Observation of Low-Lying $J^\pi = 0^+$ States in the Single-Closed-Shell Nuclei $^{192-198}$Pb

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First experimental evidence for a low-lying $J^\pi = 0^+$ excited state in $^{192-198}$Pb is obtained by study of the β decay of mass-separated Bi isotopes. It is shown that such excited states correspond to deformed two-particle, two-hole configurations.

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In many odd-mass nuclei with one or three valence particles (holes) outside a single closed shell and with a maximal number of valence nucleons of the other type, intruder states occur at very low excitation energy, compared with the regular single-particle or single-hole excitations. Detailed studies on odd-mass nuclei have been carried out throughout the nuclear mass table, especially in the $Z = 50$ (Ag, In, Sb, I) and $Z = 82$ (Au, Tl, Bi) regions.[1] It was shown both experimentally and theoretically that such intruder states are mainly due to particle-hole (p-h) excitations across the closed shell.

Also, in even-even nuclei in the $Z = 50$ region, low-lying intruder states have been observed, with the $J^\pi = 0^+$ rotationallike bands in $^{112-118}$Sn as the most conspicuous examples.[2] These intruder states remain unexplained in a standard lowest-seniority shell-model calculation, where only the interaction among the valence neutrons in the $N = 50$–82 shell is considered, but rather are related to two-particle, two-hole (2p-2h) excitations across the $Z = 50$ shell.

In this Letter, we report the first observation ever of similar intruder states in neutron-deficient even-even Pb nuclei. We show that the low excitation energy of these states is due to the combined effect of (i) the pairing correlations of the 2p and 2h configurations; (ii) the proton-neutron quadrupole interaction between the valence neutrons and the "valence" (two particles and two holes) protons.

The experimental search for intruder states in even-even Pb nuclei with $N \simeq 110$ is a difficult task. The lack of suitable targets makes the use of two- and four-nucleon transfer reactions, the most direct evidence for intruder states, impossible. Heavy-ion reactions form an alternative but the deexcitation after the fusion reaction will mainly proceed via yrast states. The β^+/EC decay of even Bi isotopes also populates levels in Pb. Unfortunately, the β-decaying state in bismuth, populated in a heavy-ion reaction, has, in the region of interest, a high spin: Most intensity comes in the set of high-spin levels, already observed in-beam.[3] In the decay of ^{196}Bi, however, the intensity ratio

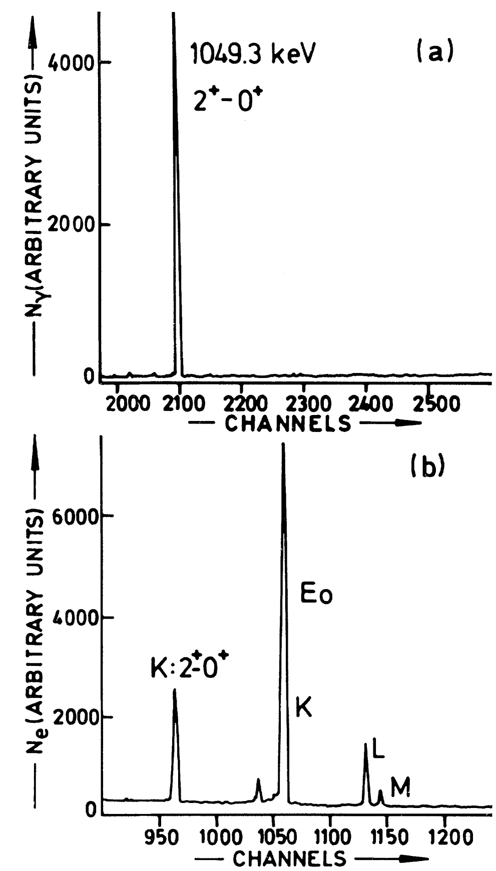

FIG. 1. Comparison between (a) the gamma, and (b) the electron spectra at mass $A = 196$.

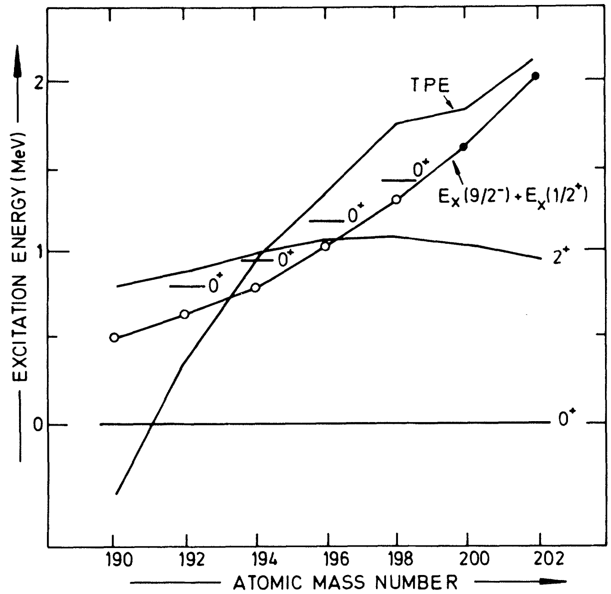

FIG. 2. The experimental energies of the $J_i^\pi=2_1^+$ and the first excited $J_i^\pi=0_2^+$ state in the Pb isotopes as a function of the atomic mass number A. Also shown are the results of the total-potential-energy calculation [Eq. (2)] and the empirical estimate [Eq. (6)]. Extrapolations (open circles) on the basis of α-decay energies of Bi isotopes are used for $A \leq 198$ in obtaining the latter curve.

$I_\gamma(4^+ \rightarrow 2^+)/I_\gamma(2^+ \rightarrow 0^+)$ drops to a value of 60%, compared to a value of 90% in the neighboring Bi nuclei.[3] This suggests the existence of a low-spin β^+-decaying state in ^{196}Bi.

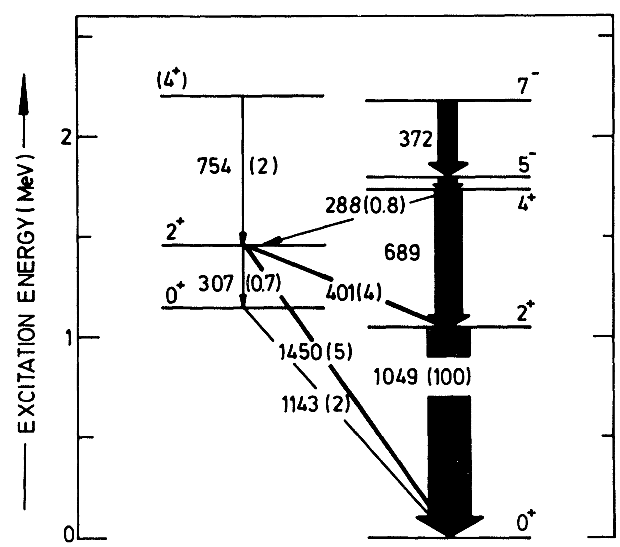

FIG. 3. A part of the ^{196}Pb level scheme. The numbers in parentheses are relative γ-ray intensities.

At the Leuven Isotope Separator On-Line (LISOL) facility (for more experimental details, see Verplanck *et al.*[4]), a systematic study of the β^+/EC decay of neutron-deficient Bi isotopes has been undertaken. The nuclei $^{192-198}$Bi were produced in the fusion reaction of (110–180 MeV) ^{16}O on the 16-mg/cm^2 $^{\text{nat}}$Re foil. After mass separation, the Bi activity was implanted on an aluminized Mylar tape and periodically transported to a detection station. Multiscaled electron, x-ray, and γ-ray spectra together with γ-γ and γ-x coincidences were taken on each mass chain from 198 to 192. The most detailed information was recorded on the mass-196 chain, where also a total of 2×10^6 e-γ coincidence events were collected.

The existence of a low-spin β^+/EC-decaying state in ^{196}Bi clearly stands out in our data. A group of γ rays with a substantially longer half-life (308 ± 6 s) than the high-spin β-decaying state

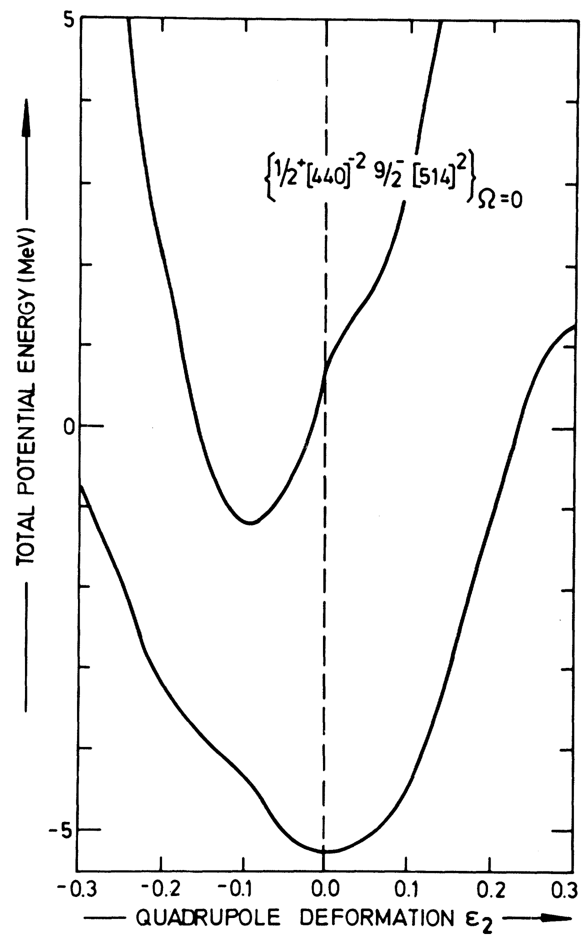

FIG. 4. Total potential energy for the ground state and for the $\{\frac{9}{2}^-[514]^2\frac{1}{2}^+[440]^{-2}\}_{\Omega=0}$ configuration in ^{196}Pb as a function of the quadrupole deformation.

(240 ± 2 s) can be placed, on the basis of x-γ and γ-γ coincidences, as transitions between low-spin ($I \leq 4$) states in ^{196}Pb. The low-spin β-decaying state in ^{196}Bi, probably poorly fed in the heavy-ion reaction, takes about 40% of the total β^+/EC ^{196}Bi decay. Internal decay of a high-spin state can explain this figure: This is supported by the observation of Bi x rays.

On the basis of the half-life (319 ± 7 s), the K to L energy and intensity difference, and the coincidence with Pb x rays an $E0$ transition of 1143.4 ± 0.2 keV is attributed to the β^+/EC decay of the low-spin state in ^{196}Bi. This, together with γ-γ and e-γ coincidences, gives evidence for an anomalous low-lying 0^+ state in ^{196}Pb only 94 keV above the first excited 2^+ state. The surprisingly low-lying 0^+ state deexcites probably completely to the ground state, giving a strong electron signal in an almost background-free region (see Fig. 1). This made it possible to observe similar $E0$ transitions in the nuclei ^{192,194,198}Pb. The corresponding 0^+ states are at 1392.0 ± 0.2 keV (^{198}Pb), 930.1 ± 0.2 keV (^{194}Pb), and 768.5 ± 0.2 keV (^{192}Pb) excitation energy, becoming for ^{194}Pb and ^{192}Pb the first excited state (see Fig. 2).

The nature of the 0^+ state is investigated in ^{196}Pb (see Fig. 3). A cascade of two strong γ rays is coincident with the $E0$ transition. The 306.9-keV γ ray establishes a level at 1450 keV, which also deexcites to the 0_1^+ ground state and the first excited 2_1^+ state. This, together with the measured conversion coefficients on these γ rays, gives a 2^+ spin and parity for the 1450-keV level. The ratio $B(E2;2_2^+ \rightarrow 0_2^+)/B(E2;2_2^+ \rightarrow 0_1^+)$ of 377 shows the strong enhancement of the $2_2^+ \rightarrow 0_2^+$ transition. The 753.6-keV γ ray, coincident with all transitions deexciting from the 2_2^+ state, gives a level at 2204 keV. The conversion coefficient [$\alpha_K = 0.011 \pm 0.001$; $\alpha_K(E2) = 0.0091$] and the lack of a competitive transition to other levels suggests that the 753.6-keV γ ray is an enhanced stretched $E2$. In conclusion, strong evidence is found for the lower part of a $\Delta I = 2$ band built upon the 0_2^+ state.

In explaining the very low excitation energy of the $J^\pi = 0^+$ excited state, one has to recall that exciting the nucleus into a spherical 2p-2h configuration costs almost twice the energy gap at $Z = 82$, i.e., $E_x \simeq 2(\epsilon_p - \epsilon_h) \simeq 7$ MeV. However, when the nucleus obtains an oblate quadrupole-deformed shape, the excitation energy is lowered when the particles are put in the strongly down-sloping $\frac{9}{2}^-[514]$ and $\frac{13}{2}^+[606]$ Nilsson orbitals above $Z = 82$ and the two holes in the strongly up-sloping $\frac{1}{2}^+[440]$ orbital. Thus, at a given deformation, the intruder configuration can become competitive with the regular configurations.

We have calculated, for the even-even Pb nuclei with $104 \leq N \leq 126$, the total potential energy in the ground state as well as the energy for the lowest deformed 2p-2h Nilsson configuration $\{\frac{9}{2}^-[514]^2 \frac{1}{2}^+[440]^{-2}\}_{\Omega=0}$, using the modified harmonic-oscillator Nilsson potential and the Strutinsky renormalization procedure.[5] We then obtain

$$E_{2p\text{-}2h}(\Omega = 0; Z = 82, N) = E(Z = 82, N) + 2E_{1qp}(\tfrac{9}{2}^-[514]; Z = 82, N) + 2E_{1qp}(\tfrac{1}{2}^+[440]; Z = 82, N), \quad (1)$$

where $E(Z = 82, N)$ denotes the ground-state energy in the even-even Pb nuclei and E_{1qp} the one-quasiparticle energy. The results for the particular nucleus $^{196}_{82}\mathrm{Pb}_{114}$ are given in Fig. 4. Here, the deformed shape of the 2p-2h state becomes clearly established. This intrinsic state cannot yet be associated with the observed $J^\pi = 0^+$ state. One still has to project out all J_π states from the intrinsic state and calculate the residual pairing interaction in the particular 2p-2h state. In the present study, we obtain an estimate of the $J^\pi = 0^+$ excitation energy by subtracting from the minimum value of the $\Omega = 0$ energy, taken relative to the spherical ground-state energy, the empirical pairing correction as deduced from tabulated proton-separation energies[6]:

$$E_x(J^\pi = 0^+; Z = 82, N) \simeq E_{2p\text{-}h}(\Omega = 0; Z = 82, N)_{\min} - E(\text{g.s.}; Z = 82, N)_{\epsilon_2 = 0} - \{[S_p(Z = 82, N) - S_p(Z = 81, N)] + [S_p(Z = 84, N) - S_p(Z = 83, N)]\}. \quad (2)$$

The terms within square brackets denote the residual pairing energy for the two holes and the two particles, respectively. These energies $E_x(J^\pi = 0^+; Z = 82, N)$ are shown in Fig. 2 and contain only the potential energy gain and the residual pairing correlations.

Since in the adjacent odd-mass Tl and Bi nuclei, the intruder orbitals $\frac{9}{2}^-[514]$ and $\frac{1}{2}^+[440]$, respectively, are known,[1] an approximate relation for the excitation energy of the $J^\pi = 0^+$ 2p-2h intruder state in the even-even Pb nuclei can be derived. The energy needed to create a 1p-1h configuration in odd-mass Tl nuclei with the odd particle moving in the $\frac{9}{2}^-[514]$ orbital is (assuming a negligible p-h interaction)

$$E_{1p-1h}(Z=81,N) \simeq E_{1qp}(\text{g.s.};Z=81,N) + E_{1qp}(\tfrac{9}{2}^-[514];Z=81,N). \tag{3}$$

Relating the ground-state one-quasiparticle energy to the odd-even mass difference, one gets, according to BCS theory,

$$E_{1qp}(\text{g.s.};Z=81,N) \simeq \Delta(Z=81,N) \simeq \tfrac{1}{2}[S_p(Z=82,N) - S_p(Z=81,N)] \tag{4}$$

and

$$E_{1qp}(\tfrac{9}{2}^-[514];Z=81,N) \simeq \Delta(Z=81,N) + E_x(\tfrac{9}{2}^-;Z=81,N). \tag{5}$$

The relations (3) to (5) can also be derived for the odd-mass Bi nuclei. The energy of the Fermi levels in both the Tl and Bi nuclei are approximately the same at the quadrupole deformation associated with the minimum in the total potential energy ($\epsilon_2 \simeq -0.10$ to -0.15) of the 1p-1h and 2p-2h configurations. Therefore, the energies $E_{1p\text{-}1h}$ can be used to obtain the unperturbed energy of a 2p-2h configuration in the Pb nuclei. Then the 2p-2h excitation energy [including the residual two-particle and two-hole pairing correlations, see Eq. (2)] becomes

$$\begin{aligned} E_x(J^\pi=0^+;Z=82,N) &= E_{1p\text{-}1h}(Z=81,N) + E_{1p\text{-}1h}(Z=83,N) - E_{\text{pairing}}(Z=82,N) \\ &= E_x(\tfrac{9}{2}^-;Z=81,N) + E_x(\tfrac{1}{2}^+;Z=83,N). \end{aligned} \tag{6}$$

This relation gives a good agreement in the Pb isotopes (see Fig. 2; a similar good agreement is obtained in the Sn nuclei).

In this Letter, we have indicated the first experimental evidence for low-lying $J^\pi=0^+$ excited states in the neutron-deficient Pb nuclei. This $J^\pi=0^+$ state even becomes the first excited state in ^{192,194}Pb. Two members of a band on top of the $J^\pi=0^+$ state were found in ^{196}Pb. We have also shown that the observed low-lying $J^\pi=0^+$ states are associated with both a large quadrupole correlation energy in the excited 2p-2h configuration and the residual pairing energy of the two particles and the two holes, separately. Thereby, the general idea of obtaining low-lying intruder states near or in single-closed-shell nuclei with a maximal number of valence nucleons of the other type is shown to be correct. Further experiments on the band structure on top of the $J^\pi=0^+$ intruder states and its dependence on the neutron number will be pursued.

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