ANGULAR DISTRIBUTIONS OF γ RAYS FROM ^{210}Bi PRODUCED IN ^{208}Pb+^{208}Pb DEEP-INELASTIC REACTIONS*

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The high-spin yrast structure of the ^{210}Bi nucleus was investigated using γ-ray coincidence spectroscopy following deep-inelastic reactions in the ^{208}Pb+^{208}Pb system. Cascades of γ rays following the decay of a new isomer were identified. Spin-parity assignments to the states known from previous studies as well as to newly located excitations were made based on the measured angular distributions of γ rays combined with a transition conversion coefficient analysis.

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1. Introduction

The ^{210}Bi nucleus is a one-proton, one-neutron system with respect to the doubly-magic ^{208}Pb core. Its ground state has spin-parity $J^\pi = 1^-$ and belongs to a fully-identified multiplet of states that originate from $\pi h_{9/2}\nu g_{9/2}$ couplings [1]. The member of this multiplet with maximum spin, $J^\pi = 9^-$, lies at 271 keV in excitation energy and is a long-lived, α-decaying isomer ($T_{1/2} = 3.04\times10^6$ y). Proton–neutron multiplets $\pi h_{9/2}\nu i_{11/2}$ and $\pi f_{7/2}\nu g_{9/2}$ have been identified in this nucleus as well [2]. The known yrast structure of ^{210}Bi also includes states arising from core excitations. They were traced up to 4595 keV [3] and an angular momentum of approx. 16 $\hbar$, although spin-parity assignments to those levels are uncertain.

In this contribution, we report on an effort to extend information on the high-spin structure of ^{210}Bi. Such structure may serve as a testing ground for shell-model calculations which involve the promotion of protons and neutrons across the $Z = 82$ and $N = 126$ shell gaps.

2. Experiment

In the experiment, which was performed at the Argonne National Laboratory, USA, a ^{208}Pb beam (1446 MeV) from the Argonne Tandem Linear Accelerator System (ATLAS) was sent on a thick ^{208}Pb target and induced deep-inelastic reactions in which neutron-rich nuclei were excited up to relatively high spins. One of these intense products was ^{210}Bi. The beam, coming in bursts of ~ 0.3 ns time width, was pulsed with a 412 ns repetition rate to provide a clean separation between prompt and isomeric decays. Gamma rays were measured with Gammasphere — an array of 101 Compton-suppressed Ge detectors. Coincidence data were collected with an event trigger requiring three or more γ rays to be measured in coincidence within a 2 μs time window. The trigger signal was correlated in time with the first coincident γ ray. Each event contained energy and timing information for all Ge detectors which fired. In the analysis, conditions were set on the time parameter in order to obtain various versions of prompt and delayed (for γ rays emitted between beam bursts) γ-coincidence matrices and cubes.

3. Data analysis and results

3.1. Construction of the level scheme

Information about the structure lying above the α-decaying isomer at 271 keV was a starting point in the search for the high-spin states in ^{210}Bi. We analyzed the spectra (which covered an energy range up to 4 MeV) of prompt and delayed γ rays by requiring coincidence relationships with the known ^{210}Bi yrast transitions. As a first step, double gating in the off-beam cube on every pair of lines at 151, 398, 653, 744, 1252, 1403, and 1514 keV was made. The resulting summed spectrum, displayed in Fig. 1, showed new transitions belonging to cascades deexciting an unknown isomeric state at some higher excitation. However, the exact placement of this isomer could not be determined. A reason for this difficulty could be the presence in the deexcitation cascades of low-energy transitions which, due to their high internal conversion and low detection efficiency, remained unobserved. Only a rough estimate of the half-life of the new isomer could be obtained as 10÷100 ns.

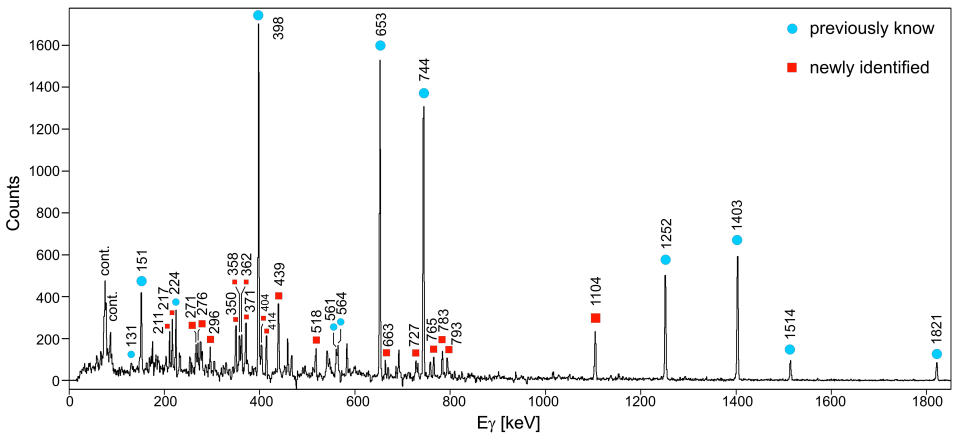

Fig. 1. Representative γ-ray off-beam coincidence spectrum for ^{210}Bi showing γ rays coincident with any of the double gates set on the 151-, 398-, 653-, 744-, 1252-, 1403-, 1514-keV transitions.

Further analysis involved also the in-beam γ-ray coincidence relationships. The detailed investigation of spectra double gated on the pairs of transitions confirmed the level scheme obtained above and resulted in the addition of new prompt lines of 371, 217, 296, 518, 783, and 663 keV, which could be used to establish levels at 4966, 5183, 5479, 5749, and 5997 keV. The ordering of these γ rays was determined by analyzing their in-beam to off-beam intensity ratio, which should decrease monotonically with excitation energy, independently of the branching ratio and detector efficiency. In particular, the existence of a 4087-keV state was confirmed by the observation of a parallel 1360-keV branch connecting it with the level at 2726 keV.

3.2. Angular distributions of γ rays

In an earlier work [4], we have shown that the spin of deep-inelastic reaction products (in the vicinity of the heavy reaction partner) exhibits an appreciable alignment in the plane perpendicular to the beam direction. This is the same situation as in fusion–evaporation reactions and, consequently, the same, well known, angular distribution formalism [5] can be applied for the transition multipolarity analysis.

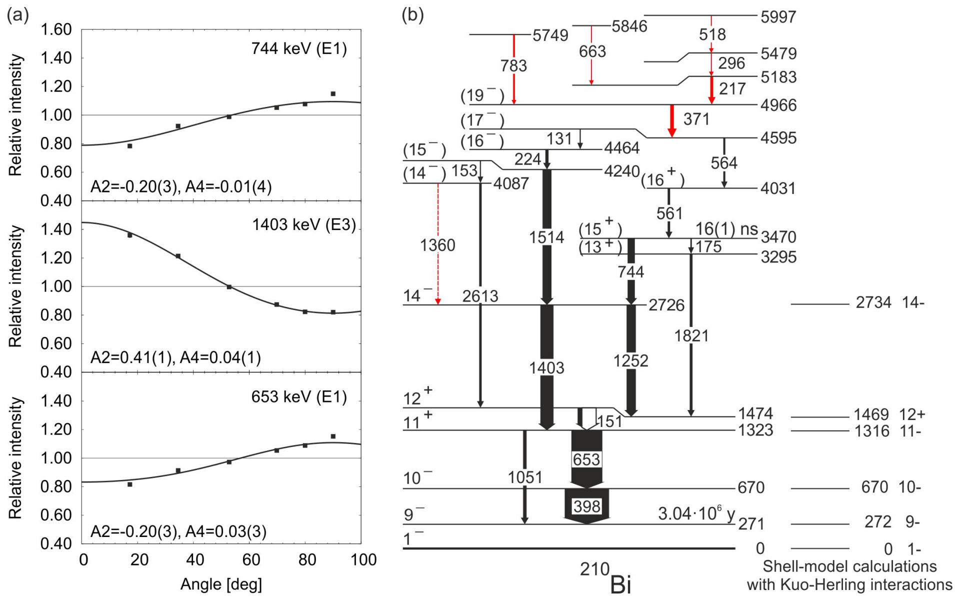

Fig. 2. (Color online) Examples of angular distribution functions (measured points and fitted curves) obtained for strong transitions (a). Yrast structure of ^{210}Bi compared with the results of a shell-model calculation (b). Transitions marked by gray/red arrows were identified in present studies. The width of the arrows indicates the observed intensity.

Each detector in Gammasphere is associated with a pair of angles (θ,ϕ) with respect to the beam direction. This allows to divide detectors into six rings around beam axis with average values of θ: 17.3°, 35.5°, 52.8°, 69.8°, 79.9°, 90.0° with equivalent rings at backward angles. The number of double γ-coincidences that was acquired during the ^{208}Pb + ^{208}Pb experiment was sufficient to carry out an analysis of the angular distribution for the strongest lines in ^{210}Bi. The gates were set on transitions in in-beam coincidence matrices and γ-ray yields detected in a specific ring were obtained. The normalized intensity of a transition can be expressed as a function of the detection angle, parametrized by A_2 and A_4 coefficients of the Legendre polynomials $P_n(\cos\theta)$

$$W(\theta) = A_0[1 + A_2P_2(\cos\theta) + A_4P_4(\cos\theta)] . \tag{3.1}$$

The angular distribution function depends on the γ-ray multipolarity (including the possibility of multipole mixing), spin-parity of the initial and final states as well as on the angular momentum alignment of the nucleus resulting from the reaction.

At first, we obtained angular distributions for pure transitions: 653 keV ($11^+ \rightarrow 10^-$) of E1 and 1403 keV ($14^- \rightarrow 11^+$) of E3 character (displayed in Fig. 2 (a)) in order to calculate the attenuation coefficient characteristic of a particular reaction. The value resulting from this analysis is 0.6(1) for the attenuation of the A_2 coefficient. This determines also the attenuation of the A_4 coefficient as 0.2(1) [6], which is in agreement with the experimental result: 0.1(1). We also observed that the attenuation coefficients do not change significantly for the remaining transitions.

The angular distribution obtained for the 744-keV line is also presented in Fig. 2 (a). The negative $A_2 = -0.20$ value indicates its pure $\Delta I = 1$ character. Investigation of the parallel 175–1821 keV cascade brought information, firstly, on the conversion coefficient of the 175-keV transition, $\alpha = 0.70(7)$, which determines its E2 character, and, secondly, on the angular distribution of the 1821-keV line which is consistent with its M1 + E2 character. These findings allowed to assign $J^\pi = 15^+$ to a 3470-keV state and, as an implication, E1 multipolarity to the 744-keV transition. Similarly, for other strong transitions, by combining information obtained from angular distributions with conversion coefficients extracted from the transition intensity balance, we assigned spin-parities to the previously known levels and some of the newly established states (Fig. 2 (b)).

The comparison of the experimental results with theoretical calculations using the modified Kuo–Herling interaction is presented in Fig. 2 (b) for the states involving promotion of a proton or a neutron to higher-lying orbitals within the valence configuration space. The maximum available spin-parity value, $J^\pi = 14^-$, results from the $\pi i_{13/2} \nu j_{15/2}$ coupling. To describe higher-lying states, the calculations must include excitations of the core.

4. Conclusions

We were able to establish spins and parities of previously identified yrast states and extend the spectroscopic information to higher excitation energy in the one-proton, one-neutron ^{210}Bi nucleus. Spin and parity assignments for known and some of the newly identified states are based on the angular distribution and conversion coefficient analysis of the relevant transitions. Excitations identified at energies up to approx. 2.7 MeV and spin 14^- can be described in terms of valence proton–neutron couplings. Higher-lying yrast states, including two isomers, one at 3470 keV with $J^\pi = 15^+$ and $T_{1/2} = 16(1)$ ns, and a second (which could not be firmly located) lying at excitation energy higher than 6 MeV, must involve neutron or proton excitations across the $N = 126$ and $Z = 82$ shell gaps, respectively. These new findings will serve as a testing ground for shell-model calculations which consider ^{208}Pb core excitations.

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