$E0$ study of 0^+ states near 5 MeV in ^{208}Pb

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Strong $E0$ lines from the 4866 and 5237 keV 0^+ states in ^{208}Pb have been identified using a new high-energy conversion-electron spectrometry technique in the study of the ^{207}Pb(d,p)^{208}Pb and ^{208}Pb(p,p')^{208}Pb reactions at $E_d = 10$ MeV and $E_p = 17.3$ MeV, respectively. No evidence for an $E0$ transition from the expected third 0^+ state was found.

In ^{208}Pb, three excited 0^+ states are expected to lie below 6 MeV of excitation energy. Two of them have been firmly identified in two-neutron transfer studies as being situated at 4859(15) keV and 5236(15) keV. The 4859 keV state has been interpreted unambiguously as the neutron-pairing-vibrational state.[1,2] The 5236 keV state was suggested[1] to be the 0^+ member of the two-octupole-phonon multiplet, because of the closeness to the unperturbed two-phonon energy. However, in Ref. 2 it was shown that also the proton-pairing-vibrational 0^+ state should lie at about 5.3 MeV. Furthermore, using the prescription of Ref. 3, an energy of about 5.2 MeV for this state is derived.[4]

A number of estimates for the energy of the two-octupole-phonon 0^+ state has been made (cf. Ref. 5). In Ref. 2 an estimate was based on an old quadrupole-moment value for the 2615 keV one-octupole-phonon 3^- state. The use of improved experimental values[6] brings this estimate closer to the unperturbed energy of 5.23 MeV. All the estimates are quite uncertain, but indicate that the two-octupole-phonon 0^+ state should lie within 0.5 MeV from 5.2 MeV. Consequently, only one 0^+ state (at 5236 keV) is observed for the two expected ones: the two-octupole-phonon state and the proton-pairing-vibrational state.

From the experimental point of view, the decay properties of a 0^+ state in the 5 MeV region in ^{208}Pb play an interesting role. A rough estimate of rates of competing transitions indicates that the K conversion of the $E0$ transition to the ground state could represent a major part of the total deexcitation of this state. This expectation offers a method for the identification of low-lying 0^+ states in ^{208}Pb. Since no conclusive $E0$ results exist for the 5 MeV excitation-energy region in ^{208}Pb,[5,7] an improved conversion-electron study was called for.

Our new combination electron spectrometer system[8] including a Siegbahn-Slätis type of magnetic lens and a Ge(HP) detector (80 mm$^2\times$5 mm) represents an improved method for detecting electrons up to about 8 MeV of energy, with an energy resolution of about 2.5 keV at 1 MeV and about 8 keV at 5 MeV.

With this spectrometer, we have obtained a conversion-electron spectrum from a bombardment of a 4 mg/cm^2 thick enriched (89%) ^{207}Pb target with 10 MeV deuterons. A high-energy part of this spectrum is shown in Fig. 1(a). A background spectrum was taken with no target. Background lines are double-escape peaks of high-energy gamma rays originating mainly from (n,γ) reactions in the surrounding Fe and Cu materials.

For the identification of $E0$ lines and other new conversion-electron lines in this spectrum, we performed a gamma-proton coincidence experiment with the same reaction and target material. The coincidence setup consisted of a 20% Ge detector and three 200 mm$^2\times$3 mm Si(Li) particle detectors, positioned at about 2.5 cm from the target, at an angle of about 140 degrees with respect to the beam direction. With this setup and a 1.1 mg/cm^2 ^{207}Pb target, the energy resolution for the proton lines in the Si(Li) spectra was about 200 keV. Figure 1(b) shows the high-energy part of the gamma-ray spectrum gated with the part of the Si(Li) spectra which corresponds to excitation energies of 2.5–8 MeV in ^{208}Pb. The background in this spectrum is dominated by escape peaks and Compton tails of the $E1$ gamma rays from the strongly populated 5292 keV and 5946 keV neutron particle-hole 1^- states in ^{208}Pb.[6] However, by setting narrower gates on the particle spectrum, it was possible to identify weak lines as well [Fig. 1(c)].

Conversion-electron and gamma-ray peaks corresponding to known $E1$ transitions from the 1^- states at 4842, 5292, 5512, 5946, and 6262 keV, a known $E2$ transition from the 4085 keV 2^+ state, and a known $M2$ transition from the 4229 keV 2^- state to the ground state of ^{208}Pb,[6] are identified in these spectra. These lines were used in the internal energy calibration, which gives an accuracy of about 2 keV for the transition energies shown in Fig. 1. New lines, observed both in the gamma-ray and the conversion-electron spectra, we identify with previously unobserved ground-state $E3$ or $M2$ transitions from known 4698 keV 3^-, 4974 keV 3^-, 5038 keV 2^- or 3^-, 5127 keV 2^- or 3^-, and 5923 keV $(2)^-$ levels in ^{208}Pb.[6] The 4626 keV line corresponds to a known $E1$ transition

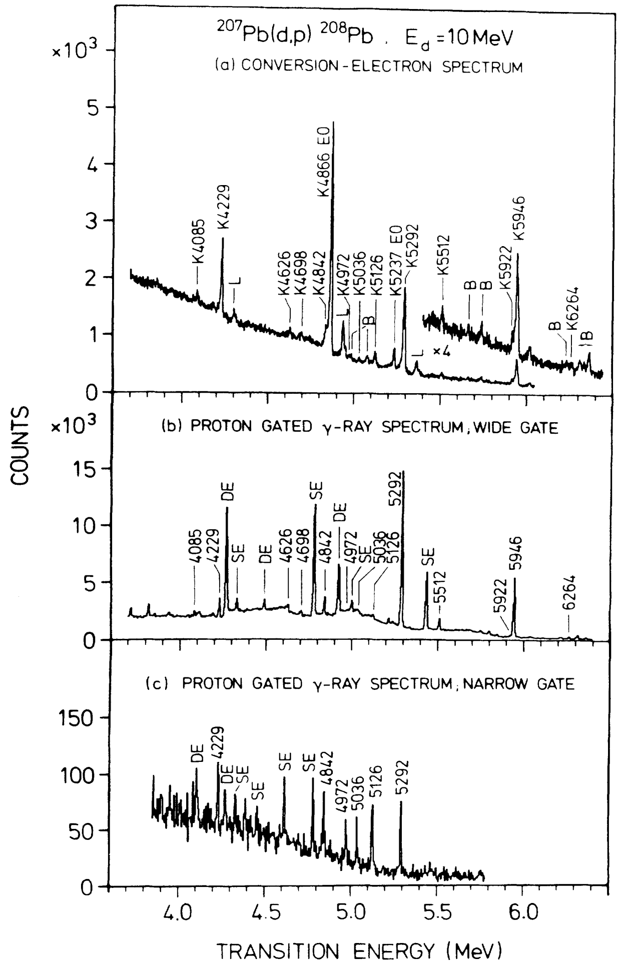

FIG. 1. High-energy parts of conversion-electron and proton-gated gamma-ray spectra from a bombardment of ^{207}Pb with 10 MeV deuterons. In (a), B indicates background lines. The gate settings for (b) and (c) correspond to excitation energies of 2.5–8 MeV and about 5 MeV in ^{208}Pb, respectively.

in ^{207}Pb.[9]

The strongest line in the conversion-electron spectrum of Fig. 1(a) represents a new 4866 keV $E0$ transition from the known neutron-pairing-vibrational 0^+ state to the ground state of ^{208}Pb. Another weaker line in this spectrum, with no corresponding gamma line, we identify with a new 5237 keV $E0$ transition from the second excited 0^+ state observed in the two-neutron transfer studies.[1] No candidate for an $E0$ transition from the sought-after third 0^+ state could be identified.

The total cross section for the K-conversion electron production of the 4866 keV and 5237 keV $E0$ transitions, derived from the spectrum of Fig. 1(a), are about 5 μb and 0.5 μb, respectively.

In another experiment, we measured a conversion-electron spectrum from the bombardment of a 5 mg/cm^2 thick enriched (98%) ^{208}Pb target with 17.3 MeV protons. The high-energy part of the spectrum shown in Fig. 2(a) exhibits again the 4866 keV and 5237 keV $E0$ transitions from the known 0^+ states. In this case, the 5237 keV state is about ten times more strongly populated than in the (d,p) reaction. The K-conversion electron production cross sections for the $E0$ transitions are about 10 μb and 6 μb, respectively.

With the same beam and target material, we also performed a gamma-proton coincidence measurement. Figure 2(b) shows the high-energy part of the gamma-ray spectrum gated with the part of the proton spectrum which corresponds to excitation energies of 4–6 MeV in ^{208}Pb. In this spectrum, the 4842, 5292, 5512, and 5946 keV $E1$ transitions and the 4085 keV $E2$ transition are identified. The K lines of these transitions are also present in the conversion-electron spectrum. The K line of the $M2$ transition from the 5923 keV 2^- state is visible, as well. No candidate for a transition from the missing third 0^+ state is present.

The selectivity for 0^+ states in the 5 MeV region shown especially by the spectrum of Fig. 2(a) is remarkable. In spite of the much larger formation cross sections for states of other spin and parity, of the order of 1 mb, the 0^+ states dominate totally in the electron spectrum because the conversion coefficients of 5 MeV dipole or quadrupole transitions are only of the order of 10^{-4}.

Relevant competing transitions deexciting a 0^+ state in

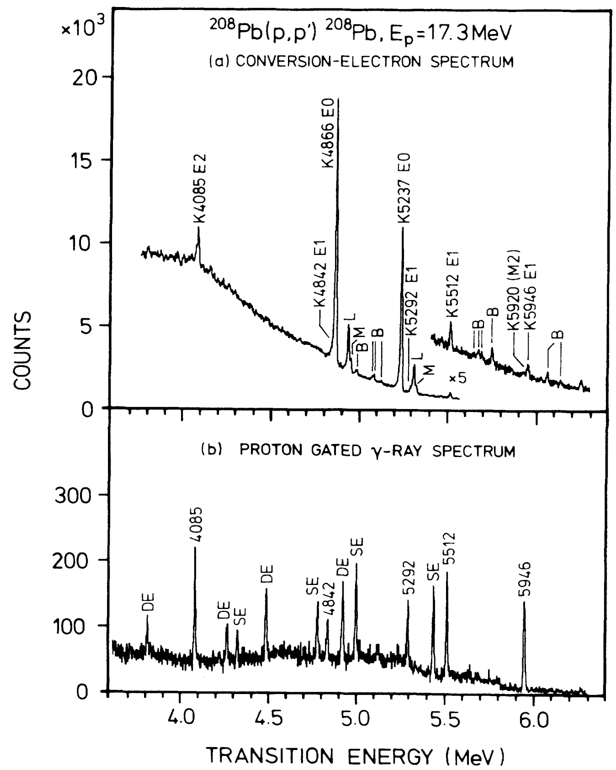

FIG. 2. High-energy parts of conversion-electron and proton-gated gamma-ray spectra from a bombardment of ^{208}Pb with 17.3 MeV protons. In (a), B indicates background lines. The gate setting in (b) corresponds to excitation energies of 4–6 MeV in ^{208}Pb.

the 5 MeV region in ^{208}Pb would be an $E1$ transition to the 4842 keV 1^- state, an $E2$ transition to the 4085 keV 2^+ state, an $E3$ transition to the one-phonon 3^- state at 2615 keV, and an $E0$ transition to the ground state. A realistic estimate reveals that even for a two-octupole-phonon state with a collective $E3$ to the 2615 keV 3^- state, the internal K conversion of the $E0$ transition to the ground state should represent on the order of 20% of the total deexcitation of such a state. Using this estimate, we obtain a cross-section limit of about 1 μb for the population of the missing 0^+ state in the 4–6 MeV region in ^{208}Pb, in our (d,p) and (p,p′) experiments. Of course, this limit is not valid if the line happens to coincide with a known line in the spectrum. Although many new high- and low-energy transitions in our gamma-proton coincidence experiments were observed, the intensities of competing gamma transitions from the 0^+ states are below our detection limit.

No significant intensity fluctuations of the $E0$ lines were observed in the (p,p′e$^-$) runs with different proton energies from 17.0 to 17.5 MeV and in the (d,pe$^-$) runs with deuteron energies between 9.5 and 10.0 MeV. This result indicates that the Coulomb barrier does not remarkably limit the population of the 0^+ levels in these reactions and that there are no strong resonances in the (p,p′) reaction favoring the population of these 0^+ states.

An intriguing question is whether the 5237 keV 0^+ state is the two-octupole-phonon or the proton-pairing-vibrational state. Using the estimate of a 20% branch for the K conversion of the $E0$ transition to the ground state, we obtain total cross sections of about 3 μb and 30 μb for the population of this state in our (d,p) and (p,p′) experiments, respectively.

The relatively large (p,p′) cross section to the 5237 keV 0^+ level compared to the limit for the missing 0^+ level may indicate that the 5237 keV level actually corresponds to the two-octupole-phonon state. This state should be much easier to form in the (p,p′) reaction by a two-step process than the proton-pairing-vibrational state.

There is also another circumstance which favors this interpretation. The expected energy of the proton-pairing-vibrational state in ^{208}Pb, based on known excitation energies of related states in neighboring odd-proton isotones ^{209}Bi and ^{207}Tl,[10–12] is about 5.5 MeV. In view of the fact that a similar estimate of the energy of the neutron-pairing-vibrational state, using ^{209}Pb and ^{207}Pb excitation energies, gives very good agreement with the experimental energy of 4866 keV, it is not very likely that the proton-pairing-vibrational state should come as low as 5237 keV.

In conclusion, high-energy conversion-electron spectrometry was found to be a sensitive method to identify 0^+ states near 5 MeV in ^{208}Pb. Strong conversion-electron lines of $E0$ transitions from the 4866(2) keV and 5237(2) keV 0^+ states, populated in the (d,p) and (p,p′) reactions at low bombarding energies, were identified. No candidate for an $E0$ transition from the expected third 0^+ state was found. From the experimental cross sections, some evidence was found to interpret the 5237 keV state as the 0^+ member of the so far unidentified two-octupole-phonon multiplet.

[1]G. Igo, P. D. Barnes, and E. R. Flynn, Ann. Phys. (N.Y.) **66**, 60 (1971).

[2]J. Blomqvist, Phys. Lett. **33B**, 541 (1970).

[3]K. Heyde, J. Jolie, J. Moreau, J. Ryckebusch, M. Waroquier, and J. L. Wood, Phys. Lett. **176B**, 255 (1986).

[4]J. L. Wood, private communication.

[5]M. A. J. Mariscotti, D. R. Bes, S. L. Reich, H. M. Sofia, P. Hungerford, S. A. Kerr, K. Schreckenbach, D. D. Warner, W. F. Davidson, and W. Gelletly, Nucl. Phys. **A407**, 98 (1983).

[6]M. J. Martin, Nucl. Data Sheets **47**, 797 (1986).

[7]T. von Egidy, W. Mampe, B. Olma, and W. Kaiser, Z. Phys. **236**, 440 (1970).

[8]R. Julin, J. Kantele, J. Kumpulainen, M. Luontama, V. Nieminen, A. Passoja, W. Trzaska, and E. Verho, University of Jyväskylä, Department of Physics Annual report, 1985, p. 16; and Nucl. Instrum. Methods Phys. Res. (to be published).

[9]M. R. Schmorak, Nucl. Data Sheets **43**, 383 (1984).

[10]C. Ellegaard, R. Julin, J. Kantele, M. Luontama, and T. Poikolainen, Nucl. Phys. **A302**, 125 (1978).

[11]K. H. Maier, T. Nail, R. K. Sheline, W. Stöffl, J. A. Becker, J. B. Carlson, R. G. Lanier, L. G. Mann, G. L. Sruble, J. A. Cizewski, and B. H. Erkkila, Phys. Rev. C **27**, 1431 (1983).

[12]B. Jonson, O. B. Nielsen, L. Westgaard, and J. Zylicz, in Proceedings of the 4th International Conference on Nuclei far from Stability, CERN Report 81-09, 1981, p. 640.