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Gamow-Teller strength distribution in the beta-decay of ^{100}Ag from total-absorption gamma spectrometry

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Abstract. The EC/β^+-decay of the odd-odd nucleus ^{100}Ag was studied by means of total absorption γ-ray spectrometry. Most of the Gamow-Teller strength was found to be concentrated at an excitation energy of 5.6 MeV in ^{100}Pd, the FWHM of this resonance being 1.5 MeV. The measured strength distribution which is interpreted within the BCS approximation as being due to the dominant population of four-quasiparticle excitations, resembles the distribution predicted by an advanced shell-model calculation for the ^{98}Ag $\rightarrow$ ^{98}Cd decay.

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1. Introduction

The EC/β^+-decay of nuclei near ^{100}Sn can be described within a very simple shell-model picture: only one channel, namely the Gamow-Teller (GT) $\pi g_{9/2} \rightarrow \nu g_{7/2}$ transformation, has to be taken into account [1]. Therefore, whenever transitions of a high beta strength are observed in this region of the nuclear chart, they have to be associated with these two l=4 orbits. Correspondingly, such data especially when combined with results from in-beam studies represent a firm basis for testing nuclear models.

Our previous studies in the ^{100}Sn region [2] were focused on even-even nuclides with decay energies Q_{EC} below or roughly equal to 5 MeV. Their decay has been found to proceed predominantly via a few well resolved $0^+ \rightarrow 1^+$ transitions. The 1^+ levels in the odd-odd daughters are supposed to contain a component of the $\pi g_{9/2}{}^{-1}$ $\nu g_{7/2}$ configuration responsible for the relevant GT transition. The excitation energies of these levels are usually below 2 MeV.

For odd-odd parent nuclei near ^{100}Sn, the Q_{EC} values exceed 7 MeV, and the β-intensity is in general spread over a wider range of excitation energies in the daughter nucleus. Some interesting results have already been obtained for ^{100,102,104}In [3, 4]: high-resolution studies and measurements of positron or β-delayed proton spectra indicate a concentration of the GT strength at excitation energies of a few MeV in the respective cadmium daughter nuclei. The predominant feeding of high-lying levels is actually expected to be a general decay feature of odd-odd nuclei in this region [2]. However, at these energies the level density is high and discrete-level spectroscopy is not suitable for a quantitative determination of the GT strength distribution. An application of other techniques is therefore needed.

Based on this motivation, we used a total-absorption gamma-spectrometer (TAGS) to investigate the β-decay of the odd-odd nucleus ^{100}Ag. The results are reported in this paper. We begin with a brief description of the experimental procedure and present evidence for the concentration of the GT strength at an excitation energy of about 5.6 MeV in ^{100}Pd. Furthermore, the role played by the $\pi g_{9/2}$ and $\nu g_{7/2}$ orbits are discussed with reference to the BCS model and to an advanced shell-model calculation [5].

2. Experimental procedure and data analysis

The β-strength distribution of a β-decaying nucleus can in principle be determined from the β-decay feeding distribution I(E) which is defined by demanding that I(E)·ΔE corresponds to the joint EC+β^+ branching ratio to all levels in the interval E,E+ΔE. Here E is the excitation energy of the daughter nucleus, and I(E) is normalized to yield $\sum$ I(E)·ΔE = 100 % for E<Q_{EC}.

The ideal tool for measuring I(E) directly would be a γ-energy calorimeter with 100% photo-peak efficiency for all γ-energies. The spectra measured by such a device in coincidence and in anti-coincidence with positrons would be proportional to the respective components I_{EC}(E) and I_{β^+}(E-1.022 MeV) of the feeding distribution. I(E) would then be derived either from the sum I_{EC}(E)+I_{β^+}(E) directly or, by using the known energy dependence of the EC/β^+ ratio [6], from the two components separately.

Today the closest approach to such an ideal calorimeter consists of an array of large scintillation detectors in a 4π geometry. The TAGS set-up used in this work represents a modified version [7] of the instrument described in [8] and is composed of three γ-ray detectors: (i) a large-volume (diameter d=20 cm, length l=20 cm) NaI crystal with a bore along its symmetry axis (d=4 cm), (ii) another NaI crystal of a disk shape (d=20 cm, l=10 cm) which closes the bore from one side, and (iii) a BGO detector (d=3 cm, l=3.3 cm) which closes the bore from the other side. The latter is placed in the bore at a distance of 2 cm from the central bore position where the radioactive source is placed. Between the source and the BGO detector a Si(Li) β-detector is mounted for coincident positron detection. The source and the β-detector are surrounded by a teflon absorber to prevent the positrons from penetrating the γ-ray detectors.

The full-energy peak efficiency of the TAGS and its response to monoenergetic γ-rays were calculated with the help of the Monte Carlo code SIGMA [11], and were checked experimentally by using calibrated single γ-ray sources. The resulting full-energy peak efficiency amounts to 67, 48 and 30 % for 0.3, 1 and 3 MeV γ-rays, respectively. The energy dependence of the Si(Li) detector efficiency was determined by measuring singles and β-gated TAGS spectra for the β-decay of different isotopes with well-known decay properties. The efficiency increases with the β-endpoint energy up to 2 MeV (In order to exclude the registration of conversion electrons, X-rays and low energy γ-rays, the threshold was set at 150 keV). Above 2 MeV it becomes practically energy independent at a value of 29.5(5)% as measured on-line during the experiment described below using mass-separated sources of ^{104}Ag.

^{100}Ag was produced in ^{58}Ni(5 MeV/u) + ^{50}Cr reactions. By using the GSI Online Mass Separator, A=100 activities were collected on a tape and transported periodically to the source position in the TAGS. The time of collection and measurement was 40 and 160 s, respectively. Total-absorption spectra, created by coincident summation of pulse-height signals from the NaI and BGO detectors, were recorded event by event and were additionally stored in multispectrum mode into 8 subgroups of 20 s each. The total number of A=100 sources amounted to 51. For an energy threshold of 2 MeV, the counting rates in the total absorption spectra decreased with a half-life of 120(2) s which was attributed to the decay of ^{100g}Ag($I^{\pi}=5^{+}$) [9].

In order to determine the source composition, two γ-ray Ge-detectors were mounted at the collection point and at the position where the source was transported to after being removed from the TAGS set-up. This measurement was carried out in multi-spectrum mode in order to determine contributions from isobaric contaminants including isomeric activity. A contribution of the 49 s ^{100}Cd activity, identified through the 0.94 MeV γ-line [10], was estimated to be 3 % of the ^{100}Ag activity at the beginning of the 160 s counting cycle (This means that the admixture of ^{100}Cd in the mass separated ion beam was less than 1.5 % compared to ^{100}Ag). A contribution from 3.6 d ^{100}Pd activity was not detected. In this context it should be noticed that both the ^{100}Cd and the ^{100}Pd activities can influence the GT strength distribution only at low ^{100}Pd excitation energies due to small Q_{EC} values of 3.89 and 0.36 MeV, respectively [12]. The admixture of ^{100m}Ag ($I^{\pi}=2^{+}$, $T_{1/2}$=2.24 min, E^{exc}=16 keV) [9] was checked by using the γ-line at E = 2.11 MeV and was found to be below 5 % at the beginning of the 160 s counting cycle.

After subtraction of contributions from the room background and the pile-up effect, the A=100 total-absorption spectrum was divided into two components corresponding to EC and β^{+}-decay. The spectrum corresponding to positron emission was measured in coincidence with the Si(Li)-detector. The EC component of the total-absorption spectrum was then obtained by subtracting the β-gated spectrum from the total spectrum where the efficiency for positron registration in the Si(Li) detector has been taken into account.

In order to determine I_{EC}(E) and I_{β^+}(E), a deconvolution of the experimental spectra with the response function of the TAGS was performed. Since the response of the TAGS is different for monoenergetic single γ-lines and a cascade of γ-lines summing up to the same energy, an assumption for the γ-ray deexcitation pattern of the daughter nucleus was required. In the case of ^{100}Ag, some information on the level deexcitation in ^{100}Pd at E< 3 MeV was used which had been obtained from high-resolution γ-ray measurements [9]. The deexcitation of high-lying ^{100}Pd levels was treated on the basis of assumptions concerning deexcitation of the I≥4 high-spin levels. The $\gamma\gamma$-coincidence information obtained from the BGO and NaI detectors was also taken into account. In the case of the positron-coincident spectrum one has furthermore to correct for the summation between the two 511 keV quanta from positron annihilation and the γ-rays deexciting levels in the daughter nucleus. The detailed procedure to derive I_{EC}(E) and I_{β^+}(E) and the corresponding uncertainties will be presented in a forthcoming paper [7].

From the relative intensities of the EC and β^{+} components of I(E), an average ratio EC/β^{+}=0.36(2) was found. The uncertainty in this ratio is mainly due to the admixture of the ^{100m}Ag activity and of other background. Due to the energy dependence of the EC/β^{+} ratio [6], I(E) can not be obtained for the whole energy range from I_{EC}(E) or from I_{β^+}(E) independently. On the one hand, for the β-decay of ^{100}Ag to ^{100}Cd levels below E≈4 MeV, the probability of β^{+}-decay exceeds that for electron-capture by more than a factor of 2. Correspondingly, the uncertainties in I(E), determined from the EC-coincident spectrum, are relatively large. On the other hand, for E>5 MeV the probability of β^{+}-decay is less than that for electron-capture by more than a factor of 10. It is thus practically impossible to determine I(E) for such high E values from the β^{+}-coincident spectrum. Therefore, we used the following procedure: i) For excitation energies E<3.8 MeV, I(E) was deduced from the β^{+}-coincident total absorption gamma spectrum; ii) for excitation energies E>4.8 MeV, I(E) was determined from the EC-coincident spectrum; iii) for the excitation energy interval 3.8<E<4.8 MeV, both components of the spectrum were used. From the experimental EC/β^{+} ratio in this energy interval, it was furthermore possible to determine the decay energy of ^{100}Ag to be Q_{EC}=6.95(16) MeV. This value agrees with the result of 7.07(8) MeV adopted from previous experiments [12].

The β-strength distribution function was obtained according to

$$S_{GT}(E) = \frac{\Delta B_{GT}}{\Delta E} = \frac{D \cdot I(E)}{100 \cdot T_{1/2} \cdot f(Q_{EC} - E, Z)},$$

where ΔB_{GT} is the sum of the GT strength for transitions to levels in the excitation-energy interval ΔE, D=3862 s [1] being a constant and f the statistical rate function [6]. The half-life $T_{1/2}$=120 s was determined in this work as has

Table 1. β-decay feeding distribution and GT-strength calculated for steps of 250 keV of the EC+β^+-decay $^{100}Ag \rightarrow ^{100}Pd$. The total uncertainty of the strength include (i) the statistical errors, (ii) the contribution from the Q_{EC}-uncertainty, and (iii) the contribution from the insufficient knowledge of the deexcitation pattern of ^{100}Pd levels

Energy [MeV]	I(E)·ΔE / %	ΔB_{GT} ×1000	Uncertainties of ΔB_{GT} (i)	(ii)	(iii)
0-1.75	< 2	< 0.5			
1.75-2.00	1.8	0.6	0.08	0.05	0.5
2.00-2.25	5.3	2.4	0.08	0.2	1.0
2.25-2.50	10.9	6.4	0.07	0.5	2.0
2.50-2.75	11.8	9.6	0.09	0.9	2.0
2.75-3.00	22.2	25.2	0.13	2.4	2.5
3.00-3.25	12.6	19.1	0.12	2.0	3.0
3.25-3.50	4.3	9.6	0.16	1.0	5.0
3.50-3.75	3.2	11.1	0.25	1.3	5.5
3.75-4.00	3.8	18.4	0.40	2.2	6.5
4.00-4.25	3.2	23.9	0.51	3.0	7.0
4.25-4.50	3.2	36.5	0.87	4.4	7.5
4.50-4.75	3.6	64	1.1	8.0	11.5
4.75-5.00	3.5	93	1.3	11	15
5.00-5.25	3.0	126	1.4	14	16
5.25-5.50	2.9	177	1.6	20	18
5.50-5.75	2.5	202	1.6	24	16
5.75-6.00	1.25	161	1.9	21	12
6.00-6.25	0.61	130	2.2	21	9
6.25-6.50	0.22	87	2.9	19	6
6.50-6.75	0.11	58	4.0	30	6
> 6.75	<0.04				

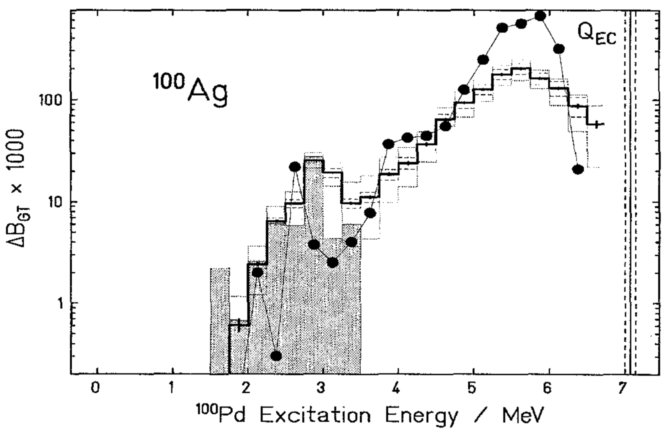

Fig. 1. GT-strength distribution for the decay of ^{100}Ag summed up for intervals of 250 keV (*solid histogram*). The vertical bars denote the statistical uncertainties for each data point. The total systematical error, displayed by the dotted histograms consists of a contribution from the uncertainty in the Q_{EC}-value (*dashed histogram*) und from uncertainties in the deexcitation pattern of ^{100}Pd. The *dashed histogram* shows the results from a high-resolution study [9] and the *smooth line* connecting *full circles* represents the calculated GT-strength of the ^{98}Ag decay from [5]. The experimental Q_{EC} value of ^{100}Ag is indicated by a *vertical line* with the uncertainty given as *dashed lines*

been mentioned above and the decay energy Q_{EC}=7.07(8) was taken from [12].

The GT-strength values summed up for energy intervals of ΔE=0.25 MeV (which corresponds approximately to the TAGS resolution) is presented in Table 1 and displayed in Fig 1. Note that the individual uncertainties in the two last columns of Table 1 are not independent from each other since they are of systematical origin. The main uncertainties in the derived strength function is due to the uncertainty in the Q_{EC}-value and to the poor knowledge of the detailed γ-deexcitation pattern of ^{100}Pd, whereas the statistical uncertainties are negligibly small. The total GT strength, obtained by summing the strength over all energy intervals, is equal to 1.26(25) corresponding to a log ft value of 3.5(1). The main contribution to this results stems from the peak of the β-strength function at an excitation energy of about 5.6 MeV, whose FWHM is approximately 1.5 MeV.

3. Interpretation of the ^{100}Ag GT-strength distribution

For an odd-odd nucleus such as ^{100}Ag the main GT-decay strength is expected to be associated with a $0^+ \rightarrow 1^+$ GT-transformation within the even-even core. The GT-transitions populate levels in the even-even daughter nuclei with spin I_f=I±1, where I is the spin of the initial state. The odd proton and odd neutron in such a decay remain spectators. If we apply the pairing model as a rough approximation, the final states should be of a four-quasiparticle nature. Such states are expected at excitation energies of a few MeV, in agreement with our observation.

In general, if an odd-odd nucleus has two isomers close in energy and the even-even core plays the decisive role in their β-decay, the relevant GT strength distributions are expected to be similar. Correspondingly, the β-decay half-lives of both states should be approximately the same. For ^{100}Ag, this expectation is confirmed: the β-decay half-lives of the two states differ by not more than 20 % (the M3 γ-deexcitation branching for the isomer is estimated to be below 10 %). Therefore, the fact that in the data analysis the small (<5 %) contribution from ^{100m}Ag was neglected will not affect our main conclusions on the GT-strength distribution.

With respect to the ^{98}Pd even-even core, the ^{100g}Ag and ^{100m}Ag states are apparently due to the $|\pi g_{9/2}\ \nu d_{5/2}, I^+\rangle$ shell-model configuration with I=5 and I=2, respectively. They decay to excited states of ^{100}Pd which represent four-particle configurations $|(\pi g_{9/2}\text{-}1\ \nu g_{7/2})1^+\ (\pi g_{9/2}\ \nu d_{5/2})I^+, I_f\rangle$ with I_f =4, 5, 6 for I=5 and I_f = 1, 2, 3 for I=2. As a result of residual interactions other than pairing, these configurations are expected to be spread over a great number of levels in the energy range corresponding to the main maximum in the strength distribution (see Fig. 1). Within the experimental uncertainties, the total strength of 1.10(24) comprised in this main peak of the ^{100}Ag distribution ranging from 4.5 to 6.75 MeV agrees with the value B_{GT}=1.21(5) found for the decay of the core nucleus ^{98}Pd [13]. However, the Q_{EC} value of ^{98}Pd is small (1.97 MeV) and its total strength might be larger.

In Fig. 1 another maximum is seen around 3 MeV. One could speculate that it corresponds to the GT transformation of the odd proton, which leads to a two-neutron configuration $\nu g_{7/2}\ \nu d_{5/2}$ in ^{100}Pd. According to formula (7) in [1], the strength associated with such a transformation should be 1/16.5 of that for the even-even core transformation. The observed strength ratio of 1/18 is very close to this prediction.

Fig. 1 shows also a distribution of the GT strength derived directly from the ^{100g}Ag decay scheme reported in the literature [9]. The difference between the two distributions is very dramatic. It reflects the fact that in high-resolution studies of complex decay schemes characterized by large Q_{EC} values, a great number of weak γ-transitions from high energy states is missed. This effect was in detail considered in [15] and was recently also discussed in connection with the ^{105}Sn decay data in [14].

The GT strength distribution derived from the TAGS data is compatible with EC/β^+ probability ratio of 0.36(2) determined from the EC and β^+ component of I(E) (see Sect. 2). Using the theoretical energy dependence of the EC/β^+ ratio [6] and the known Q_{EC} value, one can calculate that if all the decays would proceed to a single state in ^{100}Pd, its excitation energy would be 3.8 MeV. It can be shown that due to the energy dependence of the f function the average energy of the β-strength distribution lies higher than this hypothetical single-level energy. Indeed, the center of the measured strength distribution shown in Fig. 1 is localized above 5 MeV, while the distribution derived from the high-resolution decay scheme is situated below 3 MeV.

Recently, shell-model calculations for the GT decay of ^{100}Sn and some of its close neighbours have been carried out [5]. Unfortunately, the number of valence neutron particles and proton holes (with respect to the ^{100}Sn core) involved in the ^{100}Ag $\rightarrow$ ^{100}Pd decay is too high to be processed in such an approach. However, such calculations have been performed for ^{98}Ag. One may suppose that the GT strength distribution of these two silver isotopes are not too different. Therefore, the distribution obtained in the present work is compared with the theoretical predictions for ^{98}Ag. As can be seen from Fig.1 the shape of the two distributions are quite similar, while there is a difference in the total strength. The total B_{GT} in a full $^{97}Ag_{50}$ calculation is 12.83. This is close to the extreme single-particle shell-model estimate of $N\cdot 4l/(2l+1)\cdot v_\pi^2\cdot(1-v_\nu^2)$=160/9·7/10=12.44 ($N$=$2j$+1=10, l=4). Here, the occupation probabilities of the $\nu g_{7/2}$ and $\pi g_{9/2}$ orbitals are v_ν^2=0 and v_π^2=n_π/N, respectively. Because of this agreement, one can make the same simple estimate for the total B_{GT} in the case of ^{98,100}Ag which ranges from 12.44, if the $\nu g_{7/2}$ shell is empty, to $12.44\cdot(1-1/8) = 10.89$ and $12.44 \cdot (1 - 3/8) = 7.78$, respectively, if all neutrons above N=50 occupy this shell. The total B_{GT} of $^{98}Ag_{51}$ as coming from the full calculation displayed in Fig. 1 lies well inside these limits. A value of 10.67 is obtained for $^{100}Ag_{53}$ if one takes n_ν=1.14 from a full $^{103}Sn_{53}$ calculation. For cases, where most of the strength is expected in the Q_{EC} window a general hindrance factor of 4 is observed [5]. Including this factor gives finally an estimate for the total B_{GT} of ^{100}Ag ranging from 1.9 to 3.1. The total strength of 1.26(25) observed in the present experiment is significantly smaller than this estimate indicating that a part of the GT strength distribution lies above the ^{100}Ag Q_{EC} value.

4. Summary and conclusions

The TAGS technique applied to the EC/β^+-decay of the odd-odd nucleus ^{100}Ag shows clearly that the main part of the GT strength is concentrated at a relatively high excitation energy around 5.6 MeV. This strength concentration can be explained as a result of the predominant feeding of the four-quasiparticle configurations expected for the daughter ^{100}Pd from the BCS model. Such a concentration is predicted also by the advanced shell-model calculations for the neighbouring nuclei. Similar conclusions have been drawn from recent β-decay studies of ^{100,102,104}In [4].

While the accuracy of the experimental GT strength distribution at high energies is good enough at least for quantitative conclusions, the accuracy at lower energies is poor due to deficiencies of the deconvolution procedure. It is clear that detailed measurements of the γ-ray multiplicities for the investigated decay would allow one to improve this procedure.

Finally we want to mention that the decay properties of nuclei below ^{100}Sn are also of astrophysical interest. As has recently been discussed by Hencheck et al. [16] the stable isotopes ^{92,94}Mo and ^{96,98}Ru could be produced through a rapid proton capture process. However, the high-temperature hydrogen burning model predicts an overproduction of ^{92}Mo and ^{94}Mo compared to to the observed solar-abundance values. This discrepancy could at least partly be explained by unusually large β-delayed proton branching ratios of ^{96,98}Cd and/or ^{96,98}Ag [17]. The resonance-like β-feeding of high-energy states, that has been found in this work as well as in other recent experiments [2, 3, 4, 10, 13, 14], may lead to such an enhanced proton emisson.

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