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How close to the O(6) symmetry is the nucleus ^{124}Xe?

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ABSTRACT

Excited states in ^{124}Xe have been studied via the ^{12}C(^{124}Xe, ^{124}Xe*) Coulomb excitation reaction. Their population cross-sections relative to the 2_1^+ state have been determined from the γ-ray yields observed with Gammasphere. More than twenty absolute $E2$ strengths for seven off-yrast, low-spin states of ^{124}Xe have been deduced for the first time. The absolute $B(E2)$ values indicate pronounced O(5) symmetry, even for the off-yrast states with high O(5) quantum number τ, while the O(6) symmetry is substantially broken.

Symmetries offer powerful quantitative concepts in many fields of physics ranging from the formulation of the fundamental forces to the classification of many-body systems. In quantum mechanics the presence of a symmetry is related to conserved quantum numbers that can be established experimentally. Analogously, symmetry breaking is related to a situation in which the wave functions of the system contains many components with different quantum numbers. It is intriguing to study the questions when and how a symmetry dissolves on a quantitative basis. Nuclear collective excitations offer a unique quantum laboratory where this question can be studied experimentally. In nuclear physics, the three dynamical symmetries [1,2] of the Interacting Boson Model (IBM), U(5) [3], SU(3) [4], and O(6) [5] provide valuable benchmarks for the description of nuclear quadrupole collectivity at low and medium angular momenta. These three symmetries correspond to analytically solvable cases of the geometrical Bohr Hamiltonian [6] — the harmonic vibrator, the quadrupole-deformed axial rotor, and the γ-unstable rotor [7]. Such idealized cases are never exactly observed in nature. Finding nuclides with behaviours close to expectations for specific dynamical symmetries is an intriguing task because such nuclei serve as benchmarks for the evolution of nuclear collectivity [8]. However, a quantitative answer to the question to what extent a certain dynamical symmetry is preserved or broken in such benchmark nuclei requires that one measure observables that are particularly sensitive to the symmetry under investigation. It is the purpose of this Letter to study the degree of O(6)-breaking in the case of ^{124}Xe, a nucleus considered to be close to the O(6) dynamical symmetry [9].

The O(6) symmetry of the *sd*-IBM-1 is based on the chain U(6) ⊃ O(6) ⊃ O(5) ⊃ O(3) of nested sub-algebras with quantum numbers N, σ, τ, and L, respectively [1,2]. The empirical evidence for the existence of nuclei at the O(6) dynamical limit of the IBM is based on energy level patterns, branching ratios and, more convincingly, on selection rules for $E2$ transitions. Within the Con-

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sistent Q-Formalism (CQF) [10], they are such that $E2$ transitions are allowed and collective only between states with $\Delta\sigma = 0$ and $\Delta\tau = \pm 1$ [2].[1] It is the $\Delta\sigma = 0$ selection rule that is definitive of pure O(6) symmetry; the $\Delta\tau = \pm 1$ selection rule is rather ubiquitous for all nuclei between U(5) and O(6) dynamical symmetries. A nucleus exhibiting an energy spectrum and decay patterns that can be classified in terms of σ, τ, L quantum numbers and the respective selection rules is said to possess O(6) symmetry. Observation of O(6) symmetry in nuclei has first been reported in the case of ^{196}Pt [12]. This claim was based on energy level patterns and $E2$ decay branching ratios that closely follow the O(6) selections rules. It was, later on, supported by establishing a lower limit for the lifetime of the 0_3^+ state, the lowest state of the $\sigma = N - 2$ representation [13]; the resulting upper limits for the absolute $B(E2)$ values are small, in agreement with pure O(6) dynamical symmetry [13]. Another, even more extensive region of O(6)-candidate nuclei was found in the Xe–Ba–Ce region [9] around mass number $A = 130$. It has been shown that the low-spin structures of the nuclei ^{128}Xe [14], ^{126}Xe [15] and ^{124}Xe [16] manifest O(6)-like arrangements of energy levels and $E2$ branching ratios which reflect the selection rules for the $\sigma = N$ states of O(6).

On the other hand, the nuclei from the Pt and the Xe–Ba–Ce regions exhibit two systematic deviations from the exact O(6) symmetry, i.e., the smaller than expected energy staggering in the quasi-γ bands and the τ-compression effect [9]. These deviations can be accounted for by adding perturbative terms to the O(6) Hamiltonian [17]. These terms improve the description of the low-lying states with $\sigma = N$ [16]. Quantifying the degree of symmetry preservation (or breaking), introduced by such realistic symmetry-perturbing terms is not an easy task because it, ideally, requires information on absolute $E2$ transition rates, preferably between states with different O(6) quantum numbers. This crucial experimental information is either scarce [15,18,19] or often absent altogether. This is particularly true for transitions between off-yrast states, which supposedly belong to higher $\tau \geqslant 3, 4$ and lower $\sigma < N$ multiplets. Thus, due to the lack of data, a quantitative assessment of the goodness of the O(6) quantum number σ in the Xe–Ba region has not been performed to date. In this respect, the question of the extent in which the energies and the $B(E2)$ branching ratios of levels with $\sigma = N$ can serve as a unique signature for O(6)-like behaviour [20,21], especially for the off-yrast states, also remains open. To address these issues, we have measured absolute $E2$ strengths between off-yrast, low-spin states of ^{124}Xe.

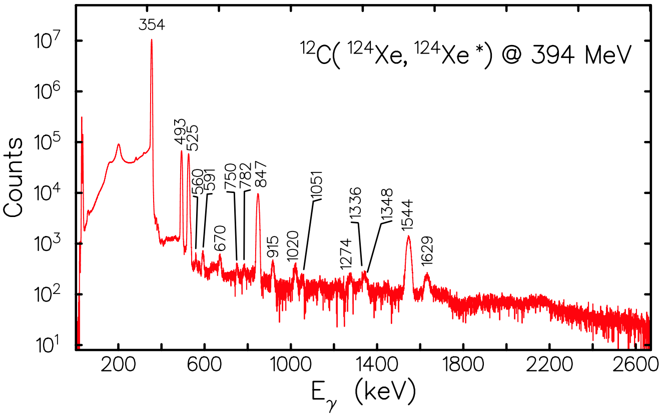

Fig. 1. (Color online.) Background-subtracted, Doppler-corrected γ-ray spectrum of ^{124}Xe observed with Gammasphere after Coulomb excitation on a carbon target. The weak transitions in ^{124}Xe are not indicated.

A Coulomb excitation experiment was carried out at Argonne National Laboratory in inverse kinematics. The ^{124}Xe beam, with intensity of ≈ 1 pnA ($\sim 6 \times 10^9$ ions/s), was delivered by the ATLAS accelerator. It was incident on a 1 mg/cm^2-thick ^{12}C target with an energy of 394 MeV. The deexcitation γ rays, following Coulomb excitation of the projectile, were detected with the Gammasphere array [22] which consisted of 98 HPGe detectors. Gammasphere was used in singles mode, resulting in an average counting rate of 8000 counts-per-second (cps), while the room background was producing about 600 cps. A total of 5.1×10^8 events of γ-ray fold 1 or higher was collected in about 12 hours. The contribution of the room background was eliminated in the off-line sort by correlating the γ rays with the accelerator radio-frequency (RF) signal. The final spectrum, which is a difference between the "beam-on" (with respect to the RF) spectrum and the "beam-off" spectrum, scaled to eliminate the 1461-keV room background transition following the decay of ^{40}K, is shown in Fig. 1. All γ rays in the spectrum originate from ^{124}Xe nuclei recoiling with $v/c \approx 6.3\%$. Most of these γ rays have already been identified in ^{124}Xe [16,23–25]. In addition, we have observed three new transitions with respective energies of 1051, 1413 and 1444 keV. About 4% of the data have γ-ray fold higher than 1. These events were sorted into a $\gamma - \gamma$ coincidence matrix. The coincidence relationships and the energy balances suggest that the 1051-keV γ ray connects the 3^- state at 1898 keV [25] to the 2_2^+ level at 847 keV. The latter two γ rays, at 1413 keV and the 1444 keV, depopulate a newly observed level at 2291 keV. The spectroscopic information is summarized in Table 1. The low-energy level scheme of positive-parity states of ^{124}Xe is presented in Fig. 2(a). It agrees well with a general *sd*-IBM-1 calculation [16] fit to energy levels and $E2$ branching ratios of ^{124}Xe (cf. Table 1 and Tables 2 and 6 in Ref. [16]). The results from this calculation are presented in Fig. 2(b).

The relative γ-ray yields with respect to the 2_1^+ state measure the relative Coulomb excitation (CE) cross-sections. The contributions from electron conversion decays to the total depopulation of the ^{124}Xe states are negligible, even for the decay of the 0_2^+ state at 1269 keV [24]. The γ-ray intensities of some transitions, unobserved in our experiment, were determined through the previously measured branching ratios in Ref. [16,24]. The experimental yields were fitted to the Winther–De Boer theory [26] with the multiple CE code CLX [27] by using the known value $B(E2; 2_1^+ \to 0_1^+) = 0.2121(54)e^2b^2$ [19] and by taking into account the energy loss of the beam in the target. The signs of the $E2$ matrix elements were chosen to be in agreement with the signs predicted by the IBM calculations [16]. Unknown quadrupole moments of excited states were varied between the extreme rotational limits, thereby introducing additional uncertainties in the deduced transition matrix elements of about 3%. Further details about the experiment and the analysis can be found in Ref. [28]. The resulting set of transition matrix elements provides the $B(E2)$ transition strengths: those are presented in Table 1.

The energy levels of ^{124}Xe with positive parity appear to form a pattern typical for O(6) symmetry (see Fig. 2). As noted in Ref. [16], for each eigenstate with O(6) quantum number $\sigma = N$ a corresponding nuclear state can be found up to O(5) quantum number $\tau = 5$ and angular momentum $10\hbar$, while the 0_3^+ and 2_4^+ states form a structure that resembles the bottom of the excited O(6) family with $\sigma = N - 2$. Therefore, it is reasonable to check whether the data on absolute $E2$ strengths can be understood qualitatively in terms of O(6) ($\Delta\sigma = 0$) and O(5) ($\Delta\tau = \pm 1$) selection rules.

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[1] The O(6) selection rules depend also on the choice of the $E2$ operator. In its most general one-body form $T(E2) = e(s^+\tilde{d} + d^+s + \chi_{E2}[d^+\tilde{d}]^{(2)})$, the $E2$ operator also generates transitions between states with $\Delta\tau = 0, \pm 2$ and $\Delta\sigma = 0, \pm 2$ [11].