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g-FACTOR MEASUREMENT ON THE FIRST EXCITED STATE OF Fe^{56} USING INTERNAL MAGNETIC FIELDS

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Abstract: The g-factor of the 0.845 MeV (2^+) level of Fe^{56} ($\tau = 1.06 \times 10^{-11}$ sec) has been measured by observing therotation of the γ-γ angular correlation of the 4^+-2^+-0^+ cascade due to internal magnetic fields in iron. The result is $g = 0.58 \pm 0.17$.

1. Introduction

The method of determining g-factors of excited nuclear states by observing the rotation and attenuation of a γ-γ angular correlation in a magnetic field has been used by many authors [1-5]).

The zero-field γ-γ correlation pattern rotates by an angle

$$\Delta\theta = \omega\tau, \tag{1}$$

where

$$\omega = g\mu_{\mathrm{nm}}H/\hbar. \tag{2}$$

Here ω is the Larmor frequency, τ is the mean life of the level, $\mu_{\mathrm{nm}} = e\hbar/2Mc$ is the nuclear magneton, and H is the magnetic field at the nucleus. For small τ, i.e., for small precession angles, the attenuation of the zero-field correlation pattern is negligible and the main effect consists in a rotation.

For some years only states with a lifetime of $\gtrapprox 10^{-9}$ sec were investigated. Recently [6, 7]), the method was extended to lifetimes of the order 10^{-10} sec. This was achieved not by any fundamental change but only by measuring smaller rotation angles of the correlation pattern.

The measurement described below was carried out using the 4^+-2^+-0^+ γ-γ-cascade in Fe^{56}. The lifetime of the intermediate state is 1.06×10^{-11} sec. In order to achieve precession angles of some tenths of a degree magnetic fields of the order 10^5 G are necessary. External fields of this strength are not yet available but internal fields especially in ferromagnetics are of this order. For fairly pure iron the local field at the position of the nuclei is 3.3×10^5 G as determined by Mößbauer experiments.

The use of internal fields broadens the field of application for such experiments. Excited levels with lifetimes of the order 10^{-11} sec are now accessible. Many of the

2^+ levels away from the region of the strongly deformed nuclei have lifetimes of this order. The determination of their magnetic moments often may provide a sensitive test of the validity of nuclear models.

2. The Experimental Setup

Two counters have been used for the measurement of the angular correlation. Counter I was fixed; counter II was movable in a plane normal to the axis of the source. The direction of the magnetic field applied to the source was perpendicular to the plane defined by the two counters.

The counters consisted of 7.6 cm × 7.6 cm NaI(Tl) crystals and 6363-DuMont multipliers. This type of multiplier is very sensitive to magnetic fields because of the large cathode area. In spite of the use of a cylindrical iron-closed magnet a special

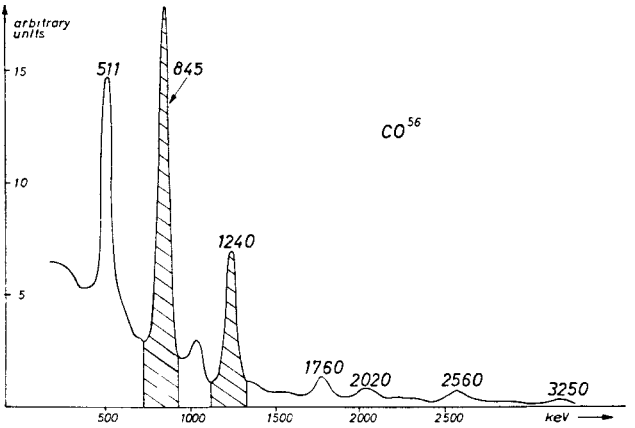

Fig. 1. The observed γ-spectrum. The hatched peaks have been selected by the single-channel analysers.

magnetic shielding was necessary to prevent the multipliers from being influenced by the fringing field. The distance between each crystal and the source was 7.6 cm. Light pipes could not be used because of the fixed mounting of the crystals onto the multipliers by the manufacturer. The advantage of these so-called integral lines consists in an optimal spectroscopic resolution of the counter. This property is important for the determination of the true anisotropy of the investigated cascade (see appendix 1).

The multiplier pulses were fed into a conventional slow-fast-coincidence circuit. The single counting rates and the triple coincidence rate were automatically registered and printed. During the printing and reset period (about 1 sec), the direction of the magnetic field was changed.

The resolving time of the fast coincidence circuit was about 3×10^{-8} sec. This comparatively poor resolution was chosen to guarantee a constant coincidence counting

rate over a wide range of delay. Therefore any variation in the transit time of the electrons inside the multiplier, eventually caused by the fringing field of the magnet did not influence the coincidence rate. Because of the weak source the chance coincidence rate was only about 0.3 % of the true coincidences.

The energy resolution of the multipliers was about 8 % for 845 keV gammas. Fig. 1 shows the complete spectrum registered by a 256-channel analyser. The low γ-energies, especially gammas of the Fe^{57} contamination in the source, have been shielded by 3 mm of lead.

3. The Spectrum of Fe^{56}

The Co^{56} nucleus decays by β^+-emission and electron capture to several excited levels of Fe^{56} (fig. 2). The transition 1240 keV (4^+)-845 keV (2^+)-0(0^+) is the cascade investigated in this experiment.

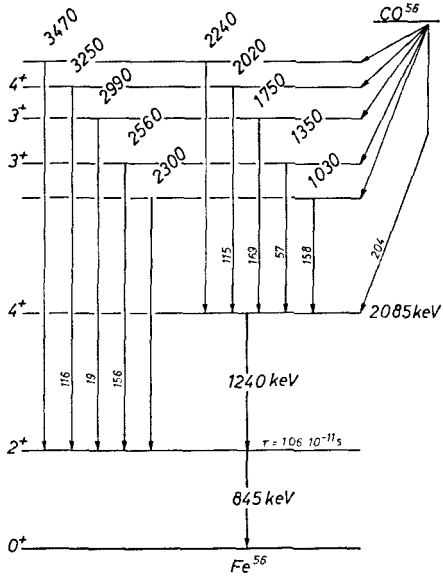

Fig. 2. The decay of Fe^{56} according to the nuclear data sheets.

In each of the two scintillation-counters the spectrum shown in fig. 1 was observed. By means of single-channel analysers, a small energy channel at 845 keV from counter I and at 1240 MeV from counter II were selected for the measurement of the angular correlation. These channels also accepted γ-energies from Compton scattered quanta of higher energies, which are all in coincidence with the 845 keV-transition. Furthermore the γ-rays of 1030, 1350, 1760 and 2020 keV are in coincidence with the 1240 keV transition. In order to get the true coincidence rate between the 845 keV and the 1240 keV transition one must correct for the contributions of higher γ-energies to the selected energy bands. This has been done graphically (see appendix 1).

4. The Lifetime of the 845 keV State

A reliable calculation of the g-factor of the 845 keV state requires the knowledge of the lifetime of this level. Numerous experiments have been carried out during the last years to investigate this lifetime. Recently Beard and Kelly [8]) compiled the available results. The most accurate experiment was performed by Metzger [9]). He found $\tau = (1.06 \pm 0.17) \times 10^{-11}$ sec in agreement with practically all other results. We, therefore, use Metzger's value for our calculations.

5. Source Preparation

Natural iron was bombarded in the cyclotron of the MPI Heidelberg with 15 MeV deuterons. The desired reaction was $Fe^{56}(d, 2n)Co^{56}$. After the irradiation, Co^{56} was separated from the target by chemical methods †.

About 10 μC of Co^{56} have been electroplated onto an iron cylinder of 0.3 mm diameter at a length of 4 mm. In a hydrogen atmosphere at a temperature of about 950°, the Co^{56} diffused into the iron. This procedure was chosen by Wertheim [10]) and a

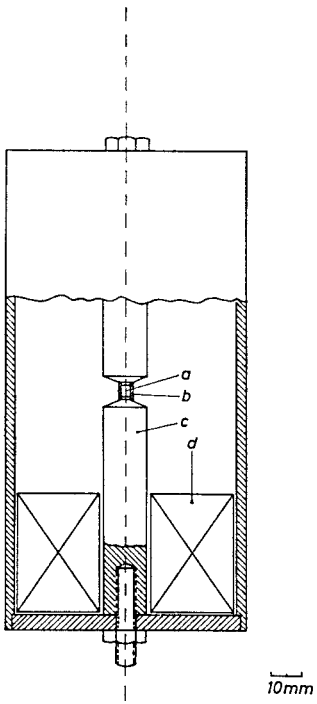

Fig. 3. The experimental setup. (a) is the source, (b) is the Lucite cylinder, (c) indicates pole pieces, and (d) indicates coils.

† We are very indebted to Professor Schmidt-Rohr for the irradiation of the probe and to Dr. Daniel for the chemical extraction of the Co^{56}.

group of the Argonne National Laboratory [11]) for the measurement of the internal magnetic field at the position of an iron atom in iron metal by Mößbauer experiments. Preparing the source under these conditions the internal magnetic field in our experiments should have the value obtained by Wertheim [10]) and Hanna *et al.*[11]), i.e. $(3.3\pm0.1)\times10^5$ G.

The iron probe was inserted into a hollow cylinder of Lucite for rigidity and then bridged the gap between the pole pieces of an electromagnet (see fig. 3).

A comparatively weak magnetic field of about 800 G was sufficient to saturate the iron cylinder. By reversing the current in the coils of the electromagnet, the field direction in the probe could be changed.

The solid angle with respect to the counters was practically the same for γ-quanta emitted from different points in the source because of its small geometrical size. Moreover the probability for a scattering of gammas in the probe was negligible.

6. Measurement and Calculation of the g-Factor

We denote the undisturbed angular correlation for a particular cascade by

$$W_i = C_{0i}+C_{0i}C_{2i}\cos 2\theta+C_{0i}C_{4i}\cos 4\theta. \tag{3}$$

Here W_i for $i = 1, \ldots, n$ refers to angular correlations of γ-γ-cascades with the 845 keV level as the intermediate state; W_i for $i = (n+1) \ldots m$ notates the cascades with the 2085 keV level as the intermediate state. The total angular correlation $\sum W_i$ is denoted by $W(\theta)$.

This undisturbed angular correlation changes with an applied magnetic field perpendicular to the momentum of both γ-quanta into

$$W_i(\theta, H) = W_i(\theta+\Delta\theta, 0). \tag{4}$$

If the 2085 keV level part of the angular correlation W_i is disturbed by a magnetic field, then $\Delta\theta$ can be neglected since this level has an estimated [13, 14]) lifetime of $\lesssim 10^{-12}$ sec, i.e.,

$$W_i(\theta, H) \approx W_i(\theta, 0) \quad \text{for } i = (n+1) \ldots m. \tag{5}$$

As far as the 845 keV level is concerned the counting rate difference for the angle θ and a reversed magnetic field becomes

$$W(\theta, H)-W(\theta,-H) = \sum_{i=1}^{n} (C_{0i}C_{2i}2\sin 2\theta \sin 2\Delta\theta+C_{0i}C_{4i}2\sin 4\theta \sin 4\Delta\theta). \tag{6}$$

For $\Delta\theta = \omega\tau \ll 1$ (in this experiment $\omega\tau \approx 10^{-3}$), eq. (6) is reduced to

$$W(\theta, H)-W(\theta, -H) = -\sum_{1}^{n} (C_{0i}C_{2i}4\Delta\theta \sin 2\theta+8C_{0i}C_{4i}\Delta\theta \sin 4\theta). \tag{7}$$

Since the 4θ terms are small, one expects a maximal difference in the counting rate for

$|\sin 2\theta| = 1$. Reversing the direction of the magnetic field the relative counting rate difference at the used angle $\theta = 135°$ becomes

$$R = \frac{W(135°, H) - W(135°, -H)}{W(135°, 0)} = \frac{4\omega\tau \sum_{i=1}^{n} C_{0i} C_{2i}}{\sum_{i=1}^{m} C_{0i}(1 - C_{4i})} . \tag{8}$$

The anisotropy of the total angular correlation is

$$A = \frac{W(180°) - W(90°)}{W(90°)} = \frac{2 \sum_{1}^{m} C_{0i} C_{2i}}{\sum_{1}^{m} (C_{0i} - C_{0i} C_{2i} + C_{0i} C_{4i})} . \tag{9}$$

In the experiment, the $W(\theta)$ are the coincidences divided by the product of the single rates for elimination of instabilities.

The shift of the angular correlation can be written in the following form:

$$\Delta\theta = \omega\tau = \tfrac{1}{4} R \left\{ \frac{A}{2 + A} \frac{\sum_{1}^{m} C_{0i}(1 + C_{4i})}{\sum_{1}^{m} C_{0i}(1 - C_{4i})} - \frac{\sum_{n+1}^{m} C_{0i} C_{2i}}{\sum_{1}^{m} C_{0i}(1 - C_{4i})} \right\} . \tag{10}$$

The term $\sum_{n+1}^{m} C_{0i} C_{2i}$ applies to those angular correlations which have the 2085 keV level as the intermediate state. It vanishes if one observes only the 1240 keV-845 keV cascade. It was therefore important for the experiment to use counters of high spectroscopic resolution and with a large ratio of photopeak to Compton-continuum.

The finite size of the crystals gives rise to an attenuation of the angular correlation. Rose [12]) showed that this attenuation may be taken into account by multiplying the C_{0i} with a factor K_{1i}. In this experiment $K_{2i} = K_2$ was taken constant for all correlations in question. It has been determined by the measurement of the attenuation of the well-known angular correlation of Co^{60}. We got $K_2 = 0.7 \pm 0.1$ for the geometry used in this experiment. The K_{4i} appear only multiplied by C_{4i} which are very small and has therefore been neglected. The magnitudes of the coefficients C_{0i}, C_{2i} and C_{4i} were taken from ref. [16]), and are shown in table 1.

The undisturbed anisotropy A was measured to be $(9.58 \pm 0.48)\,\%$. With the applied magnetic field we got $R' = (0.186 \pm 0.068)\,\%$, where R' is given by $R = R' - R''$. The quantity R' had to be corrected for the influence of the magnetic field on the multipliers. Fig. 4 shows that this influence results in a shift of the spectral peak. A change $\Delta I/I$ in the singles counting rate gives rise to an $R'' = 0.15(\Delta I/I) = -0.022\,\%$. From R' and R'' one gets $R = (0.164 \pm 0.068)\,\%$.

Using eq. (8) the rotation angle becomes

$$\Delta\theta = \omega\tau = (7.9 \pm 3.7) \times 10^{-3} \mathrel{\hat{=}} (0.46 \pm 0.21)°. \tag{1a}$$

Assuming $\tau = 1.06 \times 10^{-11}$ sec for the 845 keV level and $H = 3.3 \times 10^5$ G for the magnetic field at the position of the nuclei, the g-factor can be calculated according to eq. (2).

$$|g| = 0.47 \pm 0.21.$$

TABLE 1

Known angular correlations in the decay of iron 56 with spin assignments, branching ratios and the calculable anisotropies taken from ref. [16])

$W_{1j} = W_i$ (keV)		A_2	A_4	C_{0i} [a])	C_{4i}	C_{2i}	$C_{0i}C_{2i}$ [b])	$C_{0i}C_{4i}$ [c])
845	1350	−0.1403	0?	1				
845	1750	−0.1403	0?	31				
845	2020	?	?	17				
845	2560	−0.0714	0?	19				
845	2990	−0.0714	0?	2				
845	3250	0.1020	0.0091	11	0.0049			0.09
845	1240	0.1020	0.0091	820	0.0049			7.5
1240	1350	−0.1403	0?	25		−0.109	−2.4	?
1240	1750	−0.1654	−0.0002	34	−0.0001	−0.1295	−4.3	−0.003
1240	2020	−0.0855	0.1501	19	0.0821	−0.0172	−0.3	+1.56
1240	1030	?	?	21		?	?	?

a) $\sum_{1}^{m} C_{0i} = 1000$; b) $\sum_{n+1}^{m} C_{0i}C_{2i} = -7 \pm 2$; c) $\sum_{1}^{m} C_{0i}C_{4i} = 9 \pm 2$

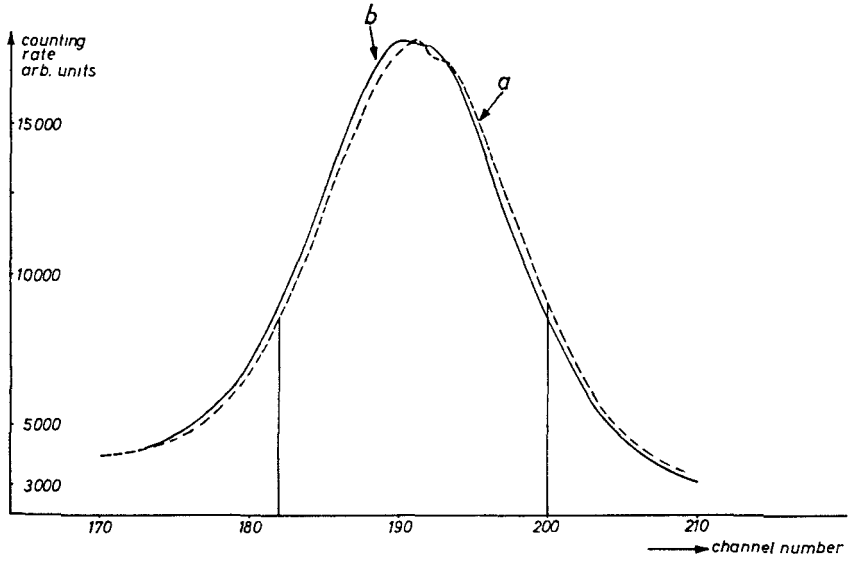

Fig. 4. The fringing field of the magnet gives rise to a shift of the spectral peak. (a) with (b) without magnetic field.

Hanna *et al.*[15]) have observed that the direction of the internal magnetic field at the position of the nuclei is opposite to the applied external field. Taking this into consid-

eration one finds that the magnetic moment of the 845 keV level of Fe^{56} forms a right hand screw with the direction of the internal magnetic field when it undergoes Larmor-precession. Spin and magnetic moment are therefore parallel and the g-factor positive.

In a previous experiment we used 3.8 cm × 3.8 cm NaI crystals and light pipes of about 20 cm length. The spectral resolution in this case was rather poor and the influence of the magnetic field of the same order because of the use of a magnet with a larger fringing field. With $R' = (0.234 \pm 0.085)\,\%$, $R'' = 0.024\,\%$ and $A = (5.5 \pm 0.5)\,\%$, the g-factor inferred from this experiment was

$$g = 0.73 \pm 0.27.$$

Both values obtained for g agree within experimental error. The quoted errors in both experiments are nearly pure statistical and can be improved. The influence of the fringing field of the magnet has been taken into consideration in both experiments (see appendix 2). Scattering of γ-quanta from one counter into the other has not been registered since even the highest energy of back-scattered quanta (about 240 keV) was far below the energies selected by the single-channel analysers.

7. Result and Discussion

The g-factor of the 845 keV-2^+-level of Fe^{56} calculated as the average from the data of both experiments is

$$g = 0.58 \pm 0.17.$$

With $I = 2$ the magnetic moment is then

$$\mu = gI = (1.16 \pm 0.34)\mu_K.$$

The calculation of $\Delta\theta$ has been carried out under the presumption that the field strength at the position of the nuclei in the 845 keV state was $(3.3 \pm 0.1) \times 10^5$ G. This value was taken from recent Mößbauer experiments of Wertheim [10]) and Hanna *et al.*[11]). In these investigations Co^{57} has been diffused into natural iron and decayed by K-capture into Fe^{57}. The level investigated there has a lifetime of about 10^{-7} sec during which time a re-organizing of the electron shell of the iron atom can take place. In our experiment the relevant re-organization time after the K-capture of Co^{56} has to be shorter than about 10^{-12} sec since the level in question has a lifetime of only 10^{-11} sec. The following facts favour the assumption that no remarkable error arises for the determination of the g-factor from the re-organizing of the electron shell.

The magnetic field H acting on Co nuclei at low concentrations in iron has been measured by several methods [17–20]). The values obtained vary between 3.0 and 3.5 $\times 10^5$ G. These values are much closer to 3.3×10^5 G for iron in iron metal than to the value 2.19×10^5 G for cobalt in cobalt metal [21]). According to Dash *et al.*[17]) it is not surprising that for these materials the effect of environment appears to dominate

those interactions which may be ascribed to the individual atom †. Cobalt differs from iron in that it has one additional 3 d electron, which is probably accepted into the unfilled 3 d band of the iron metal, thus leaving the cobalt nucleus in a state characteristic of the surrounding iron. Taking this into consideration one should not expect an appreciable change in the magnitude of the magnetic field at the iron nucleus following the transition cobalt to iron.

From the experiments of Hanna *et al.*[15]) it has been concluded that, since the effective field at the nucleus in iron is in fact negative, the dominant contribution must come from the core polarization. Extensive calculations have been carried out (see Watson and Freeman [22])) to explain the observed effective field of -3.3×10^5 G in iron. When the Co^{56} atom undergoes K-capture this core is disturbed by the hole produced. In the metal, however, this hole should be rapidly ($\lesssim 10^{-15}$ sec) refilled by conduction electrons. Even the 3 d and 4 s shells, which are essentially responsible for the core polarization, are assumed to be refilled in times $\lesssim 10^{-12}$ sec when they loose electrons by refilling the inner shells or by Auger-effect.

From measurements of the Zeeman-splitting of the 14.4 keV and the ground level of Fe^{57}, one knows that there is no quadrupole interaction if the nucleus is imbedded into iron metal. The m levels are equidistant and symmetric with respect to the unsplit line [23, 24]). No influence on the rotation or attenuation of the angular correlation pattern is to be expected therefore from quadrupole interactions.

During the progress of our experiment, Metzger [9]) published the result †† of a g-factor measurement by observation of resonance scattering from the first excited state of Fe^{56}. He got $g = +0.53 \pm 0.16$. Our result is in good agreement with Metzger's value.

We wish to express our deep gratitude to Professor H. Schopper for suggesting this experiment, his permanent encouragement and his stimulating interest in the progress of this work.

Appendix 1

DETERMINATION OF THE CONTRIBUTION OF HIGHER ENERGY GAMMAS TO THE SELECTED ENERGY CHANNELS

It is useful to divide those higher γ-energies, which contribute to the coincidence counting rate by their Compton-continua into two groups,

1) $E = 1030$, 1240 and 1350 keV,

2) $E = 1760$, 2020, 2560, 2990 and 3250 keV.

† Watson and Freeman [22]) pointed out that this is not generally true. Fe^{57} as an impurity in a copper-nickel alloy indicates, for example, that the field at the iron nucleus depends only to a small degree on the magnetization of the host.

†† We are very grateful to Professor Metzger for the communication of his result prior to publication.

The contribution of the first group can be investigated fairly correct by the available setup. For the second group one must use simplified assumptions because of the low intensity and rather high energies. Not mentioned but existing transitions may be neglected because of their very low intensity.

The ratio photopeak to Compton continuum for the first group was taken from a measurement of the corresponding ratio for the 1280 keV γ-transition of Na^{22}. The height of the Compton continuum was rather accurately one third of the height of the peak.

For the second group ihC was taken to be constant, with i being the relative intensity of the γ-transition, C the energy of the Compton edge and h the height of the continuum. The quantity ihC is the area covered by the continuum.

With these assumptions the relative contributions of the different energies to the selected energy channels have been determined graphically (figs. 5(a) and 5(b)). In the first (second) experiment the selected energy channel at 845 keV included 22 % (58 %) contributions of higher energy transitions. For the 1240 keV channel the corresponding figures are 9 % (56 %).

Appendix 2

THE INFLUENCE OF THE FRINGING FIELD ON THE COINCIDENCE COUNTING RATE

The single counting rates of counter I and counter II are $N = \sum_i N_i$ and $N' = \sum_j N'_j$, and $C = \sum_{ij} C_{oij}$ is the coincidence rate.

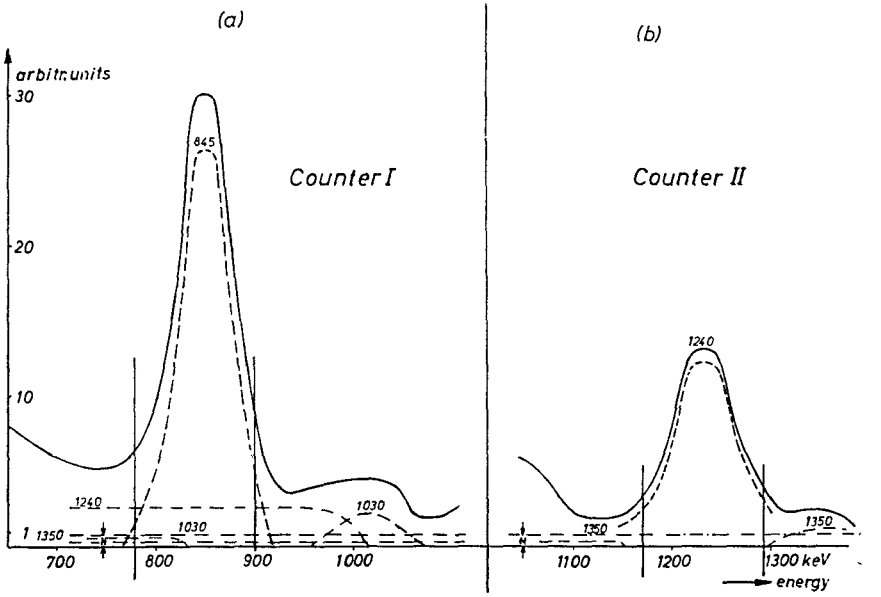

Fig. 5. The relative contributions of the different energies to the selected energy channels. Counter I is indicated by a and counter II is indicated by b.

Fig. 4 shows that the fringing field of the magnet gives rise to a shift of the spectral peak. This changes N to $N+\Delta N$, N' to $N'+\Delta N'$ and C to $C+\Delta C$. All N_l and N_j can be regarded as unchanged with the exception of N_1 and N_3', i.e., $\Delta N = \Delta N_1$ and $\Delta N' = \Delta N_3'$.

If the coincidence counting rate is divided by the product of the single counting rates in analogy to the determination of R, then the ratio

$$R'' = \frac{\dfrac{C}{NN'} + \dfrac{C \pm \Delta C}{(N \pm \Delta N_1)(N' \pm \Delta N_3')}}{\dfrac{C}{NN'}} \tag{A.1}$$

gives the influence of the fringing field on the magnet of R.

It can be shown that

$$C = \sum_{lj} C_{0lj} = \sum_{lj} J_w \frac{N_l N_j'}{i_l i_j}, \tag{A.2}$$

where J_w is the probability for the appearance of one out of essentially eight decay modes of Fe^{56}. Their relative intensity i has been taken from Cook and Tomnovec [25]).

With eq. (A.2) ΔC can be written in the following form:

$$\Delta C = \pm \frac{\Delta N_1}{N_1} \sum_j \frac{J_w}{i_1 i_j} N_j N_1 \pm \frac{\Delta N_3'}{N_3'} \sum_l \frac{J_w}{i_l i_3} N_l N_3' \tag{A.3}$$

and the ratio R'' as

$$R'' = \pm \left(\frac{\dfrac{N}{N_1} \sum_j \dfrac{J_w}{i_1 i_j} N_j' N_1}{\sum C_{0lj}} - 1 \right) \frac{\Delta N_1}{N} \pm \left(\frac{\dfrac{N'}{N_3'} \sum_l \dfrac{J_w}{i_l i_3} N_l N_3'}{\sum C_{0lj}} - 1 \right) \frac{\Delta N_3'}{N}. \tag{A.4}$$

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