INVESTIGATION OF PARITY MIXING IN $^{203}$TL BY MEASUREMENT OF
THE FORWARD-BACKWARD ASYMMETRY OF $\gamma$-RAYS AFTER $\beta$-DECAY

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Abstract

A multiple detector arrangement of fixed geometry and high inherent accuracy has been used to measure the forward-backward asymmetry coefficient $A_1$ in the $\beta$-$\gamma$ transition of $^{203}\text{Hg} \rightarrow ^{203}\text{Tl}$. Moreover, a control value has been determined which should exhibit no asymmetry. A non-zero coefficient $A_1$ is indicative of small admixtures of opposite parity in nuclear states.

The properties of a multiple detector arrangement and systematic asymmetries are discussed in detail. Sources of $^{203}\text{Hg}$ of high quality have been prepared with a mass separator. To avoid a systematic bias due to non-negligible quadratic terms in the statistical errors a new technique of data analysis has been applied. The measurements of several sources yielded for the asymmetry coefficient $A_1 = -(2.6\pm0.7) \times 10^{-4}$ and for the control value $(1.3\pm0.7) \times 10^{-4}$, with quoted errors of one standard deviation.

Radioactivity: $^{203}\text{Hg}$ from thermal neutron capture in $^{202}\text{Hg}$. $\beta$-$\gamma$ directional correlation measurement. Isotope separated source.
1. Introduction

Within the framework of the current-current theory of the weak interaction, the Hamiltonian density is the product of a total weak current $J^A$ with its Hermitian adjoint. In the Cabibbo notation, the total weak current

$$ J^A = \lambda^e_\alpha + \lambda^\mu_\alpha + \cos \theta \cdot h_\alpha^{A=0} + \sin \theta \cdot h_\alpha^{A=1} $$

is the sum of the electronic current $\lambda^e_\alpha$, the muonic current $\lambda^\mu_\alpha$, and two hadronic currents, respectively [1]. The different coupling strengths of the strangeness-conserving and the strangeness-changing hadronic currents is expressed by the Cabibbo angle $\theta = 0.24$. The universal current-current form for the Hamiltonian density

$$ \mathcal{H} = \frac{g}{2\sqrt{2}} \left[ J^A_\alpha J^\alpha_\beta + \text{h.c.} \right] $$

predicts the existence of a variety of weak processes. Whereas the "non-diagonal" processes like $\mu$-decay, nuclear $\beta$-decay, leptonic and hadronic decays of hyperons are well established, the experimental observation of the so-called "diagonal" processes is exceedingly difficult. The detection of diagonal leptonic processes suffers from the very small cross sections of $\nu_e - e$ and $\nu_\mu - \mu$ scattering, respectively. Positive evidence for the existence of $\bar{\nu}_e - e$ scattering has been reported by Reines and co-workers [2]. The detection of diagonal hadronic interactions is difficult because weak hadronic decays with conservation of strangeness don’t exist, and scattering experiments suffer from the dominant contribution of the strong interaction background.

There are already highly promising attempts [3] to perform scattering experiments at higher energies and to disentangle the weak scattering contribution by its unique feature of parity violation. But the field is still dominated by measurements on nuclei, and a large number of experiments have been reported and discussed in review articles [4], providing good evidence for the existence of weak hadronic...
Due to the small parity violating contribution to the nucleon-nucleon potential an eigenfunction \( \psi \) of a nuclear state is no longer an eigenfunction of parity but is rather of the form \( \psi_J = \psi_J^P + \psi_J^\pi \), where \( J \) and \( \pi \) denote the angular momentum and parity quantum numbers, thus giving rise to various parity violating phenomena in nuclear physics. Sign and magnitude of parity violating effects in nuclei can answer in favourable cases fundamental questions concerning the structure of the weak interaction. The possibly different coupling strength of diagonal and non-diagonal processes, the sign of the Fermi-constant \( G \), the isospin selection rules governing strangeness conserving weak hadronic interactions, the discrimination among various weak interaction models of other than the standard current-current type might be mentioned. Recently, the discovery of weak neutral currents [5] has stimulated again the interest in parity violation effects in nuclear states as well as the consequences of some recently proposed gauge models of strong, electromagnetic and weak interactions [6].

The interpretation of experimental results on parity admixtures in nuclear states is subject to three basic and difficult problems. The first one arises from the lack of a commonly adopted weak interaction theory leading to a variety of different models. Secondly, the expected order of magnitude of \( \mathcal{F} \), the amplitude of the admixture of the opposite parity state, is about \( 10^{-7} \). This is the ratio of the weak and strong interaction coupling constants at the average nucleon-nucleon distance of about 1.2 fm. Since effects of the order \( 10^{-7} \) are very hard to measure one selects favourable nuclear transitions where one measures interference effects between normal and parity forbidden transitions, the normal process being strongly hindered by nuclear structure effects. Thus the opposite parity transitions are relatively enhanced by a dynamical factor usually denoted \( \mathcal{R} \). Any theoretical prediction is therefore strongly dependent on a fairly good understanding of the nuclear structure. Thirdly, the experiments
looking for parity violation effects are extremely difficult to perform. Over the last decade an impressive progress has been made concerning the development of new experimental techniques opening up new orders of magnitude in accuracy.

So far three different methods have been widely used to observe parity violation effects in nuclei. The first one looks for the existence of decay channels being forbidden by absolute parity selection rules. The parity forbidden $2^+ \rightarrow 0^+$ ($8.88$ MeV) $\alpha$-transition in $^{16}$O has been observed \[7\]. The second method looks for the existence of a net circular polarization of $\gamma$-quanta emitted by an unpolarized source. Using an integral counting technique as first described by Lobashov and co-workers \[8\] the results of several groups became compatible in the most recent years, establishing non-zero effects in different nuclei.

The third method looks for spatial asymmetries of decay particles with respect to a nuclear polarization axis. The polarization is obtained either by the capture of polarized thermal neutrons or by the emission of $\beta^-$-particles, as a consequence of the maximum parity violation property of weak interactions. Several neutron capture experiments were performed on the nucleus $^{114}$Cd yielding in part inconsistent results \[9\].

The second type of asymmetry experiments observes essentially a forward-backward asymmetry of $\gamma$-quanta in $\beta-\gamma$ directional correlations. Three experiments of this type have been reported so far \[10, 11, 12\]. All three results are incompatible with each other thus indicating the presence of not yet eliminated systematic errors. Clearly, $\beta-\gamma$ directional asymmetry experiments are limited in statistical accuracy compared to circular polarization experiments because the latter measure single rates rather than coincidence rates. On the other hand, it seems to be advantageous to attack a difficult experimental situation by different methods.
Furthermore, a directional asymmetry experiment might be the only one feasible in the case of low energy $\gamma$-quanta, where the Compton-polarimeter efficiency to select right-left circularly polarized quanta [13] decreases substantially. Spatial asymmetry experiments also provide in some cases like in the reaction $n + p \rightarrow d + \gamma$ [14] complementary information on the isospin structure of the weak internucleon potential, compared to circular polarization experiments. Recently, experiments were proposed [15] to detect parity violation effects of weak neutral currents in atomic physics, using the spatial asymmetry technique.

We would like to give a detailed report on an experiment measuring the forward-backward \( \gamma \)-asymmetry after \( \beta \)-decay in \( ^{203}_{\text{Hg}} \). Preliminary results have been published earlier [12].

2. The transition \( ^{203}_{\text{Hg}} \rightarrow ^{203}_{\text{Tl}} \)

The decay cascade \( ^{203}_{\text{Hg}} \rightarrow ^{203}_{\text{Tl}} \) is shown in Fig. 1. The first forbidden \( \beta \)-transition (\( \Delta J = 1, \Delta \pi = -1 \), \( \log t = 6.5 \) and \( E_0 = 212 \) keV) has a halflife \( (T_{1/2} = 46.6 \) d) well suited for very precise directional correlation experiments. The \( \gamma \)-transition from the 279 keV excited state (\( \tau = 0.28 \) ns being sufficiently short) to the ground state of \( ^{203}_{\text{Tl}} \) is a mixture of M1 and E2 radiation. The amplitude mixing ratio \( q = \langle E2 \rangle / \langle M1 \rangle \) has been measured by different groups [16 - 21], yielding \( q = + (1.1 \ldots 1.5) \). The total conversion coefficient is 0.227 [22], in agreement with the results of recent experiments [20, 21]. The A_2 coefficient of the symmetric \( \beta - \gamma \) directional correlation

\[ W(\Theta) = 1 + A_2 P_2(\cos \Theta) \]

has been measured with inconsistent results. One part of experiments [11, 23 - 25] agrees with an average value
$A_2 \approx -1 \times 10^{-3}$ being only slightly dependent on the $\beta$-energy, but the second part of experiments [26 - 28] yielded $A_2$ values up to $4 \times 10^{-2}$, with a significant dependence on the $\beta$-energy.

The asymmetry coefficient $A_1$ arising in case of parity impurities in nuclear states has been derived by Krüger [29] and Blin-Stoyle [30]. It reads for the special case considered here as

$$A_1 = \mathcal{G} \cdot \mathcal{F}_\gamma = \mathcal{G} \frac{2}{1 + q^2} \mathcal{F}_\gamma$$

with

$$\mathcal{G} = \left\{ \frac{\chi^2}{c} \cdot \frac{1 - 2\lambda\sqrt{J_m(J_m+1)}}{1 + \lambda^2} \cdot \frac{J_m(J_m+1) - J_\gamma(J_\gamma+1) + 2}{2\sqrt{3J_m(J_m+1)}} \right\} \cdot \left\{ \mathcal{P}_1(11J_\gamma J_m) + q\mathcal{P}_1(12J_\gamma J_m) \right\}$$

Thus, $A_1$ is proportional to the circular polarization $\mathcal{F}_\gamma$ of the $\gamma$-transition. The constant $\mathcal{G}$ is determined by the properties of the $\beta$-$\gamma$ cascade. The first term in $\mathcal{G}$ represents the nuclear polarization after the $\beta$-decay, the second term typical for angular correlations is determined by the $\gamma$-transition. $J_\gamma$, $J_m$ and $J_\gamma$ are the spins of the initial, intermediate and final state linked by the cascade. The tabulated coefficients $\mathcal{P}_1$ [31] are determined by the angular momenta involved. Finally, $\lambda$ denotes for allowed $\beta$-transitions the ratio of the Fermi to Gamow Teller matrix elements, whereas for first forbidden $\beta$-transitions up to six higher order matrix elements are involved. $\lambda$ reads in case of the validity of the $\gamma$-approximation [32] as [21]

$$\lambda = \frac{-\mathcal{C}_f \int \mathcal{F}_f \mathcal{L} + \mathcal{C}_s \int \mathcal{F}_s \mathcal{L}}{\mathcal{C}_f \int \mathcal{L} \mathcal{F}_f - \mathcal{C}_s \int \mathcal{L} \mathcal{F}_s},$$

in the usual notation for the nuclear matrix elements. However, for a first forbidden decay $5/2^- \rightarrow 3/2^+$ the matrix elements in the numerator vanish [32] thus leading to the expectation $\lambda = 0$. The validity of the $\gamma$-approximation is supported by
the relatively small \(|A_2|\) coefficient, \(\lambda\) can be measured, too, by the \(\beta-\gamma\) circular polarization correlation or by the transverse polarization of conversion electrons. The results of different experiments are summarized by Daniel \cite{27}. They are in part inconsistent, but the most recent results are compatible with the expectation \(\lambda \approx 0\).

Unfortunately, the nuclear polarization is strongly dependent on \(\lambda\) and changes even the sign as shown in Fig. 2, where \(G\) is plotted for a realistic average \(v/c = 0.5\) and \(q = +1.1\), respectively. For \(\lambda = 0\) one gets \(G = 0.15\) and therefore the relation \(A_1 = 0.15\ P_\gamma\).

Since \(^{203}\text{Tl}\) has the proton number 81 the shell model should be well applicable to describe the nuclear structure. The states linked by the 279 keV \(\gamma\)-transition are assigned to \(d_{3/2}\) and \(s_{1/2}\) shells, respectively. The M1 transition is therefore expected to be strongly hindered by \(\ell\)-forbiddenness thus favouring the observation of parity violating effects in this transition.

Estimates of the expected \(\gamma\)-circular polarization have been given by Szymanski \cite{33}

\[ P_\gamma = -(75 \ldots 180) \text{ } \frac{\text{P}}{\text{F}} \]

and McKellar \cite{34}

\[ P_\gamma = -(3 \pm 2) \times 10^{-5} \]

yielding an expected forward-backward asymmetry coefficient \(A_1 = -(11 \ldots 22) \text{ } \frac{\text{P}}{\text{F}}\) and \(A_1 = -4.5 \times 10^{-6}\), respectively. As a consequence of all the uncertainties involved in these estimates they should be taken only as a guideline for the experiment. It is evident, however, that any set-up has to be designed to achieve the highest possible accuracy concerning the statistical error as well as the systematic one.
3. Source- and detector geometry

The conventional directional correlation technique uses two detectors, one of them being movable around the source. The method is limited in its accuracy due to inherent systematic errors of the order $10^{-3}$ even in well designed set-ups. In spite of this drawback very early exploratory experiments were carried out by Boehm and Hauser [35], and Müller and Schopper [36], to detect forward-backward asymmetries. The results were negative.

The need of an apparatus being sensitive to asymmetric distributions and insensitive to symmetric ones leads naturally to the concept of a multiple detector arrangement of high symmetry. The first multiple detector system designed to measure extremely small $\gamma$-forward-backward asymmetries after $\beta$-decay was proposed by one of the authors [37], whereas multiple detector systems to measure symmetric correlations were used even earlier [38]. Essentially similar set-ups for asymmetry measurements were used and described later on by two other groups [10, 11].

The basic idea is a 4-detector system consisting of two $\beta$-detectors (1, 2) and two $\gamma$-detectors (I, II) as shown in Fig. 3. In the ideal case of a simple $\beta-\gamma$ cascade transition, a point source and absolute stability in time one gets for the true coincidence rate between any pair (i, j) of different type detectors

$$J_{ij} = N_0 \varepsilon_i \varepsilon_j \nu_{ij} \, W(\theta_{ij}),$$

$N_0$ being the source strength in decays per unit time, $\varepsilon_i$ and $\varepsilon_j$ the overall single detection efficiencies of the counters i and j, $\nu_{ij}$ the coincidence detection efficiency, and finally $W(\theta_{ij})$ the directional correlation depending on the angle $\theta_{ij}$ subtended by the counters i and j, respectively.
Obviously, four coincidence rates can be measured simultaneously in the basic 4-detector system. Combining them like

\[
\frac{C_{1I} \cdot C_{2II}}{C_{1II} \cdot C_{2I}}
\]

the unknown source strength and single detection efficiencies cancel, yielding

\[
\frac{C_{1I} \cdot C_{2II}}{C_{1II} \cdot C_{2I}} = \frac{\omega_{1I} \cdot \omega_{2II}}{\omega_{1II} \cdot \omega_{2I}} \cdot \frac{W(\theta_{1I}) \cdot W(\theta_{2II})}{W(\theta_{1II}) \cdot W(\theta_{2I})}
\]

(1)

The coincidence detection efficiencies are still left. To get rid of them one has two choices. Either one makes a pair of one detector type interchangeable (by a rotation of 180°) or one chooses a sufficiently long coincidence interval to ensure \( \omega_{ij} = 1 \). Both methods have drawbacks. Changing detector positions one has to move quite frequently a detector axis with high mechanical position accuracy requirements, with the risk of position dependent single and coincidence detection efficiencies. The fixed detector geometry has the advantage of a completely static system, but is faced with a much more serious background of chance coincidences. We believed that a static system would allow a higher overall stability, and added to the basic 4-detector system a further \( \beta \)-detector axis, thus arriving to a static 6-detector system as shown in Fig. 4. This set-up offers the highly attractive feature to measure at the same time under the same conditions the asymmetry coefficient \( A \) as well as a control value which should be zero. The eight possible coincidence rates can be used to form six expressions of the type (1), but only three of them being independent. With the correlation function

\[
W(\theta_{ij}) = 1 + A_1 \cos \theta_{ij} + A_2 \rho_2(\cos \theta_{ij})
\]

(2)

one gets in a first order approximation in \( A_1 \) and with \( \theta = \theta_{1II} \)
\[
\frac{C_{1I} \cdot C_{2II}}{C_{1II} \cdot C_{2I}} = 1 + 4A_1 \frac{\cos \theta}{1 + A_2 P_2(\cos \theta)} ,
\]

\[
\frac{C_{1I} \cdot C_{3III}}{C_{1III} \cdot C_1} = 1 + 4A_1 \frac{\cos \theta}{1 + A_2 P_2(\cos \theta)} ,
\]

\[
\frac{C_{1I} \cdot C_{4III}}{C_{1III} \cdot C_4} = 1 ,
\]

\[
\frac{C_{2I} \cdot C_{3II}}{C_{2III} \cdot C_3} = 1 ,
\]

\[
\frac{C_{2I} \cdot C_{4III}}{C_{2III} \cdot C_4} = 1 - 4A_1 \frac{\cos \theta}{1 + A_2 P_2(\cos \theta)} , \quad \text{and}
\]

\[
\frac{C_{3I} \cdot C_{4III}}{C_{3III} \cdot C_4} = 1 - 4A_1 \frac{\cos \theta}{1 + A_2 P_2(\cos \theta)} .
\]

These expressions correspond to six 4-detector systems contained in the 6-detector system, as shown schematically in fig. 5. Apparently, the asymmetry to be measured is enhanced by a factor \(4 \cos \theta\) whereas the symmetric contribution \(A_2 P_2(\cos \theta)\) is strongly suppressed since \(|A_2|\) is small compared to 1 although being much larger than \(|A_1|\).

4. Systematic errors

4.1. Spurious asymmetries

For a more detailed discussion of the 4-detector system one has to take into account deviations from the ideal case.
To show their influence on the result in a simple way the total single detection efficiency of any detector with the subscript \(i\) which will be different for each decay due to different absorption lengths in a finite source, due to electronic drifts etc., is written as

\[
\varepsilon_{ik} = \overline{\varepsilon}_i (1 + \delta_{ik})
\]

for the \(k\)th decay (\(k = 1, \ldots N_o\)), where \(\overline{\varepsilon}_i\) denotes the sample mean over all \(N_o\) decays and \(\delta_{ik}\) the relative deviation for each decay (\(|\delta_{ik}| \leq 1\) will be expected in a good set-up).

Inserting this into expression (1) for example, one obtains in lowest order the additional "spurious asymmetry"

\[
\Delta = \frac{1}{N_o} \sum_{k=1}^{N_o} (\delta_{1k} - \delta_{2k}) \cdot (\delta_{1k} - \delta_{IIk})
\]  

(4)

This formula shows first of all that only terms of quadratic order in \(\delta_{1k}\) contribute to an additional asymmetry. However, this asymmetry is present even if the correlation function \(\gamma(\theta)\) is isotropic.

The relative variation \(\delta_{ik}\) of the overall efficiency is in first order a sum of all possible contributions due to finite source volume, different absorption paths inside the source, electronic instabilities etc. Inserting this sum over, say \(n\), effects

\[
\delta_{1k} = \sum_{r=1}^{n} \delta_{1k}^r
\]

into formula (4) one gets for the total spurious asymmetry

\[
\Delta = \frac{1}{N_o} \sum_{k=1}^{N_o} \sum_{r=1}^{n} \sum_{s=1}^{n} (\delta_{1k}^r - \delta_{2k}^r) \cdot (\delta_{1k}^a - \delta_{IIk}^a)
\]  

(5)

This important result shows that

i) the total spurious asymmetry is a product of the variations in the \(\beta\)- and \(\gamma\)-channels, respectively, and

ii) not only the diagonal terms contribute but also the non-diagonal terms like "\(\beta\)-absorption" variation times "\(\gamma\)-finite source" variation.
Taking into account that unavoidable absorption effects are much more pronounced for $\beta$-particles than for $\gamma$-quanta one has, as a consequence, to minimize all variations in the $\gamma$-channel rather than in the $\beta$-channel. In particular one concludes, in contrary to the common practice, to choose the plane of a flat source perpendicular to the $\gamma$-detector axis.

In a well-designed set-up one can obtain variations in the $\beta$-channel of the order $d \sim 10^{-2}$, and in the $\gamma$-channel $d \sim 10^{-4}$, thus enabling an inherent systematic accuracy of the order $10^{-6}$. On the other hand, the above described formalism offers a simple tool to derive with the requirement of a prefixed systematic accuracy of, say $1 \times 10^{-6}$, the tolerances of the mechanical position of the source and the counters, the maximum source thickness etc.

4.2. True asymmetries

A second class of unwanted asymmetries arises from the presence of the symmetric correlation function. When the apparatus described here was designed the available experimental results for the modulus of $A_2$ amounted up to the order $10^{-2}$. Hence a symmetric distribution with $|A_2| = 5 \times 10^{-2}$ was assumed to investigate the consequences of any imperfect alignment of the source and the detectors. This simulates an asymmetry due to an only partial cancellation of the symmetric terms. It can be shown, however, that the 4-detector system cancels such "true asymmetries" in first order. It is mechanically feasible without great difficulties to keep the contribution of these second order effects below $1 \times 10^{-6}$.

4.3. Parasitic asymmetries

The third class of errors arises from the fact that a background is always present for the true coincidence rates
needed for the analysis. The measured coincidence rates contain in addition chance coincidences, cosmic ray background, coincidences from Compton scattering and bremsstrahlung, coincidences from other decay channels or source impurities, and coincidences due to detector afterpulses. All these rates are distorted by electronic deadtime. Errors of this class may be called "parasitic asymmetries". They are dependent on the layout chosen for the apparatus which has to be described therefore in more detail.

The need to achieve the highest possible statistical accuracy suggests the use of fast detectors and a properly matched electronic system. Plastic scintillators coupled to fast high-gain phototubes are well suited for this purpose. The apparatus was equipped with plastic scintillators NE 102 A. The $\beta$-scintillators were disks of 40 mm diameter and 0.5 mm thickness, coated in front of the source with a thin reflecting Al-layer and coupled via a plexiglass lightguide to fast EMI 9594 B tubes. Since the stability of this tube was not satisfactory and the afterpulse behaviour was clearly worse than one expects from a good tube, the EMI tubes were exchanged in a later stage of the experiment against 56 AVF tubes. Those showed a good performance as well as the two 5" XP 1040 tubes coupled to the $\gamma$-plastic scintillators. These were 20 cm long cylinders with a diameter of 11.4 cm, slightly tapered towards the source and coated with $\mathrm{TiO}_2$ spray. The $\gamma$-detectors and the source carrier were mounted together onto a very rigid steel support thus meeting the tight mechanical tolerances ($2 \times 10^{-2}$ mm) of the $\gamma$-axis. The $\beta$-detectors were mounted into the wall of a cylindrical vacuum chamber ($r = 20$ cm, $h = 40$ cm) rotating around a vertical axis. For the forward-backward asymmetry experiment the apparatus was always kept in the symmetric position $\theta = 60^\circ$ as shown in Fig. 6a.

The current output pulses of the tubes were fed to fast tunnel diode leading edge triggers. The FWHM of the $\beta-\gamma$ time resolution was typically 5.5 ns. The coincidence interval had to be sufficiently long to ensure a coincidence
efficiency of 1 with an accuracy of about $10^{-6}$. Shifting gradually the time resolution peak towards one end of the coincidence interval and extrapolating the asymmetries produced that way we convinced ourselves that 40 ns was a choice being safe enough. The stability with time was no problem, since the coincidence resolution curves were monitored continuously by a TAC and a multichannel-analyzer, and showed a shift of less than 2 ns during one year.

The electronic system was a specially designed nanosecond system with overlap coincidence units as the central part. To get rid of deadtime problems, a deadtime of 85 ns was imposed already by the tunnel-diode triggers in the single channels, all following deadtimes including the counting system being shorter. The measurements were repeated every 100 s to be independent of long term drifts of the electronic thresholds.

Chance coincidences were measured by inserting regularly an additional cable delay of 42 ns into the $\beta$-channel. To ensure the same coincidence interval, the trigger output signals sent by gates either directly or via the cable delay, were mixed again and twice reshaped. However, the chance coincidence rates measured by means of a cable delay have to be corrected before subtraction. The correction for the source decay is easy. The contribution of higher order chance coincidences when using a cable delay is more serious, since the time correlation between true coincidence pulses is disturbed thus giving rise to additional chance coincidences. In our case, those higher order contributions were avoided by choosing the deadtime of the single channels at least equal to the coincidence interval of 40 ns, plus the cable delay of 42 ns, as it is sketched in Fig. 7. This choice offers at the same time another essential advantage concerning the unavoidable coincidences due to $\beta$-afterpulses. The time spectrum of the afterpulse probability measured with a TAC is shown in Fig. 8 for the $\beta$-tube No. 3 which was particularly bad in this respect. The exponential background of the Poisson distribution of zero order is already subtracted to see only
the afterpulses correlated in time with the primary pulses.

A deadtime choice as shown in Fig. 7 prevents that coincidences of primary pulses in one channel with afterpulses in the other channel can be recorded in case of the inserted cable delay. Only coincidences of afterpulses with afterpulses are possible. Moreover, short term afterpulses due to photon feedback are suppressed by the 85 ns deadtime whereas the broad long term distributions due to ion feedback are hardly affected by the 85 ns delay and are therefore subtracted together with the chance coincidences. The maximum integral afterpulse probability of the $\beta$-detectors was $8 \times 10^{-3}$ and for the $\gamma$-detectors $1 \times 10^{-3}$, respectively, in the time range from 85 ns to 5 $\mu$s. The probability for a coincidence of afterpulses was therefore negligible, taking into account the relatively short coincidence interval of 40 ns. Anyway it seems to be advantageous to use different tube types for the $\beta$- and $\gamma$-channel, respectively, to get an afterpulse time distribution being as different as possible.

Since the single rates do not enter directly into the data analysis, dead time corrections are not important because the corrections of the coincidence rate

$$C_{\text{corr}} = C_{\text{meas}} \cdot \frac{1}{1 - N_\beta t_\beta - N_\gamma t_\gamma + C_{\text{meas}} t_{\text{min}}}$$

with $t_{\text{min}} = \min(t_\beta, t_\gamma)$ cancel in first order in the coincidence product (1), thus making unnecessary to know the deadtimes $t_\beta$ and $t_\gamma$ better than to about 1% which is feasible.

Even in the absence of $\beta$-particle emission one would get a coincidence rate due to Compton scattering of $\gamma$-quanta from a $\beta$- to a $\gamma$-detector and vice versa. These events would simulate an $A_1 > 0$ because the differential cross section for Compton scattering peaks into the forward direction. In order to reduce the response of the $\beta$-detectors to $\gamma$-quanta as much as possible without decreasing the
\( \beta \)-detection efficiency the thickness of the \( \beta \)-plastic scintillators was chosen to 0.5 mm. To avoid such coincidences of Compton scattering the detectors were surrounded with lead collimators shielding them against each other. The thickness of the shielding (\( \geq 2 \) cm) made the probability of such events negligible. The \( \gamma \)-detectors cannot detect \( \beta \)-particles because they are absorbed before, whereas the \( \beta \)-detectors have a small (\( \sim 10^{-2} \)) \( \gamma \)-efficiency, too. However, such pulses can only contribute to the single rates and, as a consequence, to the chance coincidence background, but not to the true coincidences.

Obviously, the most simple choice for a 4-detector system would be a linear arrangement of the two \( \beta \)- and two \( \gamma \)-detectors yielding the maximum possible effect
\[
4A_1 \cos \theta = 4A_1 \text{ for } \theta = 0^\circ,
\]
as it was originally suggested [37]. In fact such a linear geometry was used and described later by Baker and Hamilton [11]. To get rid of the Compton scattering coincidences electronic thresholds have to suppress pulses in energy regions accessible for Compton scattering events, too. The difficulty is the danger of pile-up effects on the one hand and the bad energy resolution of plastic scintillators on the other hand. In contrary, the lead shieldings allow a clean suppression of the background of Compton scattering events, with the drawback that the measured effect was reduced in our case by a factor \( \cos 60^\circ \).

Also in the case of a pure \( \beta \)-particle emission an asymmetry \( A_1 > 0 \) would be measured due to bremsstrahlung coincidences. The bremsstrahlung \( \gamma \)-quanta are peaked into the forward direction. The contribution of external bremsstrahlung was negligible compared to the internal bremsstrahlung since the source was an extremely thin isotope separated layer, and the central chamber of the apparatus was evacuated. The contribution of the internal bremsstrahlung coincidences was calculated taking into account the absorption of the soft bremsstrahlung quanta in the preabsorbing layers of
4 mm Fe (wall of vacuum chamber) and 1 mm Pb mounted in front of the $\gamma$-detector. The result was a parasitic asymmetry of $4 \times 10^{-5}$ assuming an allowed shape of the $^{203}\text{Hg }\beta$-spectrum which is in fair agreement with experimental results [39], and thresholds of 20 keV in the $\gamma$-channel and 15 keV in the $\beta$-channel, respectively. In a later stage of the experiment, this contribution was even more suppressed by absorbing the soft quanta in a series of K-edge absorbers (Pb, Ce and Sn, each layer 1 mm thick). The asymmetry due to internal Compton effect quanta arising from the emission of conversion electrons was calculated to be negligible, too, the respective asymmetry being $1 \times 10^{-7}$. Contributions from the emission of conversion electrons and X-rays were negligible because they could not produce coincidences or their effect was small enough due to the absorbers in front of the $\gamma$-detectors.

All three types of background asymmetries, i.e. spurious, true and parasitic asymmetries, are additive and therefore critical, whereas the distortion of the correlation coefficients $A_1$ and $A_2$ due to the finite source and detector surfaces, due to particle scattering and due to depolarization processes in the intermediate state enter in a multiplicative way.

The requirements for the apparatus are summarized in Table 1.

A further advantage of the 4-detector system is its insensitivit to particle scattering. As long as the apparatus is centrally symmetric with respect to the source center, particle scattering cannot produce an asymmetry and can only smear out an already existing correlation.
5. Source preparation

The quality of the source is one of the most stringent requirements of the experiment. It concerns the thickness of the source itself, its flatness, the thickness of the carrier foil, the geometrical position, the rotational symmetry, and the purity of the source. The best way to meet all these requirements seems to be the use of a mass separator.

Fortunately, the electromagnetic mass separator available in our institute [40] is well suited for a separation work of this kind. Since the overall ion extraction efficiency is relatively small (< 1%) very high activities of the order of Ci had to be evaporated in the ion source. The charge material was Hg(II)O powder irradiated in the Seibersdorf ASTRA reactor before, yielding a ratio of active to inactive Hg of about 1 : 10³.

The source carrier foil was prepared on a water surface out of a solution of 5 g polyvinylbutyral in 50 ml cyclohexanone [41]. This foil flattens after drying and shows an impressive resistance against mechanical shocks and against heat. It was coated with an Al-layer by vacuum evaporation for two reasons. Firstly to make the foil electrically conducting, and secondly to ensure the necessary transport of heat arising from the implantation of 40 keV ²⁰³Hg ions into the Al-layer. In addition, this implantation method prevents the active Hg-atoms to evaporate into the vacuum chamber. In fact, there was never found even the faintest sign of radioactivity somewhere in the vacuum system of the apparatus during the measurement.

During the implantation the foil rotated continuously behind a diaphragm system placed into the dispersed Hg-ion beams and allowing only the passage of the active ²⁰³Hg ions. In addition, about the same amount of impurities was deposited from the tails of the inactive neighbor isotopes ²⁰²Hg and ²⁰⁴Hg being dominant by three orders of magnitude.
The source carrier foil (α ≈ 80 μg/cm²) maintains its flatness over a period of more than one year provided it is kept in good vacuum. For this reason the vacuum chamber of the apparatus had to be kept at a pressure of about $1 \times 10^{-5}$ Torr.

All together, five sources were prepared in the way described, and were used for five runs lasting over a period of two years. The achieved source strengths were 8.3, 4.2, 5.3, 0.3 and 3.2 mCi. The details of the separation procedure will be described elsewhere.

6. Data analysis

For each day and each detector the quantity

$$z_i - \overline{z} \pm \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (z_i - \overline{z})^2}$$

was plotted, as a function of the time of the measurement. $z_i$ denotes the single rate of the i.th measurement over 100 s, $N$ the total number of measurements per day, and $\overline{z}$ the single rate sample mean. Moreover, the ratio

$$R = \frac{\sqrt{\frac{1}{N-1} \sum_{i=2}^{N} (z_i - z_{i-1})^2}}{\sqrt{2} \overline{z}}$$

was calculated. $R$ is the ratio of the actual variation of the single rates to the expected one on the basis of the validity of a Poisson law. Long term trends are obviously eliminated by this procedure. In the ideal case of no systematic instabilities (no change of the PM gain, no shift of electronic thresholds) one expects $R = 1$. The deviation from 1 gives therefore a feeling for the short term stability of the combined system detector plus associated electronics.
In fact the $\gamma$-detectors showed a very good behaviour with ratios typically between 1.0 and 1.3 thus proving the satisfactory overall stability of the $\gamma$-channels according to the requirements pointed out in section 4.1. The $\beta$-channels were less stable, with ratios typically in the range of $2 < R < 10$. Since the $\beta$-channels are allowed to be less stable than the $\gamma$-channels there is no argument to reject these data. Nevertheless the $\beta$-tubes were replaced in a later stage of the experiment against 56 AVP tubes, because the EMI tubes showed in addition sometimes sudden changes of the gain in the order of a few percents, although the tubes were not overloaded at any time. With the 56 AVP tubes the $\beta$-channels had the same good stability as the $\gamma$-channels.

Sometimes, the plot of the single rates versus time showed drastic changes (i.e., $>4\sigma$) of the rates only for one period of 100 s. They were synchronous for all tubes and were assigned to sudden line voltage changes. Such data were rejected as well as some data taken during apparatus malfunctions.

To get the true coincidence rates from the measured ones, the deadtime correction was applied and the cosmic ray background was subtracted as well as the chance coincidence background, properly corrected for the source decay. The further analysis of the data seems to be rather simple. Each single 100 s measurement should provide an estimate for $A_1$ and the weighted mean over the whole sample might be the right answer. However, this simple approach is not quite correct, since the estimates for $A_1$ got this way are biased. This bias is due to second order terms in the statistical errors which may - although being small - systematically distort the result in a high precision experiment. In our analysis these higher order terms are crucial and do not permit this simple approach. Therefore, we present here a short outline of the applied statistical procedure.
The basic equation is (neglecting the $A_2$ correction and all systematic error contributions)

$$\frac{c_{1I} \cdot c_{2II}}{c_{1III} \cdot c_{2I}} = 1 + 4A_1 \cos \theta,$$

where now $c_{ij}$ denotes the theoretical true coincidence rate whose difference to the actually observed coincidence rate $C_{ij}$ is assumed to be Gaussian distributed with a known standard deviation $\sigma_{ij}$. The actual relative difference in the $k$th measurement may be denoted by $\delta_k$ with

$$C_{ij}^k = c_{ij}(1 + \delta_{ij}^k).$$

One gets the result

$$\frac{C_{1I}^k \cdot C_{2II}^k}{C_{1III} \cdot C_{2I}^k} = \frac{c_{1I}^k \cdot c_{2II}^k}{c_{1III} \cdot c_{2I}} \left\{ 1 + \delta_{1I}^k + \delta_{2II}^k - \delta_{1III}^k - \delta_{2I}^k + \delta_{1II}^k \delta_{2I}^k + \delta_{1I}^k \delta_{2II}^k - \delta_{1II}^k \delta_{1III}^k - \delta_{2II}^k \delta_{1III}^k - \delta_{2I}^k \delta_{1III}^k + (\delta_{1II}^k)^2 + (\delta_{2I}^k)^2 + \text{higher order terms} \right\}$$

If one applies now an averaging procedure, the first term gives the "right" result, being multiplied with something which does not average to zero. The linear terms do so, the mixed quadratic terms denoting correlations might do so, but the diagonal quadratic terms cannot. The result is therefore distorted by a factor of the order of the squared relative error of the single measurement, which is of the order $10^{-3}$ to $10^{-4}$ and unknown, too. The result is a systematic shift of the average of the $A_1$ distribution and a non-zero skewness, too.

The method which has been developed is a generalized least squares fit iteration method. The basic difference to the usual least squares fit method is that there is not one dependent and erroneous variable opposed to a set of independent error free variables, but one set of erroneous variables treated completely symmetrically. Basically, one
has to minimize the weighted sum

\[ \chi^2 = \sum_k \left\{ \frac{1}{(\sigma_{11}^k)^2}(c_{1I}^k - c_{1I}^k)^2 + \frac{1}{(\sigma_{22}^k)^2}(c_{2II}^k - c_{2II}^k)^2 + \frac{1}{(\sigma_{1II}^k)^2}(c_{1II}^k - c_{1II}^k)^2 + \frac{1}{(\sigma_{2I}^k)^2}(c_{2I}^k - c_{2I}^k)^2 \right\} \]

with respect to the variables \( c_{ij}^k \) (the index \( k \) runs over all measurements). The variables \( c_{ij}^k \) have to satisfy the constraints

\[ \frac{c_{1I}^k \cdot c_{2II}^k}{c_{1II}^k \cdot c_{2I}^k} = 1 + 4A_1 \cos \theta. \]

This method avoids the above mentioned distortion arising from the dominant contribution from the diagonal quadratic terms. Correlations have not been taken into account since they are expected to be relatively small because the single detection efficiencies were small compared to 1. Unfortunately the procedure is somewhat complicated since the normal equations are nonlinear and their number is proportional to the total number of measurements performed. But with a linearization and an iteration the method becomes quite easy to apply even with a small computer.

In this type of analysis the four coincidence rates of each single measurement represent a point in a four-dimensional space. The total weight of this point is determined by its errors along the four axes. Since the coincidence rates are very weakly correlated the error ellipsoid has its axes parallel to the four coordinate axes. The geometrical interpretation of the least squares fit method is to find a hyperplane in the four dimensional space of measured points by making the sum of the weighted distances to a minimum. The hyperplane itself is characterized by only one parameter, namely
A₁, with \(|A₂|\) neglected. The details of the method will be described elsewhere.

7. Measurements and results

The eight coincidence rates and the six single rates of the apparatus were accumulated for a period of exactly 100 s, controlled by a quartz oscillator with a stability better than \(10^{-7}\). The counting rates were punched onto papertape together with other data monitoring the status of the apparatus, like laboratory temperature which was regulated to \(25.0 \pm 0.5 \, ^0\text{C}\), vacuum etc. After the end of the 100 s interval gates were switched to insert a delay of 42 ns into the \(\gamma\)-channels. The chance coincidences were recorded for a further 100 s period.

The source strengths were in the order of mCi, the single overall detection efficiencies about \(3 \times 10^{-3}\) thus yielding single rates up to \(2 \times 10^5\) counts/s. Due to the relatively long coincidence interval of 40 ns the background of chance coincidences was of the same order of magnitude as the true coincidences.

Data were taken continuously around the clock. Once per week the electronic and data transfer system was carefully checked for any malfunction. Any data taken in periods when a part of the system was not perfectly reliable were rigorously rejected. Data were taken only in the highly symmetric arrangement (\(\theta = 60^\circ\)) as shown in Fig. 6. The total counting time lasted for two years with breaks in between used for auxiliary measurements, maintenance and improvement of the apparatus, and for the effort of the mass separation of new sources.

Auxiliary measurements were done with a pure \(\beta\)-emitter of an energy comparable to the \(^{203}\text{Hg} \rightarrow ^{203}\text{Fr}\) transition.
The aim of these runs was to support the calculation for the bremsstrahlung asymmetry. Sources of $^{147}$Pm were prepared with the evaporation technique. The coincidences recorded in the apparatus gave the average $0.02 \pm 0.1$ counts/100 s. Relating this result to the number of true coincidences obtained with a $^{203}$Hg source at the same single $\beta$-detector rates one arrives to an upper limit of $2 \times 10^{-5}$ for the asymmetry due to bremsstrahlung, assuming only events into the forward direction. Since the maximum energy of the $^{147}$Pm $\beta$-spectrum ($E_o = 225$ keV) is slightly higher as in the case of $^{203}$Hg ($E_o = 212$ keV), one concludes in agreement with the calculation that the background of bremsstrahlung coincidences is negligible compared to the quoted statistical error of $A_1$.

Data without a source were taken regularly to obtain an estimate of cosmic ray- and background contamination coincidences. This was mainly done to ensure that no radioactivity from the source evaporated and was deposited somewhere in the inner parts of the vacuum chamber. No background contamination was ever observed.

Using the generalized method of least squares fit for each of the six 4-detector systems contained in the 6-detector system the results summarized in Table 2 and shown in Fig. 9 were obtained.

We emphasize that the quoted results for the asymmetry measurements were obtained at the same time and under the same conditions as the results for the control value, which is expected to be compatible with zero. The average for the control value is $(1.3 \pm 0.7) \times 10^{-4}$, whereas we obtained for $A_1$ the raw value $A_1 = -(2.5 \pm 0.7) \times 10^{-4}$. In this analysis the $A_2$ correction was neglected ($|A_2| < 5 \times 10^{-2}$) as well as any additive asymmetry since these were shown to be small compared to the quoted error of $7 \times 10^{-5}$. However, the multiplicative corrections amount to a 4% increase of the observed raw asymmetry, yielding the final results.
\[ A_1 = -(2.6 \pm 0.7) \times 10^{-4} \text{ and for the control value } (1.3 \pm 0.7) \times 10^{-4}. \] The quoted errors represent one standard deviation.

Given the validity of the relation \( A_1 = -0.15 \times (75 \ldots 150) \), one gets the estimate for the amplitude \( F \) of the opposite parity admixture, \( 8.4 \times 10^{-5} < F < 3 \times 10^{-5} \).

8. Conclusion

On the basis of the current theoretical models one expects an asymmetry coefficient \( A_1 \) being compatible with zero within the quoted error limit of \( 7 \times 10^{-5} \). \( A_1 \) has been measured with similar methods as reported in this work by two other groups. Bock and Leuschner reported a non-zero asymmetry coefficient \( A_1 = (2.7 \pm 0.3) \times 10^{-4} \) \([10]\) of the same order of magnitude but with opposite sign to our result. In contrary, Baker and Hamilton quoted an asymmetry compatible with zero, \( A_1 = (5.8 \pm 7.9) \times 10^{-5} \) \([11]\).

Moreover, several \( \gamma \)-circular polarization measurements have been performed on the 279 keV \( \gamma \)-transition in \(^{203}\text{Tl}\). As discussed in section 2, \( A_1 \) and \( P_\gamma \) are related via \( A_1 = G P_\gamma \) where the constant \( G \) is strongly dependent on the details of the \( \beta - \gamma \) transition and was estimated to be 0.15. The results obtained by several groups for the \( \gamma \)-circular polarization are summarized in Table 3.

The whole experimental knowledge achieved so far does not seem to favour the existence of a parity violation effect in the transition \(^{203}\text{Hg} \rightarrow ^{203}\text{Tl}\). However, looking for the trend of the results in the field of parity violation in nuclear physics in the past decade, the observed results became typically lower as the experimental techniques were improved. In contrary to that, we observed a non-zero effect although we think that our experimental method constitutes
an important improvement in the technology of very precise measurements of asymmetric directional correlations. That means in particular the fixed 6-detector geometry allowing both the measurement of the asymmetry and of a control value with a high inherent accuracy, the mounting of a flat source perpendicular to the $\gamma$-detector axis thus avoiding large non-diagonal contributions of spurious asymmetries, the use of isotope separated sources of an outstanding quality, and finally the generalized least squares fit method for the data analysis.

A careful analysis of the systematic errors showed that they can be kept typically in the order $10^{-5}$ to $10^{-6}$. The inherent test facility of deriving from two 4-detector systems a control value is a good tool to test the sensitivity of the apparatus for background asymmetries. Since our result for the control value is with 1.9 standard deviations not incompatible with zero, in contrary to the result for $A_1$, we conclude that we have observed an asymmetry in the $\beta - \gamma$-cascade transition $^{203}\text{Hg} \rightarrow ^{203}\text{Tl}$ at the level of 3.7 standard deviations which can be explained at present only as an effect of the admixture of opposite parity in nuclear states.

Acknowledgement

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alignment of the source and the $\beta$-detectors</td>
<td>$\pm 2 \times 10^{-2}$ mm</td>
</tr>
<tr>
<td>Tolerance of the geometrical position of the $\beta$-detectors</td>
<td>$\pm 4 \times 10^{-1}$ mm</td>
</tr>
<tr>
<td>Maximum allowed source diameter</td>
<td>4 mm</td>
</tr>
<tr>
<td>Maximum allowed source thickness</td>
<td>100 $\mu$g/cm$^2$</td>
</tr>
<tr>
<td>Maximum skewness of the source plane</td>
<td>5 mrad</td>
</tr>
<tr>
<td>Short term stability of the phototube gain and the electronic thresholds</td>
<td>$1 \times 10^{-4}$</td>
</tr>
<tr>
<td>Source strength</td>
<td>about 1 mCi</td>
</tr>
</tbody>
</table>

Table 1: Design parameters of the apparatus
Table 2: Experimental results for the six 4-detector systems

<table>
<thead>
<tr>
<th>4-detector system</th>
<th>deviation from 1 theoretical value</th>
<th>experimental result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1II.2II</td>
<td>$\frac{4A_1\cos60^\circ}{1 + A_2P_2(\cos60^\circ)}$</td>
<td>$-(6.3 \pm 2.0) \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$X^2/ND = 1.004 \pm 0.007$</td>
</tr>
<tr>
<td>1II.3II</td>
<td>$\frac{4A_1\cos60^\circ}{1 + A_2P_2(\cos60^\circ)}$</td>
<td>$-(3.0 \pm 2.0) \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$X^2/ND = 1.015 \pm 0.007$</td>
</tr>
<tr>
<td>1II.4II</td>
<td>zero</td>
<td>$(1.0 \pm 2.0) \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$X^2/ND = 1.006 \pm 0.007$</td>
</tr>
<tr>
<td>2II.3II</td>
<td>zero</td>
<td>$(4.1 \pm 2.0) \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$X^2/ND = 1.013 \pm 0.007$</td>
</tr>
<tr>
<td>2II.4II</td>
<td>$\frac{4A_1\cos60^\circ}{1 + A_2P_2(\cos60^\circ)}$</td>
<td>$(7.9 \pm 2.0) \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$X^2/ND = 1.004 \pm 0.007$</td>
</tr>
<tr>
<td>3II.4II</td>
<td>$\frac{4A_1\cos60^\circ}{1 + A_2P_2(\cos60^\circ)}$</td>
<td>$(3.2 \pm 2.0) \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$X^2/ND = 1.015 \pm 0.007$</td>
</tr>
</tbody>
</table>
Table 3: Experimental results for the $\gamma$-circular polarization of the 279 keV transition in $^{203}$Tl

<table>
<thead>
<tr>
<th>authors</th>
<th>$\gamma$-circular polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boehm and Kankeleit [42]</td>
<td>$P_\gamma = -(2.0 \pm 3.0) \times 10^{-5}$</td>
</tr>
<tr>
<td>De Saintignon and Chabre [43]</td>
<td>$P_\gamma = -(3.0 \pm 1.8) \times 10^{-5}$</td>
</tr>
<tr>
<td>Kuphal [44]</td>
<td>$P_\gamma = (1 \pm 7) \times 10^{-6}$</td>
</tr>
<tr>
<td>Vanderleeden et al. [45]</td>
<td>$P_\gamma = (2 \pm 5) \times 10^{-6}$</td>
</tr>
<tr>
<td>Lipson et al. [46]</td>
<td>$P_\gamma = -(4 \pm 10) \times 10^{-6}$</td>
</tr>
</tbody>
</table>
Figure captions

Fig. 1 The decay cascade $^{203}\text{Hg} \rightarrow ^{203}\text{Tl}$

Fig. 2 $G$ as a function of $A$ ($q = 1.1$, $v/c = 0.5$)

Fig. 3 Principle of the 4-detector system

Fig. 4 Principle of the 6-detector system

Fig. 5 The six 4-detector sub-systems within the 6-detector system

Fig. 6a Vertical view of the apparatus

6b Horizontal view of the apparatus
(a) source carrier, (b) vacuum chamber
(c) $\beta$-detector lead shield, (d) $\gamma$-detector lead shield, (e) $\beta$-plastic scintillator with light guide,
(f) $\gamma$-plastic scintillator, (g) EMI 9594 B (later 56 AVP) phototube with mu-metal shield, (h) XP 1040 phototube with mu-metal shield, (i) phototube base

Fig. 7 Choice of the coincidence interval, the cable delay and the single channel deadtime

Fig. 8 Time distribution of the afterpulses of the $\beta$-phototube No. 3 (EMI 9594 B), in the range 60 ns to 5 $\mu$s.

Fig. 9 The asymmetries observed in the six 4-detector sub-systems
203\textsuperscript{Hg} \hspace{1cm} 46.59\,\text{d} \hspace{1cm} 5/2^- \\
\downarrow \hspace{1cm} 212\,\text{keV, 100%} \\
491\,\text{keV?} \hspace{1cm} (\approx 0.004\% ) \\
\downarrow \hspace{1cm} 0.278\,\text{ns} \hspace{1cm} 3/2^+ \\
\downarrow \hspace{1cm} 279.18\,\text{keV} \hspace{1cm} (\text{M1 + E2}) \\
\downarrow \hspace{1cm} \text{stable} \hspace{1cm} 1/2^+ \\
203\textsuperscript{Tl}
\[
\begin{align*}
\frac{II\cdot II}{III\cdot II} & \equiv \begin{array}{c}
\text{II} \\
\text{2} \\
\text{3} \\
\text{1} \\
\text{I}
\end{array} \\
\frac{II\cdot III}{III\cdot III} & \equiv \begin{array}{c}
\text{II} \\
\text{2} \\
\text{3} \\
\text{1} \\
\text{I}
\end{array} \\
\frac{II\cdot IV}{III\cdot IV} & \equiv \begin{array}{c}
\text{II} \\
\text{2} \\
\text{3} \\
\text{1} \\
\text{I}
\end{array} \\
\frac{III\cdot III}{II\cdot III} & \equiv \begin{array}{c}
\text{II} \\
\text{2} \\
\text{3} \\
\text{1} \\
\text{I}
\end{array} \\
\frac{III\cdot IV}{II\cdot IV} & \equiv \begin{array}{c}
\text{II} \\
\text{2} \\
\text{3} \\
\text{1} \\
\text{I}
\end{array} \\
\frac{IV\cdot IV}{III\cdot IV} & \equiv \begin{array}{c}
\text{II} \\
\text{2} \\
\text{3} \\
\text{1} \\
\text{I}
\end{array}
\end{align*}
\]

Fig. 5
without delay

\[ \text{deadtime} = 85\text{ns} > 4\tau \]

\[ \tau \]

\[ \text{delay} = 42\text{ns} > 2\tau \]

with delay

\[ \beta \text{ channel} \]

\[ \gamma \text{ channel} \]

single pulse width \( \tau = 20\text{ns} \)

coincidence interval \( 2\tau = 40\text{ns} \)

Fig. 7
deviation from 1

-8 -6 -4 -2 0 2 4 6 8 x10^-4

4-detector system

\[
\begin{align*}
\frac{(1I.2II)}{(1II.2I)} & \quad 1 + 2A_1 \\
\frac{(1I.3II)}{(1II.3I)} & \\
\frac{(1I.4II)}{(1II.4I)} & \quad 1 \\
\frac{(2I.3II)}{(2II.3I)} & \\
\frac{(2I.4II)}{(2II.4I)} & \quad 1 - 2A_1 \\
\frac{(3I.4II)}{(3II.4I)} & 
\end{align*}
\]

Fig. 9
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