Low-Lying Configurations in ^{210}Bi†

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The configurations $\pi h_{9/2}\nu g_{9/2}$ and $\pi h_{9/2}\nu i_{11/2}$ in ^{210}Bi have been studied using the γ-ray spectra following thermal-neutron caputre in ^{209}Bi. Comparison of the experimental energies of these configurations with those calculated by Kim and Rasmussen indicates a remarkable agreement.

Since ^{210}Bi has one neutron and one proton beyond the doubly closed-shell core of ^{208}Pb, its level structure has been the object of a large number of theoretical shell-model studies (see, e.g., Kim and Rasmussen,[1] Hughes, Snow, and Pinkston,[2] Newby and Konopinski,[3] Kharitonov, Sliv, and Sogomonova,[4] and Vary,[5] and references contained therein). These studies have had to contend with the experimental fact that the ground state of ^{210}Bi has spin 1, whereas shell-model theories involving reasonable, attractive, central-force mixtures between the $h_{9/2}$ proton and the $g_{9/2}$ neutron, expected to represent the ground-state configuration, inevitably produce a 0^- ground state. Newby and Konopinski[3] and Kharitonov, Sliv, and Sogomonova[4] avoided this dilemma by assigning the 1^- ground state to the configuration $\pi g_{9/2}\nu i_{11/2}$. However Kim and Rasmussen[1] were able to interpret the 1^- ground state and the other nine low-lying states observed by Erskine, Buechner, and Enge[6] in terms of the $\pi h_{9/2}\nu g_{9/2}$ configurations by including tensor forces. This theoretical comparison required a minor reinterpretation of the experimental data[6] and required that the $\pi h_{9/2}\nu i_{11/2}$ configuration lie low enough to admix to some extent into the ground state.

The present study was undertaken to verify that the reinterpretation of the ground-state configuration of ^{210}Bi was justified experimentally and to see if the previously unknown states of higher configurations could be located, identified, and compared with theory. As our experimental study progressed, it became obvious that there was indeed a remarkable correspondence with the calculations of Kim and Rasmussen.

The spectrum of γ rays following thermal-neutron capture in ^{209}Bi was observed with the internal-target neutron-capture facility[7] at the Los Alamos Omega West reactor. Data were taken with a bare, high-resolution Ge(Li) detector (15-500 keV), with a Ge(Li) detector surrounded by a NaI anticoincidence shield (100-2500 keV), and with a Ge(Li) detector operated as a pair spectrometer by requiring the deposition of annihilation quanta in each half of the NaI annulus (2000-4600 keV). In addition, low-energy spectra in coincidence with prominent high-energy primary transitions[8] were observed with two Ge(Li) detectors each with an active volume of ~40 cm^3.

In spite of the low thermal-neutron-capture cross section, 210 γ rays were observed. Using these γ rays, a level scheme has been constructed which assigns approximately 90 % of the observed γ intensity. Figure 1 is the portion of the level scheme which contains the two lowest configurations, with the levels arranged according to spin. Those levels excited by a primary high-energy γ-ray transition in the (n,γ) reaction are shown with flags to the left whereas those levels excited in the (d,p) reaction[6] are shown with flags to the right. Transitions denoted by a small circle were observed in coincidence with high-energy γ rays from the 4^-, 5^- capture state at 4604.5 ± 0.3 keV and are therefore uniquely placed in the level scheme.

Starting with the established ground-state spin, the (d,p) reaction strengths reported in Ref. 6, and the spin restrictions implied for those levels which are populated directly from the capture state in the (n,γ) reaction, it was possible to assign approximate spin values to each of the ten low-lying states which are believed to constitute the $\pi h_{9/2}\nu g_{9/2}$ configuration. The (γ,γ) coincidence data were then used to establish with confidence the γ-ray decay branching of these lowest levels. Since dipole γ transitions are expected to dominate over those of quadrupole and higher multipolarity, the observed γ-ray branching can then be used to restrict further the spin assignments of these low-lying levels. Indeed, the γ-ray data are sufficiently complete that all energetically possible dipole transitions having energies >50 keV connecting the lowest multiplet of levels have been observed. In addition, several relatively weak quadrupole transitions have been identified. It was thus established that the lowest states constitute a complete sequence with all

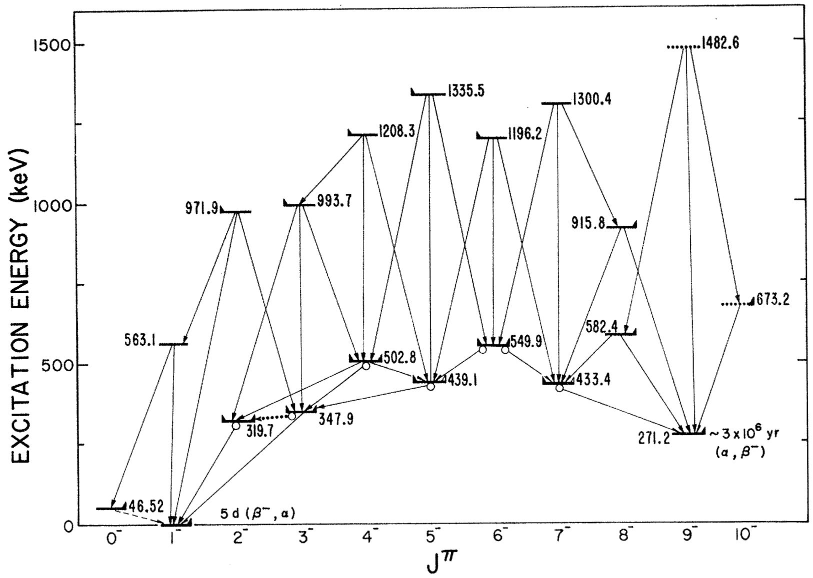

FIG. 1. A partial level scheme of ^{210}Bi. A flag to the left of a level indicates direct (n,γ) population; a flag to the right, (d,p) population (Ref. 6). Open flags represent an unresolved doublet in the (d,p) data. γ-ray transitions observed in coincidence with primary high-energy γ-ray transitions are denoted with a small circle. The dashed-line transition from the 46.52-keV 0^- state to the ground state [Ref. 9] was not observed in these experiments. The dotted-line transition between the 349.7- and 319.7-keV states was not directly observed but its existence is inferred from the coincidence data. The 9^- and 10^- assignments to the $\pi h_{9/2}\nu i_{11/2}$ configuration are the least certain, although the existence of the corresponding levels is quite definite. For this reason these levels are shown as dotted lines.

values of spin in the range 0-9 present.

Using the same approach, the spins of the higher-lying states can be defined by their γ-decay systematics. Here again the completeness of the γ-ray data simplifies the assignment of spins since, with only two exceptions, all possible dipole transitions are observed.

The level scheme of Fig. 1, which has been drawn to show the two lowest known levels of each spin value, includes *all* known levels lying below 1175 keV. Between 1175 and 1500 keV, present evidence indicates the existence of six additional levels that are not included in Fig. 1. These states are of predominantly low spin ($I \leq 5$) and presumably belong to higher configurations. We plan to present the experimental conclusions concerning these higher states, as well as a more detailed discussion of the lower states, in a full-length paper.

All ten members of the $\pi h_{9/2}\nu g_{9/2}$ ground-state configuration have been observed and placed in the level scheme. With very minor changes in energy, they agree in all respects with the interpretation of Kim and Rasmussen.[1] Thus the suggested reinterpretation of experimental data[6] is confirmed.

In addition, all ten members of the configuration $\pi h_{9/2}\nu i_{11/2}$ have been assigned. In the case of the higher-spin members (particularly spins 9 and 10), these assignments must be considered tentative. It is immediately obvious that the unusually low position of the 1^- member of the $\pi h_{9/2}\nu i_{11/2}$ configuration requires that it mix with the ground-state configuration to a greater extent than the other members of the $\pi h_{9/2}\nu i_{11/2}$ configuration. This is in part responsible for the 1^- character of the ^{210}Bi ground state as first suggested by Kim and Rasmussen.[1]

In Fig. 2 the experimental assignments for the $\pi h_{9/2}\nu g_{9/2}$ and $\pi h_{9/2}\nu i_{11/2}$ configurations are compared with the calculations of Kim and Rasmussen. It should be pointed out that there are considerable admixtures of other configurations, especially the $\pi f_{7/2}\nu g_{9/2}$ configuration, in the $\pi h_{9/2}$-$\nu i_{11/2}$ configuration. We have, however, followed the convention of Kim and Rasmussen and designated the lowest-lying state with the proper spin and parity above the ground-state configuration as belonging to the $\pi h_{9/2}\nu i_{11/2}$ configuration. In the case of the 1^- state at 563.1 keV, the calculations indicate that the state is best characterized by an almost equal mixture of the $\pi h_{9/2}\nu i_{11/2}$ and $\pi f_{7/2}\nu g_{9/2}$ configurations. In a number of cases we have tentatively located states which we believe correspond to the $\pi f_{7/2}\nu g_{9/2}$ configuration just above the $\pi h_{9/2}\nu i_{11/2}$ configuration. However,

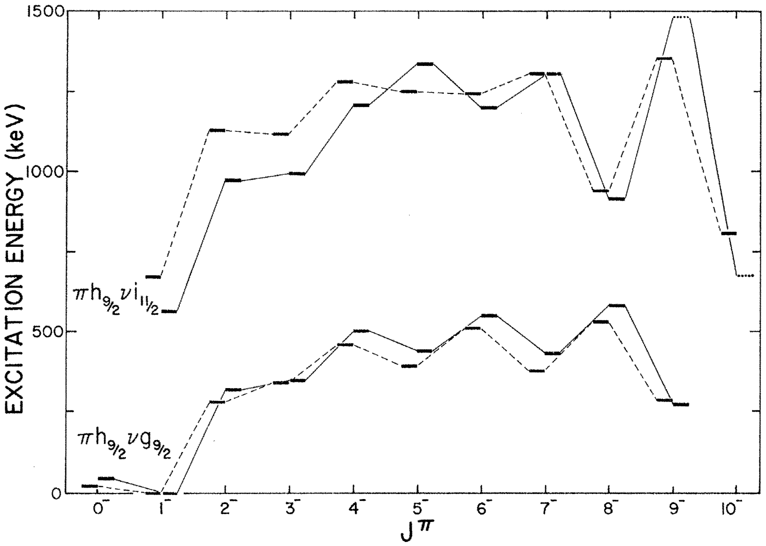

FIG. 2. Comparison of the theoretical (dashed line) and experimental (solid line) levels for the configurations $\pi h_{9/2}\nu h_{9/2}$ and $\pi h_{9/2}\nu i_{11/2}$ in ^{210}Bi. The theoretical levels are those from the calculations of Kim and Rassmussen, Ref. 1. The 9⁻ and 10⁻ members of the experimental $\pi h_{9/2}\nu i_{11/2}$ configuration are shown as dotted lines because of the uncertainty in the assignments.

the uncertainties in the spin and configurational assignments are considerably greater. Therefore these states are not presented in Figs. 1 and 2.

It is clear from Fig. 2 that the experimental observations are in excellent agreement with the calculations of Kim and Rasmussen.[1] The mean deviation $|\Delta E|$ between the energies observed and those calculated by Kim and Rasmussen is 35 keV for the ten states of the $\pi h_{9/2}\nu g_{9/2}$ configuration and 105 keV for the ten states of the $\pi h_{9/2}\nu i_{11/2}$ configuration. If the calculations of Ref. 1 are modified by the inclusion of the off-diagonal tensor-force matrix elements of Hughes, Snow, and Pinkston,[2] the value of $|\Delta E|$ for the $\pi h_{9/2}\nu g_{9/2}$ configuration becomes, for example, 18 keV. Indeed, it seems probable, since the deviations are largely systematic, that minor changes in the parameters of the theory should improve the agreement significantly. This is particularly true of the $\pi h_{9/2}\nu i_{11/2}$ configuration where a decrease in the energy difference between the zeroth order $\pi h_{9/2}\nu g_{9/2}$ and $\pi h_{9/2}\nu i_{11/2}$ configurations would clearly be beneficial.

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