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The ISOLDE collaboration, CERN, Geneva, Switzerland

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ABSTRACT

Lifetimes in the region of 10^{-16} s have been measured for excited states between 4 and 6.6 MeV in ^{73}Br . The states were produced by the $\beta^+(\text{EC})$ decay of a mass-separated source of ^{73}Kr , and they decayed by the emission of protons or γ -rays; their lifetimes were measured by the particle x-ray coincidence technique. The data yield information on both γ -ray and proton partial widths as well as on the level density, a level density parameter $a = 13.7 \text{ MeV}^{-1}$ is obtained. With the level widths so determined, a statistical model calculation yields excellent agreement with the delayed proton spectrum if a smooth Gaussian β -strength function is employed. It is concluded, however, that without the lifetime data, β -strength function information could not have been reliably extracted.

[RADIOACTIVITY ^{73}Kr [from ^{93}Nb (p,6p15n)]; measured β -delayed protons, E_p , I_p , pX-ray coin. ^{73}Br deduced level lifetimes, level density, β -strength function. Naturally monoisotopic target. Ge, surface-barrier Si detectors. Chem. mass separation.]

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1. Introduction

We have already reported in letter format¹⁾ on excited state lifetimes in ^{73}Br . Those measurements, which were made by the particle X-ray coincidence technique (PXCT), covered low-spin states between 4 and 6.6 MeV. Although limited somewhat by counting statistics, they indicated that the dependence of average lifetime on excitation energy is in qualitative agreement with the statistical model. It was impossible, though, to be more precise concerning the details of that dependence: whether, for example, it was smooth or exhibited features that might be attributed to local properties of nuclear structure. The only apparent anomaly lay in the observation that at lower energies the measured lifetimes seemed shorter than expected; more explicit conclusions were ruled out by the large uncertainties associated with such a low count-rate experiment.

We have now extended our measurements and also refined the theoretical calculations used in their analysis. By incorporating the new data with those published earlier, we have decreased the experimental uncertainties by more than a factor of two. This increase in precision provides a more demanding test generally of theoretical prescriptions for level lifetimes, but in particular, it confirms that lifetimes of levels at the low energy end of the observed region are indeed remarkably short. Since γ -emission predominates from levels at this energy, it is evident that γ -decay partial lifetimes must be shorter than those indicated by the simple predictions so far employed. It was these predictions, however, that led to the assumption made in previous analyses^{1,2)} of lifetime data for ^{73}Br and ^{69}As that the average γ -decay lifetime is considerably longer than the lifetime of an atomic K-vacancy, the effective reference standard in the PXCT. With this condition now seen to be blatantly violated, we have modified the calculations so that there are no longer any limitations placed on the range of allowed level lifetimes.

These improvements, both to experiment and to theory, result in excellent agreement between the two, and an extracted lifetime profile that can be viewed with considerable confidence. The results have particular significance since they apply not only to a region of excitation not normally accessible, but also to a nucleus that is itself in relatively unexplored territory, removed from the valley of stability.

2. Experimental Procedure and Results

The PXC technique for lifetime measurement depends upon the simultaneous creation of a particle-unstable nuclear state and an atomic-shell vacancy³⁾. The decay scheme used here is

where an atomic vacancy in the bromine atoms is created by the preceding electron-capture decay from ${}^{73}\text{Kr}$. States above ~ 4 MeV in ${}^{73}\text{Br}$ emit protons in their decay, so it is these states whose lifetimes we measure by observing coincidences between protons and the X-rays that signal filling of the atomic vacancy. Those X-rays that are emitted before a proton have an energy characteristic of bromine, while those emitted after are characteristic of selenium. Since the nuclear and atomic lifetimes are comparable, the coincident X-rays lie in two peaks whose relative intensities uniquely relate one lifetime with the other.

Krypton isotopes were produced in spallation reactions, with a 53 g/cm^2 niobium powder target being bombarded by a $1.4 \mu\text{A}$ beam of 600 MeV protons from the CERN Synchrocyclotron. Most of the reaction products diffused out of the target, which was held at about 2000°C , but then had to pass through a cooled (to 30°C) copper tube on the way to a plasma ion source;

thus, krypton nuclides reached the ion source while neighbouring elements were inhibited by condensation or by chemical reactions in the tube. The beam extracted from the ion source was separated into its constituent atomic masses by the ISOLDE electromagnetic isotope separator.

The beam corresponding to $A = 73$ was intercepted and the collected activity periodically moved to a counting position by the tape of a compact tape-transport system⁴⁾. There the activity was viewed in close geometry by a 200 mm² intrinsic Ge X-ray detector on one side and, on the other, a surface barrier counter telescope for proton detection. The telescope was composed of a 100 mm² x 16.5 μ m thick ΔE transmission counter and a 450 mm² x 250 μ m thick E counter. Its energy calibration was determined by use of a standard α -particle source (^{239}Pu , ^{241}Am and ^{244}Cm combined) that provided lines between 5 and 6 MeV; lower energies were related to the source lines through ratio measurements with a precision mercury pulser. The X-ray detector was energy calibrated with ^{57}Co (14.41 and 122.1 keV) and ^{241}Am (26.35 and 59.54 keV) sources.

The delayed proton spectrum observed from the decay of ^{73}Kr is shown in fig. 1a; the experimental energy resolution (full width at half maximum) is ≤ 100 keV. Based on this resolution figure, the spectrum was divided up into 100 keV intervals (300 keV at either end), and a spectrum of coincident X-rays extracted for each interval. Then ratios were taken from the relative numbers of counts in the selenium and bromine K_{α} peaks (at 11.2 and 11.9 keV), the results being plotted as a function of proton energy in fig. 1b.

3. Analysis

3.1 THEORY

The analysis of β -delayed proton decay in terms of a statistical model is by now a well-established technique with a considerable record of success in explaining observed properties^{2,5-7)}. The specific approach we shall follow here is that taken by Macdonald et al²⁾. If $I_p(E_p)$ is the intensity of protons with energy E_p , then

$$I_p(E_p) = \sum_{if} \langle I_{\beta}^i \rangle_{E_p} \left\langle \frac{\Gamma_p^{if}}{\Gamma_p^i + \langle \Gamma_{\gamma}^i \rangle} \right\rangle_{E_p} \quad (1)$$

where I_{β}^i is the intensity of β -decay from ^{73}Kr to excited state i in ^{73}Br , Γ_p^{if} is the partial width for proton emission between state i and a final state f in ^{72}Se , Γ_p^i is the total proton decay width of state i , and Γ_{γ}^i is its γ -decay width. Here $\langle \rangle$ denotes the statistical mean, and the summation is extended over all pairs of states i, f between which protons of energy E_p can be emitted.

Since I_{β}^i and Γ_p^{if} are both proportional to the squares of a nuclear matrix element, they are expected to scatter with a Porter-Thomas distribution; the fluctuations in I_p , which are evident in fig. 1a, reflect the statistical properties of such a distribution⁷⁾. It is most productive, initially at least, to ignore these fluctuations and concentrate on describing the general features of the spectrum in terms of the average behaviour of I_{β}^i , Γ_p^{if} and Γ_{γ}^i . First, we adopt the "gross theory" of β -decay⁸⁾, by using a Gaussian strength function and a modified Fermi gas model to calculate the Gamow-Teller matrix element--and hence, I_{β}^i --as a function of transition energy. That this approach is reasonable is borne out by the excellent agreement between the total β -decay half life predicted⁸⁾ for ^{73}Kr by this model (~ 30 s), and the measured value (28.6 ± 1.0 s).

Second, we express the average proton decay width of levels with spin J_i at excitation E_x in terms of the density of levels with that spin,

$\rho_{J_i}(E_x)$ and the transmission coefficient $T_\ell(E_p)$ of protons with energy E_p and angular momentum ℓ :

$$\langle \Gamma_p^{if} \rangle = \left[2\pi \rho_{J_i}(E_x) \right]^{-1} \sum_{\ell} T_\ell(E_p) \quad (2)$$

where the sum includes all values of ℓ permitted by the spins and parities of states i and f . As before²⁾, we compute transmission coefficients using the optical model, with parameters specifically known to reproduce low-energy scattering data for medium-weight nuclei⁹⁾; and we use the level density formulas of Gilbert and Cameron^{10,11)}, who combine a Fermi gas expression at high excitations with a constant temperature representation at low.

Third, we base our prescription for Γ_γ on the El γ -ray strength function, $f_{El}(E_\gamma)$. If it is assumed that the levels of interest in ^{73}Br decay predominantly by El radiation, then

$$\langle \Gamma_\gamma^i \rangle_{El} = \int_0^U E_\gamma^3 f_{El}(E_\gamma) \sum_{I=J_i-1}^{J_i+1} \frac{\rho_I(E_x - E_\gamma)}{\rho_{J_i}(E_x)} dE_\gamma \quad (3)$$

where $U = E_x - P$, and P is the pairing gap. In ref.²⁾, the strength function was expressed as a single Lorentzian curve,

$$f_{El}(E_\gamma) = \left[3.3 \times 10^{-6} \frac{NZ}{A} \right] \frac{\Gamma_G E_\gamma}{(E_\gamma^2 - E_G^2)^2 + \Gamma_G^2 E_\gamma^2} \quad (4)$$

the resonance energy E_G and width Γ_G being estimated from values tabulated by Bartholomew et al¹²⁾ for somewhat heavier nuclei. It now turns out that the values chosen (16.0 and 5.0 MeV, respectively) are remarkably successful in reproducing recent measurements¹³⁾ of strength functions for $A = 70-90$ nuclei, so we have not needed to alter them in our present work. However, there are at least two sources of error if equation (3) is to be used for $\langle \Gamma_\gamma^i \rangle$ in equation (1): a) no account is taken of γ -transitions to states below the pairing gap, and b) multipolarities other than El are ignored.

We acknowledge these and other possible inadequacies by writing

$$\langle \Gamma_Y^i \rangle = K \langle \Gamma_Y^i \rangle_{E1} \quad (5)$$

and treating K as a constant to be determined by experiment.

In order to evaluate the decay rate of states in ^{73}Br , it is necessary to specify the decay channels available. A number of properties of the ^{73}Kr decay have been measured previously¹⁴⁻¹⁷⁾, those pertinent to the present context appearing in the scheme inset in fig. 1a. Evidently, each state populated above ~ 5 MeV in ^{73}Br can decay by proton emission either to the ^{72}Se ground state (this branch will be denoted p_0), to the ^{72}Se first excited state (p_1), or it can γ -decay to lower states in bromine. If $N_{p_0}(t)$ is the rate at which ground state protons are emitted by an individual level in ^{73}Br , then

$$N_{p_0}(t) = \frac{\Gamma_{p_0}}{\hbar} N_0 \exp \left[-(\Gamma_{p_0} + \Gamma_{p_1} + \Gamma_Y)t/\hbar \right] \quad (6)$$

where N_0 is the initial sample size and the Γ 's are partial widths for the various decay channels. To describe the p_0 decay from an unresolved group of levels, it is necessary to average $N_{p_0}(t)$ over the Porter-Thomas distributions of Γ_{p_0} and Γ_{p_1} . The result yields

$$\langle N_{p_0}(t) \rangle = \frac{\Gamma_{p_0}}{\hbar} N_0 \left[\frac{2t\Gamma_{p_0}}{\hbar} + 1 \right]^{-3/2} \left[\frac{2t\Gamma_{p_1}}{\hbar} + 1 \right]^{-1/2} \exp \left[-\Gamma_Y t/\hbar \right] \quad (7)$$

The PXC technique is to compare the non-exponential decay rate of equation (7) with the exponential filling rate for the K-shell vacancy, whose width is Γ_K ($= 2.7$ eV for bromine¹⁸⁾). In the present case, it is necessary to calculate the fraction of events ϕ in which the proton is emitted first or, in other words, the fraction of coincident x-rays that lie in the selenium peak. The calculation of ϕ is quite straight-forward but the final expression is rather complex where two proton channels are available.

For demonstration purposes we quote the result for the case where

$$\Gamma_{P_1} = 0, \Gamma_P \equiv \Gamma_{P_0} :$$

$$\phi = 1 - \left[\frac{\Gamma_K}{\langle \Gamma_Y \rangle + \Gamma_K} \right] \sqrt{\pi \beta} e^{\beta} \operatorname{erfc}(\sqrt{\beta}) \quad (8)$$

where

$$\beta = \frac{\langle \Gamma_Y \rangle + \Gamma_K}{2\langle \Gamma_D \rangle}$$

This expression replaces equation (7) in ref.²⁾, which was valid for

$\Gamma_K \gg \Gamma_Y$ -- an assumption that experiment shows is no longer justified.

3.2 COMPARISON WITH EXPERIMENT

Since many parameters of this statistical model have been determined through global fitting of data, their values are at best approximate for any specific case, particularly one as far from stability as ⁷³Br. Consequently, in comparing calculations with the experimental X-ray ratios, we have optimized the agreement by treating two parameters as adjustable:

a) the factor K in equation (5); and b) the level density parameter a^{10,11).}

This has the effect of allowing variations in the magnitudes of Γ_{P_0} and Γ_{P_1} (through equation (2)) as well as in Γ_Y (mostly through equation (5), but weakly through equation (3)) without altering their functional dependence on excitation energy.

Although it is the X-ray ratio that reflects level widths most strongly, the proton spectrum shape at low proton energy is sensitive to the ratio Γ_P / Γ_Y , since its slope is determined by the rapid increase in proton widths near the Coulomb barrier. However, the proton spectrum is also influenced by other factors, such as the β -strength function, so we have chosen to adjust K and a solely based on agreement with the X-ray ratios,

leaving the proton spectrum simply as a check on the final results. The initial value chosen for K was unity, while a was set at the value ($=0.134A$) prescribed by Truran *et al*¹¹⁾. The calculations, illustrated by the dashed lines in fig. 1, do not agree particularly well with the experimental results. The solid lines in the same figure show the excellent agreement* obtained when K and a are optimized to achieve agreement with the X-ray data only; evidently the calculated spectrum shape also improves significantly. In all calculations we have taken the spin-parity of ^{73}Kr to be $5/2^+$; we did so because, overall, that gave best agreement¹⁷⁾ with the measured properties of the ^{73}Kr decay. Nevertheless, all values of $J \leq 7/2$, with either parity, yield tolerable agreement with experiment, so no unique spin determination can be claimed. By the same token, our conclusions concerning level lifetimes and densities are similarly insensitive to the specific choice of J^π .

To illustrate the effect that changes in the level widths have on the calculated X-ray ratios, fig. 2 shows curves for three different values of K --demonstrating changes in Γ_Y --and fig. 3 shows curves corresponding to different values of a --mostly affecting Γ_p . Since we are interested here in general trends, the experimental data are plotted at 300 keV intervals in order to improve statistical precision. For simplicity we only show widths for the states of one of the three spins ($J^\pi = 5/2^+$) that can be populated by β -decay from ^{73}Kr ; widths for the other states are similar. It is evident

* The proton spectrum exhibits fluctuations arising from the (Porter-Thomas) statistical behaviour of I_β and Γ_p ; these cannot, of course, be reproduced in detail by our calculations, which strive only for agreement with the average behaviour. On the other hand, any fluctuations in the X-ray ratio data would arise from Γ_p alone, and are expected to be less than the size of the data points in fig. 1b. Thus, detailed agreement with those data can be sought, and a χ^2 derived.

that the data provide stringent constraints on the parameterized level widths, and that good agreement is obtained for the widths represented by solid lines in figs. 2 and 3. The optimized parameters, $K=8.5$ and $\underline{a}=0.187$ A, yield $\chi^2=4.6$ when the calculated X-ray ratios are compared with experiments in fig. 2a or 3a; if the calculation is considered a two-parameter fit, then this χ^2 corresponds to a confidence level of 50%. Uncertainties in the individual parameters (at the 10% confidence level) are certainly less than $\pm 20\%$ for K and $\pm 10\%$ for $\underline{a}$. The curves in fig. 1 were also calculated with these parameters.

Lifetime data for the β -delayed proton decay of ^{69}Se have also been obtained²⁾ by the PXCT, although the counting statistics were poorer than in the present work. Since ^{69}Se is, like ^{73}Kr , a member of the $T_z=\frac{1}{2}$ family of precursors¹⁵⁾ its properties must be closely related to those of ^{73}Kr . It is, therefore, a revealing test for the validity of the parameters determined here to see if they are as successful in reproducing the ^{69}Se data. The results are shown in fig. 4. Evidently the agreement with the proton spectrum is at least as good as that shown in fig. 1 for ^{73}Kr . The agreement with the X-ray data is adequate, though not as good, with $\chi^2=13.3$ and a confidence level of 5%. This indicates the need for a slightly higher value of $\underline{a}$, but a small change in level density from one nucleus to the next would not be surprising. In short, the ^{69}Se data support the results of our ^{73}Kr analysis.

4. Discussion

4.1 LEVEL DENSITIES

General surveys of level densities are usually dominated by data obtained from slow neutron resonances. Not only are such data restricted

as to excitation energy but also they apply only to nuclei one neutron removed from stability. Thus, it is a useful test of the universality of level density prescriptions to compare our results on ^{73}Br with neutron resonance work in the same mass region, although it is not clear that any strong conclusions can be drawn from one such isolated case.

We obtain for ^{73}Br a level density parameter $\underline{a}=13.7 \text{ MeV}^{-1}$ ($=0.187 A$). This is certainly higher than most values observed in the region of $A\sim 70$, but not higher than all. A survey of level densities from neutron resonances¹⁹⁾ shows ^{75}Se and ^{77}Se with $\underline{a}$ -values of 14.5 and 13.1 MeV^{-1} respectively, and if data from evaporation spectra are included as well²⁰⁾, then several other cases with large values appear, ^{75}As with $\underline{a}=16.5 \text{ MeV}^{-1}$ being an example. Qualitative consistency is evident, certainly within our $\sim 10\%$ uncertainty estimate. Beyond that, one might simply encourage the measurement of level densities for other $A\sim 70$ nuclei far from stability to see if high $\underline{a}$ values are a marked trend, and if so to determine the structural significance.

4.2 GAMMA-DECAY WIDTHS

Like level-density information, γ -ray widths of highly excited states are generally known from neutron resonance work and so relate to states at the neutron separation energy in nuclei near stability. Again, reliable extrapolation to the region we have studied in ^{73}Br is questionable. However, it is instructive to use the formula of Cameron²¹⁾, which was derived to reproduce the experimental radiation widths as a function of excitation energy and atomic mass--although only at the neutron separation energy in any given nucleus. Even within this context, the formula is only approximately correct in the $A\sim 70$ region, yielding values about a factor of

two too low when compared with available neutron Γ_γ data²²⁾: for example, ^{77}Se has a calculated $\Gamma_\gamma = 147$ meV (at $E_x = 7.4$ MeV), while experiment yields ~ 240 meV. In the case of ^{73}Br at $E_x = 4.5$ MeV, the Cameron formula predicts $\Gamma_\gamma \sim 60$ meV; our results, as plotted in fig. 2b, give 200 meV at the same excitation energy. Thus, while high, our result is qualitatively equivalent to the experimental trend in this mass region.

4.3 OTHER PROPERTIES OF ^{73}Kr DECAY

The statistical model calculations described here yield predictions for two other experimental quantities. One is the fraction of delayed-particle decays populating the first excited state in ^{72}Sc , and here the agreement is excellent between experiment¹⁷⁾ (0.20 ± 0.04) and calculation (0.16) if our optimized values of a and K are used. The other quantity--the branching ratio for all proton emission from ^{73}Kr --provides a much less satisfactory comparison: a calculated 3.6×10^{-4} versus $(6.8 \pm 1.2) \times 10^{-3}$ obtained experimentally¹⁶⁾. This large a disagreement is unusual for such calculations (see e.g., refs. ^{2,7)}), and particularly when compared with the success of all other aspects of the calculation, it suggests the need to remeasure the branching ratio before any significant conclusions are drawn.

4.4 SIGNIFICANCE TO STRENGTH FUNCTIONS

In the data analysis presented here we have emphasized the determination of Γ_γ and Γ_p by our treatment of the measured X-ray ratios. The significant changes from the global prescriptions originally used for both partial widths is graphically demonstrated by the differences between the dashed and solid lines in fig. 1. Quite apart from their usefulness simply in establishing the values of Γ_γ and Γ_p , however, the X-ray data provide

important constraints on the interpretation of the proton spectrum itself. To illustrate: if there had been no other experimental evidence for the need to alter K and a , then the discrepancy between the initial calculation (dashed curve in fig. 1a) and the experimental proton spectrum could well have been interpreted instead as evidence for unexpected behaviour in I_β , the β -decay intensity. Yet by incorporating the X-ray data we can conclude from fig. 1 that, for ^{73}Kr β -decay, there is no appreciable deviation from the assumed Gaussian shape (see section 3.1) for the strength function. The shape of the β -strength function is of considerable interest²³⁾, particularly insofar as it may reflect the features of local nuclear structure, so this observation is significant. Even more significant is the apparently inescapable conclusion that β -decay strength functions cannot generally be extracted reliably from such delayed proton spectra without corroborative X-ray data.

DEDICATION

Sven Gösta Nilsson was a pioneer in using modern theory to predict the geography in unexplored regions of the nuclear chart, and he always expressed an enthusiastic interest in experiments that ventured to those regions. In the study of far-unstable nuclei, as in so many other areas of nuclear physics, the loss by his death is great. The authors, indebted to Sven Gösta Nilsson for many inspiring discussions, dedicate this paper to his memory.

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FIGURE CAPTIONS

- Fig. 1 a) Spectrum of protons observed following the decay of ^{73}Kr .
In the simplified decay scheme, which is inset, all energies are given in MeV relative to the ^{73}Br ground state.
- b) Ratio of X-rays from Se relative to those from Br, plotted as a function of coincident proton energy. The smooth curves in (a) and (b) are the results of calculations described in the text: $\underline{a} = 0.187 \text{ A}$ and $K = 8.5$.
- Fig. 2 a) Measured X-ray ratios for ^{73}Kr plotted in 300 keV intervals as a function of coincident proton energy. The curves are calculated ratios corresponding to level widths shown in (b).
- b) Total level widths, Γ , calculated according to prescriptions described in the text. In all cases the level density parameter $\underline{a}$ was taken to be 0.187 A ; for the dashed curve $K = 3.0$, for the solid curve $K = 8.5$, and for the dot-dashed curve $K = 14.0$. The dotted curve shows the partial γ -decay width, Γ_{γ} , for the case with $K = 8.5$.
- Fig. 3 a) Measured X-ray ratios for ^{73}Kr plotted in 300 keV intervals as a function of coincident proton energy. The curves are calculated ratios corresponding to level widths shown in (b).
- b) Total level widths, Γ , calculated according to prescriptions described in the text. In all cases, $K = 8.5$; for the dashed curve, the level density parameter $\underline{a} = 0.220 \text{ A}$, for the solid curve $\underline{a} = 0.187 \text{ A}$, and for the dot-dashed curve $\underline{a} = 0.172 \text{ A}$.

- Fig. 4. a) Spectrum of protons observed following the decay of ^{69}Se .
- b) Ratio of Ge X-rays relative to those from As plotted as a function of coincident proton energy. The data are from ref. 2); the smooth curves are the results of calculations with the parameters equivalent to those used in fig. 1 for ^{73}Kr decay.