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Internal conversion in highly stripped ^{83}Kr ions

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The total decay probabilities per unit time of the first excited 9.4-keV state in ^{83}Kr have been measured in ions of ionicity q from 28 to 32. Using a γ-decay probability per unit time of $0.255(2)\times10^{6}$ s^{-1} gives internal conversion coefficients of 14.6(11), 14.9(10), 14.1(9), 14.6(11), and 15.2(24) for $q=28$–32, respectively. These values are compared with theoretical predictions.

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The transition probability per unit time for the decay of a nuclear level via internal conversion, $\lambda_{\rm IC}$, depends on the electron environment of the nucleus. For example, inner-shell conversion in highly charged ions can change appreciably as electrons are successively removed from the ion. Magnetic dipole ($M1$) transitions are especially sensitive to this effect since the internal conversion (IC) depends strongly on the electron density at the nucleus. Hence, measurements of $\lambda_{{\rm IC},q}$, the internal conversion rate in an ion with charge state q, can provide good tests of theoretical electron wave functions if the electron configuration in the ions is known. Conversely, if one assumes that the internal conversion coefficients, α_q, can be calculated to an accuracy of better than 1–2 %, measurements on beams of ions with ionicity q can provide information on the electron configurations present in the beam.

An experimental method that identifies charge-changing events during passage of ion beams through a magnetic spectrometer has recently [1] been used to determine $\lambda_{{\rm IC},q}$ for the 14.4-keV isomer in ^{57}Fe. This paper reports measurements made using the same technique on the 9.4-keV isomer in ^{83}Kr. The isomer is the first excited nuclear state and decays to the ground state with a predominantly $M1$ transition. The ratio of the intensity of the electric quadrupole component in the transition to the $M1$ component is $1.7(2)\times10^{-4}$ [2], and the transition is highly converted. In the neutral atom the lifetime of the 9.4-keV state has been measured [2] to be 147(4) ns, and the coefficient α_0 has been deduced [2] to be 19.5(15), with about 85% of the conversion in the L shell.

A beam of ^{83}Kr with energy 650 MeV, provided by the superconducting ATLAS accelerator at the Argonne National Laboratory, bombarded a Au target of thickness 300 μg cm^{-2}. Secondary scattered beams were observed at laboratory angles of 25° and 30° to the beam direction. These angles were forward of the grazing angles for nuclear collisions and no exchange of nucleons took place. The secondary beams consisted of ^{83}Kr ions with most of the nuclei in the ground state but with a few percent in the 9.4-keV isometric state. The secondary beams were accepted and analyzed by an Enge magnetic spectrometer [3]. The numbers of excited nuclei decaying during passage through the spectrometer were deduced from the pattern of events in the spectrometer focal plane. Figure 1 shows the position distribution of ^{83}Kr ions along the focal plane. The large peaks are due to ions of different charge states q that traverse the magnet without charge change ($\Delta q=0$). In between these peaks are events corresponding to internal conversion decays of the isomers in the spectrometer. These decays increase the ion's charge by $\Delta q=+1$, and the position of such an event in the focal plane depends on where the IC decay occurred.

The focal plane distributions observed in this experiment were simpler than observed in the ^{57}Fe experiment. The time to traverse the distance from target to the spectrometer entrance was long enough ($\sim$18 ns) to ensure that the ^{83}Kr ions observed with q from 28 to 33 had full K shells with the remaining electrons occupying the L shell only. Hence if an L-shell vacancy is caused by isomer decay the hole cannot be filled by Auger emission and $\Delta q=+2$ charge changes are not possible. The analysis to deduce the total decay rates λ_q for ions of initial charge q followed the procedure outlined [1] for ^{57}Fe, simplified now because of the restriction to $\Delta q=+1$ events. The position distributions were fitted by performing a multidimensional χ^2 minimization between the

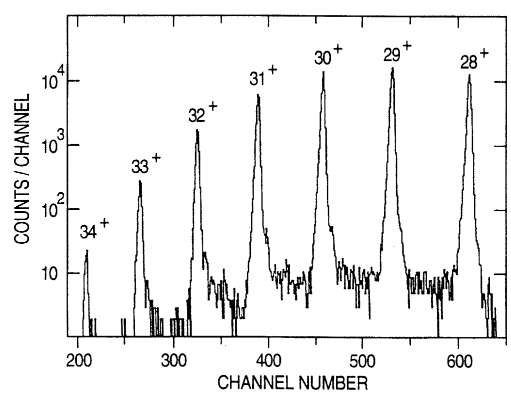

FIG. 1. The distribution of ^{83}Kr ions along the focal plane of the spectrometer, with the magnetic field set to observe ions in charge states $q=28$ to 34.

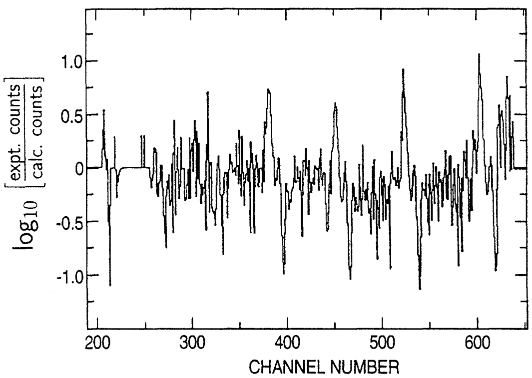

FIG. 2. The difference between the best-fit simulation and the data of Fig. 1.

spectra and Monte Carlo simulations of the experiment, which incorporated the ion-optical code RAYTRACE [4] modified to include $\Delta q = +1$ charge changes within the magnet. The fit parameters (using the notation of Ref. [1]) were the sets λ_q and N_q^0 and the fraction f_0 of nuclei exiting the Au target in the isomeric state. The γ-decay rate λ_γ of the isomer was taken to be $0.255(2)\times 10^6\ \mathrm{s}^{-1}$, as deduced from a recent lifetime measurement [5], which gave $\tau = 155(2)$ ns, and a calculated α_0 of 16.545 (see later). Figure 2 shows the difference between the best-fit simulation and the data of Fig. 1.

The results for λ_q obtained by combining the measurements made at the two scattering angles are given in Table I. These have been translated into coefficients α_q, using $\alpha_q = (\lambda_q - \lambda_\gamma)/\lambda_\gamma$ and the value of λ_γ given above. The last column of the table shows calculated L-shell IC coefficients for the electronic configurations given in the penultimate column, made using the standard formalism [6]. The bound-state electron wave functions of the different charge states q were calculated using the code GRASP [7]. The continuum electron wave functions were calculated using the code of Ref. [8]. Calculations with GRASP indicate that for $q = 28$ to 31 the ions do indeed exist in their electronic ground states, which have filled $2s$ orbits as they traverse the spectrometer; the lifetimes of excited states arising from different L-shell configurations in these ions are usually less than 10^{-11} s and none of them have lifetimes longer than a few nanoseconds. Since s electrons dominate the $M1$ IC process the agreement between experiment and calculation for the $q = 28$ to 31 ions is thus satisfactory, although the data at present are not accurate enough to probe fine details of electron distributions.

For the $q = 32$ ions the agreement of the measured α_q with the calculation for the $(1s)^2(2s)^2$ ground-state configuration is surprising. For this charge state there exist long-lived electronic states with a vacancy in the $2s$ orbit, and these should constitute a significant fraction of the $q = 32$ ensemble traversing the spectrometer. These long-lived states, described to first approximation as the $^3P_0$ and $^3P_2$ states from the $(1s)^2(2s)^1(2p)^1$ configuration, have IC coefficients much lower than that of the $(1s)^2(2s)^2{:}\,^1S_0$ ground state because of the presence of only one $2s$ electron instead of two. The last row of Table I shows the calculated value for the former configuration of the $q = 32$ ion, while the previous row gives the calculated value for the ground-state configuration. The energy-level diagram predicted by the code GRASP for $q = 32$ ions in which two electrons fill the K shell and the remaining two occupy L-shell orbits gives the $^3P_2$ state as the highest member of the ^3P triplet, with a predicted lifetime of $\sim 1.1\ \mu$s; the $^3P_0$ state is the first excited state of the $q = 32$ ion and is predicted to have a very long lifetime in an isolated ion. For the ions of interest here, a reasonable assumption to make is that the complicated processes (see, e.g., Ref. [9], and references therein) that occur during transit and on exit of the Au foil result, within about 10^{-12} s, in filled K shells, with the remaining electrons distributed statistically among L-shell states. With this assumption and using the decay patterns of the excited L-shell states predicted by the GRASP code it is estimated that more than half the $q = 32$ ions transit the spectrometer in the long-lived $^3P_{0,2}$ states. Taking the fraction in the long-lived states to be equal to one-half, the calculated α_q reduces to 11.12(10), a value that is somewhat lower than the measured value of 15.2(22). A probable explanation for this possible discrepancy is that the long-lived states are not present to the degree predicted by the simple model outlined above. It is difficult to think of mechanisms that would deplete the $^3P_{0,2}$ population in the freely moving $q = 32$ ions. Hyperfine quenching mixes the $^3P_0$, $^3P_1$, and $^3P_2$ states, thus reducing the lifetimes of the spin-0 and spin-2 members of the triplet. However, atomic-state mixing arising from the hyperfine coupling is very small and the estimated reductions in lifetimes are

TABLE I. Experimental values of λ_q, with results and predictions for the IC coefficients.

Initial charge	λ_q ($10^6\ \mathrm{s}^{-1}$)	α_q(expt.) [a]	Electron configuration	α_q (theor.) [b]
28	3.99(28)	14.6(11)	$(1s)^2(2s)^2(2p)^4$	14.43(11)
29	4.05(25)	14.9(10)	$(1s)^2(2s)^2(2p)^3$	14.24(11)
30	3.86(22)	14.1(9)	$(1s)^2(2s)^2(2p)^2$	13.56(8)
31	3.99(27)	14.6(11)	$(1s)^2(2s)^2(2p)^1$	13.63(8)
32	4.12(60)	15.2(24)	$(1s)^2(2s)^2$	14.06(12)
			$(1s)^2(2s)^1(2p)^1$	8.18(7)

[a] $\alpha_q = (\lambda_q - \lambda_\gamma)/\lambda_\gamma$, with $\lambda_\gamma = 0.255(2)\times 10^6\ \mathrm{s}^{-1}$ as evaluated using lifetime [5] and calculated IC coefficients (see text) for the neutral atom.

[b] Calculated L-shell IC coefficients (see text) for the indicated electronic configuration of ^{83}Kr ions in charge state q.

insignificant on the time scales involved in these experiments. The assumption of statistical distribution of electrons in L-shell states within $\sim 10^{-12}$ s after leaving the foil may be incorrect. The collision processes inside the foil or interactions at the foil exit may result in high-charge-state ions being preferentially produced in s orbits. There are few data on these matters and the present experiment results highlight the need for a better understanding of beam-foil interactions and the electron states present in fast, highly charged ions emerging from foils.

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[1] W. R. Phillips, J. Copnell, D. W. Banes, K. E. Rehm, I. Ahmad, B. G. Glagola, W. Henning, W. Kutschera, and J. P. Schiffer, Phys. Rev. A **47**, 3682 (1993).

[2] J. Müller, Nucl. Data Sheets **49**, 579 (1986).

[3] J. E. Spencer and H. A. Enge, Nucl. Instrum. Methods **49**, 181 (1967).

[4] S. Kowalski and H. A. Enge, MIT 1986 version of RAYATRACE (unpublished).

[5] I. Ahmad, K. E. Rehm, E. P. Kanter, W. Kutschera, and W. R. Phillips (unpublished).

[6] H. C. Pauli, K. Alder, and R. M. Steffen, in *Electromagnetic Interaction in Nuclear Spectroscopy*, edited by W. D. Hamilton (North-Holland, Amsterdam, 1975).

[7] K. G. Dyall, I. P. Grant, C. T. Johnson, F. A. Parpia, and E. P. Plummer, Comput. Phys. Commun. **55**, 425 (1989).

[8] R. Der, D. Hinnerburg, and M. Nagal, Comput. Phys. Commun. **18**, 401 (1979).

[9] H. G. Berry and M. Hass, Annu. Rev. Nucl. Part. Sci. **32**, 1 (1982).