Low-Lying One-Proton, Three-Neutron-Hole States in ^{206}Bi

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Precision conversion-electron and γ-ray measurements have revealed a strong $M1$ transition of 10.84 keV between the first and the second excited states of ^{206}Bi, resulting in a substantial revision of the previous decay scheme of ^{206}Po. Thus it has become possible to interpret some of the low-lying states in ^{206}Bi in terms of one-proton, three-neutron-hole configurations, in correspondence with the one-proton, one-neutron-hole multiplets in ^{208}Bi.

From various experimental and theoretical studies the excited states of ^{208}Bi are well understood in terms of one-proton, one-neutron-hole multiplets, and it is of interest to see how these multiplets are perturbed by the extra two neutron holes in the adjacent odd-odd nucleus ^{206}Bi. However, no detailed study has been performed concerning the level scheme of ^{206}Bi, except for an extensive study of the decay of ^{206}Po by the Uppsala group.[1] According to this work the parent even-even nucleus ^{206}Po ($J^\pi = 0^+$) feeds mainly the 1379.1- and 920.7-keV levels of ^{206}Bi, which decay, respectively, via three-step cascades of two $M1$ and one $E2$ transitions to the 6^+ ground state of ^{206}Bi; one should therefore assign $J^\pi \geq 2^+$ to the 1379.1- and 920.7-keV levels. This assignment, however, cannot be reconciled with the rather small experimental logft values[2] of 6.8 and 8.0, respectively, for the two levels; the experimental logft values for the second forbidden β decay are between 11 and 14. This discrepancy[3] seems to have baffled further studies of ^{206}Bi. The present paper reports the results of precision conversion-electron and γ-ray measurements in the decay of ^{206}Po, in which a consistent decay scheme has been constructed and, especially, the above-mentioned discrepancy has been removed. This leads to a reasonable interpretation of most of the low-lying states of ^{206}Bi.

The activity of ^{206}Po was produced by irradiating a bismuth target with a 39-MeV proton beam, and the sources were prepared by a selective adsorption of polonium onto a limited area of a silver foil. In order to avoid the interfering daughter radiations[4] the sources were treated periodically with hydrochloric acid to remove accumulated ^{206}Bi. The experiment consisted of high-resolution measurements of conversion-electron and γ-ray spectra with the Institute for Nuclear Studies iron-free $\pi\sqrt{2}$ spectrometer and a Ge(Li) detector, respectively. γ-γ coincidences employing two Ge(Li) detectors were also performed. Many transitions were newly detected in ^{206}Bi, and multipolarities were determined for 65 transitions from conversion coefficients and L- and M-subshell ratios. Especially, intense conversion lines were newly found in the L-Auger region of bismuth, and these were identified as a new transition of 10.84 ± 0.02 keV converted by the M, N, O, and P shells, as shown in Fig. 1(a). This transition has a total intensity of 93% per electron capture of ^{206}Po and has a pure $M1$ multipolarity [more specifically, $M1 + (8\times10^{-4}\%)E2$ from the present experimental M-subshell ratios]. In addition six pairs of transitions were observed both in conversion and in γ spectra, whose respective energy differences are consistent with 10.84 keV, as shown in Fig. 1(b). These data together with the result of γ-γ coincidences located the 10.84-keV transition between the 59.91-keV first-excited 4^+ and the newly introduced 70.76-keV second-excited 3^+ states. As a result, most of the energy and spin values of the previous level scheme of ^{206}Bi were revised; especially, the previous levels of 1379.1 and 920.7 keV with $J^\pi \geq 2^+$ were replaced by the 1389.45- and 931.70-keV 1^+ levels with logft values of 6.6 and 8.0, respectively (see Fig. 2). Thus the discrepancy mentioned above between the spin and parity assignment and the logft values has now been removed. In addition, seven new levels of ^{206}Bi were incorporated into the decay scheme of ^{206}Po. The level scheme of ^{206}Bi from the present work combined with the results of the α decay[5] of ^{210}At and the γ decay[6] of the 1042.6-keV 10^- isomer is shown in Fig. 2.

An interpretation of the levels of ^{206}Bi in terms of one-proton, three-neutron-hole configurations is indicated in Fig. 2 together with the correspondence with the levels[7,8] of ^{208}Bi. The interpretation is mainly on the spin-parity and energy basis. As is seen from the figure the low-lying

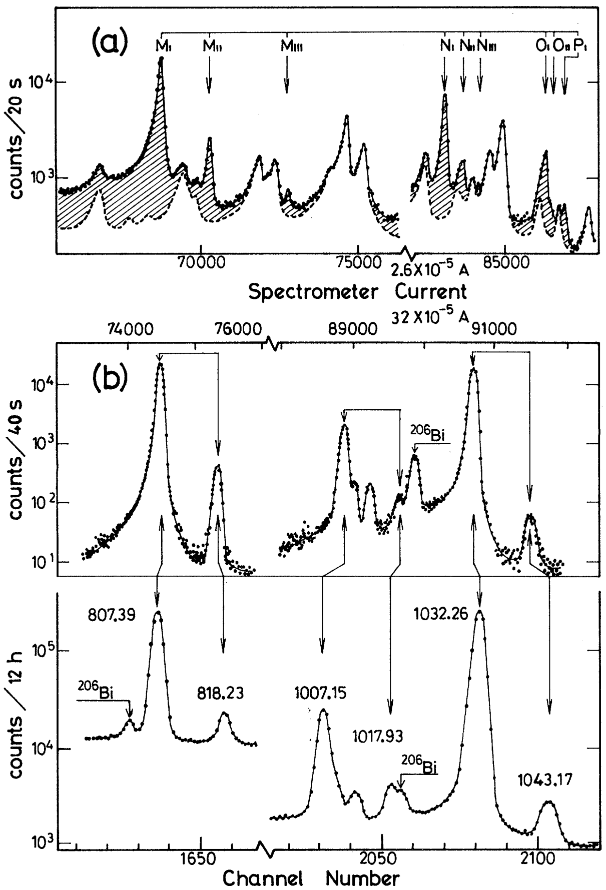

FIG. 1. (a) Conversion lines of the 10.84-keV transition from the decay of ^{206}Po observed among the L-Auger lines in bismuth. The broken line indicates the L-Auger spectrum obtained from the decay of ^{207}Po under the same experimental conditions. (b) Parts of conversion-electron (upper) and γ-ray (lower) spectra showing some of the transition pairs whose energy differences are equal to 10.84 keV within the experimental error. The transition energies are indicated in keV. The conversion spectrum was taken at an instrumental resolution of 0.1%, and the resolution of the Ge(Li) detector was 2.1 keV at 1.33 MeV. Peaks due to the daughter nuclide ^{206}Bi are also seen.

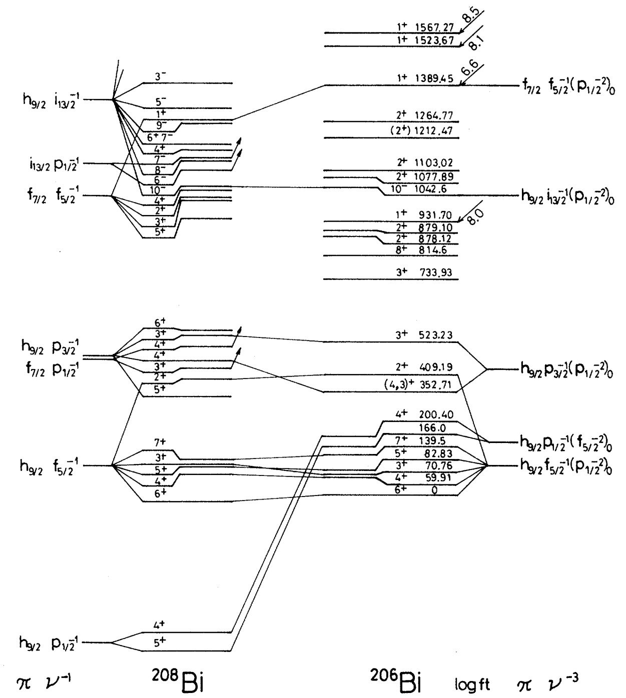

FIG. 2. Level scheme of ^{206}Bi from the present experiment combined with the results from α decay (Ref. 5) of ^{210}At (166.0-keV level) and γ decay (Ref. 6) of the 10^- isomer (1042.6-keV 10^-, 814.6-keV 8^+, and 139.5-keV 7^+ levels), in comparison with the level scheme (Refs. 7 and 8) of ^{208}Bi. The centers of gravity of the $h_{9/2}f_{5/2}^{-1}$ multiplet in ^{208}Bi and the $h_{9/2}f_{5/2}^{-1}(p_{1/2}^{-2})_{J=0}$ multiplet in ^{206}Bi are put at the same position for convenience. The error in the energy value of the levels of ^{206}Bi obtained from the present experiment is typically 0.03 keV.

levels of ^{206}Bi can be reasonably explained by assuming the proton, neutron-hole multiplets in ^{208}Bi to be little perturbed by the presence of an extra pair of neutron holes in ^{206}Bi. An exception is the relative position of the multiplet related to the $p_{1/2}$ neutron hole. The centers of gravity of the $h_{9/2}p_{1/2}^{-1}(f_{5/2}^{-2})_0$ and $h_{9/2}f_{5/2}^{-1}(p_{1/2}^{-2})_0$ multiplets in ^{206}Bi are reversed in comparison with those of the corresponding multiplets in ^{208}Bi. This is just the effect of particle-hole interchange, being affected by the pairing interaction which is stronger in the $f_{5/2}$ orbit than in the $p_{1/2}$ orbit. The same situation is observed in the odd-mass isotones of $N=123$; the $\frac{1}{2}^-$ state is always higher than the $\frac{5}{2}^-$ ground state, and the energy differences are $\Delta\epsilon = 126$, 2.3, 69, and 109 keV, respectively, for $Z=80$, 82, 84, and 86, to be compared with $\Delta\epsilon = 80$ keV for ^{206}Bi with $Z=83$. Similar energy shifts are expected for the $f_{7/2}p_{1/2}^{-1}$ and the $i_{13/2}p_{1/2}^{-1}$ multiplets, which are indicated by upward arrows in Fig. 2. Since the main configuration of the four neutron holes in ^{206}Po in its ground state is $(p_{1/2}^{-2})_0(f_{5/2}^{-2})_0$, the ground state of ^{206}Po is approximately described by

$$\Psi(^{206}\text{Po}) \approx [0.8(h_{9/2}^{\ 2})_0 + 0.4(f_{7/2}^{\ 2})_0]_\pi \times [(p_{1/2}^{-2})_0(f_{5/2}^{-2})_0]_\nu,$$

where the proton part is taken from a shell-model calculation[9] of ^{210}Po. From this wave function the allowed electron capture is most likely to feed the $f_{7/2}f_{5/2}^{-1}(p_{1/2}^{-2})_0$ configuration in ^{206}Bi via a β transition between the spin-orbit partners $\pi f_{7/2} \rightarrow \nu f_{5/2}$. Hence the $f_{7/2}f_{5/2}^{-1}(p_{1/2}^{-2})_0$ configuration is assigned to the 1389.45-keV 1^+ state, which is most strongly fed from ^{206}Po with a logft value comparable to those for the corresponding electron captures of the odd-mass Po isotopes; the logft values are 6.0 for $^{205}\mathrm{Po}(\frac{5}{2}^-) \rightarrow {}^{205}\mathrm{Bi}(1001.0$ keV, $\frac{7}{2}^-)$ and 6.6 for $^{207}\mathrm{Po}(\frac{5}{2}^-) \rightarrow {}^{207}\mathrm{Bi}(992.3$ keV, $\frac{7}{2}^-)$. Mixing of $[(f_{5/2}^{-2})_0(f_{5/2}^{-2})_0]_\nu$ and $[(f_{5/2}^{-2})_0 \times (p_{3/2}^{-2})_0]_\nu$ is expected in ^{206}Po, giving rise to electron captures to $f_{7/2}f_{5/2}^{-1}(f_{5/2}^{-2})_0$ and $f_{7/2}f_{5/2}^{-1} \times (p_{3/2}^{-2})_0$ in ^{206}Bi, but these are expected to lie close to or higher than $Q_{\mathrm{EC}} = 1.82$ MeV.

The other excited states of ^{206}Bi higher than 700 keV are hard to interpret at present. Appearance of an 8^+ state at 814.6 keV having no analog in ^{208}Bi suggests breaking of the neutron-hole pair in this energy region. Further study by other means is desirable in order to understand more fully the excited states of ^{206}Bi.

We are indebted to Professor K. K. Seth for suggesting the problem involved in the previous decay scheme of ^{206}Po.

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[3]In order to remedy this discrepancy, it was suggested in *Nuclear Data Sheets 1959-1965*, compiled by K. Way *et al.* (Academic, New York, 1966), Part 11, p. 2518, that there might be a 1^+ level just above the 1379.1-keV level or an as yet unobserved $M1$ transition in cascade with the 59.9-keV transition. The present experiment confirmed the latter of these alternatives.

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Finite-Range Calculations of the j Dependence of (^{12}C, ^{11}B) and (^{16}O, ^{15}N) on ^{62}Ni†

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Full finite-range calculations, including recoil effects exactly, have been performed for single-proton-transfer reactions on ^{62}Ni. Projectiles of ^{16}O and ^{12}C are considered. It is found that the ratios of cross sections leading to the ground and first excited states in ^{63}Cu are in good agreement with experiment. This is not true when recoil is neglected.

In a recent paper,[1] a study of the j dependence of heavy-ion–induced reactions was reported. In particular, ^{12}C and ^{16}O projectiles (at energies of 78 and 104 MeV, respectively) were used to transfer protons to states in various nuclei of $j_>$ $(j=l+\frac{1}{2})$ and $j_<$ $(j=l-\frac{1}{2})$. Kovar *et al.*[1] attempted to calculate the ratios of these cross sections by the use of the finite-range computer code RDRC[2] (which neglects recoil) and were unsuccessful. Overpredictions by factors of 2–10 were found. It was argued that the no-recoil feature of the calculations was responsible. The purpose of this Letter is to report that, indeed, the use of the exact finite-range computer code MERCURY,[3,4] which also includes recoil exactly, provides reasonable ratios for one of the targets studied (^{62}Ni).

Differential cross sections were calculated here for proton transfer to the ^{63}Cu ground state and its first excited state. These levels were assumed to be pure single-particle states with configurations $2p^{3/2}$ and $2p^{1/2}$, respectively. The distorted waves were generated by use of a volume Woods-Saxon plus Coulomb potential. The parameters characterizing the interaction are shown in Table I. The first set was found by Becchetti *et al.*[5] to match the elastic scattering of both ^{16}O and ^{12}C at forward angles and for targets in the region of the nuclei considered here. The energy, however, was 38 MeV (60 MeV) for ^{12}C (^{16}O) which is about half that used here. The second set was picked somewhat arbitrarily to test the