpha$-particles. The fraction ($n_1$) of the $\alpha$-particles that hits the wall of the counter has thus been calculated as

$$n_1 = \frac{s}{2R} - \frac{1}{64} \cdot \frac{s^3}{k^3} - \frac{3}{6144} \cdot \frac{s^5}{R^5}$$

where $s$ is the range of the $\alpha$-particle in the actual counter gas and $R$ is the radius of the counter. If $s \ll R$, $n_1$ is approximately given by

$$n_1 = \frac{s}{2R}$$

A comparison between values calculated with this formula and from our experimental determinations is presented in Table III. It shows that the theoretical value gives a good estimation of the size of the wall effect.
### TABLE III

Comparison between calculated and measured wall effect.

<table>
<thead>
<tr>
<th>Gas filling</th>
<th>Gas amplification</th>
<th>Calculated value $n_1 = s/2R$</th>
<th>Experimental value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10 \text{mmHg} , ^{10}\text{F}_3 + 250 \text{mmHg argon, Fig. 3}$</td>
<td>7</td>
<td>79 %</td>
<td>89 %</td>
</tr>
<tr>
<td>$10 \text{mmHg} , ^{10}\text{F}_3 + 1 \text{atm argon, Fig. 4}$</td>
<td>7</td>
<td>27 %</td>
<td>35 %</td>
</tr>
<tr>
<td>$10 \text{mmHg} , ^{10}\text{F}_3 + 3 \text{atm argon, Fig. 5}$</td>
<td>7</td>
<td>10 %</td>
<td>12 %</td>
</tr>
<tr>
<td>$100 \text{mmHg} , ^{10}\text{F}_3 + 1 \text{atm argon, Fig. 6}$</td>
<td>8</td>
<td>25 %</td>
<td>33 %</td>
</tr>
</tbody>
</table>

The remaining part of the $\alpha$-particles ($n_2$)

$$n_2 = 1 - \frac{s}{2R}$$

will contribute to the line spectrum of the reaction. By assuming that the counter gives a gaussian distribution the pulse height spectrum of the $\alpha$-particles can be approximately described by

$$N(E) \approx (1 - \frac{s}{2R}) \frac{1}{\sigma \sqrt{2\pi}} \exp \left(-\frac{(E-E_0)^2}{2\sigma^2}\right) + \frac{s}{2RE_0} \int_0^\infty \frac{1}{\sigma \sqrt{2\pi}} \exp \left(-\frac{(E-x)^2}{2\sigma^2}\right) dx$$

where $\sigma$ is taken from the experimentally measured spectrum, $E_0$ is the initial energy of the $\alpha$-particle. The second term in the equation is the so called error integral. It will be found in, e.g., Jahnke-Emde-Lösch's "Tables of higher functions".

A calculation of the pulse height spectrum has been performed for a gas filling of $100 \text{mm Hg} \, ^{10}\text{F}_3 + 1 \text{atm argon}$. By inserting the actual values of $\frac{s}{2R}$ and $\sigma$ in equation 1, the pulse spectrum from the $\alpha$-particles is
obtained. To this the constant contribution from the Li$^7$ fragments is then added, which results merely in a displacement of the spectrum by 0.84 MeV further up on the energy scale. In Fig. 6 the calculated values have been plotted together with the measured distribution. The agreement is as good as can be expected by this method. The edge at 1.46 MeV does not appear in the theoretical spectrum. It arose, as was shown in section 4, due to wall effect from the Li$^7$ fragments, which was neglected in this calculation.

7. The energy resolution as a function of the gas amplification

In a fundamental work by Hanna, Kirkwood and Pontecorvo 1949(18) an investigation was made of how the proportionality between the number of originally formed ion pairs and the out-pulse from the counter change with the high voltage to the detector. It was found that the proportionality remained constant within 1.5% for gas amplification factors smaller than a certain critical value $M_c(E)$, which was dependent on the amount of the absorbed energy. The energy dependence of $M_c(E)$ was proved to be approximately expressed by the relation

$$M_c(E) \times E = \text{const.} \approx 10^8,$$  

(eq. 2)

where $E$ is the absorbed energy in electron volts. The critical value of the gas amplification factor is caused by a space charge of positive ions around the central wire that reduces the intensity of the electrical field. As a consequence it can be stated that the energy resolution of the counter decreases when the voltage to the tube becomes too high. In order to investigate the conditions in boron counters the gas amplification factor has been measured as a function of the voltage. If $P_i$ and $P_p$ are the electronic amplifications in, respectively, the ionization and the proportional regions, the gas amplification factor ($M$) is obtained by

$$M = \frac{P_p \cdot F_i}{P_i \cdot F_p}$$

where $P_i$ and $P_p$ are the measured pulse heights in the ionization and the
proportional regions. The results are shown in Fig. 7. In connection with these measurements, a series of pulse height spectra was recorded with different gas amplification factors. In each spectrum the half-value width ($\Delta E$) of the 2.30 MeV-peak was estimated. The resulting dependence of $\frac{\Delta E}{E}$ as a function of $M$ is presented in Fig. 8. The diagram shows that the resolution of the counter is maximum for $M$-values between 3-15. For $M < 3$ the resolution decreases slowly, which is due to the anisotropic pulse height in the ionization region. For $M > 25$ the resolution decreases quickly. Equation 2 gives $M_c (E) = 43$ for an absorbed energy of 2.3 MeV. This is in reasonable agreement with the experimental result considering the approximative character of equation 2. Figures 5 and 9 show two measurements with the same counter containing 10 mm Hg $BF_3 + 3$ atm. argon. The gas amplifications in the two cases were 7 and 40 respectively. It is obvious that an amplification factor above the critical value causes a broadening of the peak towards the low-energy side. The reason for this phenomenon is that the amplification depends on the direction of the ionization track in the counter tube. A track that goes at right angles to the anode wire will create an ion cloud which is concentrated to a point of the wire, while a track which runs parallel with the wire gives an ion cloud that is more extended and not so dense. If the tube works at a voltage where the ion cloud considerably affects the gas amplification factor, a lower pulse height is obtained in the first mentioned case.

The conclusion that can be drawn from these results is that $BF_3$ counters have to be operated with a gas multiplication factor chosen in a rather limited range if optimum energy resolution is to be attained.

8. The pulse height distributions from counters with a high $BF_3$ pressure

The spectra hitherto discussed relate to counters that contained $BF_3$ at pressures between 10-100 mm Hg. Higher pressures, up to 2 atm, are, however, very commonly used in order to obtain a better neutron sensitivity. Figures 11 and 12 show spectra from counters filled with, respectively, 205 and 1140 mm Hg $BF_3$. They show what has been proved to be a pervading tendency, namely that the energy resolu-
tation deteriorates with increased partial pressure of BF$_3$. The reason for this may be that there are impurities in the gas that have not been removed by the purification process or that the boron trifluoride has a certain electron affinity. The qualities of counters taken from different production series are the same. Repeating the purification process brings no improvement. A comparison has been made with tubes delivered from 20th Century Ltd., England, and Nuclear Chicago Corp., USA. They also indicate a deterioration of the energy resolution at an increased pressure. For counters with the same diameter and B$_{10}F_3$ pressure the resolution is almost the same for tubes from the two mentioned firms as for tubes of our own production.
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15. E. Bujdosó, Investigation of the $^{10}\text{B}(n,\alpha)^7\text{Li}$-reaction by the photoemulsion method.
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FIG. 1

NEUTRON COUNTER TYPE BA
MATERIAL COPPER 0.5 mm
ANODE TUNGSTEN 0.03 mm

FIG. 2

BLOCK DIAGRAM OF THE ELECTRONIC EQUIPMENT
FIG. 3
Type BA
BF$_3$  10 mm Hg
Argon  250 mm Hg
Gas ampl. 7

Counts/Channel

FIG. 4
Type BA
BF$_3$  10 mm Hg
Argon  1 atm
Gas ampl. 7

Counts/Channel
FIG. 5
Type BA
BF₃ 10 mm Hg
Argon 3 atm.
Gas ampl. 7

FIG. 6
Type BA
BF₃ 100 mm Hg
Argon 1 atm
--- Measured spectrum
•••• Calculated spectrum
FIG. 7
Type BA
BF$_3$ 10 mm Hg
Argon 3 atm.

FIG. 8
Type BA
BF$_3$ 10 mm Hg
Argon 3 atm.
FIG. 9

Type BA
BF₃ 10 mm Hg
Argon 3 atm.
Gas ampl. 40

FIG. 10

Type BA
BF₃ 70 mm Hg
Argon 3 atm
Type BC spec.
Diam 15 mm
BF₂ 205 mm Hg
Argon 4.70 mm Hg
HT 1375 V

Counts/Channel

FIG. 11

Type BC
Diam 15 mm
BF₂ 1140 mm Hg
HT 2500 V

Counts/Channel

FIG. 12
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22. The temperature coefficient of the resonance integral for uranium metal
23. Definition of the diffusion constant in one-group theory. By N. G. Sjö-
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20. Optimisation of gas-cooled reactors with the aid of mathematical compu-
19. Determination of elements in normal and leukemic human whole blood
17. Radioactive nuclides formed by irradiation of the natural elements with
12. The effect of a diagonal control rod in a cylindrical reactor. By T. Nils-
11. On the spherical harmonic expansion of the neutron angular distribution
10. Equipment for thermal neutron flux measurements in reactor R2. By E.
9. The space-, time- and energy-distribution of neutrons from a pulsed
8. One-group perturbation theory applied to substitution measurements with
6. Modified Sucksmith balances for ferromagnetic and paramagnetic mea-
5. On the calibration and accuracy of the Guinier camera for the deter-
4. Quantitative determination of pole figures with a texture goniometer by
3. Critical and exponential experiments on 19-rod clusters (R3-fuel) in heavy
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0. The spherical harmonic expansion of the neutron angular distribution
-2. The effect of a diagonal control rod in a cylindrical reactor. By T. Nils-
-3. On the spherical harmonic expansion of the neutron angular distribution
-4. Transmission of thermal neutrons through borail, By P. Akerheim. 2nd rev.
-6. The fast fission effect in a cylindrical fuel element. By I. Carlvik and
-7. Determination of elements in normal and leukemic human whole blood
-8. One-group perturbation theory applied to substitution measurements with
-9. The space-, time- and energy-distribution of neutrons from a pulsed
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