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Radiative Capture of *s* Electrons in the Decay of ^{7}Be†

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The high-energy part of the spectrum of internal bremsstrahlung (IB) photons accompanying the allowed electron-capture (EC) transition from ^{7}Be to the ground state of ^{7}Li has been measured with a Ge(Li) γ-ray spectrometer supplied with a pileup rejector. The probability for emission of internal bremsstrahlung photons with energies higher than 523.7 keV per ground-state EC decay of ^{7}Be was determined to be $(9.0 \pm 0.6)\times10^{-5}$. Comparable theoretical results for radiative capture of $1s+2s$ orbital electrons are 8.61×10^{-5}, deduced from the theory of Martin and Glauber, and 8.60×10^{-5}, deduced from recent improved calculations of Intemann. The confirmation of the predicted rate of radiative to ordinary $1s+2s$ capture in ^{7}Be is in good agreement with our recent similar experiment on ^{51}Cr, but is partly at variance with previous IB γ-coincidence experiments on ^{7}Be. The transition energy of ^{7}Be was determined to be 851 ± 12 keV, in agreement with accepted atomic mass differences.

RADIOACTIVITY ^{7}Be; measured internal bremsstrahlung, γ; deduced I_{IB}, Q. Ge(Li) detector, pileup rejection, extrapolation method.

INTRODUCTION

In a recent paper by the author[1] (hereafter referred to as I) the measurement of internal bremsstrahlung (IB) photons in ^{51}Cr with energies exceeding the nuclear γ-ray energy of ^{51}Cr was reported. The results obtained for the shape of the IB spectrum as well as for its relative intensity per ordinary capture event agree excellently with the predictions of the relativistic theory of Martin and Glauber[2,3] for $1s+2s$ radiative capture. In the present paper, the results for our similar experiment on radiative capture in ^{7}Be will be presented.

Because of the nature of the Martin and Glauber theory, its predictions should be even more accurate for the very low-Z nucleus ^{7}Be than for the moderately light ^{51}Cr. For $Z=4$, relativistic and Coulomb effects account for a less than 10% reduction of the IB yield, compared to the early "Coulomb-free" theory of Morrison and Schiff.[4] For the most important shape factor $R_{1s}(Z,k)$ for radiative K capture, Martin and Glauber[3] derived several formulas including different low-Z approximations. All these results as well as the numerically calculated result of Intemann[5] agree within 0.5% for ^{7}Be (see Fig. 1). For the less accurately calculated $2s$ IB shape factor, agreement within 10% is noted between Intemann's and Martin and Glauber's results, respectively.

Previous experiments[6,7] on the IB in ^{7}Be, however, are partly at variance with this theory. In these experiments the IB associated with the electron-capture (EC) branch from ^{7}Be to the first excited state in ^{7}Li (transition energy $Q^{*}_{\text{EC}}=384.1$ keV) was measured in coincidence with the nuclear γ rays from the deexcitation of this state. Lancman and Lebowitz[6] determined the IB yield in the energy range from 120 to 360 keV to be about 30% lower than the predicted one. On the other hand, Persson and Koonin,[7] who used a similar detector arrangement but a widely improved experimental technique, found an about 20% excess of IB photons in the same energy range, but a deficiency of about the same order at lower energies. The total IB yield determined in the latter experiment comes into fair agreement with theory.

The present IB/γ experiment on the IB associated with the higher-energy ground-state EC branch in the ^{7}Be decay ($Q^{0}_{\text{EC}}=871.75$ keV) may contribute to clear up the present discrepancies. Since ^{7}Be decays by nearly 90% via this branch, the associated IB contributes noticeably to the ^{7}Be γ spectrum which has to be corrected[8] for IB in accurate γ counting of ^{7}Be. This is, e.g., important for a precise determination of the γ-branching ratio in the ^{7}Be decay.[9]

EXPERIMENT

Our experimental method is described in detail in I. In short, γ-ray spectra of differently strong ^{7}Be sources were measured with a Ge(Li) spectrometer supplied with a pileup rejector. In the energy range above the nuclear γ-ray energy of 477.6 keV, the spectrum of IB photons and the residual pileup contributions from the γ-ray pulses were separated by linearly extrapolating the ratios $n(E)/N$ versus N' to $N' \to 0$ [$n(E)$ = pulse-height spectra corrected for background and contributions from impurity isotopes; N = total counting rates; N' = total counting rates corrected for over-all rejection losses].

In two series of measurements, seven and eight spectra, respectively, have been recorded, using five sources each. The disintegration rates of the sources were in the range from 5.2×10^5 sec^{-1} to 7.8×10^6 sec^{-1}, and from 3.3×10^5 sec^{-1} to 4.0×10^6 sec^{-1}, respectively. The time of the individual measurements ranged from 240 to 4000 min, according to the avitivity of the sources. The spectrum of the background radiation was measured in eight runs for, in total, 11 900 min.

The sources used in the first series of measurements (I) were prepared from a commercially obtained carrier-free $^7\text{BeCl}_2$ solution. In the measured spectra, contributions from the impurity isotopes ^{65}Zn, ^{88}Y, ^{48}V, ^{54}Mn, and ^{22}Na (written in sequence of descending relative intensity) were observed. All of these γ impurities contributed less than 0.01% to the integral counting rates N, but, on the average, 30% to the IB counting rates above the ^{7}Be photopeak. In order to correct for these impurities, additional spectra of stronger sources were recorded. Then in all available spectra, the areas of the impurity peaks were determined relative to the ^{7}Be peaks and, for each impurity isotope, a weighted average of these ratios was calculated considering decay-time corrections. Finally, γ spectra of the impurity isotopes were recorded separately and, after proper intensity normalization, subtracted from the ^{7}Be spectra.

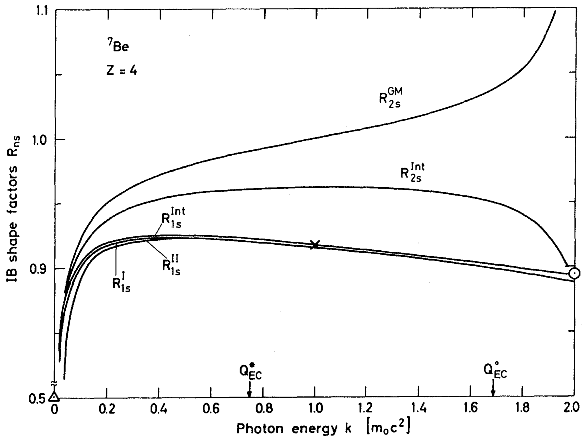

FIG. 1. IB shape factors R_{1s} (Z,k) and R_{2s} (Z,k) for allowed nuclear decay by capture of 1*s* and 2*s* orbital electrons, respectively, for an atomic number $Z=4$. The different results for 1*s* IB deduced from the relativistic theory of Martin and Glauber (Ref. 3) are denoted as R_{1s}^{I} [Eqs. (4.3) and (4.4)] and R_{1s}^{II} [Eq. (4.5)]; the results for the particular photon energies $k_0 = 0$ [Eq. (4.6)], $k_1 = 1 - k_B^{1s}$ [Eq. (4.7)], and $k_2 = 2 - k_B^{1s}$ [Eq. (4.8)], are plotted by symbols: Δ, X, $\odot$, respectively. The result for 2*s* IB from the approximately relativistic theory (Ref. 2) of Martin and Glauber is denoted as R_{2s}^{GM}. The results for 1*s* and 2*s* IB deduced from the calculations of Intemann (Ref. 5) are denoted as R_{1s}^{Int} [Eq. (A2)] and R_{2s}^{Int} [Eq. (A5)], respectively. The transition energies Q_{EC}^{0} and Q_{EC}^{*} for both branches of the corresponding EC decays of ^{7}Be to the ground state and first excited state, respectively, of ^{7}Li are marked on the energy scale.

The sources used in the second series (II) were prepared from a $^7\text{BeCl}_2$ solution, which had been purified by repeated mixing with ethylene diamine tetraacetic acid and extracting of ^{7}Be with acetyl acetone.[10] No spurious peaks were observed with these sources, with an upper limit of $\lesssim 10^{-6}$ compared to the ^{7}Be γ rays for the energy range from 0.5 to 2 MeV.

For both series of measurements, the integral ratios N_{int}/N, the quantities N_{int} representing the sums over the spectra $n(E)$ in the energy range 523.7 keV $\leqslant E \leqslant$ 980.0 keV, are plotted in Fig. 2 versus the corrected counting rates N'. Weighted linear least-squares fits[11] to these data have yielded for the average integral counting rate of IB photons ($E \geqslant$ 523.7 keV) per recorded ^{7}Be γ quantum values of:

$(5.04 \pm 0.15) \times 10^{-5}$ for series I;

$(5.05 \pm 0.15) \times 10^{-5}$ for series II.

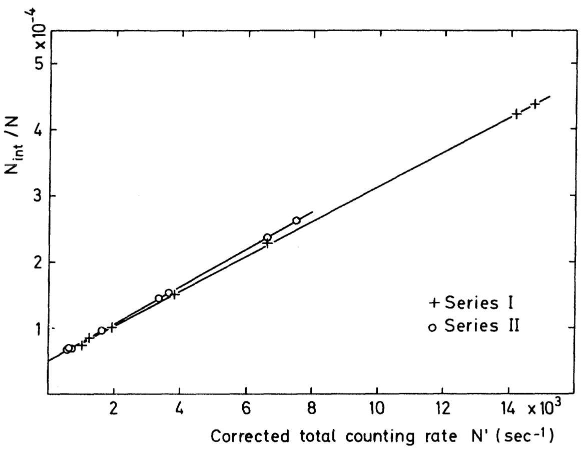

FIG. 2. Ratios of integral counting rates N_{int} in the energy range 523.7 keV $\leq E \leq$ 980.0 keV and total counting rates N (0 to 980.0 keV) versus the total counting rates N' that are corrected for over-all rejection losses. Results of two series of measurements are shown. The straight lines fitted to the data have slightly different slopes due to a readjustment of the pileup rejection system between both series of measurements. The extrapolated values for $N' \to 0$ are in good agreement (see text).

Figure 3 shows the final IB pulse-height spectrum $n_{\mathrm{IB}}^{\exp}(E)$ per energy interval of 1 keV and per ground-state EC decay of ^{7}Be. This spectrum has been derived as a weighted mean from the results of both series and was normalized according to Eq. (2.5) in I. For the normalization, a value[9] of 0.104 ± 0.002 was used for the γ-branching ratio P_γ; the total counting efficiency ϵ_γ^0 for ^{7}Be γ rays was determined to be $(1.639 \pm 0.023) \times 10^{-2}$.

COMPARISON WITH THEORY, RESULTS

In ^{7}Be only two K electrons and two L electrons are available for the capture process. From the latter, only those in $2s$-orbital states are captured with nonnegligible probability.[12] Thus, the total theoretical IB spectrum $w_{\mathrm{IB}}^{\mathrm{th}}(k)$, with k denoting the photon energy, is completely described by $1s+2s$ IB, according to Eq. (3.1) in I. This spectrum, calculated with $Q_{\mathrm{EC}} = 861.75 \pm 0.09$ keV[13] and shape factors $R_{1s}(Z,k)$ and $R_{2s}(Z,k)$ derived from both Martin and Glauber's theory and Intemann's work (Fig. 1), will be compared to our experiment. IB associated with the EC decay to the first excited state in ^{7}Li do not contribute to the energy range investigated.

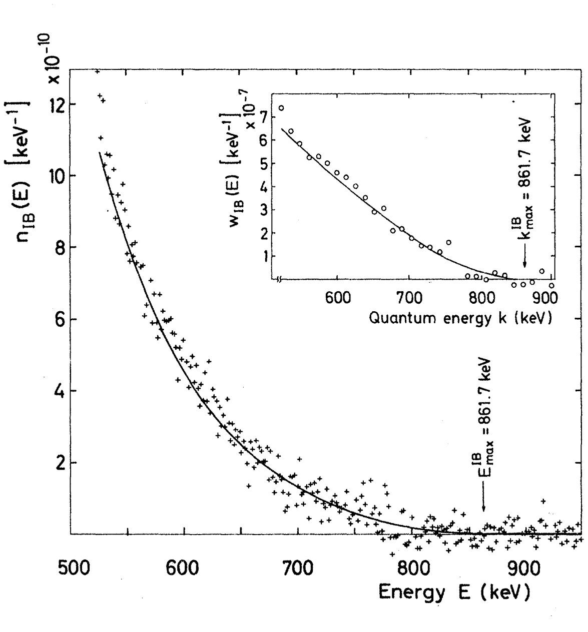

FIG. 3. Pulse-height spectrum $n_{\mathrm{IB}}(E)$ of ^{7}Be internal bremsstrahlung photons per ground-state EC decay of ^{7}Be. The experimental spectrum (+++) was determined as a mean from both series of measurements. The full line represents the IB pulse-height spectrum, that was calculated from the Martin-Glauber theory using $Q_{\mathrm{EC}} = 861.75$ keV, and was folded with the response function of the γ-ray spectrometer. The inset shows the theoretical IB spectrum (full line) and the response corrected experimental spectrum (ooo).

For calculating $w_{\mathrm{IB}}^{\mathrm{th}}(k)$, the relative capture probabilities P_K and P_{L_1} for $1s$ and $2s$ orbital electrons in ^{7}Be must be known. Experimental values for these quantities are not available. Theoretical results for the ratio P_{L_1}/P_K are 0.033[14] and 0.039,[12] which change to values between 0.11 and 0.15 if exchange-overlap corrections[15] are applied. These values, however, are based on ^{7}Be in its atomic ground state $1s^2 2s^2$ neglecting completely chemical effects on the L electrons, being the valence electrons. For Be metal, band-structure calculations[16] as well as a Compton line-shape measurement[17] indicate that the L electrons are to a large extent in p-type orbital states. In this case, the capture rate for $2s$ electrons must be much smaller than expected from the theoretical values above. A similar reduction in the population of the $2s$ states may be expected for other Be compounds, since the ^{7}Be half-life measured in various ^{7}Be compounds and metallic ^{7}Be are observed[18,19] to differ only little ($\lesssim 0.2\%$). For sufficient consideration of chemical effects on the IB yield we, thus, adopted a value of 0.07 ± 0.07 for P_{L_1}/P_K, and accordingly 0.935 ± 0.065 for P_K, and 0.065 ± 0.065 for P_{L_1}. These values give rise to an error of $\lesssim 0.8\%$ on $w_{\mathrm{IB}}^{\mathrm{th}}(k)$, due to the difference between the $1s$ and $2s$ shape factors.

The spectrum $w_{\mathrm{IB}}^{\mathrm{th}}(k)$ was folded with the response function of the spectrometer, as described in I. In Fig. 3 the resulting "theoretical" pulse-height spectrum is compared with the experimental one. Numerical results of IB counting rates

$$N_{\mathrm{IB}}(E_1) = \int_{E_1}^{Q_{\mathrm{EC}}} n_{\mathrm{IB}}(E)\,dE$$

are listed in Table I for both spectra and for various low-energy limits E_1. The quoted experimental errors are rms errors, calculated from the integral quantities $N_{\mathrm{int}}(E_1)/N$ (2.1% for $E_1 = 530$ keV to 30% for $E_1 = 750$ keV), and the errors on P_γ (2.0%), ϵ_γ^0 (1.4%), and on the energy interval per channel width, ΔE (0.2%). The errors on the

TABLE I. Measured IB counting rates $N_{\mathrm{IB}}^{\exp}(E_1)$ per ground-state EC decay of ^{7}Be, compared with those calculated from the theoretical IB spectrum (see text).

E_1 (keV)	$N_{\mathrm{IB}}^{\exp}(E_1)$	$N_{\mathrm{IB}}^{\mathrm{th}}(E_1)$
	(per 10^9 ground-state	EC decays of ^{7}Be)
530.0	85.3 ± 3.1	82.1 ± 3.3
550.0	66.4 ± 2.6	63.9 ± 2.6
600.0	34.2 ± 1.9	32.9 ± 1.3
650.0	15.6 ± 1.6	15.8 ± 0.6
700.0	6.6 ± 1.3	6.6 ± 0.3
750.0	1.9 ± 0.6	2.03 ± 0.08

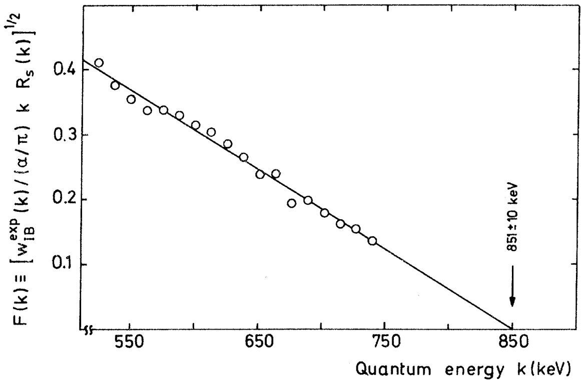

FIG. 4. Jauch plot of ^{7}Be yielding an IB end-point energy of 851 ± 10 keV.

theoretical rates, given in Table I, are composed of the errors due to P_{L_1}/P_K (0.8%), and Q_{EC} (0.1%), and the average accuracy of the determined response matrix (3%).

In the inset of Fig. 3, the IB photon spectrum $w_{IB}^{exp}(k)$, deduced by unfolding $n_{IB}^{exp}(E)$ with the response matrix, is compared with $w_{IB}^{th}(k)$. Integrating over the energy range from 523.7 keV $\leq k \leq Q_{EC}$ has yielded an integral intensity of $(9.0 \pm 0.6)\times 10^{-5}$ IB photons per ground-state EC decay of ^{7}Be. Here, the quoted error is the error of 3.5% on the corresponding rate N_{IB}^{exp} ($E_1 = 523.7$ keV), plus 3% due to the response correction. Comparable theoretical figures are $(8.61 \pm 0.08)\times 10^{-5}$, derived using shape factors from Martin and Glauber (with R_{1s}^{I} from Fig. 1), and $(8.60 \pm 0.08)\times 10^{-5}$, derived from Intemann's work. The calculation in the "Coulomb-free" approach of Morrison and Schiff, using $R_{1s} = R_{2s} = 1$, yields 9.38×10^{-5}.

Finally, an average value of the over-all shape function $R_s(Z, k)$ for s IB has been calculated, as described in I. In the energy range 523.7 keV $\leq k \leq 753.7$ keV, $\langle R_s(\text{exp})\rangle = 0.94 \pm 0.07$ (standard deviation of 18 values) has been obtained, compared with the theoretical value $\langle R_s(\text{theor})\rangle = 0.92 \pm 0.01$.

A Jauch plot constructed from $w_{IB}^{exp}(k)$ in the same energy range (Fig. 4) has yielded for the transition energy Q_{EC} of ^{7}Be a value of 851 ± 10 keV, using shape factors from Martin and Glauber, and 849 ± 10 keV, if the energy dependence of these figures is neglected by setting $R_{1s} = R_{2s} = 1$. The adopted final result of $Q_{EC} = 851 \pm 12$ keV is in agreement with the accepted mass differences.[13]

DISCUSSION

The present results and those of both previous IB γ-coincidence experiments[6,7] on the ^{7}Be EC decay that leads to the first excited state in ^{7}Li are summarized in Table II. The EC transition energies obtained from all these measurements are in good agreement with the accepted mass differences. In order to compare the experimental findings for the IB yields associated with both EC branches in ^{7}Be, ratios of observed to predicted IB intensities are listed in Table II. The theoretical intensities, used to derive these ratios, have been consistently calculated with Q_{EC} values from Ref. 13 and an L_1/K capture ratio of 0.07 ± 0.07, as discussed earlier. As can be seen, the present result comes into fair agreement with the results obtained by Persson and Koonin,[7] but is somewhat at variance with the lower value given by Lancman and Lebowitz.[6] Here it should be noted, that we are in complete agreement with Persson and Koonin in evaluating the Martin and

TABLE II. Ratios of measured to predicted IB yields in ^{7}Be.

Decay	Transition energy (keV)	Energy range (keV)	Exp.-to-theor. IB yield [a] with theor. values of Martin and Glauber and Intemann	Morrison and [b] Schiff	Reference
^{7}Be(EC)^{7}Li*	384.1 ± 0.1				13
	388 ± 8	50 – 360	1.12 ± 0.08	1.03 ± 0.07	7
		100 – 360	1.18 ± 0.09	1.07 ± 0.07	
		120 – 360	1.21 ± 0.10	1.12 ± 0.08	
	395 ± 25	120 – 360	0.77 ± 0.17 [c]	0.71 ± 0.15 [c]	6
^{7}Be(EC)^{7}Li	861.75 ± 0.09				13
	851 ± 12	523.7 – 861.7	1.05 ± 0.08	0.96 ± 0.07	this work

[a] The theoretical values were calculated with transition energies Q_{EC} from Ref. 13. The quoted errors correspond to the sum of the stated experimental errors and the uncertainties on the theoretical values, that are introduced by the errors on Q_{EC} (0.7% for Q_{EC}^*, 0.1% for Q_{EC}), and P_{L_1}/P_K (see text).

[b] Calculated from Eq. (3.1) in Ref. 1, using $R_{1s} = R_{2s} = 1$.

[c] The experimental values, given for IB/EC$_K$ (Table I in Ref. 6), were converted to IB/$\gamma = (4.9 \pm 1.0)\times 10^{-5}$ (see also Ref. 7).

Glauber theory.

The experimental excess of IB photons, however, found by Persson and Koonin in the energy range from 120 to 360 keV, is also at variance with the present result, which agrees with theory at much higher energies. The shape factor for the predominant 1s IB component (Fig. 1), as predicted by theory, is constant within 2% for energies higher than about 50 keV. An increase of this factor with photon energy, as might be suggested from Persson and Koonin's result, is not observed in the higher energy range covered by our experiment.

In Table II, ratios of experimental IB yields to those calculated from the "Coulomb-free" theory of Morrison and Schiff are included also. As can be seen, no experimental evidence for the small influence of relativistic and Coulomb effects on the IB yield in ^{7}Be can be derived due to the experimental errors.

The confirmation of the predicted rate of radiative to ordinary capture by the present experiment is in good agreement with our previous experiment on ^{51}Cr, suggesting that the present theory satisfactorily describes s IB in allowed EC decays of light and moderately light nuclei.

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