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Solution of controversy over 1583-keV levels in ^{204}Pb

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Data from ^{204}Pb$(p,p')^{204}$Pb conversion-electron and gamma-ray experiments, together with previous results, prove the existence of two levels (0^+ and 2^+) at 1583-keV excitation energy in ^{204}Pb. Modified values (limits) of the ρ^2_{21} and X_{211} are $0.0013<\rho^2_{21}<0.015$ and $X_{211}>0.073$. New experimental evidence indicates that all the three observed excited O^+ states in ^{204}Pb can be explained as belonging to the four-neutron-hole valence space and, therefore, there is no clear candidate for the proton 2p-2h intruder state in this nucleus.

As one of the results of our earlier work,[1] we established the existence of a 1582.7-keV 0^+ level in ^{204}Pb. This was done using the $(p,2n)$ reaction at proton energies around 14.5 MeV on natural and enriched Tl targets. The electron spectra showed a prominent ground-state $E0$ transition with a half-life of 65(20) ps. The gamma-gamma coincidence spectra revealed the existence of a 683.5-keV gamma-ray transition depopulating a level at 1582.7 keV (this energy matched with the energy of the $E0$ from our electron spectra). Therefore, we assumed that the 683.5-keV transition depopulates the 1583-keV 0^+ level and, thus, extracted the values of $\rho^2_{21}=7.4(25)\times10^{-5}$ and $X_{211}=0.0032(3)$.

However, data from a later study[2] of ^{204}Pb via a $(n,n'\gamma)$ reaction produced contradictory results concerning the 1583-keV level: the spin and parity of a level at this energy were firmly established as 2^+. In this experiment, no evidence was found for a gamma-ray transition between a 0^+ level at an energy close to 1583 keV and the 899.2-keV 2^+_1 level. This result brought new light into the level scheme of ^{204}Pb but, unfortunately, the authors of Ref. 2 questioned whether our previous work[1] proved beyond any doubt the existence of a 0^+ state in ^{204}Pb at the excitation energy around 1583 keV (within 1 keV). In fact, our result confirmed a tentative assignment from an earlier study[3] reporting a 1585(18)-keV ground-state $E0$ transition. The only quantities that needed verification were the energy and the decay modes of the 0^+ state and, consequently, the X_{211} and ρ^2_{21} values.

Even-even lead isotopes attract considerable experimental and theoretical interest associated with the study of shape coexistence, the intruder state systematics, and the onset of deformation. Since the location and characteristics of the 0^+ states are among the most vital pieces of information needed in these studies, we decided to make new experiments aimed at proving the existence of two levels at 1583 keV (thus removing the arguments against the existence of a 0^+ state at that energy) and at determining the spectroscopic characteristics of the 0^+_2 state.

This time we populated the levels in ^{204}Pb in the (p,p') reaction at proton energies close to and equal to the isobaric analog resonance (IAR) energy[4] of 12.3 MeV. The electron spectra from a 66% enriched ^{204}Pb target displayed again a prominent $E0$ transition that resonates at the IAR energy (Fig. 1). However, our data indicate a decrease of the ratio of the 683.5-keV gamma ray to the K1582-keV $E0$ line by a factor of 25 as compared with the results from the earlier ^{205}Tl$(p,2n)^{204}$Pb experiment. This, together with the results from the (n,n') experiment, clearly shows that there are two different decay modes and, therefore, two levels in ^{204}Pb at the excitation energy near 1583 keV.

The current characteristics of the 0^+ level are as follows:

$$\text{energy}=1582.4\pm0.7\text{ keV}$$

(energy of the 2^+ level is[2] 1582.8 ± 0.1 keV),

$$t_{1/2}=65\pm20\text{ ps},$$

$$I_{K(E0)}/I_{K(E2)}>14,$$

$$X_{211}>0.073,$$

$$0.0013<\rho^2_{21}<0.015.$$

A relatively poor energy determination of the 0^+ level comes from the fact that it is solely based on the electron measurement. We have no information as to whether the 683.5-keV gamma ray depopulates the 0^+ or the 2^+ level, or both. This is also the reason why we are only able to give limits on the I, X, and ρ^2 values.

The existence of two states at 1583 keV might look disturbing but, because of the unambiguous data, it has to be accepted. The 1583-keV 0^+ state cannot, as suggested in Ref. 2, be assigned to ^{202}Pb. Already our previous study[1] ruled out that possibility; our present work makes it even clearer: ^{202}Pb is not stable and cannot be a target impurity in the ^{204}Pb(p,p') reaction, and the (p,t) reaction is excluded by the observed resonance in the yield curve. Also, since spectra from a ^{206}Pb$(p,t)^{204}$Pb study[5] show a peak at 1582(2) keV, the statement in Ref. 2 that the 1583-keV 0^+ state is not excited in any of the two-neutron transfer studies is incorrect. (Due to limited resolution, this peak is not separated from the strong 1563-keV 4^+ line.) Therefore, there is no contradictory evidence to the interpretation of the observed 0^+_2 and 0^+_3 states (at 1583 and 1730 keV) as neutron states.

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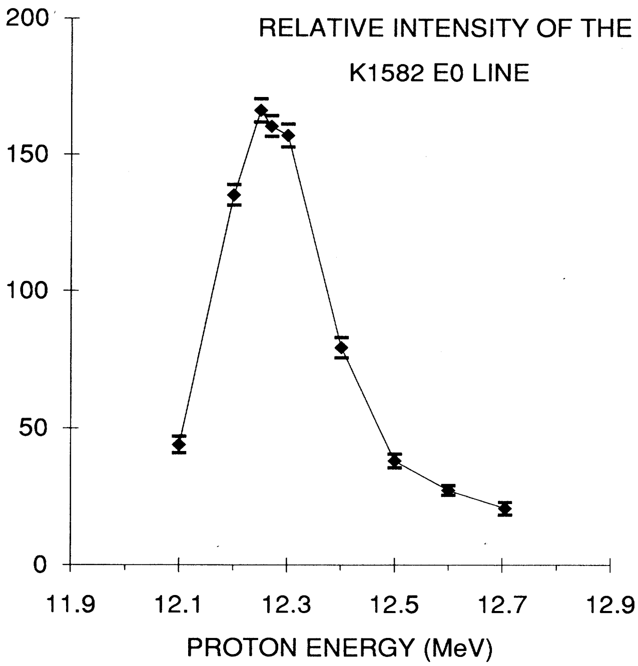

FIG. 1. Relative intensity of the K1582-keV $E0$ line from the ^{204}Pb$(p,p')^{204}$Pb reaction at proton energies around the 12.3-MeV IAR.

The following theoretical calculations predict (in agreement with our observation of the 0_2^+ and 0_3^+ states) two excited 0^+ levels below 3 MeV in the four neutron-hole space of ^{204}Pb: a quasiparticle model,[6] a conventional shell model,[7] and a multistep shell model.[8] The remaining 2433-keV 0_4^+ state is not accounted for in these calculations. This energy agrees with a possible location of the proton $\{\frac{1}{2}^+[440]^{-2},\frac{9}{2}[514]^2\}$ intruder state, as suggested by systematics. This was also the tentative conclusion in our previous work.[1] However, there is new evidence contradicting such an assignment. The $(n,n'\gamma)$ study[2] showed a 751.8-keV transition exhibiting isotropic angular distribution, with an excitation threshold of 2450(50) keV, in cascade with the ground-state transition from a 1^+ level at 1681.2 keV. This cascade probably belongs to the decay of the 0_4^+ state. Thus, as already pointed out in Ref. 2, the 0_4^+ state could belong to the four neutron-hole valence space (as apparently does the 1681.2-keV 1^+ state). There is one more argument in support of this possible new interpretation of the 0_4^+ state: from one of the two-neutron transfer studies,[5] a state (without spin assignment) at 2430 keV is reported. This state is probably the 2433-keV 0^+ level. A proton-intruder state is not likely to be populated in two-neutron transfer (except via configuration mixing). Finally, the new, detailed fits[9] based on intruder-state systematics both in Pb and Bi isotopes suggest 3.2 MeV for the intruding 0^+ state energy in ^{204}Pb—considerably more than the 2.433 MeV of the 0_4^+ state.

The presence of three excited 0^+ states belonging to the neutron-hole space would not be entirely unexpected. According to early calculations by True,[10] there should be three relatively low-lying excited 0^+ states even in ^{206}Pb with only two quasiparticles. Clearly, improved shell-model calculations are called for to reproduce the energies.

The possible absence of the proton 2p-2h state from the known 0^+ levels in ^{204}Pb would leave a gap in the experimental intruder-state systematics in the $Z=82$ region. A similar situation exists now in ^{208}Pb, as well: recent calculations[11] identify the 5237-keV 0^+ state in ^{208}Pb as a two-octupole-phonon vibrational excitation and validate 5.5 MeV as the expected energy[12] of the unobserved two-proton pairing vibrational 0^+ state.

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