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Decay properties of the 0_2^+ state and spin-parity assignments in ^{78}Kr

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The lifetime τ of the 0_2^+ state in ^{78}Kr has been measured by means of the Doppler shift attenuation method in gases. From the value of τ and the measured value of the K-internal conversion branching $I_K(0_2^+\rightarrow 0_1^+)/I_K(0_2^+\rightarrow 2_1^+)$ the value of the electric monopole strength $\rho^2(E0)$ of the $0_2^+\rightarrow 0_1^+$ transition has been deduced. Restriction or assignments for the spin parity of several levels in ^{78}Kr, populated in the decay of ^{78}Rb, have been deduced by measuring K-internal conversion coefficients of the relevant transitions.

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As a part of a systematic investigation of the $E0$ and $E2$ decay modes of 0^+ excited states in even krypton isotopes, we recently reported some spectroscopic data on ^{80}Kr concerning, in particular, the decay properties of the 0_2^+ state [1].

In even krypton isotopes this state was interpreted by some authors [2] as belonging to the standard space of the interacting boson model in its IBM-1 version [3], while other authors [4], applying the IBM-2 model [3], interpreted it as an "intruder state," i.e., as lying outside the IBM model space. In Refs. [2,4] the comparison between experimental and calculated data relevant to 0_2^+ states was necessarily limited to excitation energies, due to the lack of experimental data on transition strengths from these states. In Ref. [1] we compared the available spectroscopic data on low-lying levels of ^{78,80,82}Kr with the values predicted by the IBA-2 model, when a set of parameters different from that adopted in Ref. [4] is used. We found that it is still possible to give a consistent description both of excitation energies of the 0_2^+ state in these nuclei and decay properties of the 0_2^+ state in ^{80,82}Kr, without introducing configurations lying outside the IBA-2 model space.

In this paper we report on measurements in ^{78}Kr concerning (i) the decay properties of the 1017 keV, 0_2^+ state, which could provide further support to the proposed description of the 0_2^+ states in ^{78,80,82}Kr and (ii) the determination of several internal conversion coefficients, which enable us to assign the parity of several levels as well as to restrict the possible range of their spin values. This information is necessary for an analysis of the low-lying positive-parity levels of the even krypton isotopes (that we plan to perform in the near future) aimed at the identification of states having predominant mixed symmetry character under exchange of proton and neutron bosons [3].

The low-lying levels in ^{78}Kr were populated in the β^+/EC decay of ^{78}Rb [5] collected at the ISOLDE mass separator (CERN). The conversion electrons were analyzed by means of a compact magnetic transport system [6] coupled to a 5 cm$^2\times$6 mm Si(Li) detector cooled down to the liquid nitrogen temperature. Under typical experimental conditions the energy resolution (full width at half maximum) at 1 MeV was about 2 keV. Due to the large number of γ rays in the decay of ^{78}Rb, which generate considerable background in the silicon detector, it has been necessary to increase, with respect to the standard setup [6], the distance of the detector from the collection point so as to enable the insertion of additional shielding external to the spectrometer vacuum chamber. This greatly improved the signal to background ratio in the electron-energy spectra. The resulting loss of efficiency in electron detection was of no concern in this case since the source intensity was such as to give rise to a counting rate close to the maximum tolerable in the silicon detector in order not to significantly spoil its energy resolution. Gamma rays were recorded by means of a HPGe detector (having 25% relative efficiency at 1.3 MeV), placed about one meter away from the collection point. Details of the experimental procedure and data analysis can be found in Ref. [1]. Sections of typical electron-energy spectra are given in Fig. 1, in several energy windows centered on the indicated transitions.

To study the decay properties of the 0_2^+ state the K-conversion electron intensity ratio $q^2=I_K(0_2^+\rightarrow 0_1^+)/I_K(0_2^+\rightarrow 2_1^+)$ has to be determined. From q^2 one can deduce the ratio X of the electric monopole $B(E0;0_2^+\rightarrow 0_1^+)$ to electric quadrupole $B(E2;0_2^+\rightarrow 2_1^+)$ reduced transition probabilities *via* the expression [7]

$$X=2.56\times 10^9 A^{\frac{4}{3}}E_\gamma^5[\mathrm{MeV}]\ \frac{\alpha_K(E2)q^2}{\Omega_K[\mathrm{s}^{-1}]},$$

where Ω_K is the electronic factor for the K conversion of the $E0$ transition (tabulated, e.g., in Ref. [8]) and α_K is the K-internal conversion coefficient of the $0_2^+\rightarrow 2_1^+$ transition.

The electric monopole strength $\rho^2(E0;0_2^+\rightarrow 0_1^+)$ is related to the quantities X and $B(E2)$ by the expression

$$\rho^2(E0)=\frac{XB(E2)}{e^2R^4},$$

where R is the nuclear radius ($R=1.2A^{1/3}$ fm).

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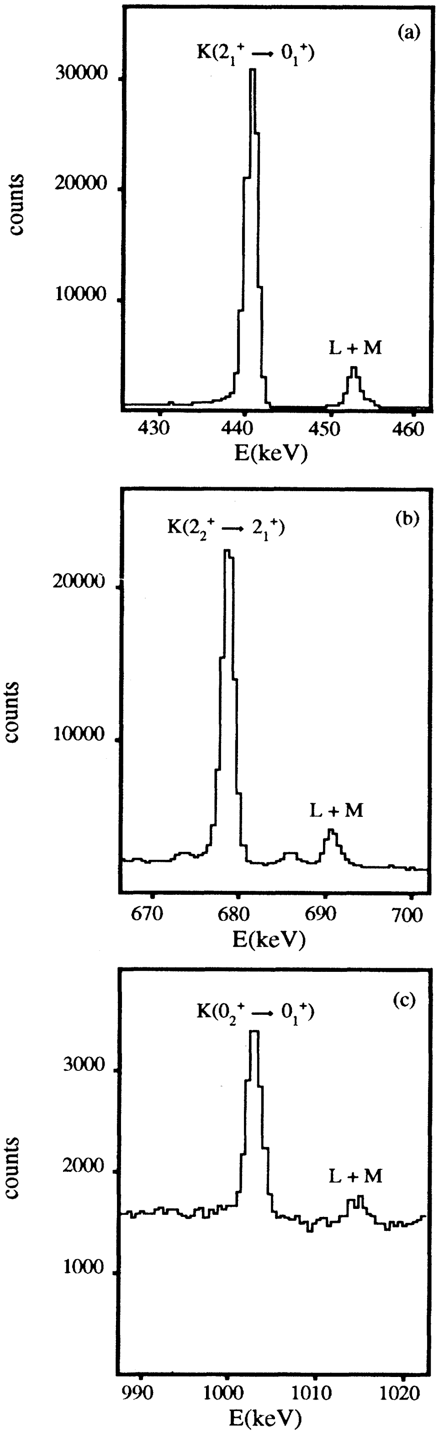

FIG. 1. Relevant sections of the electron-energy spectra showing the K- and $L+M$-conversion lines of the (a) 455 keV, $2_1^+ \rightarrow 0_1^+$, (b) 692 keV, $2_2^+ \rightarrow 2_1^+$, and (c) 1017 keV, $0_2^+ \rightarrow 0_1^+$ transitions.

From the value $q^2 = 0.136 \pm 0.006$ we deduce the ratio $X = 0.024 \pm 0.001$, using for the K-conversion coefficient of the $0_2^+ \rightarrow 2_1^+$ transition the theoretical value from Ref. [9].

In order to determine the value of $\rho^2(E0;0_2^+ \rightarrow 0_1^+)$, we measured the lifetime of the 0_2^+ level by means of the Doppler shift attenuation method in gases [10,11]. The measurement was performed at LNL (Padua). The 0_2^+ level was populated via inelastic proton scattering on a 94.4% enriched sample of ^{78}Kr at a beam energy of 6.5 MeV. The gas was contained in a 0.1 cm^3 chamber having a thin nickel window [12]. The centroid energy of the 562 keV, $0_2^+ \rightarrow 2_1^+$ gamma ray was measured for eleven different pressure value in the range $(1-50) \times 10^5$ Pa. By performing an analysis based on the procedure given in detail in Ref. [1], we deduced for the lifetime of the 0_2^+ level the value $\tau = (11 \pm 3)$ ps, which translates in the reduced $E2$ transition probability

$$B(E2;0_2^+ \rightarrow 2_1^+) = 0.13 \pm 0.04 \quad e^2\mathrm{b}^2 .$$

We then found from the X and τ values

$$\rho^2(E0;0_2^+ \rightarrow 0_1^+) = 0.047 \pm 0.013 .$$

In Table I the new data on the 0_2^+ level in ^{78}Kr, together with previous data on ^{80,82}Kr [1,13,14], are compared with the predictions of the IBM-2 model calculated for the same set of parameters given in Ref. [1]. It is seen that the decay properties of the 0_2^+ state in ^{78}Kr are well reproduced, thus strengthening our belief that also for this state there is no need to invoke configurations lying outside the model space. Particularly noteworthy is also the fact that the model correctly reproduces the value of $\rho^2(E0;0_2^+ \rightarrow 0_1^+)$ which increases by a factor of about 5 from ^{82}Kr to ^{78}Kr.

We plan to extend our measurements to ^{76}Kr and possibly to ^{74}Kr for which there is some suggestion that the first excited 0^+ state might be more spherical than the ground state [15].

Besides studying the decay of the 0_2^+ state, we measured, by means of the NPG (normalized peak to gamma) method [16], the K-internal conversion coefficients of several transitions deexciting levels for which no definite assignment of spin and parity exists in the literature. The 455 keV, $2_1^+ \rightarrow 0_1^+$ transition was used as reference line for the NPG method. In a few cases it has been necessary, in order to avoid the overlap in energy of internal conversion lines pertaining to different transitions, to exploit the different half lives of the ground ($T_{1/2} = 17.7$ min) and isomeric level ($T_{1/2} = 5.7$ min) in ^{78}Rb, by stopping the ion collection and inserting appropriate "waiting" times before spectra recording. The experimental results, together with other relevant quantities, are reported in Table II. The information available previous to this work on spin and parity of initial levels [5] is given in the second column. Theoretical K-conversion coefficients [9] are reported only for $E1$, $M1$, and $E2$ multipolarities since, in the given energy range, the values of α_K for $M2$ and higher multipolarities are at least a factor of 2 larger. Parity and range of possible spin values deduced directly from the measured values of α_K are reported in column 9(a). Further restrictions on spin values arising from (a) the observed gamma decay, (b) the logft values from the ground state ($J^\pi = 0^{(+)}$) and isomeric state ($J^\pi = 4^{(-)}$) of ^{78}Rb (as reported in Ref. [17]) lead to the adopted assignments given in column 9(b). As to point (b), we observe that the logft values [17] from the $J=0$ and the $J=4$ states of ^{78}Rb to the 2_2^+ and 2_3^+ states allow one to assign negative parity to both

TABLE I. Experimental values of $B(E2)$ (in $e^2\mathrm{b}^2$) and $\rho^2(E0)$ in $^{78,80,82}\mathrm{Kr}$ are compared to the theoretical ones, calculated with the Hamiltonian parameters of Ref. [1]. For the quadrupole and monopole effective charges the values $e_\pi = 0.075$ e b, $e_\nu = 0.090$ e b and $\beta_{0\pi} = 0.10$ e fm^2, $\beta_{0\nu} = 0.25$ e fm^2 have been used.

	$^{78}\mathrm{Kr}$		$^{80}\mathrm{Kr}$		$^{82}\mathrm{Kr}$	
	Expt.	Theor.	Ref. [1]	Theor.	Refs. [13,14]	Theor.
$B(E2;0_2^+\rightarrow 2_1^+)$	0.13(4)	0.09	0.07(3)	0.07	0.030(10)	0.055
$\rho^2(0_2^+\rightarrow 0_1^+)$	0.047(13)	0.064	0.021(9)	0.032	0.008(3)	0.014

TABLE II. Experimental values of the K-internal conversion coefficients (in units of 10^{-4}) for the specified transitions are compared with the theoretical values for $E1$, $M1$, and $E2$ transitions. In column 9(a) parity assignment and restriction on possible spin range based only on the values of α_K are reported. Final spin-parity assignment are given in column 9(b) (see text).

E_{level}	J_i(Ref. [5])	E_γ	J_f(Ref. [5])	$\alpha_K^{\mathrm{expt.}}$	$\alpha_K^{\mathrm{theor.}}(E1)$	$\alpha_K^{\mathrm{theor.}}(E2)$	$\alpha_K^{\mathrm{theor.}}(M1)$	J_i (present work)	
								(a)	(b)
1017.2	0_2^+	562.1	2_1^+	1.99(6)	6.50	20.0	14.7		
1147.9	2_2^+	1147.9	0_1^+	3.27(15)	1.47	3.20	3.13		
		692.9	2_1^+	11.6(3)	4.07	11.1	9.20		
1755.9	(2_3^+)	1300.8	2_1^+	2.26(16)	1.18	2.45	2.40	2_3^+	2_3^+
		738.7	0_2^+	9.43(48)	3.55	9.38	7.99		
		636.2	4_1^+	14.5(23)	4.90	14.0	11.1		
		607.9	2_2^+	15.6(26)	5.43	16.0	12.3		
1772.9	$(1,2^+)$	1317.9	2_1^+	2.06(66)	1.15	2.39	2.36	0^+-4^+	$1^+,2^+$
1872.9	4_2^+	1417.9	2_1^+	1.90(35)	1.02	2.06	2.05		
		753.4	4_1^+	8.89(22)	3.40	8.91	7.65		
2234.2		1779.1	2_1^+	1.53(37)	0.718	1.34	1.35	0^+-4^+	0^+-4^+
2240.7	$(1^+,2^+)$	1785.6	2_1^+	2.9(10)	0.714	1.33	1.34	1^+-4^+	$1^+,2^+$
2299.8	5_1^+	1180.5	4_1^+	3.04(49)	1.40	3.03	2.95		
2413.4		1265.6	2_2^+	2.40(14)	1.23	2.60	2.56	1^+-4^+	2^+-4^+
		848.6	3_1^+	6.6(17)	2.65	6.59	5.92		
2443.4	$(1,2^+)$	1988.2	2_1^+	3(1)	0.609	1.10	1.11	0^+-4^+	$1^+,2^+$
		1295.4	2_2^+	2.30(33)	1.18	2.48	2.45		
		687.5	(2_3^+)	11.4(30)	4.14	11.4	9.35		
2573.3		1425.6	2_2^+	1.10(26)	1.01	2.03	2.03	1^--3^-	1^--3^-
2677.6	(3,4)	1529.8	2_2^+	0.85(23)	0.901	1.77	1.77	1^--3^-	3^-
2764.1	(4^-)	1644.6	4_1^+	0.826(69)	0.806	1.55	1.55	$3^-,4^-$	$3^-,4^-$
		1199.3	3_1^+	1.32(5)	1.36	2.93	2.86		
2999.4		1879.9	4_1^+	0.73(28)	0.662	1.22	1.22	3^--5^-	3^--5^-
3064.6	$(4^+,5,6^+)$	1086.8	6_1^+	1.58(27)	1.63	3.65	3.51	5^--7^-	5^-
3105.4	(3,4,5)	1232.4	4_2^+	1.31(10)	1.29	2.76	2.71	3^--5^-	3^--5^-
		341.3	(4^-)	50.8(58)	23.9	96.5	47.6		
3161.2	(3,4)	2013.3	2_2^+	0.537(74)	0.598	1.08	1.08	3^-	3^-
		1288.4	4_2^+	1.46(17)	1.20	2.51	2.47		
3233.6	(3,4,5)	2114.1	4_1^+	0.527(71)	0.556	0.987	0.991	$3^-,4^-$	$3^-,4^-$
		1668.6	3_1^+	0.83(43)	0.789	1.51	1.51		
		1360.6	4_2^+	0.62(23)	1.09	2.23	2.22		
3361.1	$(3^-,4,5)$	611.4	5_1^-	12.1(5)	5.36	15.7	12.1	4^--6^-	4^--6^-
3669.2	$(3,4,5^-)$	1270.2	3_1^-	2.38(14)	1.23	2.58	2.54	1^--5^-	3^--5^-
		1096.0		3.25(33)	1.60	3.58	3.45		
3725.4	$(3,4^+)$	1852.6	4_2^+	1.17(21)	0.676	1.25	1.27	2^+-4^+	2^+-4^+
		1326.5	3_1^-	1.30(26)	1.14	2.36	2.33		
3774.7	(3,4)	1375.6	3_1^-	1.93(12)	1.07	2.19	2.17	1^--5^-	3^-

states, on the basis of the rules given in Ref. [18]. This assignment in turn implies a restriction, based on the observed log*ft*, on possible spin values of several levels in ^{78}Kr.

To give an idea of the overall consistency of the data, some experimental values of α_K for transitions having known multipolarity are also reported in Table II. Altogether, the conversion coefficients allow us to assign the parity of about twenty levels and to set significant restrictions on their spins. Particularly important is the definite assignment of $J^\pi = 2^+$ to the 1756 keV level, which is therefore the third excited state of such a spin. We recall that in the U(5) and O(6) limit of the IBM-2 model the first mixed symmetry state is predicted to have $J^\pi = 2^+$ and that in some nuclei having a structure close to these limits the largest mixed symmetry component has been found in the 2_3^+ level [19–22]. The 1756 keV level, which decays to the triplet 0_2^+, 2_2^+, 4_1^+ but also to the 2_1^+ and 0_1^+ states [5], shows properties compatible with a large mixed symmetry component [23].

Noteworthy is also the negative parity assignment to the 2764 keV level, which has been considered as the head of a negative parity band [24].

As to the $2_2^+ \rightarrow 2_1^+$ transition, from the value of α_K and of the mixing ratio $\delta(E2/M1) = 0.5 \pm 0.1$ [5], it is possible to deduce the value 0.90 ± 0.37 for the intensity ratio $q^2 = I_K(E0;2_2^+ \rightarrow 2_1^+)/I_K(E2;2_2^+ \rightarrow 2_1^+)$ of the $E0$ to $E2$ component of the K-conversion transition. This translates into a value 0.39 ± 0.16 for the ratio $X = B(E0;2_2^+ \rightarrow 2_1^+)/B(E2;2_2^+ \rightarrow 2_1^+)$.

As a byproduct, we also measured the K-conversion coefficients of several transitions in ^{78}Kr which have not yet been positioned in the decay scheme. These data, not reported here, could be useful when γ-γ coincidence measurements will be performed.

Finally, we determined the K-conversion coefficient of the 103 keV transition, which shows the same lifetime as the isomeric 4^- state in ^{78}Rb and presumably populates the ground state of this nucleus [17]. From the value $\alpha_K = (70 \pm 10) \times 10^{-4}$, we deduce an $E2$ multipolarity for this transition, leading to the assignment $J^\pi = 2^-$ for the hypothetical level lying 103 keV above the ground state of ^{78}Rb. The long lifetime of the isomeric level could possibly be explained (as suggested in Ref. [17]) by its excitation energy being very close to that of the 103 keV level.

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