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Beta decay of the proton-rich T_Z = -1/2 nucleus, ^{71}Kr

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Abstract

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I. INTRODUCTION

Studies of neutron-deficient nuclei above A ~ 60 are important for understanding the evolution of nuclear structure for systems with nearly equal number of protons and neutrons [1]. Due to the increasing importance of the Coulomb interaction, these nuclei are only weakly bound or even unbound, and consequently small effects due to the proton-neutron interaction, the shell structure and the deformation become essential in determining the nuclear properties. These properties are also of prime importance for a deeper understanding of the rp-process above Ni [2].

Pairs of mirror nuclei with T = 1/2 provide an ideal laboratory for probing the evolution of fine details of nuclear properties. Qualitatively, the decays of Tz = - 1/2 nuclei are characterized by fast combined Fermi and Gamow-Teller (GT) decays and short half-lives (~100 ms) due to the high decay energies determined by the well-defined Coulomb-energy differences. These nuclei have been studied with high enough precision only up to 59Zn [3,4,5]. Above 59Zn, experimental information is incomplete. Nucleon stability of Tz = -1/2 nuclei has been studied mainly via fragmentation reactions. Particle stability, i.e. T1/2 > 100 ns, has been confirmed up to 75Sr with two exceptions, namely 69Br and 73Rb [6,7,8]. Above strontium, particle stability has been observed for 87Ru, 89Rh and 91Pd [9]. Despite the success in identifying these exotic nuclei, progress in the study of their decay and structure has been slow. This is mainly due to the experimental difficulties in performing high-accuracy experiments on these fast-decaying nuclei produced in low yields. Beta-decay half-lives have been measured for 61Ga, 63Ge and 65As and their main decay mode could be characterized to be fast beta decay [10]. More detailed information was obtained for the decays of 67Se, 71Kr and 75Sr in studies performed at ISOLDE and GANIL. At ISOLDE, beta-delayed gamma-ray spectroscopy has been exploited for ^{67}Se [11] and detection of high-energy beta particles for ^{71}Kr [12]. Recently, projectile fragmentation studies of ^{78}Kr at GANIL allowed the observation of weak beta-delayed proton branches in the cases of 67Se, 71Kr and 75Sr

[13] and induced also some discrepancies with the previous measurements. In the GANIL study, the half-life for 71Kr was determined to be 64 +8/-5 ms using the detection of β-delayed protons. This value disagrees significantly with the previous result 97±9 ms, where only β-particle detection was used to obtain the half-life [12]. Short half-lives for these decays, in which the transition to the analog state should be predominant, indicate enhanced transitions that are difficult to account for theoretically. Therefore, to obtain relevant information on Gamow-Teller matrix elements involved in these decays one has to use both beta-delayed proton and -gamma detection techniques. The present experiment on 71Kr, performed using the General Purpose Separator of the ISOLDE Facility located at the CERN PS Booster [14], was undertaken with these requirements in mind. In addition, the experiment had as other goal the search for the radioactive decays of other, lighter isotopes of Kr. We report here only on the 71Kr decay; information obtained on 69Kr and 70Kr will be presented separately. It should be mentioned that beta-delayed proton emitters along the Tz = +1/2 line have been studied in detail up to 77Sr [15,16,17], providing an excellent data set for comparison with the Tz = -1/2 nuclei, especially concerning the statistical features of the beta-delayed proton decay.

II. EXPERIMENTAL INFORMATION

Short-lived Kr isotopes were produced in spallation reactions by using the pulsed 1 GeV proton beam from the PS Booster at CERN and mass-separated in the ISOLDE facility [14]. Very clean conditions for producing Kr-beams were obtained with a Nb-foil target connected to the plasma ion-source via a cooled transfer line. The average proton-beam intensity in this experiment was 2.1 μA. The beam consisted of subsequent short-duration proton pulses with a 2.4 μs length and spacing of an integer multiple of 1.2 s between the pulses. Production rates for the 73Kr and 72Kr -isotopes and the short-lived 71Kr were 7.6×10^4, 1.5×10^3 and 1.7 atoms/μC, respectively. The production rate for 71Kr was two times higher than in the previous experiment at the SC-ISOLDE facility [12].

The isobarically pure Kr-beam was implanted into an aluminized-mylar tape, which was tilted to 45¡ with respect to the beam axis. This angle allowed undisturbed beta-delayed proton detection by a special detector telescope system facing the point of implantation. The transport tape was moved at every 10th proton pulse, 800 ms after the pulse impact, to reduce the background due to long-lived activities. The beam-on period for the radioactive-ion beam following the proton pulse was set to 250 ms. This short time associated with the selectivity of the target/ion source for noble gases and the periodic movement of the tape reduced the background remarkably. The only contaminants present in the beam were the long-lived activities 71As and 71Zn.

The detection set-up consisted of a gas-Si detector telescope for protons, a 70% HP coaxial and a 20 mm thick planar HPGe detectors for gamma- and X-rays, and a combination telescope detector for high-energy betas, all in close geometry around the implantation position**.** Low-energy beta-delayed protons could be identified with the specially designed gas-silicon detector telescope [18], in which the gas detector has an effective thickness of only 70 μg/cm2, consisting of a 45 μg/cm2 thick polypropylene entrance window and an 8.5 mm thick volume of CF_4 gas at a pressure of 10 mbar. Three equally spaced tungsten multiwire electrodes were used to extract the signal produced by the transmitted particle. The thickness of the E-detector was 300 μm. Due to the very small energy loss in the transmission detector, it was possible to obtain nearly linear energy calibration for the E detector without adding the measured ΔE-energy, which was used for particle identification only**.** The beta telescope consisted of a 2mm thick plastic scintillator, used as a transmission detector, and of the previously mentioned large (3800 mm^2, 20 mm thick) HPGe-planar diode as an energy detector. Amplifiers associated with the latter detector provided low- and high-gain signals for beta- and low-energy photon detection, respectively. Either the plastic scintillator or the Si detector of the proton telescope was used as a main trigger. Altogether 15 parameters were registered including energy and timing signals from each counter. Two fast-timing-signals (TAC), between the Si detector of the proton telescope and the plastic scintillator as well as between the γ-detector and the plastic scintillator, were recorded. Additionally, the time between the proton pulse and the main trigger of the acquisition system was registered to obtain information for the half-life determination of the isotopes of interest.

Efficiency calibrations for the γ and X-detectors were made using standard 152Eu, 56Co and 133Ba sources. Efficiency calibration for the beta scintillator was determined by using the β-gated and singles spectra of protons following the beta decay of 33Ar produced in large enough yields on-line. The efficiency of the proton telescope was measured to be 6.2 ± 1.9 % from the 73Kr decay, whose βγ and βp branches are well known [19]. Energy calibration for the proton telescope was obtained using an external α source which included 239Pu, 241Am and 244Cm. Two additional calibration points were obtained from the proton spectrum of 33Ar, in which the 2096 and 3167.6 keV proton peaks were clearly observed. The energy resolution of the telescope for protons was determined to be about 30 keV.

The internal energy calibration of the beta-detector was made using the previously mentioned γ-ray sources and as a high-energy calibration point the 6.130 MeV γ-ray from a 13C(α, n)16O* source. The error due to the calibration around 10 MeV was less than 20 keV. In addition, the calibration was tested by measuring the known beta-decay end-point energy for the 73Kr decay.

III. RESULTS

III. 1. Beta-delayed gamma-decay

Gamma spectra in coincidence with betas and gated with the short-lived (30-800 ms) and the long-lived part (801-4800 ms) of the time spectrum, respectively, are shown in Fig. 1. Two lines of interest for 71Kr are seen at 198 and 207 keV; they are short-lived and their relative intensity is in agreement with those observed in an in-beam study on 71Br by Arrison et al [20]. Hence, they are associated with the β-decay of 71Kr, and de-excite the 207 keV level in 71Br. No other gamma-lines related with the decay of 71Kr could be identified. The level scheme of 71Br is given in refs. [20], including the cascade of the 198 keV and (unobserved) 9 keV γ-rays, de-exciting the 207 keV level, i.e. E_X=207; $J^\pi=(3/2)^-$ ♦ E_X=9; $J^\pi=(1/2^-)$ ♦ g.s; $J^\pi=(5/2)^-$. These values fix also the spin $J^\pi=(5/2)^-$ for the ground state of the mirror nucleus 71Kr and account well for the observed β-branchings. It should be noted that the low-energy structure of 71Br is found to be similar to the one of 73Br, see ref. [21], except for the inversion of the low-energy $1/2^-$, $5/2^-$ doublet. The summary of the transitions observed and the upper limits of the unobserved transitions are collected into Table 1.

A second $J^\pi = (3/2^-)$ level at E_X=262 keV in 71Br is given in refs. [20], and would be a candidate as a final state for an allowed β-transition. However, no evidence for the feeding of this state is found in our γ-spectra; this absence could be due to a particular configuration of this state; questioning the assignment of the 262 keV level would contradict the consistency of the published 71Br level scheme [20]. In the case of the (7/2-) -state at 806 keV the situation is similar. According to refs. [20] this state would decay via a 599 keV transition following the allowed beta decay. However, no sign of this transition was observed. Although the emission order of the 198 - 9 keV cascade cannot be established by a direct measurement, only the adopted level scheme (intermediate state at 9 keV) can account for the observed relative intensities of the 198 and 207 keV γ rays. Indeed, if the intermediate state were at 198 keV, de-excitation of the 207 keV level via the 9 keV M1 transition followed by the 198 keV transition would be much weaker than the 207 keV M1 transition, i.e. by a factor of 120 using the Weisskopf estimate.

III. 2. Beta-delayed proton-decay

A two-dimensional display of the events recorded using the gas-Si particle telescope is presented as a ΔE-E matrix in Fig. 2a. The two-dimensional gate used to generate the proton spectrum and to determine the decay half-life was defined by the delayed protons from 73Kr and by using additional fast coincidence requirement between protons in the telescope and positrons in the thin plastic beta detector. Fast coincidence selection removed all the events below 580 keV from the two-dimentional ΔE-E matrix and thus determined the low-energy limit for protons.

The proton spectrum in Fig. 2b reveals a bell-shaped structure between 0.6 and 5.1 MeV. The spectrum shows a maximum at the energy of 2.3 MeV. Although the resolution of the detector was excellent (30 keV), no distinct peaks could be clearly observed. Moreover, the simultaneously recorded gamma-spectra show no indication for the population of excited states in 70Se, in particular of the 2+ state at 945.4 keV [22] but the sensitivity of our gamma measurement prevents the observation of a 945 keV line below a level of about 1 % of the total beta decay. In fact, in the proton spectrum of Fig. 2b the energy separation of the two intensity maxima at 3.2 and 2.3 MeV may suggest feeding of the ground and the first excited state in 70Se.

III. 3. Beta-decay energy of 71Kr

The use of the 20 mm thick HPGe-detector as a beta-detector gave the possibility to obtain also information on the QEC -value of 71Kr. Beta spectra were measured by requiring a fast coincidence between the HPGe and the plastic transmission detectors. Fermi-Kurie analyses of the beta spectra were not possible due to the lack of the detailed knowledge of the response function for this particular detector, as well as to the relatively large feeding of other low-lying states, which distorts the spectrum shape. Therefore the estimates of the maximum decay energies of both 71Kr and 73Kr have been made using graphical extrapolations of the logarithmic representation of the beta spectra shown in Fig.

3. The simple analysis resulted in QEC = 6860 ± 220 keV for 73Kr, which is in a reasonable agreement with the reported value of 6670 ± 190 keV [22]. For 71Kr, our analysis gives QEC = 10140 ± 320 keV, which can be compared with the value of 10490 ± 420 keV given in the 1995 Mass Tables [23]. Our value is the first experimental measurement of the QEC -value for 71Kr.

For 71Kr the uncertainty of the extrapolated value only using the minimum-maximum estimate is 250 keV. In addition, other error contributions result from energy loss in the plastic scintillation detector and various dead layers between the source and the HPGe-detector as well as from annihilation summing effects in the detector volume. Energy loss for 9 MeV positrons was calculated to be 525 ± 180 keV where the error is due to spread in energy loss caused by the large solid angle of the ΔE-detector, uncertainty in the detector position and energy loss calculations. Annihilation summing causes correction of roughly same magnitude but of different sign. Summing effects have been studied with a Monte-Carlo -method for Ge-detectors of smaller volume than in the present experiment and the correction for 9 MeV positrons was determined to be 321 keV for the planar detector with a diameter d = 40 mm and a thickness x = 10 mm [24]. This effect can be estimated for larger planar Ge-crystals by calculating the absorption of annihilation quanta in the detector volume. Reasonable assumption is that this effect depends linearly on the amount of absorbed 511 keV γ-rays produced by annihilation. Using the same assumption as in ref. [24] that the annihilation occurs in the centre of the detector volume, the effect can be extrapolated to be 500 ± 75 keV. The two effects nearly compensate each other in the final energy but contribute to the final error of the QEC-value. Summing the different error contributions quadratically, including the 25 keV error from the energy calibration, we obtain an error of ±320 keV for the QEC of 71Kr. Similar evaluation leads to an error of ±220 keV for 73Kr.

III. 4. Beta-decay half-life of 71Kr

In the present experiment, the half-life of the 71Kr beta decay was determined from the proton and the high-energy beta spectra. Results of the one-component fits of the data taken during the decay periods, i.e. after the 250 ms collection-period, are shown in Figs. 4a and 4b for the delayed proton and the high-energy beta-decay data, respectively.

The time spectrum of the proton events corresponds to the condition shown in Fig. 2b. In this case only a single-component fit was used to extract the half-life. In the time spectrum of the beta decay only high-energy events were included by setting the threshold at 5.5 MeV. This lower limit was found to be the end-point energy of the long-lived component in the beta spectrum, being related with the decay of the daughter nucleus 71Br. However, a constant background in the high-energy region of the beta spectrum was observed, extending up to 20 MeV**.** This was related to the large volume of the detector, which makes it sensitive to cosmic rays. Arrival times of these events were distributed over the whole time spectrum and these events were taken into account as a constant offset added to the exponential decay of positrons. These fits to the decay curves resulted in the half-life values of 95 ± 6 ms for the proton measurement and 101 ± 4 ms for the beta-measurement, averaging to 100 ± 3 ms. These values are in excellent agreement with the previous value of 97 ± 9 ms given in ref. [12], but in disagreement with the recently published value from the projectile fragmentation experiment [13]. The summary of the results from all available measurements of the half-life of 71Kr is given in Table 2. The reason for the discrepancy with the result of ref. [13] is not understood.

III. 5. Branching ratios

In our experiment, a value of 2.1±0.7 % for the proton branching was deduced from the total intensity of the proton spectrum and the estimated total production rate. The production rate was obtained by summing the events in the short-lived component of the beta-gated time spectrum between 40-800 ms and by subtracting the constant, long-lived background obtained in the single exponential plus background fit between 250 and 800 ms. The obtained value for the beta-delayed proton branching should be compared with the value of 5.2 ± 0.6 % as measured by Blank et al. [13]. Again, as for the half-life, the discrepancy with ref. [13] is not understood.

Based on the relative efficiency calibration of the gamma-ray detectors with respect to the particle telescope, a value of 15.8 ± 1.4 % was obtained for the beta-decay to the 207 keV state in ^{71}Br. This results in the branching ratio of 82.1 ± 1.6 % for the decay to the ground state.

IV. BETA STRENGTH AND THE DECAY SCHEME

Feeding by allowed decays of the order of a few percent to low-lying excited states, which subsequently decay by γ-emission, has been observed to be characteristic for almost all T_Z = -1/2 mirror nuclei in the fp-shell. In this experiment, a relatively large feeding of 15.8 ± 1.4 % to the known state at 207 keV with $J^{\pi}=(3/2)^{-}$ in 71Br was observed, in addition to a sizeable feeding of the proton-unbound states above 3 MeV excitation.

In determining the experimental Gamow-Teller matrix elements for the main β-transitions, we have used the following formula [3], which is valid for the allowed beta transitions,

$$(1 + \delta_R)\, f\, t \;=\; C / (\langle \mathbf{1} \rangle^2 (1-\delta_C) + R^2 \langle \sigma\tau \rangle^2), \qquad (1)$$

where we have used the following values for the radiative correction (δ_R), the correction for isospin impurity (δ_C), the constant C and the axial-vector to vector coupling constant ratio g_A/g_V :

$(1 + \delta_R) = 1.026$	[12]
$(1-\delta_C) = 0.997 \pm 0.003$	[25]
$R = g_A/g_V = 1.266 \pm 0.004$	[26]
$C = 6145 \pm 4$ s	[27]

The statistical rate function $f(Z,E_{max})$ was calculated on the basis of the Tables given by Ph. Dessagne and Ch. Miehé [28]. The summary of the beta-decay properties of 71Kr are collected in Table 3. This decay represents the largest beta-branching ratio to the excited states among the known mirror nuclei. Consequently, due to the observation of the new βp and βγ branches, the GT matrix element for the ground state transition is reduced in comparison with the previous value [12], which was based on the 100 % ground state feeding. The decay scheme for 71Kr based on the experiment presented in this work is shown in Fig. 5.

V. DISCUSSION

High-precision measurements of the mirror beta decays provide important information on the charge-dependent effects in nuclei and on fundamental aspects of beta decay. The experiment presented here is the first study of reasonable precision on mirror nuclei above 59Zn. The decay information on 71Kr allows us to extract two important quantities, i.e. the Coulomb energy difference between 71Kr and 71Br and the Gamow-Teller matrix element for the ground state decay, to be compared with the model calculations and the systematics from the previous data. In addition, for heavier nuclei, important contributions for the understanding of beta decay to high-lying states as well as statistical features of the levels at high excitation are obtained through the measurements of beta-delayed particle emission.

The total decay energy of 71Kr was measured as 10140 ± 320 keV in this work. The experimental result is lower than the value of 10490 ± 420 keV from the systematics given in the 1995 Mass Tables, but still within the error bars. Better agreement is obtained using the Coulomb energy equation of Comay and Jänecke [29,30] which gives 10300 keV. The latter model provides the most dedicated basis for the extrapolation of QEC -values of Tz = -1/2 nuclei above 59Zn.

The beta strengths extracted for the transitions to the ground state and the excited state at 207 keV clearly imply characteristics of the Gamow-Teller decay, see Table 3. They possess substantial strength in comparison with the single-particle estimate based either on the p3/2 or the f5/2 orbital. It is of general interest to compare the strengths of the ground state transitions to the earlier data available in the literature. The updated values of the experimental ground state GT-matrix elements in the fp-shell are given in Fig. 6, and compared to the theoretical results from ref. [31,34]. The experimental values have been recalculated using the equation (1) and the most recent experimental data on the isotopes with Tz = -1/2 [4,11,31-34]. Within the error, our result for 71Kr is consistent with the magnitude of the GT-matrix elements observed in the lower fp-shell.

In the case of 67Se, whose half-life is T1/2 = 107 ± 35 ms, a similar ground-state GT-matrix element has been reported [11] in comparison to 71Kr. However, our reanalysis of the data reveals that the error in the lifetime value induces very large uncertainty in the GT-matrix element of the ground-state transition, i.e. $\langle\sigma\tau\rangle = 0.34 \pm 0.39$. The recently observed βp branch of 0.5 % [13] has only a very small effect on the discussed matrix element. However, if the 60 +17/-11 ms half-life reported in ref. [13] is used, the value of the ground-state matrix element is close or even larger than the single-particle estimate. The QEC value required to compensate that increase of the GT-matrix element would be of the order of 11.5 MeV, which is much larger than the value QEC = 9870 keV obtained from the Coulomb energy calculation of refs. [29,30]. From the discussion of 67Se and 71Kr, it appears that the half-life values given in ref. [13] are systematically too short to be compared with the general trend observed for the other fp-shell nuclei.

Although the calculations for Fig. 6 were made with a truncated model space, they seem to reproduce the experimental GT-strength fairly well, at least when the lowest states in the β-decay daughter are considered. In particular, the model where one or two particles are allowed to be excited from the 0f7/2 orbital to upper fp-shell orbitals (3p-2h model), shows good results for mirror nuclei which are characterized by strong GT-feedings to low-energy states. Quenching of the ground-state matrix elements is more visible for nuclei in the vicinity of the closed shells and the GT-strength will reach its minimum in the middle of the shells due to increase of collective effects in nuclei such as ground-state correlations. For this reason it would be of clear interest to extend the shell-model calculations towards the heavier mirror nuclei.

Due to low statistics a detailed analysis of the beta-delayed proton spectrum of 71Kr is not possible. However, the magnitude of the beta feeding to the high-lying states above 3 MeV can be estimated. Most of the strength, about 50 %, is located in a broad bump at about 2.3 MeV proton energy corresponding to about 4.25 MeV excitation energy in 71Br, if protons are populating the 70Se ground state. If a proton decay to the 2+ state is present, the strength would be mostly located around 5.2 MeV excitation energy. The former corresponds to an effective log ft -value of about 4.3. Since this value represents an estimate for the upper limit of the log ft -value it implies that a substantial strength is located in this energy region. This observation is in accordance with the recent predictions by Frisk et al. for the light Kr isotopes [35], where a significant part of the Gamow-Teller giant resonance is calculated to lie within the decay-energy window. However, a more detailed statistical analysis would require better data to make solid statements on the strength to the high-lying states.

VI. CONCLUSIONS

To conclude, we have measured the beta-decay half-life of 71Kr by two independent ways. The result, accurate to 3 %, together with the determination of the βp and βγ branches, gives a revised value for the GT ground state transition between the A=71, T = 1/2 mirror nuclei. The measured and deduced QEC value of 71Kr is in good agreement with the Coulomb energy systematics of the mirror nuclei. However, more high-quality measurements on the Q-values as well as on the beta decay properties are required above 59Zn to obtain detailed information on the charge symmetry effects in mirror nuclei close to the proton drip-line and to shed new light on the evolution of the structure of nuclei with Z ~ N.

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FIGURE CAPTIONS

Fig. 1. Beta-gated gamma-ray spectrum measured at mass 71 using the large 70 % coaxial Ge-detector (a) and the 20 mm thick planar Ge-detector (b). The total time of the measurement was 25.3 h. The peaks shown by arrows belong to the decay of 71Kr. The background spectrum (c) measured during the time period from 801 to 4800 ms is shown for comparison.

Fig. 2. (a) Two-dimensional presentation of the events recorded in the gas-Si detector telescope.
(b) Proton spectrum generated by the gate shown in the part (a).

Fig. 3. Logarithmic positron spectra measured at masses A=73 (a) and 71 (b). The end-points given are deduced from the spectra using graphical extrapolation. The magnitude of the observed constant background has been determined as an average of the counts/channel above 6 MeV and 9.5 MeV for 73Kr and 71Kr, respectively. Extrapolated crossing points between the beta spectra and the constant backgrounds are shown with the minimum-maximum values indicated by the dotted vertical lines.

Fig. 4. The decay curves measured at A=71 for the high-energy betas and protons. See text for details.

Fig. 5. The decay scheme of 71Kr. Unobserved possible final states for Gamow-Teller beta decay at 262 and 806 keV are also shown in the scheme by dashed lines.

Fig. 6. The summary of the ground state Gamow-Teller matrix elements for the mirror decays above A=40. The dashed line represents the shell-model calculation described in the text. The dotted lines denote the single particle values for the GT-decays.

Table 1. The intensities of the observed gamma-transitions and the upper limits for the unobserved expected transitions in ^{71}Br and ^{70}Se.

Eγ [keV]	Iγ [rel. unit]	Ji	Jf	in
198	100	(3/2)-	(1/2-)	71Br
207	36	(3/2)-	(5/2)-	71Br
262	< 8	(3/2-)	(5/2)-	71Br
599	< 10	(7/2-)	(3/2-)	71Br
945	< 1 % a	2+	0+	70Se

a) Upper limit of all beta decays of ^{71}Kr

Table 2. Beta-decay half-lives of ^{71}Kr measured in four independent experiments. See text for details.

Reference	$T_{1/2}$ [ms]	Method
[12]	97 ± 9	high-energy beta counting
[13]	64 +8/-5	beta-delayed proton counting
this work	101 ± 4	high-energy beta counting
this work	95 ± 6	beta-delayed proton counting

Table 3. Beta decay of 71Kr to the levels of 71Br. See text for details.

Ex [keV]	Iπ	Iβ [%]	log ft	|<στ>|
0	(5/2)-	82.1 ± 1.6	3.71 ± 0.07	0.33 ± 0.19
207	(3/2)-	15.8 ± 1.4	4.38 ± 0.08	0.40 ± 0.04
262	(3/2-)	< 1a	> 5.6	
806	(7/2-)	< 1.1a	> 5.4	
p-unbound		2.1 ± 0.7		

a) not seen, the intensity value is estimated upper limit