Lifetime Measurements in $^{120}$Xe

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Abstract

Lifetimes for the lowest three transitions in the nucleus $^{120}$Xe have been measured using the Recoil Distance Technique. Our data indicate that the lifetime for the $2^+_1 \rightarrow 0^+_1$ transition is more than a factor of two lower than the previously adopted value and is in keeping with more recent measurements performed on this nucleus. The theoretical implications of this discrepancy and the possible reason for the erroneous earlier results are discussed. All measured lifetimes in $^{120}$Xe, as well as the systematics of the lifetimes of the $2^+_1$ states in Xe isotopes, are compared with predictions of various models. The available data are best described by the Fermion Dynamic Symmetry Model (FDSM).

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The neutron deficient $^{120}$Xe nucleus ($Z=54$, $N=66$) lies in a transitional region where the neutrons occupy orbitals located midway between the closed shells of $N=50$ and $N=82$. The low-lying collective states of the nuclei in this region appear to be described well in the O(6) limit of the Interacting Boson Model (IBM) [1], with a clear test of the model being the measured lifetimes of these states. The first lifetime measurements in this nucleus, by Kutschera et al. at Heidelberg [2], yielded a lifetime of $\tau = 124(15)$ ps for the $2^+_1 \rightarrow 0^+_1$ transition. Subsequent measurements made at Notre Dame [3] gave a value of $\tau = 122(26)$ ps, which appeared to confirm the value of Ref. [2]. Indeed, the extensive compilation of Raman et al. [4], gives $\tau = 122$ ps as the adopted value for the lifetime of this transition. This compilation also shows a "saturation" effect of the $B(E2; 0^+ \rightarrow 2^+)$ value for the even-even Xe isotopes at mid-shell (around $N=66$). This effect has been attributed to the filling of the neutron orbitals [5] since their contribution to the total quadrupole moment is very small. This effect also has been explained in IBM-2 by incorporating Pauli spin factors into the Hamiltonian operators [6]. Very recently, however, a discrepancy has arisen over the value of the lifetimes in this nucleus, in that Dewald et al., in a series of measurements at Köln, have reported the lifetime of the $2^+_1 \rightarrow 0^+_1$ transition to be $\tau = 66(3.9)$ ps (cited in Ref. [7]), $\tau = 53(2)$ ps [8], and $\tau = 75(7)$ ps [9]. These values differ by roughly a factor of two from the earlier measurements of Refs. [2] and [3] and a direct consequence of the new value is the disappearance of the aforementioned "saturation" effect.

This paper describes our attempts to resolve this discrepancy. We have remeasured the lifetimes of states in $^{120}$Xe using the Recoil Distance Method (RDM) [9] and our new result for the lifetime of the $2^+_1 \rightarrow 0^+_1$ transition ($\tau = 64(5)$ ps) is consistent with the Köln results. Further, this result is in very good agreement with the lifetime for this state obtained in a contemporaneous measurement by Mantica et al. who used the fast-timing coincidence technique, with the nucleus $^{120}$Xe populated via $\beta^+/EC$ decay of $^{120}$Cs [10]. We have also identified the most likely reason for the earlier erroneous results. A preliminary report on these measurements has been made previously [11].

The experiment was carried out at the University of Notre Dame’s Nuclear Structure
Laboratory, using the $^{106}\text{Pd}(^{18}\text{O}, 4n)^{120}\text{Xe}$ reaction at a beam energy of 70 MeV; CASCADE calculations and a brief excitation function measurement were employed to determine the beam energy for the optimal population of the 4n channel. The target was a stretched, self-supporting, $^{106}$Pd foil of 762 $\mu g/cm^2$ thickness. It was mounted in the Notre Dame 'plunger' device, consisting of three dc actuators which are used for precision placement of the target foil with respect to a stopper foil (a stretched, self-supporting, Au foil of 2.9 $mg/cm^2$ thickness). The shortest target-stopper distance, as determined through capacitance measurements, was 18 $\mu m$. $\gamma$-ray spectra were recorded in singles mode using four Compton-suppressed HPGe detectors of the Pittsburgh $\gamma$-ray Array placed at angles of 31.3°, 90.2°, 146.5°, and -32.3° with respect to the beam direction. Data were collected for approximately 4 hours at each of 24 target-to-stopper distances, ranging from the closest attainable distance (corresponding to electrical contact) of 18 $\mu m$ to a maximum distance of 2600 $\mu m$. This gave us an effective measurable lifetime range of $\sim 2$ ps to $\geq 1$ ns.

Sample spectra for several recoil distances, taken with the detector placed at 31.3°, are shown in Fig. [1], with the corresponding recoil distance given in the upper right corner of each spectrum. The transitions of interest are labelled and the brackets mark the positions of the Doppler-shifted and unshifted peaks. Lifetime information was reliably extracted for the first three yrast transitions of $^{120}\text{Xe}$. For each transition, a set of ratios, $R_d$, defined as the ratio of the unshifted $\gamma$-ray intensity to the total intensity at recoil distance $d$, were determined. Each set of $R_d$ defined a decay curve for a given transition. All such $R_d$ curves were fitted with a combination of exponential functions and the lifetime for each level was extracted from these fits. This fitting was performed using the computer code LIFETIME [12]. In extracting lifetime information, this code allows the following corrections to be applied to the data: changes in the solid angle subtended by the detectors due to the changing ion position along the flight path; changes in solid angle subtended by the detector due to the relativistic motion of the ion; changes in the angular distribution due to the attenuation of alignment while the ion was in flight; and, slowing of the ion in the stopper material. Corrections were also made to the data to account for the detector efficiency and internal
conversion. The most significant correction made, however, was that for the effects of cascade feeding, both observed and unobserved, from higher lying states. To account for this, we assumed a two-step feeding process into each level for which the observed intensity feeding into the level was less than the observed intensity decaying out of the level. One of the feedings is from the next highest transition in the yrast cascade, while the other represents all unobserved feeding (i.e. feeding from the γ-ray continuum and non-yrast states). The relative intensities for the observed states were determined from the data collected by the detector placed at 90.2°. Initial relative intensities for the levels representing the unobserved feeding were determined by taking the difference between the observed intensity into a given level and the observed intensity out of the said level. In the fitting, then, both the lifetimes and the initial relative strengths (at t = 0) of all levels representing unobserved feeding were treated as variables to obtain the best fits to the experimental data.

The fits to the data for the $2^+ \rightarrow 0^+$, $4^+ \rightarrow 2^+$ and $6^+ \rightarrow 4^+$ transitions are shown in Fig. 2 and the lifetimes (as well as the $B(E2)$ values) corresponding to these fits are presented in Table I. Also included in Table I, for comparison, are: the previously adopted value from Ref. [2], the most recent results from Köln [8], and the results from Ref. [10]. As can be seen, our results are in agreement (within errors) with those of Ref. [7,8] and in remarkably good agreement with that of Ref. [10].

We have investigated in some detail the difference between our present result for the lifetime of the $2^+$ state and that of Refs. [2,3] and can attribute it to: (a) a more accurate treatment of the side-feeding into the ground state band; and, (b) a larger range of recoil distances (and hence flight times) covered in the present measurement. In effect, the two are related since the larger range of recoil distances was crucial in identifying the side-feeding lifetimes. Indeed, our data is best fitted by assuming a long-lived transition (of unknown origin) feeding into the $6^+$ state (or higher) with an estimated lifetime of 3500 ps. If this feeding transition were ignored in the current analysis, and only the data corresponding to the range of distances covered in Refs. [2] and [3] included in the fits, the resulting lifetime for the $2^+ \rightarrow 0^+$ transition would be $\tau \sim 130$ ps, almost identical to that of Ref. [2].
We have calculated the B(E2) values for the first few yrast states in $^{120}$Xe in the framework of the Fermion Dynamic Symmetry Model (FDSM) and the calculated values also are included in Table I. The building blocks of the FDSM are the correlated $S$ and $D$ (monopole and quadrupole) fermion pairs. This model was recently extensively reviewed [13] and thus only the salient features will be discussed here.

For the Xe isotopes, the combined neutron–proton FDSM highest symmetry is $SO^\nu(8) \times SO^\pi(8)$, and the Hamiltonian is:

$$H = -0.064S_\pi^\dagger S_\pi - 0.087S_\nu^\dagger S_\nu + 0.059P_\pi^2 \cdot P_\pi^2 - 0.010P_\nu^2 \cdot P_\nu^2 - 0.255P_\pi^2 \cdot P_\nu^2. \quad (1)$$

All the operators in Eq.(1) are defined in [13], and the strengths of the interactions of Eq. (1) are in units of MeV. In computing the $B(E2)$’s, the proton (neutron) effective charge $e_\pi$ ($e_\nu$) is fixed at 0.19 eb (0.16 eb).

The model space is restricted to the $S$–$D$ subspace in the normal-parity shells (heritage $u = 0$, corresponding to no broken pairs). Although the particles in the abnormal-parity levels are not included explicitly, they are included effectively by the constraint that there is a distribution of particles between the normal and the abnormal parity levels. The number of pairs ($N_1$) in the normal-parity levels is treated as a good quantum number and is calculated from the semi-empirical formula determined globally from the ground state spin of the odd-mass nuclei [13]. For instance, according to the semi-empirical formula, $N_{\pi 1}=3$ for $^{126}$Xe and $^{128}$Xe, while $N_{\pi 1}=4$ for $^{122}$Xe and $^{124}$Xe. This difference in neutron pair number causes the staggering of the B(E2) values with neutron number.

In Fig. 3, the xenon $B(E2; 0^+ \rightarrow 2^+)$ values as a function of the neutron number from the present work, along with the results reported in Ref. [2], Ref. [8] and Ref. [10] are shown. The calculated $B(E2)$’s for these states using the IBM-2 (with Pauli factors) [6] and the FDSM [13] are also presented in the same figure. From the figure, it is quite clear that the previously accepted experimental $B(E2; 0^+_1 \rightarrow 2^+_1)$ value for $^{120}$Xe and the inclusive systematic behavior of the $B(E2; 0^+_1 \rightarrow 2^+_1)$ values in the even-$A$ Xe isotopes can be reproduced well by the IBM-2 calculations including Pauli blocking, as was pointed out.
previously. However, when the present measurements are included, the IBM-2 calculations do show a significant deviation from the experimental value for the N=66 (\(^{120}\text{Xe}\)) case and this “deviation” appears to be contrary to the ”saturation effect” predicted by these calculations for the mid-shell nuclei. The FDSM calculations, on the other hand, reproduce the data well, not only for the specific case of \(^{120}\text{Xe}\), but also in terms of the overall trend of the B(E2) values for these isotopes in the mid-shell region. It should be pointed out, however, that in the FDSM calculations, there is a transition from the O(5) symmetry (specifically, the O(5) scheme of a O(6)-pairing Hamiltonian \cite{14}) for the heavier Xe isotopes to the O(6) symmetry for the lighter ones. This transition between group structures occurs from \(^{126}\text{Xe}\) to \(^{124}\text{Xe}\) because of the change in the particle number used in the calculations. Intuitively, this transition is due to the linear versus quadratic particle number dependence of the pairing and quadrupole-quadrupole interactions, respectively.

In summary, we have remeasured the lifetimes for the first three yrast transitions in the nucleus \(^{120}\text{Xe}\), in order to investigate a factor of two discrepancy in the measured lifetime of the lowest \(2^+ \rightarrow 0^+\) transition. Our results show an agreement with more recent measurements, which are in contrast with the previously adopted lifetime for this transition. We have determined that this difference can be attributed to the presence of a long-lived \((\tau \sim 3500 \text{ ps})\) transition feeding into the \(6^+\) (or higher) state. If the present results are taken into account, the \(B(E2; 0^+_1 \rightarrow 2^+_1)\) values for the Xe isotopes are no longer best described by the IBM-2 (with Pauli spin factors) model. Instead, the relatively new FDSM seems to model the present results rather well and, indeed, appears to best fit the overall trend of the B(E2) values in this neutron mid-shell region.

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### TABLE I. Lifetimes and associated B(E2) values for $^{120}$Xe

| E(keV) | $I_i \rightarrow I_f$ | $\tau$(ps) | B(E2)(e$^2$b$^2$) | $\tau$(ps) $^a$ | $\tau$(ps) $^b$ | $\tau$(ps) $^c$ | B(E2) (e$^2$b$^2$) $^d$ |
|--------|------------------------|-------------|---------------------|-----------------|-----------------|-----------------|------------------------|
| 323.0  | $2^+ \rightarrow 0^+$   | 64±5        | 0.36±0.03           | 124±15          | 75±7            | 64±4            | 0.36                   |
| 473.3  | $4^+ \rightarrow 2^+$   | 8.1±0.8     | 0.42±0.004          | 8.8±1.8         | 8.7±0.9         | 8.7±0.9         | 0.48                   |
| 600.9  | $6^+ \rightarrow 4^+$   | 2.5±0.3     | 0.44±0.005          | (< 5.0)         | 1.5/3.0         | 1.5/3.0         | 0.51                   |
| 701.7  | $8^+ \rightarrow 6^+$   | 2.6±0.3$^e$ | (> 0.18)            | 0.9±0.4         |                 |                 | 0.48                   |

$^a$ Ref. [2].

$^b$ Ref. [8].

$^c$ Ref. [10].

$^d$ see text.

$^e$ Lifetime of the $8^+$ level could not be separated from the side feeding lifetime. The value given is, thus, an upper limit.
FIGURES

FIG. 1. Sample spectra from the RDM data for $^{120}$Xe at the indicated recoil distances. The transitions of interest are marked by brackets.

FIG. 2. Fits to the ratios $R_d$ as a function of the recoil distance for the lowest three yrast transitions in $^{120}$Xe as obtained from LIFETIME (see text).

FIG. 3. $B(E2; 0^+ \rightarrow 2^+)$ values vs. neutron number for the Xe isotopes. The calculated values from different models are also shown superimposed.
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