Gamow–Teller strength distribution near $^{100}$Sn.
The beta decay of $^{102}$In

M. Gierlik$^{a,*}$, A. Płochocki$^{a}$, M. Karny$^{a}$, W. Urban$^{a}$, Z. Janas$^{a}$, L. Batist$^{b}$, F. Moroz$^{b}$, R. Collatz$^{c}$, M. Górska$^{c}$, H. Grawe$^{c}$, M. Hellström$^{c}$, Z. Hu$^{c}$, R. Kirchner$^{c}$, W. Liu$^{c}$, M. Rejmund$^{c}$, E. Roeckl$^{c}$, M. Shibata$^{c}$, J. Agramunt$^{d}$, A. Algora$^{d}$, A. Gadea$^{d}$, B. Rubio$^{d}$, J.L. Tain$^{d}$, D. Cano-Ottec, S. Harissopulos$^{f}$

$^a$ Institute of Experimental Physics, University of Warsaw, PL-00681 Warsaw, Poland
$^b$ St. Petersburg Nuclear Physics Institute, 188-350 Gatchina, Russia
$^c$ Gesellschaft für Schwerionenforschung mbH, D-64291 Darmstadt, Germany
$^d$ Instituto de Física Corpuscular CSIC, Universitat de Valencia, Spain
$^e$ CENMAF, Avda. Complutense 22, 28040 Madrid, Spain
$^f$ Institute of Nuclear Physics, NCSR “Demokritos”, 153.10 Aghia Paraskevi, Athens, Greece

Received 5 February 2003; received in revised form 19 May 2003; accepted 3 June 2003

Abstract

In two complementary measurements, an array of high-resolution germanium detectors and a total-absorption $\gamma$-spectrometer were used to investigate the $\beta$ decay of $^{102}$In, a one proton–hole, three-neutron particle nucleus with respect to the $^{100}$Sn core. A total of 509 $\beta$-delayed $\gamma$ rays (494 new) were observed for $^{102}$In, and a scheme comprising 234 levels (223 new) was constructed for the decay daughter $^{102}$Cd. The $Q_{EC}$ value of the decay and the half-life were determined, the latter one being 23.3(1) s. The summed Gamow–Teller strength deduced from the high-resolution experiment is as low as 0.60 ± 0.07 ± 0.11 compared to a value of 4.70 ± 0.05 ± 0.20 ± 1.0 obtained from the total absorption measurement, and to a shell-model prediction of 13.3.

© 2003 Elsevier B.V. All rights reserved.

PACS: 23.20.Lv; 27.80.+w; 29.30.Kv

* Corresponding author.
E-mail address: gierlik@zsjlin.igf.fuw.edu.pl (M. Gierlik).
1. Introduction

The combination of two complementary experimental techniques, the high resolution germanium detector array (Cluster Cube) [1] and the low-resolution but high-efficiency total-absorption spectrometer (TAS) [2], has been demonstrated to be a powerful tool for investigating complex Gamow–Teller (GT) $\beta$ decays of nuclei around the doubly magic nucleus $^{100}$Sn [3,4]. The same technique was also applied in the region of the semi-magic nucleus of $^{146}$Gd [5]. This double strategy is especially useful for investigating the problem of missing GT strength and for determining the corresponding GT hindrance factor. In this paper, we report on experimental data obtained from the $^{102}$In decay by means of the Cluster Cube and TAS array at the GSI on-line mass separator. While making another step toward $\beta$-decay measurement of $^{100}$Sn we also extend the series of the previously investigated indium isotopes $^{100}$In [6] and $^{103−107}$In [7,8].

This paper is structured as follows. In Section 2 the experimental setup and the results obtained from the Cluster Cube experiment are described. Since the technical details have already been published [3,4], only substantial differences are outlined there. Section 3 deals with the TAS experiment and its data analysis, with the emphasis being put on the latter topic. Section 4 includes the experimental $^{102}$In $\beta$-decay properties, a comparison with shell-model predictions, and an attempt to explain the striking differences between the GT-strength ($B_{GT}$) distribution and the GT hindrance factor obtained from the Cluster Cube and TAS results, respectively. Finally, a summary is given in Section 5.

2. Results from the Cluster Cube measurement

2.1. Experimental technique

The details of the experimental set-up were extensively described in the work of Hu et al. [3,4] and are thus only briefly outlined here. $^{102}$In was produced in a $^{58}$Ni($^{50}$Cr, 3p3n) fusion–evaporation reaction of a 5.0 MeV/u $^{58}$Ni beam on a 3.4 mg/cm$^2$ thick $^{50}$Cr target, enriched to 96.2%. The $A = 102$ beam, delivered by a FEBIAD ion source of the GSI on-line mass separator was implanted into the tape of a moving-tape collector. The resulting activity was then transported out of the vacuum through a differentially-pumped slit system to the center of the Cluster Cube, which is an array of 42 germanium crystals [1]. The measurement was performed in consecutive, 40 s collection-measurement cycles for a
total of about 18 hours. The intensity of the mass-separated $^{102}\text{In}$ beam, deduced from the high-resolution data amounted to about 1700 atoms/s for a $^{58}\text{Ni}$ beam intensity of 40 particle nA.

2.2. Data analysis and experimental results

The array of 42 germanium detectors provided data to build a $\gamma-\gamma$ coincidence matrix. 240 gates were set on lines in the matrix projection, with over half of them being later assigned to the $\beta$ decay of $^{102}\text{In}$. The efficiency calibrations of the 42 detectors were taken from [1]. The analysis of the $\gamma-\gamma$ coincidences yielded 509 $\gamma$ transitions assigned to the $\beta$-decay of $^{102}\text{In}$, including 494 new ones, with the intensity of the weakest ones being 0.01%. The identified $\gamma$ transitions have been placed in a level scheme of 234 levels including 223 new ones. The half-life that was derived on the basis of the $\gamma$-time coincidence matrix, played only an auxiliary role in assigning the $\beta$-delayed $\gamma$-rays to the $^{102}\text{In} \rightarrow ^{102}\text{Cd}$ decay scheme.

Fig. 1 displays a partial scheme, composed of transitions that exceed 1% of absolute intensity. It includes 22 excited $^{102}\text{Cd}$ levels all the way to an excitation energy of 4266 keV. Our analysis, however, indicates 70 more levels in this energy range. The partial scheme is in agreement with the data from previous $\beta$-decay [10] work as far as the states at 777, 1638, 2034, 2231, 2387, 2561 and 2718 keV are concerned. The in-beam studies [11,12] confirm these level energies except for those at 2034 and 2387, agree with our finding of 2678 and 2718 states, and identify higher-lying ones within the excitation energy under consideration, which mostly have spins $\geq 8\hbar$. However, these studies also mention states at 3188, 3578 and 3909 keV that were not identified in our work.

By combining the information from our work with that of Refs. [10–12], we conclude that unambiguous spin and parities assignment can only be made for excited $^{102}\text{Cd}$ levels at 777 and 1638 keV, whereas the partial assignments for higher-lying states are tentative (see Fig. 1). In view of the restricted spectroscopic quality of the high-resolution results, we refrain from a further discussion of these data which, as will be discussed in Section 4, are apparently incomplete. The importance of the $^{102}\text{Cd}$ level scheme, obtained in this way, lies in the support of the analysis of the TAS spectra, as described in Section 3.3. The detailed results of the high-resolution experiment will be published elsewhere [9].

For the sake of the on-line control of the measurement and for precise half-life determination, $\gamma$-singles events from four different germanium crystals were accumulated in multi-spectra mode (see Ref. [1] for details). During the experiment they were used to appraise the amount of isobaric contamination, namely $^{102}\text{Ag}$ and $^{102}\text{Cd}$. As can be seen from Fig. 2, this contamination had a large contribution to the overall spectrum.

The analysis of the time characteristics of the 397, 593, 749, 777, 861 and 924 keV $\gamma$-lines was used to determine the half-life of $^{102}\text{In}$. A weighted average of $T_{1/2} = 23.3(1)$ s was obtained that is in a good agreement with, but more accurate than the previously reported values of 22(1) s [10] and 24(4) s [13]. The insert in Fig. 2 depicts the decay of the 777 keV line.
Fig. 1. Partial $^{102}$In → $^{102}$Cd level scheme derived from the high-resolution data. Only transitions with an absolute intensity higher than 1%, along with the corresponding levels, are placed in the scheme.
3. Results from the TAS measurement

3.1. Experimental technique

Like in the Cluster Cube experiment, during the TAS measurement $^{102}$In was produced in the $^{58}$Ni($^{50}$Cr, 3$p$3$n$) fusion–evaporation reaction. In spite of its lower efficiency and shorter operation time, a W(Re)-TIS-C ion source [14] was applied instead of the FEBIAD ion source in order to reduce the isobaric contaminants $^{102}$Ag and $^{102}$Cd. The intensity of the mass-separated $^{102}$In beam, determined by using a separate tape station and a large-volume germanium “monitor” detector [2], was on average 8 times lower than in the case of the FEBIAD ion source, amounting to about 210 atoms/s at a $^{58}$Ni beam intensity of 40 particle nA. The advantage of this measure was, however, that the contamination of the $A = 102$ beam by $^{102}$Ag was suppressed below the level of detecting isobaric contaminants in the TAS. Furthermore, the $^{102}$Cd contamination was reduced to a level that had a negligible impact on the data analysis (see Section 3.2). Fig. 3 includes a part of the singles spectrum accumulated by the monitor detector. By comparing these data to those obtained from one of the Cluster Cube detectors (see Fig. 2) the lack of $^{102}$Ag and reduction of $^{102}$Cd activity can be clearly seen.

While the monitor set-up played only an auxiliary role, the very measurement was performed by TAS. The TAS [2] consists of a large NaI(Tl) crystal and several auxiliary detectors. Radioactive samples are inserted into a cylindrical well of the main crystal by
Fig. 3. Section of the $\gamma$-singles spectrum accumulated by the monitor detector. The presence of the 481 keV line, assigned to the $\beta$-decay of $^{102}$Cd, and the lack of $^{102}$Ag lines indicate that $^{102}$Cd is the only isobaric contaminant. In this experiment the TIS ion source was used.

means of a tape transport system, where they are viewed by a pair of silicon detectors as well as a germanium X-ray detector. The well is closed by another, independent NaI(Tl) crystal. The coincidences between the NaI(Tl) and the silicon or germanium detectors, with a gate set on $^{102}$Cd X-rays in the latter case, yield the $\beta^+$ or electron capture, $\text{TAS}(\beta^+)$ and $\text{TAS(EC)}$, spectra related to the relevant component of the $^{102}$In decay, respectively. As the details of using TAS for $\gamma$-decay measurement have been presented in earlier publications [3,4,7,8], they will not be discussed further in this paper. It suffices to mention that the $A = 102$ beam was shared between TAS and the monitor station with a ratio of 3 : 1. Each source was collected and measured for 48 s, and this mode of beam sharing was continued for a total measurement time of 80 hours.

3.2. Experimental spectra

The $\text{TAS}(\beta^+)$ spectrum was generated by accumulating signals in coincidence with NaI(Tl) and both silicon detectors. The ratio between the $^{102}$Cd and $^{102}$In activity measured by the TAS was estimated, by means of the monitor detector mentioned in Section 3.1, to be not higher than 28%. Out of this number, 20% stem from activity accumulated during the source collection, whereas the remaining 8% were due to the decay of $^{102}$In during the measurement periods. As, the $\beta^+$ branch of the $^{102}$Cd decay amounts to merely 12.8%, the $^{102}$Cd to $^{102}$In ratio in the $\text{TAS}(\beta^+)$ spectrum is smaller than 3.5%. Additionally, only 4% of the $^{102}$Cd $\beta^+$ decay intensity feeds the 1047 and 1369 keV levels in $^{102}$Ag lying above 777 keV, i.e., the energy of the first excited state of $^{102}$Cd [15]. As the TAS response functions to $\gamma$ cascades are smeared over some energy range (due to the limited full-absorption efficiency of the TAS), only about one-third of the $^{102}$Cd events is found
at TAS energies above 777 keV. Even though the resulting 0.1% $^{102}$Cd contamination is completely negligible in the TAS($\beta^+$) analysis it was subtracted from this spectrum.

The EC component of the $^{102}$In decay (TAS(EC)) was investigated by accumulating signals from the NaI(Tl) detector in coincidence with K X-rays of cadmium. The latter ones were recorded by the TAS germanium detector. This condition almost completely removed all $A = 102$ contaminants from the TAS(EC) spectrum. The small efficiency of the TAS germanium detector combined with the large value of the $\beta^+/EC$ ratio of $^{102}$In (see Section 3.3) resulted in a statistics of this spectrum ($1.2 \times 10^5$ events), which is lower by a factor of about 70 than that of the TAS($\beta^+$) spectrum ($8 \times 10^6$ events).

The results of the Cluster Cube experiment has revealed that there are only a handful of low-energy $\gamma$ transitions of significant intensity. Thus the corrections for internal conversion are expected to be small. To prove this assumption we compared the TAS(EC) spectrum with that obtained by an additional condition which demanded anticoincidence with both silicon detectors. The latter condition is supposed to remove most of the contributions of conversion electrons to the TAS(EC) spectrum. Even though no significant difference was found between these two spectra the one with the anticoincidence condition was used for further analysis.

Since the $B_{GT}$ distribution is particularly sensitive to effects near the $Q_{EC}$ value, a special emphasis was put to the subtraction of distortions related to the pile-up effect. According to [16], a fraction of about 0.16% in the entire energy range might be due to pile-up for an average count rate of 2.2 kHz. This yields on average of 0.4 and 25 counts per 20 keV bin for the TAS(EC) and the TAS($\beta^+$) spectrum, respectively. We decided to neglect this effect in the case of the TAS(EC) spectrum, where the pile-up effect is on the level of the statistical uncertainties. For the TAS($\beta^+$) spectrum, however, the pile-up response function was taken into account on the basis of the amplifier true pulse-shape [16].

### 3.3. Data analysis

The analysis of TAS data can be basically reduced to solving the equation:

\[ \mathbf{d} = \mathbf{R} \times \mathbf{f}, \]  

where \( \mathbf{d} \) represents the total absorption spectrum, \( \mathbf{R} \) the matrix of the response functions of the TAS, and \( \mathbf{f} \) the feeding distribution that produces the measured spectrum. The numerical procedures applied for solving the Eq. (1) required the use of 20 keV energy bins rather than individual levels. Thus each \( i \)th column of \( \mathbf{R} \) represents the average response of the TAS to the decay into the \( i \)th energy bin of the feeding distribution \( \mathbf{f} \). The task of obtaining the correct response matrix \( \mathbf{R} \) is the main problem of the TAS data analysis. Its complexity is dominantly related to the fact that the total absorption efficiency of the TAS, though comparatively large (67% at 1 MeV), is lower than 100%. Other effects, such as a non-linear light production in NaI [17] have to be considered as well. The main consequence of these effects is that a response function of a decay to a given level (i.e., a single column of the matrix \( \mathbf{R} \)) depends on all deexcitation modes of that level. A correct response function (or a matrix column of \( \mathbf{R} \)) requires the knowledge of the energies and intensities of all \( \gamma \) rays that deexcite the given level(s).
The first step of deconvoluting the experimental TAS spectra is to reproduce the response of the TAS to a monoenergetic $\gamma$ ray for a possibly wide range of energies. For this purpose the GEANT 3 code and a highly detailed description of TAS geometry [18] were used.

The next step requires knowledge about the level scheme of the decay-daughter and its deexcitation pattern. Data from high-resolution experiments serve as a source of this information. For example, during the analysis of the $^{106-107}\text{In}$ data [8] and particularly $^{58}\text{Cu}$ [19] considerably more “meager”, high-resolution spectroscopic data were used to construct level schemes that yield satisfactory agreement between simulated and experimental TAS response. However, for odd–odd nuclei with large decay energies a lot of weak $\gamma$ transitions deexciting high-lying levels of the daughter nucleus are expected (see, e.g., the work of Hardy et al. [20] concerning the fictitious “pandemonium” nucleus). These transitions would remain unobserved in the continuous background including Compton tails of a few but strong, high-energy $\gamma$ transitions, even if the best high-resolution detectors are used. The existence of this effect has been confirmed as will be described later (see Section 4.1). In such a case experimental data can be supplemented or even replaced by theoretical model predictions of levels and their deexcitation patterns [6].

Based on these arguments the data from the Cluster Cube experiment provided a partial $^{102}\text{In} \rightarrow ^{102}\text{Cd}$ decay scheme that was used as a basis in the unfolding procedure. This “backbone” was supplemented and extended by generating additional, random $\gamma$ transitions deexciting both known and unknown excited levels of $^{102}\text{Cd}$. Numerous decay scheme-models with adjustable parameters were introduced and tested to obtain the best result. For every set of parameters a number of level schemes was generated. The quality of the results was appraised by comparing the simulated TAS response with the corresponding experimental TAS(EC) and TAS($\beta^+ \gamma$) spectra. Fig. 4 depicts such a comparison, with the simulations obtained by using the most successful model. The procedure of designing suitable models was simplified by bunching the discrete energy levels into 20 keV bins. This allowed some additional flexibility in the low-energy part of the scheme (up to about 3.5 MeV) where the exact number and position of $^{102}\text{Cd}$ levels fed by the $\beta$ decay of $^{102}\text{In}$ is unambiguous. We allowed the higher energy bins to deexcite to potential levels lying as low as the energy bin related to the (6$^+$) 2034 keV excited $^{102}\text{Cd}$ level and, in some models, to the 2$^+$, 777 keV and 4$^+$, 1638 keV excited $^{102}\text{Cd}$ state. However, the basic assumption was made that there are no other levels up to an excitation energy of 2.6 MeV, i.e., somewhat above the third excited state of $^{102}\text{Cd}$.

In order to verify the assumptions made concerning high-lying $^{102}\text{Cd}$ levels, we tried to reproduce the experimental TAS spectra on the basis of the statistical model. As can be seen from Fig. 5, the results of this attempt were not satisfactory. This may be explained by the high spin of the $^{102}\text{In}$ ground state and the corresponding yrast-like deexcitation pattern.

The following parameters have been identified to independently and noticeably affect the $^{102}\text{In} \rightarrow ^{102}\text{Cd}$ decay scheme and thus the TAS response functions:

- Separation between low and high excitation energies of $^{102}\text{Cd}$ levels (BL)
  We started out by dividing the available excitation energy range of $^{102}\text{Cd}$ into two sections, expecting that the lower-energy part would be fairly well reproduced by the
Fig. 4. TAS results for EC (left column) and $\beta^+$ (right column) component of the $^{102}$In decay, the dotted vertical lines indicating the $Q_{EC}$ value. Middle panel: experimental (grey histogram line) TAS spectra compared with simulations (thin, continuous line); as abscissa the energy absorbed in TAS is given. Lower panel: difference between the experimental and simulated spectra; the abscissa being the same as that in the middle panel. Upper panel: $\beta$ feedings (normalized to 1) deduced from the spectra shown in the middle panel. The abscissa is $^{102}$Cd excitation energy.

Fig. 5. Upper panel: TAS result for EC decay of $^{102}$In (grey histogram line) in comparison with a fit (thin, continuous line) obtained by using the statistical model for generating an $^{102}$In $\rightarrow$ $^{102}$Cd level scheme. Lower panel: difference between the experimental and simulated spectra. The abscissa is the energy absorbed in TAS.
high-resolution data and modifications would be required only for the high-energy part. Initial researches were aimed at finding the optimal position of the border line between the two sections. However, this approach forced us to introduce changes in the low-energy part. Eventually we realized that instead of separating the energy range into two relatively independent parts, this line turned out to be the upper limit of a 2 MeV wide band of intermediary levels through which all the higher-lying levels deexcite. The presence of such a band effectively increases the average multiplicity of γ cascades and turned out to be the most important factor in shaping the TAS response function. On the basis of the best agreement between simulated and experimental TAS(β⁺) and TAS(EC) spectra the final border line (BL) value was found to be marking the upper end of the band at the energy of 5.75 MeV. In order to obtain this result, the excitation-energy range from 4 to 6 MeV was probed by using 0.25 MeV intervals.

- **Number of deexciting γ rays (Nγ)**

For the number of γ rays deexciting a given excitation-energy bin, various model assumptions were tested. We started from simple variants such as Nγ being a constant or a random number. Eventually, the best results were obtained for an exponential dependency between Nγ and the excitation energy. The normalization factor was chosen to preserve the agreement with the number of γ rays deexciting the low-energy levels. Also, due to Nγ getting very large for higher excitation energies, the limit of 80 transition per bin has been set in order to prevent occupying all possible states below the given energy.

- **Energies of deexciting γ rays (Eγ)**

The γ-ray energies (Eγ) were randomly generated from various probability density distributions that ranged from flat to proportional to Eγ³. The range available for generated transitions (R) was defined by the excitation energy (E) of the deexcited level:

\[
R = \begin{cases} 
0.3 \text{ MeV} & \leftrightarrow (E - (BL - 2.0 \text{ MeV})) \\
0.02 \text{ MeV} & \leftrightarrow (E - E_3) 
\end{cases} 
\]

for \( E > BL \)

for \( E \leq BL \).

E_3 denotes the energy of the third excited state of 102Cd. The flat distribution has become the final choice in order to give the model description an additional degree of freedom. This measure presumably includes the unknown information about the true 102In → 102Cd decay scheme, such as the unknown spin distribution.

- **Intensities of deexciting γ rays (Iγ)**

Assuming that dipole transitions have the highest probability, we used the \( I_γ(E_γ) \sim E_γ^3 \) approximation for the dependence of the branching ratios of the γ-rays (Iγ) deexciting a given level upon the γ-ray energies (Eγ). Attempts to introduce quadruple transitions in significant quantities worsened the quality of the simulated spectra.

The test of hypothetical decay schemes required an efficient algorithm for solving Eq. (1). For this purpose, an iteration procedure based on Refs. [22,23] was developed. The TAS(β⁺) and TAS(EC) spectra were analyzed independently, thus separate feeding
Fig. 6. Beta intensity for the decay of $^{102}$In as a function of $^{102}$Cd excitation energy, obtained from the Cluster Cube (dashed line histogram, shaded area) and the TAS (solid line histogram). The intensities are normalized do 1.

Distributions $I_{EC}^{Exp}(E)$ and $I_{\beta}^{Exp}(E)$ were obtained. In order to get the total $\beta$ feedings of $^{102}$Cd levels from the decay of $^{102}$In we started by defining a $\lambda(E)$ parameter as

$$\lambda(E) = \frac{I_{EC}^{Exp}(E)}{I_{EC}^{Th}(E)} \frac{I_{\beta}^{Exp}(E)}{I_{\beta}^{Th}(E)}.$$  

(2)

From the experimental $\lambda(E)$ distribution a mean value of $\langle \lambda \rangle = 1.9(0.2)$ was derived for a $Q_{EC}$ value of 8.95(12) MeV (see below). The $E$ range, over which $\lambda$ was averaged, was chosen to extend from 4.5 to 7.0 MeV in order to include only those parts of the TAS data where both $\beta^+$ and EC feedings had sufficiently high intensity. The ratios $I_{EC}^{Th}(E)/I_{\beta}^{Th}(E)$ were calculated according to Ref. [24]. Since the TAS(EC) spectrum was gated only by $K$ X-rays the total feeding intensity $I_{total}(E)$, corresponding to the feeding distribution $f$ defined above, is

$$I_{total}(E) = \frac{I_{\beta}^{Exp}(E)}{\langle \lambda \rangle} + I_{EC}^{Exp}(E) \left(1 + \frac{L + M + N + \cdots}{K}(E)\right).$$  

(3)

where $\frac{L + M + N + \cdots}{K}(E)$ describes the correction corresponding to the electron capture from higher subshells. The partial EC and $\beta^+$ feedings are displayed in the upper panels of Fig. 4. The full, combined $\beta$ feeding distribution is presented in Fig. 6 where it is also compared with the corresponding result obtained from the Cluster Cube data.

The total $\beta^+/EC(Q_{EC})$ ratio can be obtained in two ways. The first approach is to calculate it according to the formula $\sum E[I_{\beta}^{Th}(Q_{EC} - E) \cdot I_{total}(E)]$. Note that the $\beta^+/EC$ ratio obtained this way is a function of the assumed $Q_{EC}$ value. It has been calculated for several $Q_{EC}$ values as displayed in Fig. 7. The second approach is to decompose the ungated TAS spectrum after background subtraction in a region
free of isobaric contaminants into EC and $\beta^+$ components. In the latter way a value of the $\beta^+/EC(Q_{EC}) = 4.0(6)$ ratio has been obtained. By combining this result with the previously mentioned $\beta^+/EC(Q_{EC})$ function a $Q_{EC}$ value of 8.91(17) MeV was obtained (see Fig. 7) in good agreement with our earlier measured value of 8.97(15) [25]. The weighted mean of the two values yields 8.95(12) MeV which was used throughout this work.

The $B_{GT}$ values were calculated as a function of $E$ according to

$$B_{GT}(E) = \frac{I_{total}(E)}{f(Q_{EC}, E) \cdot T_{1/2}} \cdot 3860 \text{ s},$$

(4)

where $T_{1/2} = 23.3(1)$ s is the $^{102}$In half-life (see Section 2.2) and $f(Q_{EC}, E)$ the statistical rate function calculated according to Ref. [24]. The integrated value of $B_{GT}$ ($\sum B_{GT}$) amounts to $0.60 \pm 0.07 \pm 0.11$ in the case of Cluster Cube and $4.70 \pm 0.05 \pm 0.20 \pm 1.00$ in the case of TAS. The uncertainties given stem from the data analysis method ($\pm 0.05$), statistical uncertainties of the experimental spectra ($\pm 0.07$ and $\pm 0.20$), and the determination of the $Q_{EC}$ value ($\pm 0.11$ and $\pm 1.00$), respectively. No uncertainty due to the data analysis method is given for the $\sum B_{GT}$ result obtained from the high-resolution data. The analysis was limited to $^{102}$Cd excitation energies below 8.4 MeV, i.e., the range where statistical uncertainties of the TAS(EC) and TAS($\beta^+$) data do not exceed 100% (see Fig. 4).
4. Discussion

4.1. General properties of the $^{102}\text{In}$ decay

When discussing the properties of the $^{102}\text{In}$ decay one should take the known isomeric states in neighboring, even-$A$ indium isotopes into account. The corresponding systematics (see Ref. [10]) suggests the existence of a low-spin $\beta$-decaying isomer in $^{102}\text{In}$ and a value of $6^+$ or $7^+$ for the spin and parity of the $^{102}\text{In}$ ground state. In the case of such an isomer, in order to avoid a competition of the $\beta$-decay with a fast $\gamma$ transition the multipolarity of the latter would have to be sufficiently high. Thus the spin of the isomeric state cannot be higher than $3^+$ (or $4^+$ if the ground-state assignment is $7^+$). Correspondingly, the $\beta$ decay of the isomer would feed the first two excited states ($2^+$ and $4^+$) of $^{102}\text{Cd}$. The analysis of the TAS data shows, however, that the $\beta$ feeding to those states is below 1%, that is of the order of the estimated uncertainty of these $\beta$ intensities. Thus we conclude that there is no experimental evidence for a $\beta$ decay of the $^{102}\text{In}$ isomer.

According to Ref. [10] the branching ratio for $\beta$-delayed proton emission is $9.3(13) \times 10^{-5}$ per precursor decay. The analysis of the energy spectra of $\beta$-delayed protons published in [10] yielded a correction to the $\Sigma B_{\text{GT}}$ value, that is not higher than 0.017. The latter conclusion was drawn under the following assumptions. First, the relative branching ratios for $\beta$-delayed proton emission to the ground state and to the first excited state of $^{101}\text{Ag}$ (98 keV) amount to 80% and 20%, respectively [10]. Second, there is no significant difference between the proton energy spectra of these two proton decay modes. Such a small correction of the $\Sigma B_{\text{GT}}$ was found to be negligible and thus disregarded it in the data analysis.

As it was described in Section 3.3 an effort was made to determine the range of reliability of the level scheme obtained from the high-resolution analysis. Although in limited use for $B_{\text{GT}}$ determination, the high-resolution data form a suitable basis for creating a complete level scheme. For the decays that were previously studied by using a high-resolution array and TAS [8], simplified level schemes based on the high-resolution data required only limited extensions to achieve satisfactory agreement between the experimental and simulated TAS response. The analysis of the $^{102}\text{In}$ data revealed, however, that the amount of the total intensity missed by the Cluster Cube array was too big to be ignored (see Section 3.3). Thus the $^{102}\text{Cd}$ level scheme had to be reconstructed under the condition that the reconstructed part consists of “artificial” $\gamma$ transitions that could have escaped the detection by the high-resolution array. As can be seen from Fig. 8 (right panel), the majority of the $\gamma$ rays, that have been found in the analysis of the TAS data to be unobserved by the Cluster Cube array, have energies between 1.3 and 3 MeV. In the TAS analysis we have introduced over 6000 $\gamma$ rays (apart from those obtained from the high-resolution data). Their average intensity is as low as $(1.7 \times 10^{-2})\%$ that is comparable to the intensity of the weakest $\gamma$ transitions detected by the Cluster Cube. However, it is also ten times weaker than the average intensity of other $\gamma$ rays in this region identified by the high-resolution technique. Additionally, occurring in an energy range in which Compton tails from the higher-energy $\gamma$ rays are present, they would be undistinguishable from the background. It becomes clear from the left panel of Fig. 8 why the low-energy part of the level scheme has been reproduced so well on the basis of the Cluster Cube data. The $\gamma$
Fig. 8. Intensities of $\gamma$ rays for the $\beta$ decay of $^{102}$In as a function of $^{102}$Cd excitation energy (left panel) and $\gamma$-rays energy (right panel), derived from the TAS (solid-line histograms) and the Cluster Cube data (shaded area). The $\gamma$ intensity is defined as the number of quanta emitted per $\beta$ decay, integrated over an energy range of 200 keV.

Rays missed by the high-resolution detectors deexcite, in general, levels in $^{102}$Cd around 6.2 MeV, i.e., the excitation energy corresponding to the maximum of the $\beta$-decay feeding. As can be concluded from the left panel of Fig. 8, a major part of the missed $\gamma$ transitions occurs between levels in the vicinity of 6 and 4 MeV, with a good deal of subsequent transitions between the 4 MeV region and the lower lying levels being detected by the Cluster Cube. In other words, $\gamma$ cascades observed by the Cluster Cube array lack, on average, the one or two uppermost $\gamma$ rays. In the level scheme built solely on the basis of high-resolution data, $\beta$ feeding is assigned to levels that are in fact fed by deexcitation of higher-lying levels. The average multiplicity of $\gamma$ cascades deduced from the TAS data is 4.66 and thus higher than the value of 3.95 derived from the Cluster Cube data. This corroborates the $6^+$ or $7^+$ assignment of the ground state of $^{102}$In. This state decays by feeding high-spin levels in $^{102}$Cd which deexcite through the observed cascades of higher multiplicity.

4.2. Deexcitation patterns of $^{102}$Cd in comparison with in beam data

The experimental results indicate that the $\beta$ decay of $^{102}$In is characterized by a strong GT resonance positioned approximately between $^{102}$Cd excitation-energies of 6 and 7.5 MeV. These GT transitions connect the ground state of $^{102}$In and 4 quasi-particle states of $^{102}$Cd of the following structures:

\[
\pi g_{7/2}^{-1}d_{5/2} \rightarrow \pi g_{9/2}^{-1}g_{9/2}\left[2d_{5/2}2g_{7/2}\right],
\]

\[
\pi g_{9/2}^{-1}g_{7/2} \rightarrow \pi g_{9/2}^{-1}g_{7/2}\left[2g_{7/2}2g_{7/2}\right].
\]

According to shell-model calculations [26], the $^{102}$In ground-state wave function is dominated by the combinations of the neutrons in either $d_{5/2}$ or $g_{7/2}$ states, and the
unpaired proton hole in the $g_{9/2}$ state. These calculations as well as some experimental results [12,26] suggest that the spin and parity of the $^{102}$In ground state is $6^+$ even though Stolz et al. [21] consider it to be $7^+$. Among the available spin combinations in the 4 quasi-particle states the GT decay of a $6^+$ or $7^+$ state selects daughter states with $5^+$, $6^+$, $7^+$ or $6^+$, $7^+$, $8^+$ assignments, respectively. Eventually, these states deexcite to 2 quasi-particle states in the energy range between 2 and 4 MeV via M1 or E2 $\gamma$ transitions. There are indications [6,11] that the transitions of multipolarity M1 have the predominant character. Consequently, we should observe 2 quasi-particle states with spins and parities ranging from $4^+$ to $8^+$, assuming a $6^+$ assignment of the ground state of $^{102}$In and an excess of M1 transitions in $^{102}$Cd. If the spin of the ground state was $7^+$ and if E2 transitions between 4 and 2 quasi-particles states were dominant, the known $9^+$ and $10^+$ states of $^{102}$Cd should have been easily detected. During the analysis of the Cluster Cube data we identified 19 positive-parity levels with spins greater than 4 and 55 such states with spin greater than 6 in the energy range of 2–4 MeV. The spins were assigned by observing the deexcitation pattern to the low lying $4^+$, $6^+$, $8^+$ levels. For comparison, the shell-model calculations performed by Brown and Rykaczewski [27] predict 28 $5^+$, $6^+$ or $7^+$ states in this energy region (see Section 4.3). Finally, as was already mentioned in Section 2.2, our results confirm those obtained from the in-beam experiments [11,12], i.e., the $6^+$ states at 2231, 2561, 2678 keV, and the $8^+$ level at 2718 keV. However, we observe neither the 3578 keV, ($8^+$) level, nor any other state of spin greater than $8\hbar$. Thus, the tentative conclusion is that the combination of the $7^+$ assignment for the $^{102}$In ground-state and the dominance of M1 cascades deexciting levels in $^{102}$Cd.

4.3. Gamow–Teller strength distribution

We now turn to a comparison between the experimental and theoretical $B_{GT}$ distribution. The latter is based on the above-mentioned theoretical calculations which use the shell-model space denoted as SNC in Ref. [27] which was also applied in the case of $^{97–98}$Ag [3,4] and $^{103–107}$In [7,8]. Its main difference from the SNB model is that the value of the particle–hole normalization factor has been increased from $N_{pn} = 0.7$ to 0.77. The $N_{pn}$ factor defines the ratio of the proton hole–neutron interaction compared to that obtained from the bare G matrix [28]. The reason for this increase of $N_{pn}$ was a better agreement with the centroid of the $B_{GT}$ distribution for $^{97}$Ag (see Ref. [3] for details). The SNC model space consists of $1p_{1/2}$, $0g_{9/2}$, $0g_{7/2}$, $1d_{9/2}$, $1d_{3/2}$, $2s_{1/2}$, and $0h_{11/2}$ orbitals. The active protons are restricted to the $1p_{1/2}$ and $0g_{9/2}$ orbitals that are assumed to be filled for the case of neutrons. This restriction has been applied due to the computational limitations for parent nuclei with $N_\pi + N_\nu \leq 4$, where $N_\pi$ and $N_\nu$ are the numbers of valence proton holes and valence neutron particles, respectively. For nuclei like $^{97–98}$Ag and, in particular, $^{102}$In it is possible to perform the calculations with the unrestricted model space.

Unlike the extreme single-particle model, the SNB or SNC calculations allow one to predict the distribution of the $B_{GT}$ strength, additionally to its summed value ($\sum B_{GT}$). In
Fig. 9. Gamow–Teller strength distribution for the decay of $^{102}\text{In}$. In the upper panel, the shell model predictions (solid line) are compared to TAS results (dashed line). The lower panel depicts distributions obtained from the Cluster Cube (solid line) and TAS (dashed line) measurements. In order to make the distributions comparable, the Cluster Cube data have been smoothed by using a Gaussian function with a FWHM of 100 keV. The uncertainties shown for the high-energy tail of the TAS data represent the statistical uncertainties related mainly to the poor statistics of the EC component of the experimental results. See text for details such as those concerning the uncertainty of the $\sum B_{GT}$ values.

Fig. 9 (upper panel) the SNC prediction is compared to the experimental result obtained from the TAS data analysis. The striking differences in the high-energy part can at least partly be explained by large experimental uncertainties above 8 MeV, that are as high as 100%. This is due to the poor statistics of the TAS(EC) spectrum. In this energy range, the $\beta$ feedings are determined on a basis of very few counts which are hardly distinguishable from the background. The even more noticeable discrepancy between the theoretical (13.3) and the experimental (4.70 ± 0.05 ± 0.20 ± 1.00) $\sum B_{GT}$ value is interpreted as being due to the intrinsic limitations of all shell-model approaches including SNC. It is expected that a hypothetical model with unrestricted basis and a larger model space would yield a theoretical $\sum B_{GT}$ that is by a factor of 2–3 lower. Such a model would have to include all possible baryon (nucleon and delta particle) and meson configurations. The impact of the known limitations of shell models on $\sum B_{GT}$ is discussed, e.g., in Refs. [3,27].

In Fig. 10 (upper panel) the experimental $\sum B_{GT}$ value for $^{102}\text{In}$ is compared to the corresponding data for other indium isotopes. In order to compare the discrepancies between the theoretical predictions and the experimental results, the hindrance factor $h$ has been defined as $h = \sum B_{GT}^{SP}/\sum B_{GT}^{GT}$ and a value of 2.8 ± 0.6 was obtained for $^{102}\text{In}$. In the lower panel of Fig. 10 the $h$ values of light indium isotopes are presented as calculated on a basis of the extreme single-particle shell model and the SNC model. As far as the $\sum B_{GT}$ value of $^{102}\text{In}$ is concerned, we excluded the influence of the substantially different analysis method of this work by applying the same approach (see Section 3.3) to the $^{104}\text{In}$ data, which yielded, within 5%, the same $\sum B_{GT}$ value as the one presented by Karny et al. [8].
Fig. 10. Upper panel: systematics of the summed $B_{GT}$ value ($\sum B_{GT}$) for indium isotopes. The uncertainties include also the respective $Q_{EC}$ contributions. Lower panel: hindrance factors calculated for the single-particle shell model (circles) and SNC (squares). The dashed lines connecting the data points are meant to guide the eye. The uncertainties of the hindrance factors, that are proportional to the respective uncertainties from the upper panel, have been omitted.

The much larger uncertainty of the $\sum B_{GT}$ value of $^{102}\text{In}$ stems mainly from the 1.3% uncertainty of the $Q_{EC}$ value ($8.95 \pm 0.12$ MeV). The smaller uncertainties obtained for the heavier indium isotopes can be explained by taking the following features of the $^{103-107}\text{In}$ decays into account. First, there was little or no $\beta$ feeding observed to daughter states close to the respective $Q_{EC}$ values. Second, even if some feeding would occur, its impact on the $\sum B_{GT}$ uncertainty would be small as the $Q_{EC}$ uncertainties are much lower than in the case of $^{102}\text{In}$. Nevertheless, for $^{104}\text{In}$, where the conditions were similar to those of $^{102}\text{In}$, the $\sum B_{GT}$ uncertainties are somewhat larger than for neighboring indium isotopes, as can be seen from Fig. 10. Also, better statistics of experimental TAS spectra tends to move the energies of the levels populated in the daughter nucleus towards the $Q_{EC}$ value. As a consequence we observed a higher sensitivity of the $\sum B_{GT}$ value to the uncertainties of the high-energy part of the experimental TAS spectra, in particular, the TAS(EC) component,
and to the uncertainty of the $Q_{EC}$ value. In spite of higher statistics accumulated for $^{102}$In, the uncertainties of the $\sum B_{GT}$ values of $^{102}$In and $^{106}$In [6] are similar (see Fig. 10). The reason is that the energy range used for the analysis of the $^{100}$In data was narrowed to $(Q_{EC} - 1$ MeV) for analyzing the $\beta$-delayed proton spectrum and $(Q_{EC} - 1.5$ MeV) for analyzing the TAS spectra. For $^{102}$In this limitation is smaller as the analysis includes energies as high as $(Q_{EC} - 0.55$ MeV) (see Section 3.3).

In view of the large uncertainties of the experimental data on the $\sum B_{GT}$ and $h$ values of $^{100}$In and $^{102}$In, definite conclusions cannot be drawn concerning the mass dependence of these quantities for light indium isotopes. However, a tentative observation is that $h$ seems to reach a value around 3, i.e., the value expected for $^{100}$Sn (see Ref. [3]).

5. Summary

We performed two separate experiments, using different experimental methods, and obtained new and interesting data on the $\beta$ decay of the very neutron-deficient isotope $^{102}$In. The high-resolution results have been discussed mostly as a basis for the analysis of the TAS data. Moreover, the results of the Cluster Cube experiment served to deduce spins and parities of $^{102}$Cd levels and of the $^{102}$In ground-state. The spins of the $^{102}$Cd levels identified for excitation energies between 2 and 4 MeV do not exceed the value of 8. We did not observe the known $9^+$ and $10^+$ states in $^{102}$Cd. The evaluation of the TAS data reveals strong M1 transitions deexciting the GT resonance and feeding levels in the above-mentioned 2 to 4 MeV region. The average multiplicity, deduced from the TAS measurement, is greater by one compared to the high-resolution result. These observations are in favor of a $6^+$ assignment for the $^{102}$In ground-state.

The complex properties of the $^{102}$In $\beta$-decay required a further development of the TAS analysis technique. Several models describing different ways of deexcitation of $^{102}$Cd levels were tested. All of the models used the high-resolution level scheme as a starting hypothesis. Then randomly generated $\gamma$ transitions were added, for which energy, intensity and branching ratio were chosen according to various model assumptions. Their quality was tested on the basis of independent fits to the experimental TAS($\beta^+$) and TAS(EC) spectra. The fitting procedure yielded $\beta$-feeding data from which the $B_{GT}$ distribution was derived. The $\sum B_{GT}$ value was found to be as high as $4.70 \pm 0.05 \pm 0.20 \pm 1.0$, where the major contribution to the uncertainty is related to the $Q_{EC}$ determination. The systematics of the GT hindrance factors for indium isotopes, including the value of $2.8 \pm 0.6$ for $^{102}$In, indicates a decrease with decreasing mass numbers and seems to asymptotically approach the value of 3. This observation may be considered to support the expectations regarding the $h$ value for $^{100}$Sn.

Acknowledgements

The authors would like to express their gratitude to K. Burkard and W. Hüller for their valuable contributions to the development and operation of the GSI on-line mass separator as well as to thank the German Euroball Collaboration for making the Euroball Cluster
array available for the experiment. The Cluster detectors were supported by the German BMBF, the KFA Jülich, the GSI Darmstadt, and the MPI-K Heidelberg. This work was supported in part by the Polish Committee of Scientific Research and by the Program for Scientific Technical Collaboration (WTZ) under Project Nos. POL 99/09 and RUS 98/672.

References