Excitation energy of the $T=0$ β-decaying 9^+ isomer in ^{70}Br

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The total absorption spectrometer installed at the GSI on-line mass separator was used to study the β-decay of the $J^\pi=9^+$ isomer in ^{70}Br. The decay energy Q_{EC} of the isomer was found to be $12.19(\pm 7_{\mathrm{stat}} \pm 4_{\mathrm{sys}})$ MeV. By comparing this value with the estimated Q_{EC} value for the ground state of ^{70}Br, the excitation energy of isomer is found to be 2.23(9) MeV. The latter result removes ambiguities that can be found in literature.

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I. INTRODUCTION

High-lying high-spin states of the atomic nucleus are generally studied by means of in-beam spectroscopy involving heavy-ion induced fusion-evaporation reactions, while information on low-lying low-spin "collector" states can be gained, for example, by β-decay measurements. An unambiguous location of levels at high excitation energy, that are obtained from the former method, requires reliable knowledge of the collector states. The properties of the ^{70}Br nucleus have been studied so far by in-beam [1,2] and β-decay experiments [3–6]. The experimental data indicate that this self-conjugate $N=Z=35$ nucleus has a $T=1$, $J^\pi=0^+$ ground state which β-decays with a half-life ($T_{1/2}$) of 78.54(59) ms [4], whereas the $T=0$, $J^\pi=9^+$ isomeric state is more long lived ($T_{1/2}=2.19(9)$ s [6]). The isomer energy had been unknown until recently, when two groups reported evidence for the 9^+ state in their in-beam data. In the work of de Angelis *et al.* [1], the excitation energy of the 9^+ isomer was proposed to be 1214 keV while Jenkins *et al.* [2] place the 9^+ state at an excitation energy of 2293 keV and established that it has a lifetime longer than 30 ns. While Refs. [1] and [2] do not give uncertainties for the isomer energy, modern in-beam spectroscopy generally yields accuracies of the order of keV. The discrepancy of about 1 MeV is thus surprising indeed. Moreover, by combining β-decay data and systematics of the lowest $T=0$ and $T=1$ states, Piechaczek *et al.* [5] suggested the excitation energy of the 9^+ isomer to lie between 500 and 1000 keV. This suggestion, though, is not fully justified since the 9^+ state does not have to be the lowest $T=0$ level in ^{70}Br.

The large discrepancies in the 9^+ isomer energies reported by different groups was the motivation to undertake a measurement of the excitation energy by means of a different technique. The method applied involves the determination of the $Q_{EC}(9^+)$ value for the decay of the isomer and a comparison to the $Q_{EC}(0^+)$ value of the ground-state decay. In this way, it is possible to deduce the isomer energy with an uncertainty of about 100 keV. Such an accuracy is sufficient to rule out one or both of the results from in-beam work. The present paper reports the results of such a study.

II. EXPERIMENTAL TECHNIQUE

The ^{70m}Br activity was produced in ^{40}Ca(^{36}Ar, αpn)^{70}Br fusion-evaporation reactions by using a 4 MeV/nucleon ^{36}Ar beam and a 3.2 mg/cm^2 thick CaO target, deposited on a 10–15 μg/cm^2 thick carbon foil. Due to the fragile nature of CaO targets, the ^{36}Ar beam intensity was intentionally kept below 30 particle nA. For calibration purposes, which will be discussed below, ^{34}Cl was produced by using ^{28}Si(^{16}O, $2\alpha pn$) reactions. The recoiling reaction products were stopped in the graphite catcher inside the gaseous discharge ion source of the GSI on-line separator [7,8] which provided a 55 keV mass-separated beams of singly charged ^{70}Br ions and $A=61$ molecules containing ^{34}Cl, respectively.

The $Q_{EC}(9^+)$ value for the decay of the 9^+ isomer of ^{70}Br was determined by using the total absorption spectrometer (TAS) consisting of a large NaI(Tl) crystal (diameter: 14 in., length: 14 in.), a NaI(Tl) "plug" detector, two silicon (Si) wafers (diameter: 16 mm, thickness: 0.45 mm) and one germanium (Ge) detector (thickness: 10 mm, diameter: 16 mm) [9]. The mass-separated beam was implanted into a mylar tape, with the resulting radioactive samples being periodically placed by means of a transport system in the center of the TAS between the two Si detectors, with the implantation side of the tape facing downward. The implantation/measurement and transport times amounted to 5.6 and 0.8 s, respectively. The upper Si detector together with the Ge detector served as a $\Delta E-E$ telescope for β particles. Time and energy signals were recorded from the NaI(Tl) crystals, upper (TOP) and lower (BOT) Si detector, and Ge detector. The energy signal from the latter one was split and amplified with high-gain (GeX) and low-gain (GeG) amplifiers in order to distinguish between low-energy photons and (mainly) positrons, respectively. In measurements of β endpoints with $\Delta E-E$ telescopes, special care has to be taken concerning the energy calibration of both detectors. We applied a three-step procedure including: (i) The use of standard γ-ray sources for calibrating the Ge detector and conversion electrons for the upper Si wafer, (ii) a linearity check of the electronics by means of a pulser, and (iii) a correction to the calibration of the $\Delta E-E$ signals derived from measuring the well-known β

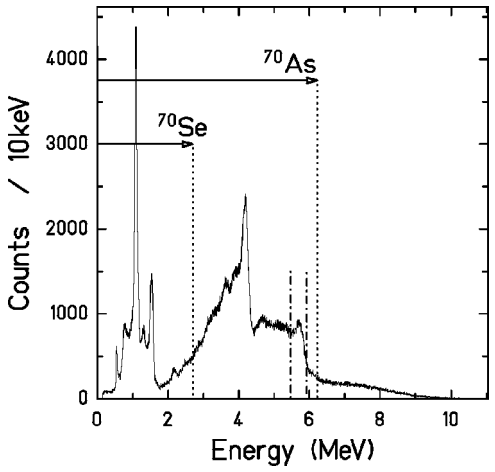

FIG. 1. Experimental TAS spectrum related to the β^+ component of the decay of $A=70$ nuclei implanted into the transport tape. Arrows show the Q_{EC} range for the lower-Z isobars of ^{70}Br which were identified in this work, namely ^{70}Se and ^{70}As which have Q_{EC} values of 2300(80) and 6220(50) keV, respectively [10]. The gate marked by dashed-dotted lines was used to select ^{70m}Br decay events.

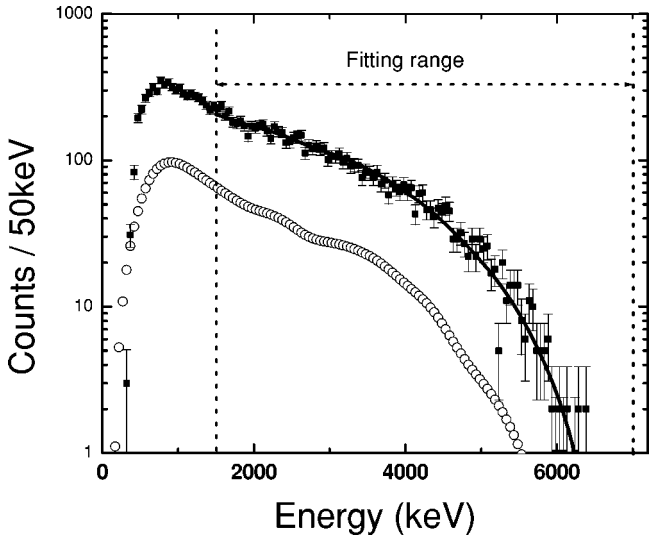

FIG. 2. Positron energy spectrum obtained by summing ΔE and E signals from the telescope in coincidence with TAS events in the range of 5470 and 5920 keV (full squares with experimental uncertainties). The theoretical β spectrum folded with the response function and fitted to the experimental spectrum is shown as a solid-line curve. The fit range is indicated by dotted lines. The normalized and smoothed background spectrum (TAS gate between 5930 and 6300 keV) used during the fitting procedure is given by open circles.

endpoint energies of 4470.01(15) keV [10,11] and 2488.81(15) keV [10] of ^{34}Cl and ^{34m}Cl, respectively. As mentioned above, the latter sources were produced on-line.

III. MEASUREMENTS

Figure 1 displays the β^+ component of the total TAS spectrum obtained by implanting the $A=70$ beam. The abscissa represents the energy deposited in the main crystal and the plug detector. The β component was selected by gating on the TOP signal and selecting events with an energy between 94 and 4800 keV (i.e., energy loss in ΔE).

In Fig. 1, one can clearly identify contributions from the decay of ^{70}Se and ^{70}As. The former is characterized by peaks occurring at 1022+82, 1022+235 and 1002+458 keV, which correspond to the β feeding of 82, 235, and 458 keV levels in the daughter (^{70}As) nucleus [12]. In the latter case, one expects 3048+1022 and 3060+1022 keV peaks in the TAS spectrum, corresponding to the β feeding of 3048 and 3060 keV levels in the daughter (^{70}Ge) nucleus [12]. However, these two peaks are not resolved and thus lead to a broad structure around 4 MeV. Both the ^{70}Se and ^{70}As isobaric contaminants are produced either by the heavy-ion reaction used for the experiment or as daughter products from the decay of ^{70}Br.

The decay of the 9^+ isomer of ^{70}Br is characterized by a dominant ($\approx$78% [6]) population of the 4605 keV $J^\pi=8^+$ level in ^{70}Se. The corresponding 4605+1022 keV peak can be clearly seen in Fig. 1. The dashed-dotted lines in Fig. 1 mark the limits of the window covering TAS energies between 5470 and 5920 keV. By demanding coincidence between such TAS events and summed ΔE and E signals from the telescope, we obtained the positron spectrum displayed in Fig. 2. These data will form the basis for determining the β endpoint of the β transition from the 9^+ isomer of ^{70}Br to the 4605 keV level in ^{70}Se. With reference to the total Q_{EC} ranges for ^{70}Se and ^{70}As decays, indicated in Fig. 1, it is clear that ^{70}Se events lie outside the above-mentioned coincidence window and thus cannot contribute to the spectrum shown in Fig. 2. The situation is different for ^{70}As events whose Q_{EC} range includes the coincidence window. However, ^{70}As contributions can safely be neglected since the beta feeding of levels around 4.6 MeV in ^{70}Ge is around 0.06% [12] of all ^{70}As decays, resulting in a contribution of approximately 0.05% from the decay of ^{70}As to the experimental data displayed in Fig. 2.

IV. EVALUATION OF TAS AND POSITRON SPECTRA

A. Introductory remarks on determination of Q_{EC} values by β-endpoint analyses

Although theoretically simple, the β-endpoint analysis is a complex procedure. In principle, one may use the following approaches:

(1) Fitting a straight line to the Fermi-Kurie plot of a β energy spectrum is possible provided the β decay populates one and only one daughter state, and a detector with a delta-function like response function is used. One may disregard the latter requirements to some extent (due to the cancellation of the systematic uncertainties) if a careful calibration with well-known β emitters is performed, and the number of events registered in the spectrum is large enough to allow one to restrict the fit range to the vicinity of the end of the spectrum.

(2) Another method starts from a theoretical β shape which is folded with the measured detector response function

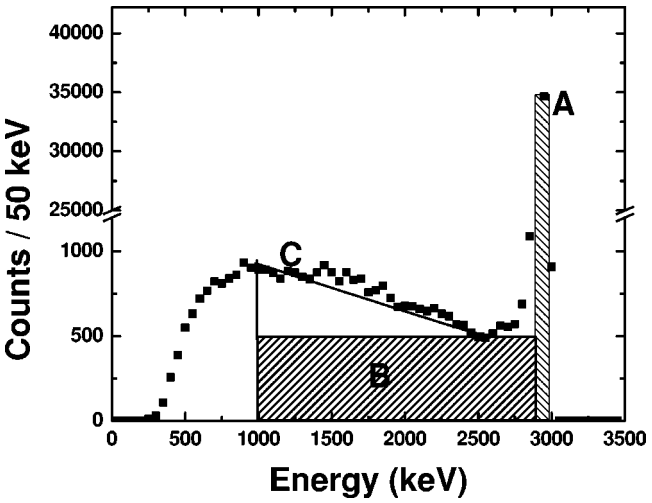

FIG. 3. Response function of the $\Delta E-E$ TAS telescope, resulting from a simulation based on 10^5 events of 3 MeV electrons (full squares). The areas A, B, and C were used for the parametrization of the response function.

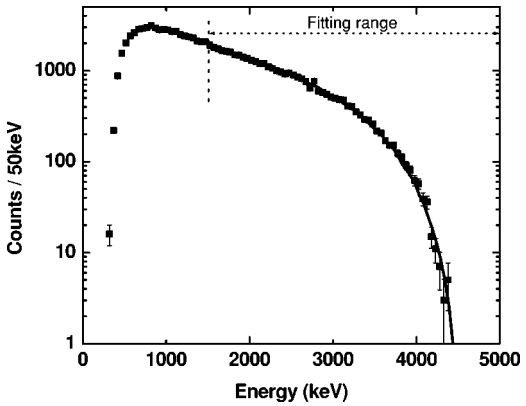

FIG. 4. β-energy spectrum of ^{34}Cl ground state to ground state decay. Theoretical β-spectrum folded with response function and fitted to the experimental spectrum is shown as a solid-line curve.

and fitted to the experimental β spectrum. The latter is derived by selecting a β-transition through a coincidence condition with a γ-ray recorded in an independent detector. This method (see, e.g., [13,14]) may lead to reliable results provided the decay scheme is well known and a multicomponent fit is performed to account for β transitions to higher-lying states in the daughter nucleus which deexcite to the level emitting the above-mentioned γ-ray.

(3) A third approach is specific to the TAS equipped with a β detector. In this case, a coincidence gate on the peak in the TAS spectrum selects the state to which the β transition proceeds. This method works best when TAS peaks can be clearly identified and, hence, an unambiguous coincidence condition on the peak can be defined. The experimental β spectrum, resulting from this coincidence procedure, is then fitted by using the theoretical β shape folded with the response function of the β detector.

In this work, the third approach was chosen for deducing the β endpoint energy from the data displayed in Fig. 2.

B. Determination of the response function of the telescope for positrons

An important prerequisite for the evaluation procedure chosen here is the knowledge of the response function of the telescope for positrons. We used the Monte Carlo code GEANT4 to simulate the response functions of the $\Delta E-E$ telescope for monoenergetic positrons between 1 and 8 MeV with 100 keV energy steps. The energy spectrum of the $\Delta E-E$ telescope was obtained by requiring coincidence between positron signals from the telescope and those corresponding to the detection of two 511 keV annihilation quanta in the NaI(Tl) crystals of the TAS. The resulting simulated response function of the telescope was then binned to 50 keV intervals and parametrized as a sum of three components, i.e. a full energy absorption peak (A), a rectangular base (B), and a triangular part (C). This procedure is illustrated in Fig. 3. Such a parametrization was found to be sufficient to calculate the response functions of the telescope for energies above 1 MeV (see also [14]).

C. Determination of the Q_{EC} value for the β decay of 9^+ isomer of ^{70}Br

In Fig. 2, the experimental positron-energy spectrum, obtained for the ^{70m}Br decay, is compared with the theoretical β spectrum, folded with the response function and fitted to the experimental spectrum. The fit range, indicated in Fig. 2, covers positron energies from 1500 to 7000 keV, corresponding to approximately 75% of the full energy range. In order to reduce systematic uncertainties of the response function parametrization, the lower limit of the fitting range was chosen to be 500 keV above the low-energy limit (1 MeV) of the parametrization (see Figs. 2 and 3). The upper limit of the fit range was set to 7 MeV, i.e., above the apparent end of the experimental β spectrum where only zero-count events occur (see Fig. 2). The quality of the response function simulation and its parametrization were checked by using the fit of the ^{34}Cl and ^{34m}Cl on-line calibration sources. Figure 4 shows the β energy spectrum used for this check. It was obtained by gating on a 1022 keV line in TAS spectrum and represents β decay of ^{34}Cl to the ground state of ^{34}Ar. The fit yields 4.51(2) MeV for the β-endpoint of this spectrum. This value corresponds to $Q_{EC}=5.54(2)$ MeV, which is approximately 40 keV above the corresponding literature value of 5492.01(15) MeV [10]. A 20 keV higher Q_{EC} value was obtained for the ^{34m}Cl β-end point fit (decay from the 3^+ to 2^+ with a Q value of 2488.6 keV). Those values served as the estimates for the correction for systematic errors. The linear extrapolation yields a correction of $-0.06(4)$ MeV for Q_{EC} value of ^{70m}Br and this value was applied to the final result of ^{70m}Br β-spectrum fit. The uncertainty of this correction, i.e., 40 keV was adopted as a systematic uncertainty of the final ^{70m}Br result.

The least-squares fit, characterized by a χ^2 value of 0.84, yielded a β-endpoint energy of 6.62(7) MeV. This corresponds to a $Q_{EC}(9^+)$ value of $6.62(7)-0.06(4_{\mathrm{sys}})+4.605+1.022=12.19(\pm 8\pm 4)$ MeV for the β decay of the 9^+ isomer

TABLE I. Values used for calculating the f value for the ^{70}Br $0^+ \rightarrow 0^+$ decay.

Symbol	Value	Reference
Ft	3072.2(8) s	[17]
$T_{1/2}$	78.54(59) s	[4]
b	98.49%	[18]
δ_R	0.0144(11)	[17]
δ_C	0.0135(21)	[17]

of ^{70}Br. For the cross check of the fitting results and statistical uncertainties, the maximum likelihood method was also applied. Results of both methods, i.e., least-squares and maximum likelihood agree well within their statistical uncertainties.

V. ESTIMATES OF THE Q_{EC} VALUE FOR THE β DECAY OF THE ^{70}Br GROUND-STATE

As mentioned in Sec. I, the knowledge of the $Q_{EC}(0^+)$ value of the ^{70}Br ground-state decay is essential for determining the excitation energy of the 9^+ isomer. The experimental result of 9.97(17) MeV, obtained for the former quantity by Davids *et al.* [15], has a relatively large uncertainty, which makes it marginally useful for the present analysis. Therefore, we preferred to estimate the $Q_{EC}(0^+)$ value of the ^{70}Br ground-state decay based on the $\mathcal{F}t$ and then average both values.

The $\mathcal{F}t$ values have been accurately measured for a series of super-allowed $0^+ \rightarrow 0^+$ Fermi decays, taking radiative (δ_R) and isospin-symmetry breaking (δ_C) corrections into account. The quantity t represents the partial half-life, and the symbol $\mathcal{F}$ indicates that, in contrast to the statistical rate function f, the above-mentioned corrections have been taken into account. The Q_{EC} value of such decays can be estimated by calculating f and using the $f(Q_{EC})$ dependence given by Wilkinson and Macefield [16]. We determined the f value by using the relation

$$f = \frac{\mathcal{F}t \cdot b}{T_{1/2} \cdot (1 + \delta_R) \cdot (1 - \delta_C)}, \qquad (1)$$

where $T_{1/2}$ is the half-life and b the branching ratio for the $0^+ \rightarrow 0^+$ transition. We used the experimental data and theoretically calculated corrections (b, δ_R, δ_C) listed in Table I to determine an f value of $f = 3.85(10) \times 10^4$ for the $0^+ \rightarrow 0^+$ decay of ^{70}Br. The corresponding Q_{EC} value amounts to 9.96(5) MeV.

As both the $\mathcal{F}t$-based method and the experimental result yield consistent results, we use their weighted average of 9.96(5) MeV for the $Q_{EC}(0^+)$ of the ^{70}Br ground-state. This value deviates at a 2σ level from the value of 10.62(30) MeV estimated on the basis of systematic trends and presented in the mass tables of Audi and Wapstra [10]. We do not consider this discrepancy to be worrisome since acceptance of 10.6 MeV as a $Q_{EC}(0^+)$ value for ^{70}Br would imply almost 40% change in $\mathcal{F}t$ value, which we find hard to accept.

VI. RESULTS AND DISCUSSION

The Q_{EC} value measured for the 9^+ isomer of ^{70}Br together with that estimated for the ^{70}Br (0^+) ground state allows us to determine the excitation energy of the isomer to be $12.19(\pm 7 \pm 4) - 9.96(5) = 2.23(\pm 9 \pm 4)$ MeV. When compared to data obtained by in-beam spectroscopy, our result confirms the isomer energy of 2.293 MeV suggested by Jenkins *et al.* [2] but is in striking disagreement with that of 1.214 MeV proposed by de Angelis *et al.* [1] as well as suggestions of Piechaczek *et al.* [5]. In addition, if one assumes the excitation energy of the 9^+ isomer to be 2293 keV according to [2] and the $Q_{EC}(9^+)$ of the isomer decay to be $12.19(\pm 7 \pm 4)$ MeV as measured in this work, the Q_{EC} of the 0^+ ground-state decay of ^{70}Br is found to be $9.90(\pm 7 \pm 4)$ MeV, which is in good agreement with the previous measurement [15].

The conclusions drawn so far have been based on the estimates given in Sec. V. If one would take the ^{70}Br ground-state Q_{EC} value of 10.62(30) MeV derived from systematic trends [10], both high-resolution results would be excluded with 1σ probability, and the excitation energy of the 9^+ isomer would be found to be 1.6(3) MeV.

VII. SUMMARY

By using a total absorption spectrometer the Q_{EC} value of the beta decaying $T=0$, $J^\pi = 9^+$ isomer of ^{70}Br ($T_{1/2} = 2.19(9)$ s) has been measured to be $12.19(\pm 7_{\text{stat}} \pm 4_{\text{sys}})$ MeV. This result confirms the value of 2293 keV found in the in-beam work of Jenkins *et al.* [2] for the excitation energy of the isomer but is in disagreement with values proposed by Piechaczek *et al.* [5] and de Angelis *et al.* [1].

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