Rietjens, L. H. Th.
Van den Bold, H. J.
1955

Physica XXI
701–718

GAMMA RADIATION IN THE DECAY OF ^{67}Ga

L. H. TH. RIETJENS and H. J. VAN DEN BOLD

Physisch Laboratorium der Rijksuniversiteit, Utrecht, Nederland

Synopsis

The level scheme of ^{67}Zn has been investigated by scintillation coincidence spectrometry. Angular correlation measurements of the 206 keV – 182 keV and 485 keV – 296 keV gamma cascades result in anisotropies of -0.216 ± 0.008 and $+0.27 \pm 0.05$.

The following spins have been allocated to the levels of ^{67}Zn: ground state 5/2, 92 keV 3/2, 182 keV 5/2, 388 keV 3/2 and 870 keV 3/2. Evidence has been found for the existence of another level at 595 $\pm$10 keV, for which a spin of 5/2 is suggested. By delayed coincidences a value of 9.3 $\pm$ 0.2 μsec has been found for the half-life of the 92 keV metastable level in ^{67}Zn.

§ 1. *Introduction.* ^{67}Ga decays by electron capture of 78 hours half-life to a number of levels in ^{67}Zn. The decay has been subject to various investigations which at the end of 1952 had produced the level scheme [1]) consisting of three levels at excitation energies of 92 keV, 182 keV and 388 keV. Starting from this scheme the original object of the present investigation was the measurement of the angular correlation of the 206 keV–182 keV γ-cascade (relative intensity 2.2 per 100 disintegrations). When this investigation had just been started Ketelle, Brosi and Porter [2]) and Meyerhof, Mann and West [3]) published papers on ^{67}Ga which added to the level scheme a number of γ-transitions of higher energy originating from a level of 870 keV in ^{67}Zn.

Moreover a rough measurement of the angular correlation coefficient of the 206 keV – 182 keV γ-cascade by Meyerhof *et al.* resulted in a value of -0.22 ± 0.04.

Both research groups agreed as to the sequence and energies of the levels in ^{67}Zn but there was a definite disagreement regarding the allocation of the spins.

In particular contradictions existed about the spin of the 92 keV metastable ^{67}Zn level. Ketelle *et al.* found a value of 0.63 for the K-conversion coefficient of the 92 keV transition, on which they based their assignment of E2 for the transition and a spin 1/2 for ^{67}Zn^{m}. The lifetime of ^{67}Zn^{m} according to the Weisskopf formula [4]) is in agreement with an

E2 transition. M e y e r h o f *et al.*, however, decided on a mixture of 50% E2 and 50% M1 based on their value of 0.47 for the K-conversion coefficient, from which they concluded to a spin 3/2 for $^{67}Zn^{m}$. So the allocation of the spin to the 92 keV level, as well as the allocation of the spins to the 182 keV and 870 keV levels still remained a matter for discussion and consequently the course of the present investigation has been directed towards a solution of this problem.

§ 2. *The source.* The sources used in these measurements consisted of a solution of $^{67}GaCl_3$ in hydrochloric acid. The ^{67}Ga was produced by a (d, n) reaction on chemically pure zinc metal in the Philips cyclotron at Amsterdam. By exposing the targets for a two hour period to a 10 μA beam of 26 MeV deuterons, sources were prepared which after a week still retained 200 μC activity of ^{67}Ga.

The chemical separation and purfication of the gallium was carried out by the radiochemistry department of the "Instituut voor Kernphysisch Onderzoek" at Amsterdam. The target was dissolved in 38% HCl, NH_4Cl solution and holdback carriers were added and the solution was extracted with isopropyl ether. Gallium chloride was recovered from the isopropyl ether solution by shaking with distilled water, whereupon the watery solution was concentrated by evaporation and the gallium precipitated as hydroxyde by ammonia. The precipitate was then dissolved in a few ml of dilute HCl.

As positron emitters can be very troublesome when angular correlation measurements are carried out in the 180° position, greatest care had to be taken to avoid the presence of ^{66}Ga and ^{65}Zn in the sources. The 15 min ^{65}Ga was to have vanished completely before the gallium was separated from the zinc to avoid contamination of the source with the daughter ^{65}Zn and the source had to be stored for a week to allow the 9.4 hour ^{66}Ga to die out to a negligible activity.

§ 3. *The equipment.* The γ-ray intensity, coincidence, angular correlation and half-life measurements have been carried out using two identical scintillation spectrometers and coincidence circuits of resolving times of 0.3 μsec and of 0.03 μsec. The scintillation spectrometers are of a conventional type consisting of a scintillation counter, a linear amplifier of 0.1 μsec risetime, a differential discriminator and a counting equipment. In the counter NaI(Tl) crystals in the standard Harshaw mounting and selected E.M.I. 6260 photomultipliers are used, mounted horizontally in tubes of aluminium.

The crystals are circular cylinders and they have a diameter and a length of 25.4 mm. The photopeak halfwidth is about 10% at $E_\gamma = 511$ keV (annihilation radiation) for both spectrometers.

The 0.3 μsec coincidence circuit is of the Elmore[5]) type and is fed by the differential discriminator output pulses thus allowing only selected pulses to contribute to the coincidence pulse.

The 0.03 μsec coincidence circuit is a slightly modified version of the DeBenedetti and Richings[6]) type. The equalizer section was largely taken from De Waard[7]). The scheme is given in Fig. 1. The output pulses from the amplifiers are equalized to 2 volts. After being reduced to 0.08 μsec pulse length by 50 cm coaxial cables of 330 Ω characteristic impedance, they are fed to the coincidence circuit, consisting of two crystal diodes, followed by a crystal diode pulse lengthener. This third diode is essential, for it prevents the addition of two single pulses

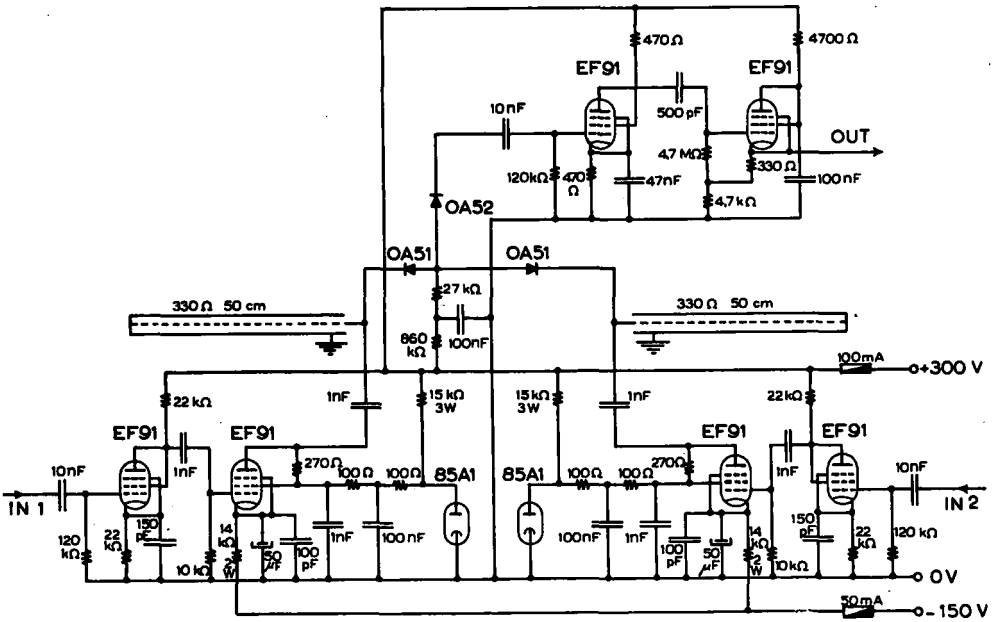

Fig. 1. Schematic circuit diagram of the fast coincidence circuit. The resolving time using NaI(T1) scintillation pulses is 0.03 μsec.

which arrive within the risetime of the subsequent amplifier. The coincidence pulse, which exceeds single channel pulses by a factor of 5, is then delayed for 3.4 μsec to allow for the delay in the differential discriminators, amplified and led through a discriminator to elimate all traces of single channel pulses.

In the complete arrangement with a coincidence resolving time of 0.03 μsec, the remaining output pulse of the discriminator and the output pulse of the 0.3 μsec coincidence circuit mentioned above are fed to a similar 0.3 μsec coincidence circuit (see Fig. 2). The output pulses of the latter

circuit are pulses due to γ-quanta with energies $E_{\gamma 1}$ and $E_{\gamma 2}$ selected by the differential discriminators and coincident within 0.03 μsec.

For the measurement of angular correlation one of the counters is fixed to a round table. The other counter is mounted on an arm fixed to a vertical axis which can be slowly rotated by an electromotor. At predetermined times this counter moves to its next position. The motor is started, stopped and the direction reversed by a switching system which answers to the signal of an electric clockwork, which allows a fully automatic operation.

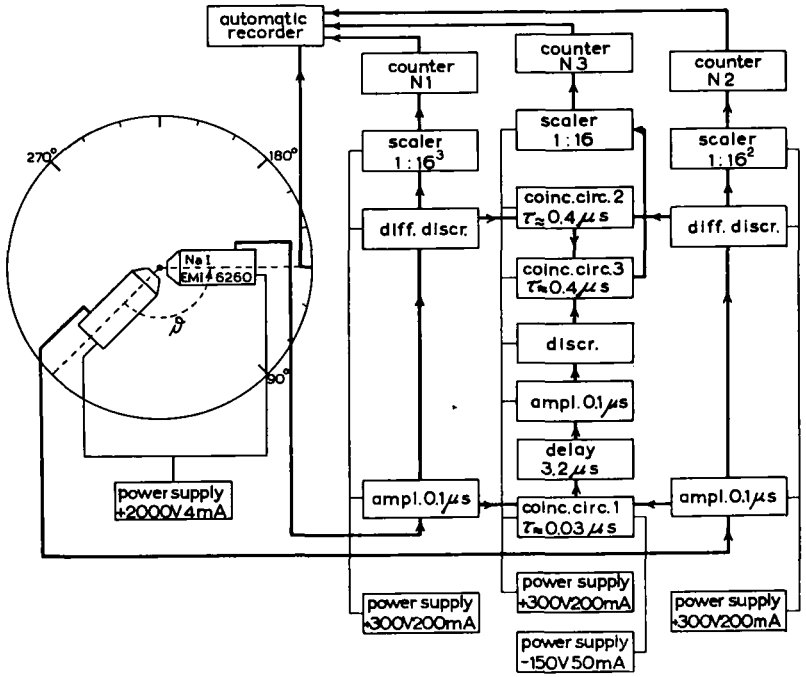

Fig. 2. Block diagram of the complete arrangement for the measurement of $\gamma - \gamma$-angular correlation coefficients.

The results are recorded by a number of registers mounted in the panel under the table (see Fig. 3).

A more detailed account of the equipment will be given in the doctorate thesis of one of us, which is to appear shortly [8]).

§ 4. *Analysis of the scintillation spectrum.* The γ-ray spectrum was first examined by a single channel spectrometer. For this measurement a crystal with a diameter and a length of 25.4 mm and a crystal with a diameter of 40 mm and a length of 51 mm were used. Spectra were taken without and with lead absorbers between 1 and 7 mm thickness. A typical γ-spectrum ($E_\gamma < 520$ keV) taken with the smaller crystal and without absorber is

given in Fig. 4. The higher energy spectrum ($E_\gamma > 450$ keV) was taken with the larger crystal using a 7.9 g/cm^2 lead absorber (see Fig. 5). The spectrometers were calibrated for energy and intensity measurements using the sources ^{22}Na, ^{54}Mn, ^{88}Y, ^{137}Cs and ^{203}Hg. As the detection efficiency of the crystal depends on the distance between source and crystal [9]), in all measurements the sources were placed at a known distance from the crystal surface.

The spectra were analyzed by calculating the shape and intensity of the Compton distribution belonging to each photopeak, for which particular calibrations under the same circumstances as the ^{67}Ga measurements have

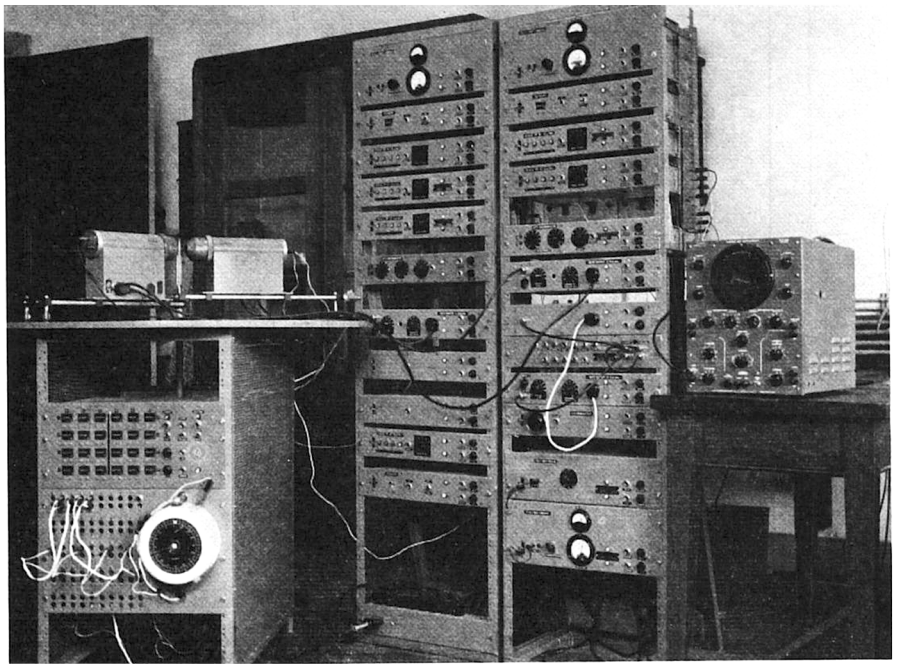

Fig. 3. The experimental equipment: two γ-scintillation spectrometers, coincidence arrangement and automatic system.

been made. An example of this analysis is given in Fig. 5, from which can be concluded not only to the existence of a γ-ray with $E_\gamma = 690 \pm 10$ keV but also to the existence of a γ-ray with $E_\gamma = 595 \pm 10$ keV. The 595 keV photopeak is not immediately evident in Fig. 5, but if the photopeaks due to the γ-rays with $E_\gamma = 870$ keV, 780 keV and 690 keV and their Compton distributions are subtracted from the measured spectrum, the remaining spectrum consistently contains a peak at about 595 keV, which can only for 5% be attributed to pile-up. The measured energies and intensities of the various γ-transitions which contribute to the scintillation spectrum have been given in Table I.

TABLE I

Energy(keV)		Rel. $N\gamma$	Rel. N_e-**)	Exp. α_k	Theor. α_k [10]) M1	Theor. α_k [10]) E2	Rad. char. from α_k	Intensity ††) present measurements	Intensity ††) Ketelle *et al.* [2])	Intensity ††) Meyerhof *et al.* [3])
γ_1	90 *)	5 ±1		7.4 (–2) [2])	7.2(–2)	9.1(–1)	M1	2.4 ±0.5	2.7	3.5
γ_2	92 *)	95 ±1	100	5.5 (–1) §)	6.8(–2)	8.6(–1)	M1+E2	69 ±4	63.9	72.2
γ_3	182 *)	53.5 ±5	1.3	1.3±0.2(–2) †)	1.1(–2)	6.0(–2)	M1	24 ±2.5	29.6	22.6
γ_4	206 *)	5.3 ±0.7	0.081	8 ±1.5(–3) †)	8.4(–3)	4.1(–2)	M1	2.4 ±0.3	1	1.5
γ_5	200±10	~ 0.2						~ 0.1	—	—
γ_6	296 *)	49 ±6	0.21	2.3±0.5(–3) †)	3.6(–3)	1.1(–2)	M1	21.8 ±2.7	20.2	13.9
γ_7	388 *)	15 ±3	0.036	1.3±0.5(–3) †)	1.7(–3)	4.0(–3)	M1	6.7 ±1.4	4.9	4.9
γ_8	485±7	0.5 ±0.1						0.22±0.05	0.4	0.1
γ_9	595±10	~ 0.2						~ 0.1	—	—
γ_{10}	690±10	~ 0.2						~ 0.1	—	0.05
γ_{11}	780±10	0.2 ±0.05						0.1 ±0.03	0.2	0.1
γ_{12}	870±10	0.45±0.1						0.2 ±0.05	0.4	0.3

*) from conversion electron energies [2]).
**) mean value of [1]), [2]), [11]).
§) mean value of [2]), [3]), [14]).
†) calculated using §), **) and rel. $N\gamma$.
††) per 100 disintegrations, electron capture to ground state not included.
$(-k)$ signifies $\times 10^{-k}$.

The relative intensities of the different γ-rays were obtained from the areas under the photopeaks. For the 90 en 92 keV and the 182 and 206 keV γ-transitions, which were not resolved in the scintillation spectrometer, the relative intensities were obtained from the coincidence spectra (see Fig. 7). Moreover, the ratio of the 206 keV to the 182 keV γ-intensity was

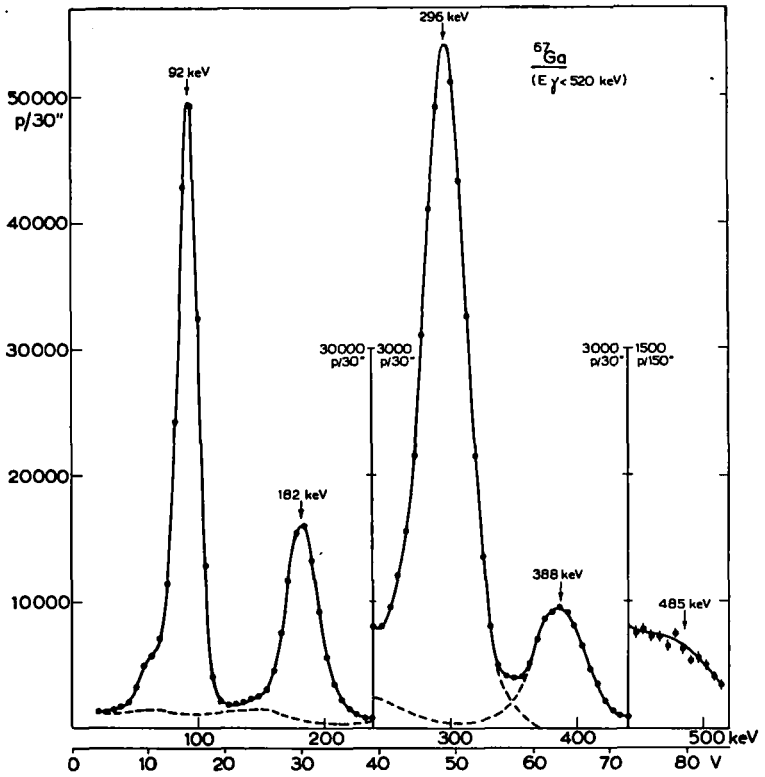

Fig. 4. Pulse-height distribution of ^{67}Ga γ-rays in the scintillation spectrometer for energies up to 520 keV.

determined from the ratio of the prompt coincidences and single channel counts in the angular correlation experiment using the formula:

$$N_c/N_{1,2} = N_0 . \Omega_{1,2}\, \varepsilon_1 . \varepsilon_2/(\varepsilon_1 a + \varepsilon_2)\varkappa,$$

where:

N_0 = number of disintegrations per second,
N_c = coincidence counting rate averaged over all angles,
$N_{1,2}$ = single channel counting rate (same for both spectrometers),
$4\pi\Omega_{1,2}$ = solid angle from source to crystal (same for both crystals),
ε_1, ε_2 = photopeak efficiency for the 206 keV and 182 keV γ-quanta respectively,

$\varkappa$ = 90 keV/182 keV branching ratio, determined from curve B of Fig. 7,

a = ratio of the 206 keV to the 182 keV γ-intensity.

For the K-conversion coefficient of the 92 keV γ-transition the main value from three earlier investigations [2], [3], [14] was taken. The other conversion data were calculated, using the relative γ-intensities of the present investigation and the mean relative conversion electron intensities from previous publications [1], [2], [11]. For comparison the intensity data of Ketelle *et al.* [2] and Meyerhof *et al.* [3] have also been given in Table I.

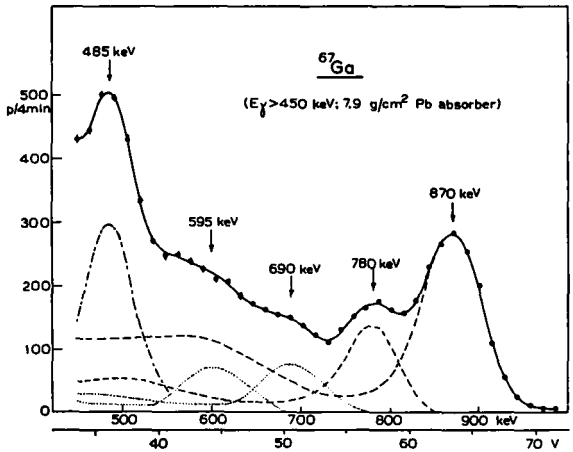

Fig. 5. Pulse-height distribution of ^{67}Ga γ-rays in the scintillation spectrometer for energies larger than 450 keV, taken through a 7.9 g/cm^2 Pb absorber.

§ 5. *Coincidence measurements.* The arrangement shown in Fig. 6 has been used for coincidence measurements. A lead shield of sufficient thickness to reduce false coincidences from Compton scattering to an almost negligible minimum was sandwiched between the sodium iodide crystals.

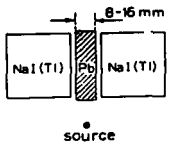

Fig. 6. Arrangement of the source and the crystals for coincidence measurements. Pb indicates the lead shielding, for which different thicknesses between 8 and 16 mm have been used.

Throughout the coincidence experiments the 0.03 μsec coincidence arrangement was used. The fixed channel was kept at maximum width (10 volts) and set to contain the photopeak of one γ-transition while the

spectrum was scanned by the other channel set at 2 volts width. Before and after every coincidence experiment the resolving time of the coincidence circuit was measured for several channel positions, using two independent sources and applying the formula:

$$N_t = N_1 . N_2 . 2\tau,$$

where N_1 resp. N_2 = number of output pulses of the two differential discriminators per second,
N_t = number of chance coincidences per second,
τ = resolving time of the fast coincidence circuit.

The spectra coincident with the 182 and 206 keV, the 296 keV and the 388 keV transitions, after subtraction of chance coincidences are given in Fig. 7. They were subjected to a thorough analysis in order to eliminate eventual peaks resulting from false coincidences. In the arrangement of Fig. 6 sources of false coincidences are:

a) one of the two channels or both of them will contain, besides the photopeak of the selected transition, parts of one or more Compton distributions of coincident higher energy transitions. A correction for the contribution of this effect can be calculated from the known Compton distributions relative to the photopeak, which have been measured under the same geometrical conditions;

b) false coincidences can also appear if the channels will contain pulses originating from coincident higher energy γ-quanta which have been scattered in the lead shield. The correction for this effect can be made in the same way;

c) some γ-quanta, originating from higher energy transitions, which have been scattered in one of the crystals, may still penetrate the lead shield and, by striking the other crystal, cause false coincidences. This effect can be detected and eliminated using lead shields of different thicknesses;

d) a chance coincidence of two lower energy γ-quanta in the same crystal within the resolving time of the spectrometer may cause a sum pulse in the fixed channel (pile-up). Due to this effect a small percentage of the spectra coincident with the mentioned lower energy transitions are added to the spectrum coincident with the selected transition. This phenomenon can be investigated, respectively eliminated, by using weaker sources or by placing a thin lead absorber between the source and the crystal which corresponds to the fixed channel.

Of the different coincidence spectra shown in Fig. 7 curve B represents the spectrum coincident with γ-energies in the 150–220 keV range. In this spectrum the broad dominant peak at $E_\gamma = 195$ keV and the smaller peaks at $E_\gamma = 90$ keV and $E_\gamma = 485$ keV can be fully explained from the decay scheme suggested by earlier investigators [2], [3]. This decay scheme is indicated in Fig. 11 by thick lines. The smaller peaks at $E_\gamma = 296$ keV

and $E_\gamma = 388$ keV, which are due at the utmost for 30% to the false coincidence effects mentioned before, can only be explained if a γ-transition in the 150–220 keV range is coincident with the 296 keV as well as with the

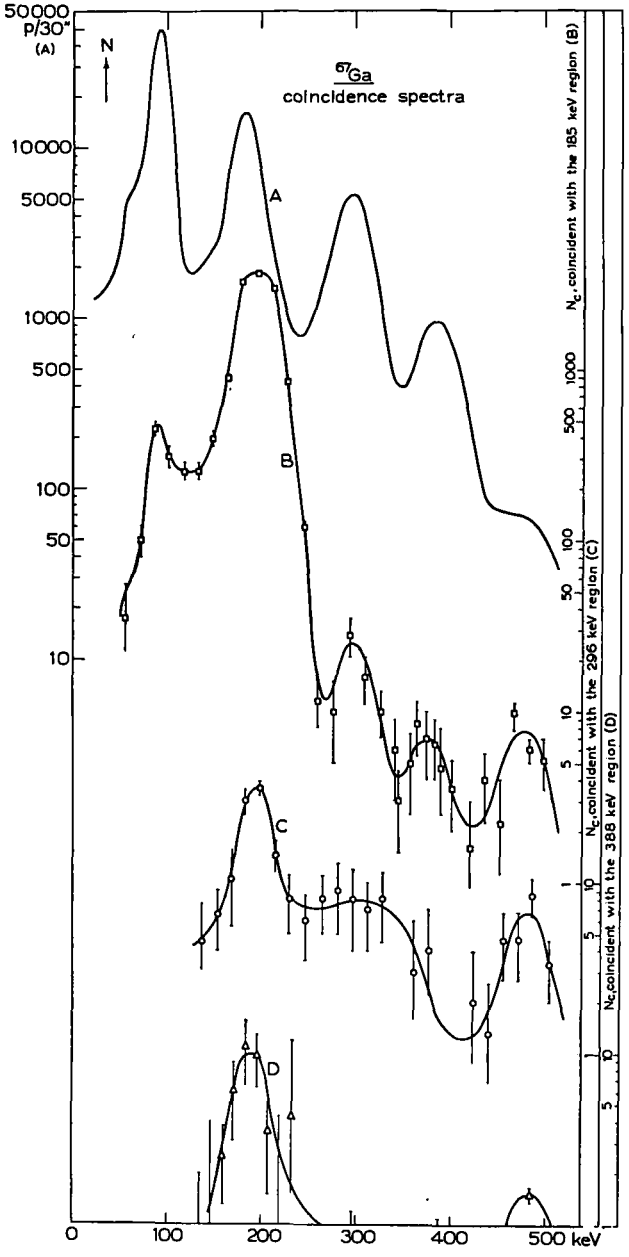

Fig. 7. Coincidence pulse-height distributions of ^{67}Ga γ-rays. Curve A shows the single channel distribution. Curve B, C and D represent the pulse-height distributions coincident with γ-energies in the 190 keV, 296 keV and 388 keV range.

388 keV transition. This is an indication for the existence of a new γ-transition of $E_\gamma \approx 200$ keV.

Of the spectrum coincident with γ-energies in the 260–330 keV range (curve C) only the 485 keV peak can be directly explained from the decay scheme indicated by thick lines in Fig. 11. The pulses at $E_\gamma \approx 300$ keV can be fully explained by the false coincidence effect mentioned in point *a*) of this paragraph. The intensity of this part in the coincidence spectrum just equals twice the intensity of the coincident Compton distribution of 485 keV γ-quanta. The peak at $E_\gamma \approx 200$ keV can only for 30% be ascribed to false coincidence effects. The greater part of this peak can again only be explained if a new γ-transition with $E_\gamma \approx 200$ keV is introduced.

Curve D of Fig. 7 represents the spectrum coincident with γ-energies in the 350–425 keV range. The accuracy of these data is not very high due to: 1) the weak intensity of the 388 keV transition, 2) the rather small solid angles which the source subtends to the crystal owing to the thick lead shield and 3) the relative small detection efficiency for 388 keV γ-quanta. Nevertheless a coincidence peak is present at 200 keV, which cannot be sufficiently accounted for by false coincidences.

It may therefore be concluded that evidence exists of a weak 200 keV γ-transition in coincidence with the 296 keV as well as with the 388 keV transition. The intensity ratios of the different coincidence peaks confirm this conclusion. Moreover, from the relative intensities of the coincidence peaks the intensity of the new 200 keV transition can be determined as about 0.1 per 100 disintegrations.

§ 6. *Angular correlation measurements.* For angular correlation measurements both single channels were used at maximum width (10 volts) while the channel position and the amplification of the pulses were chosen so as to set each channel on the photopeak of one of the transitions of the cascade to be examined, taking care to exclude as much as possible of other transitions. The resolving time of the coincidence circuit was determined using the method mentioned in § 5. This value was checked after each angular correlation measurement. Single channel and coincidence counts were registered with the counters in the 90°, 120°, 150°, 180°, 195°, 225°, 255° and 270° positions or alternatively in the 90°, 105°, 135°, 165°, 180°, 210°, 240° and 270° positions. No systematic deviations of the number of counts in the 90°–180° positions from the equivalent ones in the 180°–270° positions have been observed. All results have been corrected for half-life and for finite detector size. The angular correlation coefficients have been calculated following the method outlined by Rose [12]).

The 206 keV — 182 keV cascade. 2.2% of the total number of disintegrations decay via this cascade. To measure the anisotropy both channels were set to contain the combined photopeaks of the two transitions. The

angular correlation data are given in Fig. 8. The correlation was found to be $W(\theta) = 1 - (0.216 \pm 0.008) \cos^2 \theta$ in agreement with the measurement of Meyerhof *et al.* [3]), who found -0.22 ± 0.04.

The 485 keV — 296 keV cascade. Only 0.15% of all disintegrations of ^{67}Ga decay via this cascade. Other γ-transitions consequently greatly surpass this cascade in intensity. Of the 296 keV transition less than 1% contributes to the cascade. This involves a decrease in the ratio of true to chance coincidences. Moreover, as the energy resolution of the spectrometer was not high enough to separate the 485 keV photopeak completely from the 388 keV photopeak, the number of chance coincidences was still more

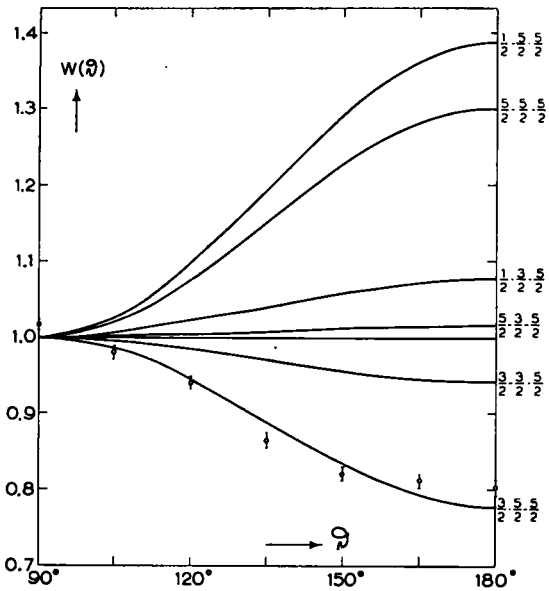

Fig. 8. Angular correlation for the 206 keV – 182 keV cascade in the decay of ^{67}Ga. The drawn curves represent the theoretical possibilities.

enlarged. The weak intensity and the great number of chance coincidences necessitated a measurement of long duration. The following results were obtained in about 800 hours of operation using 6 sources:

I. $W(\theta) = 1 + (0.35 \pm 0.08^5) \cos^2 \theta$ (without the automatic system and $\tau = 0.3\ \mu$sec),

II. $W(\theta) = 1 + (0.31 \pm 0.07^5) \cos^2 \theta$ (using the automatic system and $\tau = 0.3\ \mu$sec),

III. $W(\theta) = 1 + (0.24 \pm 0.06^5) \cos^2 \theta$ (using the automatic system and $\tau \approx 0.03\ \mu$sec),

average total $W(\theta) = 1 + (0.29 \pm 0.04^5) \cos^2 \theta$.

As in the 180° position the detection of annihilation radiation quanta and scattered quanta cannot be completely excluded, it is comprehensible

that the average number of coincidences in the 180° position is rather high (see Fig. 9). The average total of all data excluding the 180° value is:

$$W(\theta) = 1 + (0.27 \pm 0.05) \cos^2 \theta$$

The angular correlation data averaged for every direction separately are given in Fig. 9.

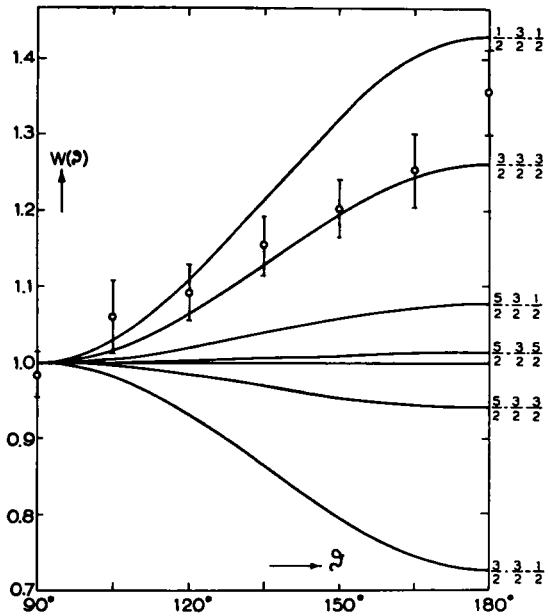

Fig. 9. Angular correlation for the 485 keV – 296 keV cascade in the decay of ^{67}Ga. The drawn curves represent the theoretical possibilities, assuming the 485 keV γ-transition to be pure M1 (see also Fig. 12).

§ 7. *The half-life of the 92 keV level in ^{67}Zn.* The availability of a variable delay line enabled us to include in the measurements a determination of the half-life of the short-lived ^{67}Zn isomer. A low intensity source of ^{67}Ga was sandwiched between the two crystals while the channels were set on the 296 keV and 92 keV photopeaks. The delay line was inserted between the cathode follower and the amplifier feeding the 296 keV channel, and coincidence counts were taken while the delay was varied by intervals of 1.05 μsec from 0 to 12.6 μsec using the 0.3 μsec coincidence circuit. The result of this measurement is given in Fig. 10. From the experimental data the half-life was calculated as 9.3 $\pm$ 0.2 μsec, which is in good agreement with other measurements: 8.5 μsec [2]) and 9.5 $\pm$ 1.0 μsec [3]).

§ 8. *Discussion.* The experimental data from which to start a discussion of the level scheme of ^{67}Zn can be summarized as follows:

a. the γ-transition energies and intensities given in Table I;

b. the measured coincidences (§ 5);

c. the conversion coefficients given in Table I;

d. the half-lives of ^{67}Ga (78 hours) and of ^{67}Cu (39 hours), the 1005 keV energy difference between the ^{67}Ga and ^{67}Zn ground states measured by Trail and Johnson [13]) by means of a (p, n) reaction on ^{67}Zn, and the β-transition energies measured by Easterday in the β-spectrum of ^{67}Cu [14]);

e. the measured half-life (9.3 μsec) of the isomeric 92 keV level in ^{67}Zn (§ 7);

f. the measured angular correlation coefficients of the 206 keV–182 keV and 485 keV–296 keV γ-cascades (§ 6);

g. the ground state spin of ^{67}Zn, measured by several authors to be 5/2 [15]).

The K/L ratios have not been take into account as only vague conclusions can be drawn from them in this case.

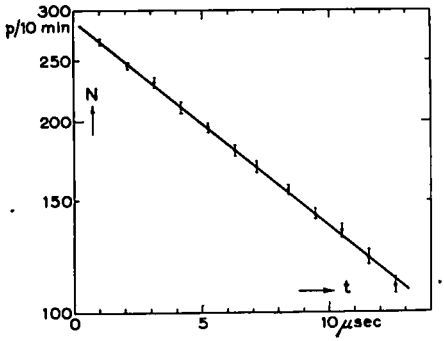

Fig. 10. Half-life measurement results of the decay of the ^{67}Zn metastable level.

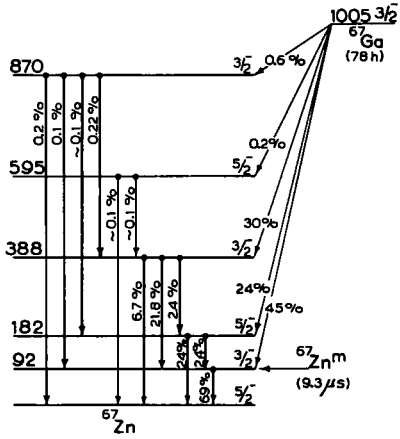

Fig. 11. Decay scheme of ^{67}Ga.

The single channel spectra given in Fig. 4 and 5 and the coincidence spectra of Fig. 7 are all consistent with the level scheme given in Fig. 11, which for the greater part confirms the level schemes given in earlier publications [2]), [3]). Two transitions are new: the 595 keV transition is inserted proceeding from a new level at 595 keV to the ground state, while the weak 200 keV transition, found to be in coincidence with the 296 keV and 388 keV transitions, is figured proceeding from this new level to the 388 keV level. Weak transitions from the new level to other levels might be present but will apparently be masked by transitions of neighbouring energy. As the evidence for this new level is still somewhat scanty it has been indicated as a thin line only.

For the allocation of spins to the levels, the data mentioned in this

paragraph under *a*, *c*, *d*, *f* and *g* have been taken into account. The energy difference of 1005 keV between the ^{67}Ga and ^{67}Zn ground states and the relative intensities of electron capture transitions to the various levels calculated from the γ-intensities and given in Fig. 11 provide the means to calculate the log ft values for the electron capture transitions of ^{67}Ga. The log ft values for the β-transitions from ^{67}Cu calculated from the results of Easterday [14]) have been added (see Table II).

According to the classification of Mayer, Moszkowski and Nordheim [16]) transitions 2 and 6 (Table II) should be classified at least *l*-forbidden. In view of the fact that according to the shell model [17]) no even parity states can exist in the lower levels of ^{67}Zn, *l*-forbiddenness should be assumed.

TABLE II

	Proceeding to level	E.C. percentage	E.C. energy	^{67}Ga log ft	β-energy [14])	^{67}Cu log ft
1	870 keV	0.6	135 keV	5.5	—	—
2	595 keV	$\sim$ 0.2	410 keV	$\sim$ 7	—	—
3	388 keV	30	617 keV	5.2	189 keV	5.2
4	182 keV	24	823 keV	5.5	395 keV	5.3
5	92 keV	45	913 keV	5.3	485 keV	5.7
6	ground state	< 5	1005 keV	> 6.3	577 keV	6.3

Transition 6 indicates a change of 2 $\hbar$ in the orbital momentum, indicating a $p_{3/2}$ state for the ground state of ^{67}Ga (the ground state of ^{67}Zn being $f_{5/2}$) in accordance with the shell model assignment for 31 protons and with the measured ground states of ^{69}Ga and ^{71}Ga [15]).

As the other electron capture and β-transitions are allowed only 1/2, 3/2 and 5/2 spin values can be allocated to the levels to which they proceed. So for a discussion of the angular correlation coefficient values, the possible spin sequences are restricted to a small number.

The 182 keV and 206 keV γ-transitions are indicated by their measured K-conversion coefficients (see Table I) to be pure M1. Therefore the possibilities for the 206 keV – 182 keV cascade are: 1/2 – 3/2 – 5/2 (+ 0.077), 3/2 – 3/2 – 5/2 (– 0.059), 5/2 – 3/2 – 5/2 (+ 0.015), 3/2 – 5/2 – 5/2 (– 0.222) and 5/2 – 5/2 – 5/2 (+ 0.302). The numbers in brackets indicate the associated theoretical anisotropy values. In that case the measured angular correlation coefficient of -0.216 ± 0.008 leaves only one possibility: 3/2 – 5/2 – 5/2, for which case the theoretical value is – 0.222 (see Fig. 8).

From the spin value of 3/2 for the 388 keV level and the measured angular correlation coefficient of the 485 keV – 296 keV cascade ($+0.27 \pm 0.05$), the spins of the 92 keV, and 870 keV levels can be found. The 296 keV transition is indicated by its measured K-conversion coefficient to be pure M1. For the 485 keV transition no conversion data are available.

Therefore all possible angular correlation coefficients for a cascade with spin 3/2 intermediate and spins 1/2, 3/2 or 5/2 in the other positions are represented in Fig. 12 for the case of the second transition being pure M1

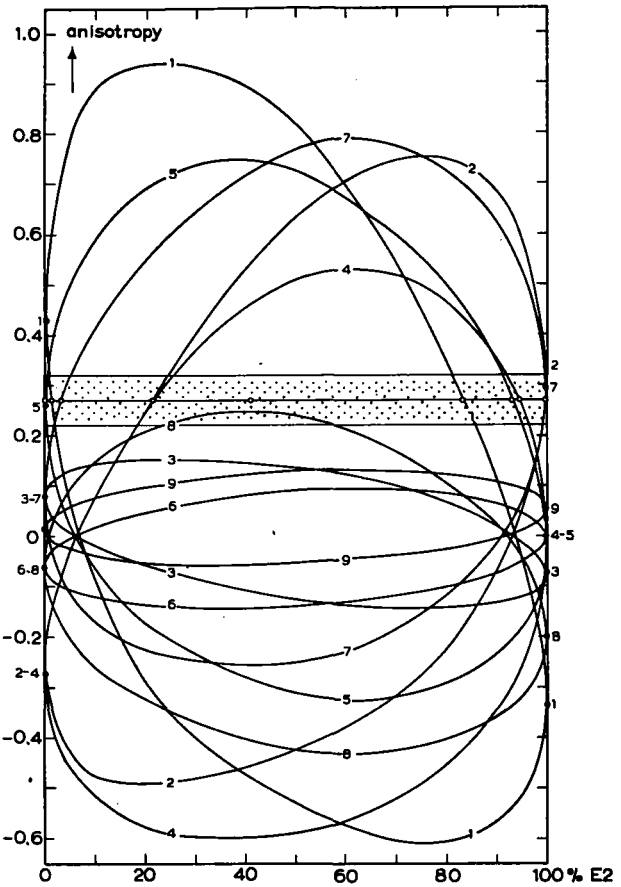

Fig. 12. The theoretical angular correlation anisotropies for all possible spin sequences of the 485 keV – 296 keV cascade represented as a function of the E2 mixing percentage of the first (485 keV) transition. The experimental value of + 0.27 ± 0.05 is indicated as a dotted area. The numbers inserted in the lines represent the following spin sequences: 1 = 1/2 – 3/2 – 1/2, 2 = 1/2 – 3/2 – 3/2, 3 = 1/2 – 3/2 – 5/2, 4 = 3/2 – – 3/2 – 1/2, 5 = 3/2 – 3/2 – 3/2, 6 = 3/2 – 3/2 – 5/2, 7 = 5/2 – 3/2 – 1/2, 8 = 5/2 – 3/2 – 3/2 and 9 = 5/2 – 3/2 – 5/2.

and the first transition a M1 — E2 mixture [18]), [19]). In view of the measured angular correlation coefficient (+ 0.27 ± 0.05), the possibilities are then restricted to those given in Table III. Mixture percentages of more than 50% E2 would lead to slow-down factors of more than 2300 and have therefore been left out of consideration.

TABLE III

Spin sequence		Mixture percentage E2 for the 485 keV transition	Calculated minimum slowing down factor compared to 100% M1 [4])
1	1/2 – 3/2 – 1/2	1– 2 % E2	23 ×
2	1/2 – 3/2 – 3/2	18–24 % E2	500 ×
4	3/2 – 3/2 – 1/2	18–25 % E2	500 ×
5	3/2 – 3/2 – 3/2	0– 0.5% E2	1 ×
7	5/2 – 3/2 – 1/2	2– 5 % E2	47 ×
8	5/2 – 3/2 – 3/2	23–57 % E2	690 ×

The presence of 3 other γ-transitions proceeding from the 870 keV level provides means to evaluate the possibility of slowing down of the 485 keV transition when compared with pure M1. The relative intensities are: 870 keV 0.9; 780 keV 0.4; 690 keV 0.4; 485 keV 1. If each value is divided by the theoretical M1-transition probability according to the W e i s s k o p f formula [4]) the ratios become: 0.4, 0.16, 0.12, 1. Evidently the 485 keV transition is the fastest of the four. So if this transition by virtue of being a mixture of M1 and E2 is slowed down a few hundred times, the lifetimes of the other transitions are also to be enlarged. This seems rather unlikely in view of the fact that four lower levels with spins 3/2 or 5/2 are available for γ-transitions from the 870 keV level.

The possibilities of the lowest mixture percentages, with spin sequences 1/2 – 3/2 – 1/2 (1 — 2% E2) and 5/2 – 3/2 – 1/2 (2 — 5% E2), have to be considered separately. Both sequences indicate spin 1/2 for the 92 keV level, a spin value which is consistent with the half-life of this level: 9.3 μsec. However, the preceding 90 keV transition proceeding from a 5/2 level should then also be E2. This is in contradiction to the promptness of the 206 keV — 90 keV coincidences (see Fig. 7) and to the measured conversion coefficient of the 90 keV transition (Table I). By these arguments the allocation of spin 1/2 is untenable. Therefore the above mentioned spin sequences 1/2 – 3/2 – 1/2 (1 — 2% E2) and 5/2 – 3/2 – 1/2 (2 — 5% E2) must be ruled out. Then the only spin sequence really consistent with all experimental data is 3/2 – 3/2 – 3/2 with both transitions pure M1.

From the experiments presented in this work the following conclusions have been drawn regarding the spin values of the main levels in ^{67}Zn: 92 keV 3/2, 182 keV 5/2, 388 keV 3/2 and 870 keV 3/2. The new 595 keV level is fed by an electron capture transition of at least l-forbidden character. Therefore it has been tentatively assigned a $f_{5/2}$ character.

The 9.3 μsec half-life of the 92 keV isomeric state in ^{67}Zn is rather unexpectedly long for a transition between levels of spins 3/2 and 5/2. This increase by a factor of 2.10^5 over the theoretical M1 lifetime [4]) may be ascribed to l-forbiddenness of the transition if the 5/2 ground state be pure $f_{5/2}$ and the 3/2 isomeric level pure $p_{3/2}$ in which case the transition is

M1-forbidden *). Other possibilities e.g. a many-particle transition, may also be considered.

Acknowledgements. This investigation is part of the research program of the group Utrecht (under the direction of Professor J. M. W. Milatz) of the "Stichting voor Fundamenteel Onderzoek der Materie" and was made possible by a subvention from the "Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek". The authors are indebted to Professor P. M. Endt and Dr C. J. Kluyver for valuable discussions and comments, to Professor A. H. W. Aten Jr., Mr. L. Lindner and the chemical staff of the "Instituut voor Kernphysisch Onderzoek" for the many chemical separations and the careful preparation of the sources, and to the staff of the Philips Cyclotron at Amsterdam for the deuteron bombardments.

Received 28-6-55.

REFERENCES

1) Mukerji, A. and Preiswerk, P., Helv. phys. Acta **25** (1952) 405.
2) Ketelle, Brosi and Porter, Phys. Rev. **90** (1953) 567.
3) Meyerhof, Mann and West, Phys. Rev. **92** (1953) 758.
4) Blatt, J. M. and Weisskopf, V. F., "Theoretical nuclear Physics", John Wiley & Sons, New York (1952) 627; Montalbetti, R., Can. J. Phys. **30** (1952) 660.
5) Elmore, W. C., Rev. sc. Instr. **21** (1950) 649.
6) DeBenedetti, S. and Richings, H. J., Rev. sc. Instr. **23** (1952) 37.
7) De Waard, H., Thesis Groningen 1954.
8) Rietjens, L. H. Th., Thesis Utrecht (to appear in 1955).
9) Rietjens, Arkenbout, Wolters and Kluyver, Physica **21** (1955) 110.
10) Rose, M. E., Appendix IV of Siegbahn, K., "Beta and gamma ray spectroscopy", North-Holland publishing company, Amsterdam (1955) 905.
11) Siegbahn, K., Arkiv Fysik **4** (1952) 223.
12) Rose, M. E., Phys. Rev. **91** (1953) 610.
13) Trail, C. C. and Johnson, C. H., Phys. Rev. **91** (1953) 474.
14) Easterday, H. T., Phys. Rev. **91** (1953) 653.
15) Mack, J. E., Rev. mod. Phys. **22** (1950) 64.
16) Mayer, Moszkowski and Nordheim, Rev. mod. Phys. **23** (1951) 315.
17) Mayer, M. G., Phys. Rev. **78** (1950) 16.
18) Ling, D. S. and Falkoff, D. L., Phys. Rev. **76** (1949) 1639.
19) Lloyd, S. P., Phys. Rev. **81** (1950) 161; **83** (1951) 717.

*) Note in [3]), page 764.