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EXCITED STATE LIFETIMES IN ^{73}Br MEASURED
BY THE PARTICLE X-RAY COINCIDENCE TECHNIQUE

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ABSTRACT

The 10^{-16} -second lifetimes of proton unstable states in ^{73}Br have been measured by using the particle X-ray coincidence technique. Comparison with statistical model calculations shows no significant evidence of lifetime anomalies that might be attributed to local properties of nuclear structure.

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The measurement of excited state lifetimes in the region of 10^{-16} seconds has only been accomplished by two techniques, one which depends upon crystal blocking¹⁾ and another which compares the time scale of a nuclear process to that of the filling of a vacancy in the atomic K-shell²⁾. The former technique is rather well established, but is also limited by the availability of suitable crystal targets. The recent development of the latter technique was consequently of some interest since it extends the range of accessible nuclei. So far, though, the states of only one nucleus, ^{69}As , have actually been studied in this way^{2,3)}. We now wish to report the measurement of a second case: ^{73}Br .

The particle X-ray coincidence technique (PXCT) depends upon the simultaneous creation of a particle-unstable nuclear state and an atomic-shell vacancy. In the present case, as with ^{69}As , this occurs in the process of β -delayed proton emission. A nucleus (with atomic number Z) that decays by electron capture to excited states in the daughter ($Z-1$) produces simultaneously a vacancy in an atomic shell. If those states are unstable to proton emission, then the energy of the X-ray emitted with the filling of the atomic vacancy will depend upon whether the proton has already been emitted (in which case the X-ray would be characteristic of a $Z-2$ element) or not (a $Z-1$ element). If the nuclear and atomic lifetimes are comparable, then for example the K_{α} X-rays observed in coincidence with protons will lie in two peaks whose relative intensities uniquely relate one lifetime with the other. For bromine, the lifetime of a K-shell vacancy is known^{4,5)} to be about 2.3×10^{-16} s.

The decay sequence under study is

Krypton isotopes were produced in spallation reactions by bombarding a 53 g/cm^2 niobium powder target with $1.4 \mu\text{A}$ of 600 MeV protons from the CERN Synchro-cyclotron. The temperature of the target was held at about 2000°C , so that most of the elements produced by

the bombardment diffused out of the target. They then had to diffuse through a cooled (to 30°C) copper tube before reaching a plasma (FEBIAD⁶) ion source; the tube had the effect of passing krypton nuclides but retaining all neighbouring elements (through condensation or chemical reactions). The beam extracted from the ion source was separated into its constituent atomic masses by the ISOLDE electromagnetic isotope separator.

The selected A=73 beam was intercepted and the collected activity periodically moved by means of a tape-transport system to a counting position. There the activity was viewed in close geometry by a 200 mm² intrinsic Ge X-ray detector and a surface-barrier counter telescope for proton detection. The telescope was composed of a 100 mm² x 16.5 µm thick ΔE transmission counter and a 450 mm² x 250 µm thick E counter. Its energy resolution and calibration were determined by use of a standard alpha source (²³⁹Pu, ²⁴¹Am and ²⁴⁴Cm combined) and a mercury pulser. The X-ray detector was energy calibrated with ⁵⁷Co and ²⁴¹Am sources.

The spectrum of delayed protons recorded from the ($t_{1/2}=28$ s) decay of ⁷³Kr is shown in Fig. 1a together with a simplified decay scheme⁷⁻⁹). The X-rays observed in coincidence with protons appear in Fig. 2. The energy resolution of the X-ray detector (FWHM ~ 350 eV) under experimental conditions is clearly sufficient to permit a complete separation between the K_α peak of Br and that of Se, which are ~ 700 eV apart. The intensity ratio of the two peaks could thus be determined directly and the results, plotted as a function of coincident proton energy, are given in Fig. 1b.

If all proton-emitting states in ⁷³Br decayed exclusively to the ground state of ⁷²Se, then the plot of X-ray peak ratios in Fig. 1b would need only relabelling in order to relate average level lifetimes with excitation energy in ⁷³Br. Such a simple interpretation was possible in the earlier work²⁾ on ⁶⁹As. However, it is known^{8,9)} that 20 ± 4% of the proton decays from ⁷³Br lead to the first excited 2⁺ state in ⁷²Se at 862 keV, so any interpretation of the ratio data in terms of level lifetimes must depend on a model to describe the distribution of proton decay widths to each final state.

A statistical model is known^{3,10,11)} to reproduce many of the observed properties of delayed proton emission with remarkable fidelity. We only outline the approach here, since the details as applied to the similar decay of ⁶⁹Se have appeared in ref. 3. The intensity I_p^{if} of an individual proton transition between a state i in ⁶⁹Br and a state f in ⁷²Se is given by

$$I_p^{if} = I_\beta^i \frac{\Gamma_p^{if}}{\Gamma_p^i + \Gamma_\gamma^i} \quad (1)$$

where $\Gamma_p^i = \sum_f \Gamma_p^{if}$. Here Γ_p^{if} is the partial width for proton emission between the two states, Γ_p^i is the total proton decay width of state i , and Γ_γ^i is its γ -decay width. In our case, where the density of states i is high ($\sim 0.2 \text{ keV}^{-1}$), the proton energy spectrum is given by

$$I_p(E_p) = \sum_{if} \langle I_p^{if} \rangle_{E_p} \quad (2)$$

where $\langle \rangle$ denotes the (Porter-Thomas) statistical mean, with the sum being extended over all states i, f between which protons of energy E_p can be emitted.

In applying equations (1) and (2) to the analysis of data in Fig. 1, we have as before^{2,3)} used a Gaussian β -decay strength function¹²⁾ to determine I_β , and a Lorentzian strength function¹³⁾, assuming only E1 radiation, for Γ_γ . The proton decay width was calculated from

$$\langle \Gamma_p^{if} \rangle = [2\pi\rho_{J_i}(E_x)]^{-1} \sum_\ell T_\ell(E_p) \quad (3)$$

where $\rho_{J_i}(E_x)$ is the density of states (at excitation energy E_x in ⁷³Br) with the same spin and parity as state i , and $T_\ell(E_p)$ is the transmission coefficient for protons of energy E_p and angular momentum ℓ . We used the level density formulas of Gilbert and Cameron¹⁴⁾ and calculated T_ℓ values using the optical model with parameters derived from low-energy proton scattering data¹⁵⁾. It was also assumed that ⁷³Kr is $5/2^-$, as are all other known (odd-A) nuclei with thirty-seven neutrons. The "end-point energy" of the proton spectrum was taken to be 3600 keV ⁷⁾.

In obtaining the calculated results, which appear as smooth curves in Fig. 1, two parameters were allowed to vary: the level density parameter¹⁴⁾ $\underline{a}$ and the absolute magnitude of Γ_γ (but not its energy dependence). Both are specified quite sensitively by the data, with the low energy behaviour of the proton energy spectrum controlling the ratio Γ_γ/Γ_p , while the X-ray ratio controls $\Gamma_p + \Gamma_\gamma$ ($= \hbar/\tau$). Since the level density (and thus, parameter $\underline{a}$) is related through Eq. (3) to the level lifetimes τ , it is most convenient to regard the value of $\underline{a}$ as an embodiment of our lifetime measurement even though it does depend upon our choice of model in the analysis. Our derived value of $\underline{a}$ for ^{73}Br is 9.8 MeV^{-1} , which compares with measured values between 10 and 12 MeV^{-1} for ^{69}As (ref. 2,3), ^{71}As and ^{73}As (ref. 16). The surveys in refs. 14,17) exhibit a range between 9 and 13 MeV^{-1} for $A \approx 70$.

For definiteness, we express the derived Γ_γ in terms of the average width at $E_x = 4.75 \text{ MeV}$ in ^{73}Br (the region in which the proton spectrum is most sensitive to Γ_γ), where we find $\Gamma_\gamma \approx 2.5 \text{ eV}$. This result is more than an order of magnitude larger than the simple El predictions, but while this is surprisingly large, other experimental evidence in the same region of mass and excitation energy^{2,3,18)} also favours rather large widths.

The calculations yield predictions for two other experimental quantities not already used in determining the two free parameters. One is the fraction of delayed particle decays populating the first excited state in ^{72}Se (0.09, compared with 0.20 ± 0.04 experimentally^{8,9)}); the other is the branching ratio for all proton emission from ^{73}Kr (1.9×10^{-4} , compared with $[6.8 \pm 1.2] \times 10^{-3}$ experimentally⁸⁾). The former constitutes reasonable agreement, while the latter disagrees with experiment by a far greater margin than is normal with such calculations (e.g. see ref 10). The discrepancy can be diminished by reducing Γ_γ to the El prediction, which increases the proton branching ratio to $\sim 2 \times 10^{-3}$. However, this is hardly satisfactory since it destroys the similarity between the calculated and experimental proton spectra, with the former being peaked to considerably lower energy.

Such a problem did not arise in the otherwise similar case³⁾ of ^{69}Se so an experimental confirmation of the ^{73}Kr branching ratio would be desirable. If the discrepancy survives a remeasurement, the PXCT data (Fig. 1b) become instrumental in pinpointing the source of the problem. To the level of the present experimental accuracy there is no incontrovertible evidence for non-statistical behaviour in the total level widths, although there is some indication at low energies - as there was²⁾ for ^{69}Se decay - of shorter lifetimes than predicted by the statistical model. Thus if there are any major anomalies that arise from local nuclear structure, we see already that they must play their role in the β -decay probabilities, and not in the level widths. More explicit conclusions must await further branching ratio measurements, and PXCT results with considerably improved counting statistics.

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FIGURE CAPTIONS

- Fig. 1: (a) Spectrum of protons observed following the decay of ^{73}Kr ; the experimental resolution (FWHM) was ~ 90 keV. A simplified decay scheme is also shown, in which 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.
- Fig. 2: Spectrum of X-rays observed in coincidence with all delayed protons from the decay of ^{73}Kr .

Fig. 1

Fig. 2