Investigation of Natural-Parity High-Spin States in ^{208}Pb by (e,e') Reactions

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Natural-parity high-spin states of $J^\pi = 12^+$ (6.10 MeV) and 10^+ (4.89, 5.07, and 5.92 MeV) were observed and identified via inelastic electron scattering. Dominant single-particle-hole configurations in these excitations were deduced. The measured cross sections indicate a reduction of the transverse transition amplitude to 65% of the shell-model prediction, and the absence of an effective charge for the neutron.

The number of single particle-hole (SPH) excitations within $1\hbar\omega$ in ^{208}Pb that can couple to high spins (14^-, 12^+, or 10^+) is rather limited. The experimental establishment of levels dominated by these SPH excitations and the measurement of their properties provides important information about the residual nuclear interaction. We report here the inelastic electron scattering measurements and an analysis of high-multipolarity electric transitions in ^{208}Pb, studying one state of $J^\pi = 12^+$ at 6.10 MeV and three 10^+ states at 4.89, 5.07 (Refs. 1 and 2), and 5.92 MeV. The cross sections presented here were measured both at forward and backward angles so that for the first time both logitudinal and transverse form factors of these states could be investigated. The dominant SPH components in these excitations were obtained by comparing the cross sections to shell-model calculations. This comparison also indicates a significant reduction in the observed transverse strength similar to the findings in the excitations of the 12^- and 14^- states in ^{208}Pb.[3] Furthermore, it indicates the absence of a neutron effective charge.

The experiment was done at the Bates Linear Accelerator, with incident beam energies between 70 and 335 MeV. The scattered electrons were detected at 90° and at 160°. The momentum-transfer range $0.7 < q < 2.5$ fm^{-1} was covered at both angles. The detection system and the experiment details are described elsewhere.[4,5] The excitation energies of the observed states were determined to ± 10 keV.

We show in Fig. 1 the reduced cross sections[6] $(d\sigma/d\sigma_{\rm Mott})$ for the excited state at 6.10 MeV, measured at 90° and 160°, plotted versus $q_{\rm eff} = q(1+4Z\alpha/3EA^{1/3})$ to correct for the distortion of the electron waves (E is the electron incident energy). Applying criteria similar to those used to identify the magnetic high-spin transitions in ^{208}Pb,[3] we assign to this state spin and parity $J^\pi = 12^+$. According to the simple shell model, the

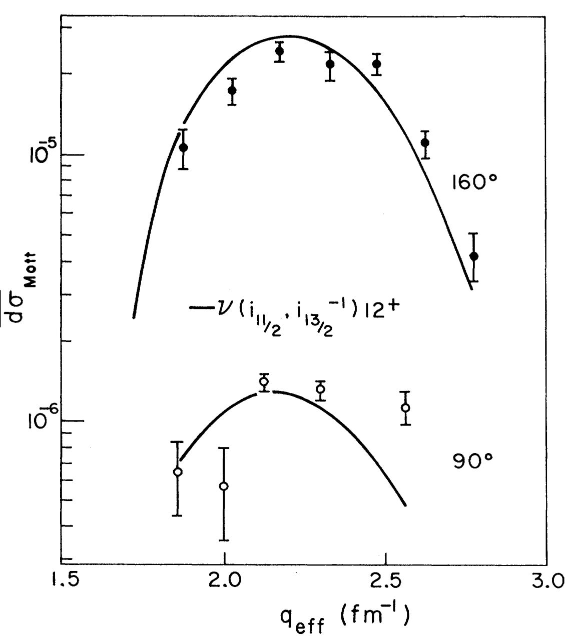

FIG. 1. Reduced (e,e') cross sections from the excited 12^+ state at 6.10 MeV, measured at 90° and 160°. Solid lines are DWBA calculation of the SPH transition $\nu(1i_{11/2}, 1i_{13/2}^{-1})_{12^+}$, scaled down by $0.65g_{\rm free}$.

$\nu(1i_{11/2}, 1i_{13/2}^{-1})$ configuration is the only 1p-1h transition within $1\hbar\omega$ which can couple to $J^\pi = 12^+$. Its PH energy is 5.84 MeV,[7] close to the excitation energy of the observed state. The q dependence of the measured form factor agrees very well with that predicted for this transition. For this comparison the transition current and charge densities[8] were produced using SP wave functions obtained from a Hartree-Fock calculation by Negele and Vautherin.[9] The densities were folded with the proper nucleon magnetization or charge distribution[10] and were then used to calculate the (e,e') cross sections in the distorted-wave Born approximation (DWBA). No radial parameters were adjusted in the nuclear potential which produced the SP wave functions. The ratio between the cross sections measured in forward and backward angles indicates that this state is dominantly transverse. This is in agreement with the interpretation of a neutron transition where the cross section is generated primarily by the spin term in the transition current density without a longitudinal form factor. It implies that the neutron in this transition induces an effective charge of $(0.0 \pm 0.16)e$. The 12^+ transition strength was adjusted to fit the data, and was found to be $(42 \pm 2.5)\%$ of the SPH strength. Since the transition current is produced almost entirely by the magnetic moment of the neutron, this is equivalent to introducing an effective magnetic moment $g_{\rm eff} = 0.65 g_{\rm free}$. A similar reduction to 50% of the SPH strength was observed in the magnetic transitions to the high-spin states of $J^\pi = 14^-$ and 12^-.[3] (e,e') cross sections calculated similarly for the $\nu(1j_{15/2}, 1i_{13/2}^{-1})_{13^-,11^-}$ and the $\pi(1i_{13/2}, 1h_{11/2}^{-1})_{11^-}$ transitions do not fit the data. A weak 12^+ state with $|F_{\rm max}(q)|^2 = 0.9\times 10^{-9}$ based on the same configuration was predicted by Weber *et al.*[11] at 5.56 MeV. Our measurements show the need for more detailed calculations that consider also the dominant transition current densities not taken into account in the work of Weber *et al.*

In the shell model, there are four SPH components which can couple to $J^\pi = 10^+$ with PH energies below 7 MeV. These are (1) $\pi(1h_{9/2}, 1h_{11/2}^{-1})$ at 5.65 MeV, (2) $\nu(2g_{9/2}, 1i_{13/2}^{-1})$ at 5.06 MeV, (3) $\nu(1j_{15/2}, 2f_{5/2}^{-1})$ at 5.42 MeV, and (4) $\nu(1i_{11/2}, 1i_{13/2}^{-1})$ at 5.84 MeV. We observe three 10^+ states below 6 MeV. These include the known 10^+ states at 4.89 and 5.07 MeV (Refs. 1 and 2) and a state at 5.92 MeV. Their measured reduced cross sections are shown in Fig. 2. There is an indication of a fourth 10^+ state at 5.54 MeV, but this state was not completely resolved from other close states.

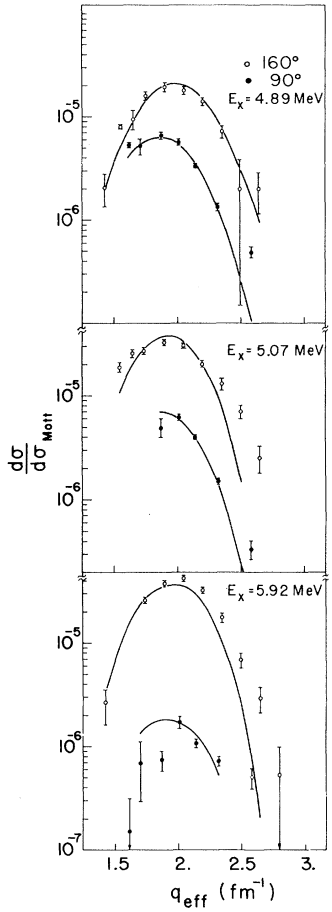

FIG. 2. Reduced (e,e') cross sections from the three 10^+ excited states. Solid lines are DWBA calculations of the following admixtures: (i) 4.89 MeV: 0.65 $\langle A\rangle$, $-0.68\langle B\rangle$, $0.30\langle C\rangle$, and $-0.17\langle D\rangle$. (ii) 5.07 MeV: 0.73 $\langle A\rangle$, $0.68\langle B\rangle$, $-0.02\langle C\rangle$, and $0.03\langle D\rangle$. (iii) 5.92 MeV: $0.12\langle A\rangle$, $-0.16\langle B\rangle$, $-0.07\langle C\rangle$, and $0.98\langle D\rangle$. Quenching factors are $0.65 g_{\rm free}$, and $0.92 e(\pi)$. $\langle A\rangle \equiv \nu(2g_{9/2}, 1i_{13/2}^{-1})_{10^+}$; $\langle B\rangle \equiv \pi(1h_{9/2}, 1h_{11/2}^{-1})_{10^+}$; $\langle C\rangle \equiv \nu(1j_{15/2}, 2f_{5/2}^{-1})_{10^+}$; $\langle D\rangle \equiv \nu(1i_{11/2}, 1i_{13/2}^{-1})_{10^+}$.

From the absence of a neutron effective charge in the 12^+ state the residual interaction is likely to be sufficiently weak[12] to assume that only those four components listed above would mix and be observed in this excitation region. We have tried to evaluate the mixing amplitudes of these SPH components in the observed states from the q dependence and the strengths measured in forward and backward directions. Again SP wave functions were used to generate the transition charge and current densities for each component. The cross sections were calculated from admixtures of these densities in DWBA.

The states at 4.89 and 5.07 MeV have both large longitudinal and transverse form factors while the state at 5.92 MeV is almost purely transverse. One can approximate these results by assuming that the first two states are equal mixtures of the $\pi(1h_{9/2}, 1h_{11/2}^{-1})_{10^+}$ and the $\nu(2g_{9/2}, 1i_{13/2}^{-1})_{10^+}$ configuration while the latter is entirely the $\nu(1i_{11/2}, 1i_{13/2}^{-1})_{10^+}$ configuration. Better agreement between predictions and experimental data can be obtained by composing each state from all four SPH configurations mentioned above. Using Woods-Saxon SP wave functions[13] the mixing amplitudes (A_i, $i=1,\ldots,4$) were fitted to best fit the data in DWBA. The combinations for each state were constrained to be orthogonal to each other and normalized ($\sum A_i^2=1$). With the assumption of identical quenching for the magnetization current densities, the common scaling factor is equivalent to $0.65g_{\text{free}}$, or to $(42\pm5)\%$ of the SPH prediction. This is the same fraction observed for the 12^+ state. Similarly the proton charge had to be scaled down to $0.92e$, since only $(85 \pm 7)\%$ of the SPH charge scattering was observed. These scale factors were necessary in order to match the total observed strengths to the predicted ones maintaining normalized combinations for each state. The resultant calculation using the best-fit amplitude is shown in Fig. 2 with the respective data. Our data suggest a fourth 10^+ state at 5.54 MeV. There is no other single state below 6 MeV which can carry the remaining 10^+ strength expected for that fourth state. Upper limits obtained for the cross section measured at 5.54 MeV indicate that the above conclusions concerning the quenching factors will not change if this state is the fourth expected 10^+ level.

The reduction in the transverse strength of the SPH components which is observed in the high-spin states in ^{208}Pb is interesting. It can be attributed to all the effects not considered in our simple interpretation. We have not considered core polarization, meson-exchange corrections, mixing with multiparticle/multihole transitions, and correlations in the nuclear ground state affecting the orbital occupation numbers. A reduction of the transition current density was observed also in SP transitions in ^{17}O (Ref. 14) and ^{207}Pb (Ref. 15). It has been suggested by Arima and Suzuki[16] that a significant part of the reduction in the SP case originates from second-order renormalization due to 2p-2h correlations in the nuclear ground state. These originate from a combination of random-phase–approximation long-range effects and the tensor interaction. Because of the time-reversal symmetry of the current operator these correlations reduce the transition current density. Unlike core-polarization and meson-exchange currents, this renormalization does not change the q dependence of the SP form factor and can be expressed as g_{eff}. Similar effects may cause part of the quenching in the SPH transitions introduced in this Letter. This effect is independent of the multipolarity to which the components couple, thus it should normalize the 1^+ strength in the $\pi(1h_{9/2}, 1h_{11/2}^{-1})$ and the $\nu(1i_{11/2}, 1i_{13/2}^{-1})$ transitions by the same amount. Our experimental results do not determine the dominant cause for the quenching, however, if ground-state correlations were the dominant cause, it would help to explain the missing $M1$ strength in this nucleus of which only a small fraction has been observed so far.[17,18] Our observation on these high-spin states is consistent with this interpretation and suggests further theoretical studies on the magnitude of the various contributions to the quenching mentioned.

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Autoionization Accompanying Emission of Internal Bremsstrahlung in Beta Decay

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K-shell autoionization accompanying internal bremsstrahlung in the decay of ^{204}Tl has been observed. Its probability was determined to be $P_{IB,K}=(8\pm 3)\times 10^{-8}$ per β decay for internal bremsstrahlung in the energy range from 88 to 394 keV. A comparison with theoretical expectations is presented.

In our recently reported measurement[1] of the internal bremsstrahlung (IB) in the K-capture decay of ^{204}Tl a continuous photon spectrum was observed in coincidence with lead x rays. In the present paper we show that the origin of this observation is simultaneous K-shell autoionization and emission of IB in the β^- decay of ^{204}Tl. Autoionization accompanied by IB in β decay has not been reported before, nor have theoretical predictions of this effect been published, to our knowledge.

The experimental setup and procedures were described before.[1] Coincidences between K x rays recorded by a Ge(Li) detector and γ rays detected by a NaI(Tl) crystal were analyzed and stored in a two-parameter mode. The x-ray spectrum summed over the whole energy range of the IB is shown in Fig. 1(a). The prominent Hg K–x-ray peaks are due to coincidences with IB accompanying the K-capture decay of ^{204}Tl.

The presence of the Pb x rays may be due to several processes which had to be carefully examined. The contributions due to scattering of the Hg $K\beta$ x rays from the collimator located between the source and the Ge(Li) detector, contributions of Pb x rays excited within the source and in the lead bricks of the housing as well as the contributions due to source impurities were found negligible. The only other contribution could arise from autoionization followed by external bremsstrahlung (EB) produced by the β particles interacting with matter surrounding the source. The experimental setup could not distinguish between EB and IB which occur in coincidence with the Pb K x rays following autoionization.

In order to prevent the β particles from reaching the detectors it was necessary to sandwich

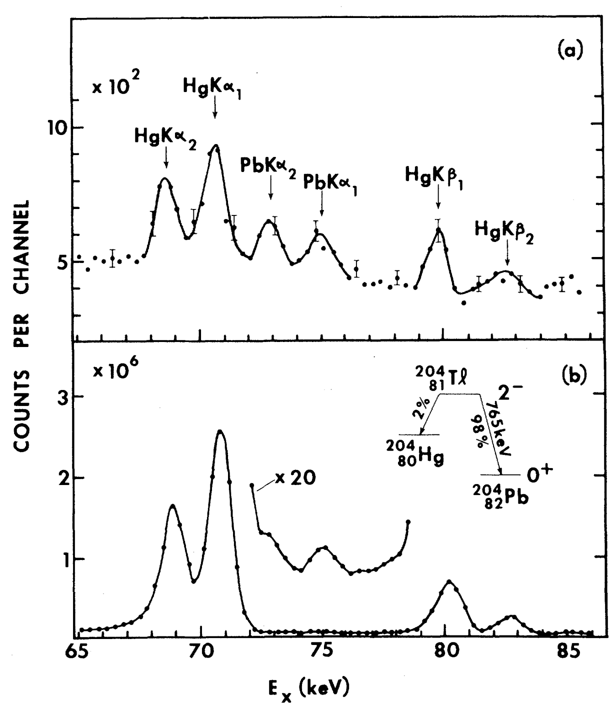

FIG. 1. (a) The x-ray spectrum in coincidence with IB in the energy interval 88–600 keV obtained in 329.5 h. (b) The x-ray singles spectrum. The inset shows the decay scheme of ^{204}Tl.