Effective Charge of Neutron Quasiparticle Pairs in ^{206}Pb and ^{204}Pb

C. N. Papanicolas
University of Illinois at Urbana-Champaign, Urbana, Illinois 61801

and

J. Heisenberg
University of New Hampshire, Durham, New Hampshire 03824

and

J. Lichtenstadt[(a)]
Bates Linear Accelerator Center and Physics Department, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

J. S. McCarthy
University of Virginia, Charlottesville, Virginia 22901

and

D. Goutte, J. M. Cavedon, B. Frois, M. Huet, P. Leconte, Phan Xuan Ho, and S. Platchkov
Departement de Physique Nucléaire et Hautes Energies, Commissariat à l'Energie Atomique de Saclay, F-91191 Gif-sur-Yvette, Cedex, France

and

I. Sick
Physics Department, University of Basel, CH-4056 Basel, Switzerland
(Received 3 August 1983)

The transition charge densities to the lowest $J^{\pi}=2^{+}, 4^{+}$ states in ^{204,206}Pb have been determined through inelastic electron scattering. Their shape is insensitive to the microscopic structure of these states, dominantly of neutron character, but it bears striking similarity to that of the low-frequency phonon of the core. This is regarded as strong evidence supporting the view that the "dressing" of these neutron excitations is mediated through core polarization with the lowest-frequency phonon acting as the most important doorway.

PACS numbers: 21.10.Pc, 25.30.Dh, 27.80.+w

We have measured with high precision and to high momentum transfers ($q_{\rm eff} \leq 3.4$ fm^{-1}) the inelastic electron scattering cross section of the lowest $J^{\pi}=2^{+}$ and 4^{+} states in ^{208}Pb, ^{206}Pb, and ^{204}Pb. Our measurements allow for the first time the empirical determination of the spatial distribution of an effective charge. The extracted transition densities exhibit remarkable spatial similarity despite the radically different microscopic structure of the corresponding states. We view this striking similarity as a manifestation of the dominant role that the low-frequency collective excitations play in mediating core polarization. Finally we present evidence which strongly suggests that the proper inclusion of these collective excitations in effective-charge calculations can bridge the longstanding discrepancy between theory and experiment.

^{208}Pb is the heaviest doubly closed shell nucleus. It is spherical and tightly bound. The removal of two neutrons from the $3p_{1/2}$ shell of ^{208}Pb leads to ^{206}Pb which has a subshell closure for neutrons. The removal of another neutron pair leads to ^{204}Pb with the $2f_{5/2}$ orbit partially filled. The proton shell remains closed for all three isotopes. The lowest excited states of ^{206}Pb and ^{204}Pb have simple microscopic makeup dominated by few neutron configurations, a fact established long ago through transfer reactions[1] and successfully accounted for by a number of shell-model calculations.[2] The observation of strong electromagnetic transition rates to these states is a manifestation of the "dressing" of the neutron quasiparticles by an effective charge. While it is generally believed that we have a sound understanding of the underlying dynamics in the theory of core polarization,[3] published calculations[4,5] for these transitions underestimate the observed rates by an order of magnitude.

The measurements were conducted at the linacs of Bates Linear Accelerator Center and Accélérateur Linéaire de Saclay at forward scattering angles. Incident beam energies ranging between 52 and 502 MeV were delivered covering the momentum transfer range of 0.4 to 3.4 fm^{-1}. Thin (30-mg/cm^2), isotopically enriched metallic foils were used as targets. The high-intensity beams of the linacs ($I_{av} \gtrsim 25$ μA) and special cooling mechanisms were employed in order to compensate for the weak rates. Cross sections were extracted with use of line-shape techniques based on a theoretical estimate of the radiative tail folded with an empirical resolution function. Systematic error in the cross sections including normalization is estimated to be of the order of 5%. It was added in quadrature to the statistical error which in most cases does not exceed 5%. The extracted cross sections were fitted with use of the Fourier Bessel expansion method[6] in order to reconstruct the transition charge densities. The transverse contribution in the cross section is assumed to be insignificant. This assumption is based on the study of the transverse response of the $J^\pi = 2^+, 4^+$ states in ^{208}Pb,[7] and two 160° measurements on ^{206}Pb and ^{204}Pb.

The derived densities are shown in Figs. 1 and 2. The error envelope includes contributions from statistical and systematic errors and an estimate of the completeness error derived by imposing an exponential upper limit to the form factor[6] above the highest q value measured. The details of the analysis and the results of the ^{208}Pb states have been reported previously.[7] The extracted densities for the low-lying ^{206}Pb and ^{204}Pb transitions are reminiscent of collective core excitations, being strongly surfaced peaked and with very small but distinct interior structure. The similarity between the ^{204}Pb and ^{206}Pb densities is remarkable: Except for the difference in strength (the ^{204}Pb transitions are strong-

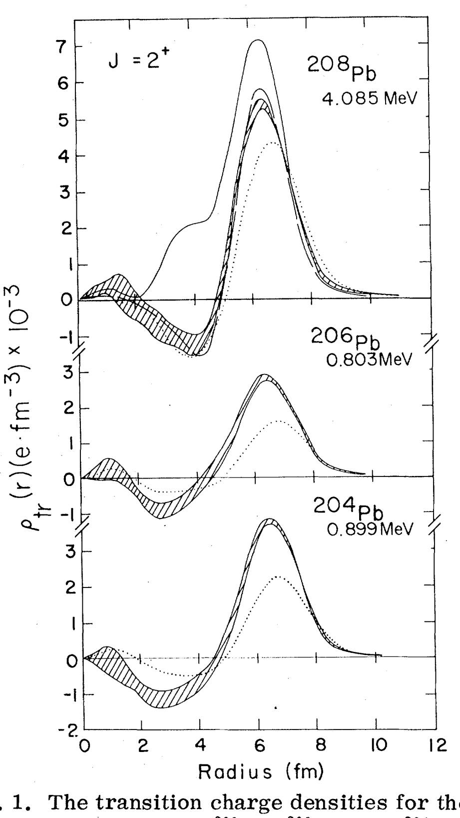

FIG. 1. The transition charge densities for the lowest quadrupole transitions in ^{208}Pb, ^{206}Pb, and ^{204}Pb. The shaded area indicates our best estimate for experimental and model errors. The calculations by Palchick, Pyatov, and Fayans (Ref. 8) for the GQR and the low-frequency (4.085-MeV) collective state are shown by solid and dashed curves, respectively. The dotted curves are due to the recent calculation of Lombard and Mas (Ref. 9).

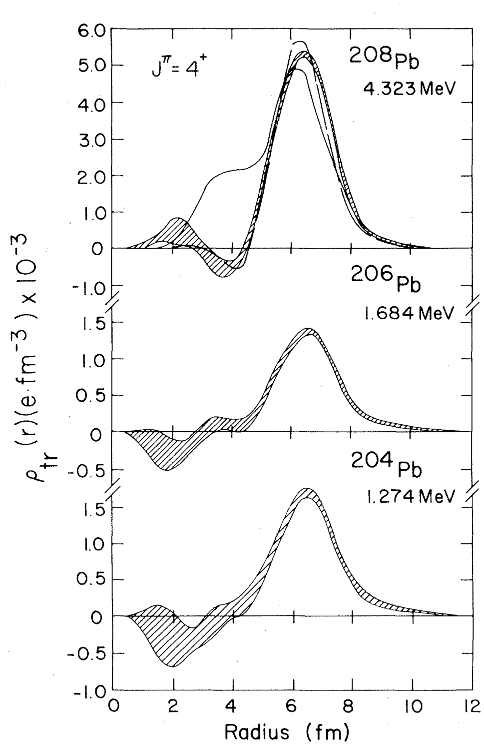

FIG. 2. The transition charge densities for the lowest hexadecapole transitions in ^{208}Pb, ^{206}Pb, and ^{204}Pb. Same conventions as in Fig. 1.

er by a factor of 1.8 for both multipoles) the shapes are identical within our experimental accuracy. A comparison of the densities of the corresponding low-lying collective excitations of the core (^{208}Pb) reveals that the shapes are again very similar even though the core states lie some 3 MeV higher in excitation and have radically different microscopic content. Collective core excitations identical in shape to those of ^{208}Pb, shown in Figs. 1 and 2, but with slightly reduced strength have been identified in ^{206}Pb at 4.112 MeV ($E2$) and at 4.340 MeV ($E4$).

Calculations[4,5] which are quite representative of current theoretical notions on effective charge are in serious disagreement with our results. Traditionally, the degree of success of effective-charge calculations has been judged by their ability to reproduce reduced transition probabilities [$B(E\lambda)$]. As can be seen in Table I the published theoretical $B(E\lambda)$ values[4,5] differ from the empirical ones by at least an order of magnitude. This discrepancy is particularly significant given that the nuclear structure of the lead isotopes is well understood.

Reduced transition probabilities provide a well understood and convenient meeting point between theory and experiment. Unfortunately, they offer little insight as to the origins of the discrepancy. This insight can be provided by examining the underlying assumptions of each calculation and by comparing the resulting transition densities to the ones obtained empirically.

Giant resonances in heavy nuclei exhaust more than 90% of the energy-weighted sum rule. It has therefore been assumed that they are primarily responsible for mediating core polarization. Barranco, Lombard, and Mas[5] carry this assumption to its extreme by assuming that core polarization is exclusively mediated by giant resonances. The $B(E2)$ values resulting from their calculation are 10–20 times weaker than the observed ones and the transition densities are totally incompatible with our results. Given that the energies of the states are reasonably well reproduced, one has to conclude that the problem lies not in the derivation of the quasiparticle spectrum but rather in the core-polarization calculation. The relative importance of the giant quadrupole resonance in mediating core polarization can be further examined by comparing the empirical ^{204}Pb and ^{206}Pb transition densities to those of (a) the giant resonance and (b) the low-lying collective state (at 4.086 MeV). All empirical densities shown in Fig. 1 are characterized by a negative lobe in the nuclear interior. In the case of ^{208}Pb, this structure can be recognized as the signature of the $\pi(h_{11/2}{}^{-1}, 2f_{7/2})$ configuration. Microscopic calculations[9,10] confirm this observation. In addition, they show that the transition charge density of the giant quadrupole resonance has a pronounced positive interior lobe instead (see Fig. 1). This comparison leads us to conclude that the low-lying quadrupole collective excitation plays a more dominant role than the giant resonance in dressing the two-neutron-quasiparticle excitation. Similar conclusions can be drawn for the case of the hexadecapole transitions where a more delicate interplay between the giant resonance and the other core phonons seems to be at work (see Fig. 2).

Taking note of the results presented here and drawing similar conclusions, Lombard and Mas[9] have performed a new calculation where all configurations that energetically lie below the giant

TABLE I. The empirical $B(E\lambda)$'s for the excitations discussed in this paper are tabulated. A comparison to the $B(E2)$ values of the theoretical estimates (Refs. 4, 5, and 9) is also presented.

		This work		Barranco *et al.*[a]		Lombard *et al.*[b]		Gillet *et al.*[c]	
Nucleus	J^{π}	E_{ex} (MeV)	$B(E\lambda\uparrow)$ ($e^2 \cdot fm^{2\lambda}$)	E_{ex} (MeV)	$B(E2)$	E_{ex} (MeV)	$B(E2)$	E_{ex} (MeV)	$B(E2)$
^{208}Pb	2^+	4.085	3.18×10^3	...	...	4.63	3.2×10^3	...	...
	4^+	4.323	1.54×10^7						
^{206}Pb	2^+	0.803	9.57×10^2	1.45	9.6×10^1	1.38	4.0×10^2	0.98	0.63×10^1
	4^+	1.684	1.67×10^6						
^{204}Pb	2^+	0.899	1.74×10^3	1.51	1.3×10^2	1.44	8.0×10^2	0.96	0.10×10^2
	4^+	1.274	2.90×10^6						

[a]Ref. 5. [b]Ref. 9. [c]Ref. 4.

resonance are allowed to couple directly with the two-quasiparticle excitation. This prescription tries to minimize the problems of double counting while permitting the important proton $0\hbar\omega$ configurations to contribute. It yields reasonable $B(E2)$ values and acceptable densities as one can observe in Fig. 1 and Table I. The success of this approach, especially when contrasted with that of Ref. 5, supports our conclusions on the significance of the low-lying phonon in the core-polarization process.

Finally, the results obtained by Gillet, Giraud, and Rho[4] are also in disagreement with our measurements. Their treatment of core polarization does not preselect special states. First, the quasiparticle spectrum is generated by solving the inverse gap equation. Then, the transition properties of the lowest 2^+ and 4^+ states in ^{204}Pb and ^{206}Pb are calculated in the framework of the random-phase approximation. Good agreement is obtained for the excitation energies but the $B(E2)$ and $B(E4)$ values are underestimated by at least an order of magnitude (see Table I). The shortcomings of this calculation must be attributed to the limited configuration space used. As a result, not enough coherence is built into the low-lying core phonon for it to mediate the polarization of the core. In the final analysis this calculation seems to suffer from the same weakness as the one by Barranco, Lombard, and Mas.[5] Namely, it fails to account properly for the role of the low-frequency core phonon. In view of the new precise measurements it would be most interesting to repeat the calculations of Ref. 4 in an expanded basis. Given the generality of the theory and its parsimonious assumptions it would be surprising, with important ramifications, if the present discrepancy were not removed.

In summary, we have found that the transition charge densities to the lowest two-neutron-quasiparticle excitations in ^{204}Pb and ^{206}Pb exhibit a remarkable similarity among them as well as between them and the lowest collective excitation of the core. Our data thus strongly suggest that these collective excitations act as an important doorway in the dressing of the lowest two-neutron-quasiparticle configurations by an effective charge. Their proper description and inclusion in any core-polarization calculation appears essential in achieving agreement between theory and experiment.

We would like to thank Professor Lombard for stimulating discussions and for communicating his results prior to publication. We would like to thank the Department of Nuclear Physics of Saclay and the Bates Linear Accelerator Center for their warm hospitality and support during the course of this experiment. This work was supported in part by the U. S. National Science Foundation and the U. S. Department of Energy through Grants No. NSF PHY 80-23603 and No. DE-AS02-ER10338, and the Schweizerische Nationalfonds.

[a]Present address: Tel Aviv University, Ramat, Aviv, Israel.

[1]R. Tickle and J. Bardwick, Phys. Rev. 166, 1167 (1968).

[2]R. J. Liotta and C. Pomar, Nucl. Phys. A362, 137 (1981), and references therein.

[3]A. Bohr and B. Mottelson, *Nuclear Structure* (Benjamin, New York, 1975).

[4]V. Gillet, B. Giraud, and M. Rho, J. Phys. (Paris) 37, 189 (1976).

[5]M. Barranco, R. J. Lombard, and D. Mas, Phys. Lett. 91B, 321 (1980).

[6]J. Heisenberg, in *Advances in Nuclear Physics*, edited by J. W. Negele and E. Vogt (Plenum, New York, 1981), Vol. 12, p. 61.

[7]J. Heisenberg, J. Lichtenstadt, C. N. Papanicolas, and J. S. McCarthy, Phys. Rev. C 25, 2292 (1982).

[8]V. V. Palchik, N. I. Paytov, and S. A. Fayans, Yad. Fiz. 35, 1374 (1982), and 34, 903 (1981) [Sov. J. Nucl. Phys. 35, 801 (1982), and 34, 504 (1981)].

[9]R. J. Lombard and D. Mas, private communication.

[10]D. Gogny, in *Nuclear Physics with Electromagnetic Interactions*, edited by H. Arenhovel and D. Drechsel, Lecture Notes in Physics Vol. 108 (Springer, Berlin, 1979).