Microscopic Structure of the Magnetic High-Spin States in ^{208}Pb

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Consideration of both the effect of the one-pion and ρ-meson exchange potentials in the particle-hole interaction and the inclusion of 2p-2h configurations explains why the magnetic high-spin states discovered recently in ^{208}Pb are close to the shell-model energies although the cross sections are only 50% of the single-particle estimate.

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Recently magnetic high-spin states have been discovered in ^{208}Pb by inelastic electron scattering at backward angles.[1] These states are of considerable physical interest because, as a consequence of the high multipolarity, the cross sections have maxima at a momentum transfer of approximately $q = 2\ \mathrm{fm}^{-1}$. Therefore these states are very sensitive to the high-momentum components of the spin- and isospin-dependent part of the particle-hole (p-h) interaction. The number of one-particle, one-hole (1p-1h) excitations which can contribute to these states is severely restricted by the high multipolarity. Since the experimental excitation energies are close to the shell-model p-h energies, the 12^- state at 6.43 MeV and the 14^- state at 6.74 MeV were tentatively interpreted as pure $\nu(1j_{15/2}, 1i_{13/2}^{-1})_{12^-,14^-}$ p-h excitations, while the 12^- state at 7.06 MeV was assumed to be a pure $\pi(1i_{13/2}, 1h_{11/2}^{-1})_{12^-}$ configuration. This simple interpretation faces one problem, however, because the experimental cross section is only 50% of the 1p-1h prediction.[1]

In this Letter it is shown that the fragmentation of the single-particle (s.p.) strength is mainly responsible for this reduction of the cross section. Fortunately the nuclear structure still is simple enough so that conclusions concerning the high-momentum components of the p-h interaction can be drawn.

The theory of finite Fermi systems[2] successfully describes many electromagnetic moments and transitions in the lead region, with use of a density-dependent contract interaction:

$$F(q) = C(f_0 + f_0'\vec{\tau}\cdot\vec{\tau}' + g_0\vec{\sigma}\cdot\vec{\sigma}' + g_0'\vec{\sigma}\cdot\vec{\sigma}'\vec{\tau}\cdot\vec{\tau}'). \quad (1)$$

Here $C = 302\ \mathrm{MeV\ fm}^3$ is used. The Landau parameters g_0 and g_0', which describe unnatural-parity states, were determined from magnetic moments and $M1$ transitions in odd-mass nuclei. In order to take into account mesonic corrections and core-polarization effects, effective magnetic operators were used. Although this ambiguity does not allow a precise quantitative deduction, the experimental data at low momentum transfer definitely require repulsive spin-dependent Landau parameters.

For the region of high momentum transfer, however, a zero-range interaction might be too simple. In the spin-isospin channel, at least the one-pion exchange potential (OPEP) should be considered, as was pointed out in connection with pion condensation.[3] At high momentum transfer, it entirely cancels the repulsive zero-range interaction in the spin-isospin channel. This explains qualitatively why the experimental excitation energies of the magnetic high-spin states coincide with the shell-model prediction. The ρ meson is the only other meson with isospin 1, so that it should also be included in the effective interaction. The ρ meson cuts off the tensor force of the one-pion exchange at short distances. Following Ref. 4, the δ-function contributions to the OPEP and ρ-meson exchange potential were removed and

$$G(q) = 4\pi\tau\cdot\tau'\left(\frac{1}{3}\frac{f_\pi^2}{m_\pi^2}\sigma\cdot\sigma' - \frac{f_\pi^2}{m_\pi^2}\frac{\vec{\sigma}\cdot\vec{q}\,\vec{\sigma}'\cdot\vec{q}}{q^2+m_\pi^2} + \frac{2}{3}\frac{f_\rho^2}{m_\rho^2}\sigma\cdot\sigma' - \frac{f_\rho^2}{m_\rho^2}\frac{(\vec{\sigma}\times\vec{q})\cdot(\vec{\sigma}'\times\vec{q})}{q^2+m_\rho^2}\right) \quad (2)$$

was added to the p-h interactions (1). This interaction fulfills the Pauli-principle sum rules for the Landau parameters[5] and has been used to analyze unnatural-parity states in ^{12}C, ^{16}O, and ^{208}Pb.[6] The Landau parameters $g_0 = 0.7$ and $g_0' = 0.76$ were found to give the best agreement between theory and experiment. Since predominantly isovector states were analyzed, the value of g_0 still remains ambiguous.[6] The magnetic high-spin states, however, are very sensitive to both g_0 and g_0'. In the limit of a δ force, the interaction between the two 12^- single-particle configurations is given by the proton-neutron interaction $g_0 - g_0'$. We find that $g_0 = 0.25$ has to be used in order to reproduce the excitation energies of the $M12$ and $M14$ states. These Landau parameters are very close to the values $g_0 = 0.22$ and $g_0' = 0.65$ determined by Bäckman, Sjöberg, and Jackson[7] from the Reid soft-core potential. In Table I, the energies and $B(M,L)$ values of the magnetic high-spin states are shown. With use of a zero-range force the $B(M,L)$ values are reduced, but the excitation energies are pushed far above the shell-model values. Only the one-pion and ρ exchange provide a mechanism to reduce the excitation energy.

It is well known that the coupling to the phonons may modify the single-particle states appreciably, e.g., Ref. 8. Especially the inclusion of the OPEP and ρ-exchange contributions to the p-h force enhances the fragmentation of the s.p. strength.[9] The $\nu j_{15/2}$ state comes at an excitation energy of 1.42 MeV relative to the ground state of ^{209}Pb which is only 1.2 MeV below the $(3^- \otimes \nu 2g_{9/2})_{15/2^-}$ configuration. Therefore a considerable mixing of these configurations has to be expected, which strongly reduces the single-particle strength

$$Z_m^{(\alpha)} = |\langle A+1, \alpha | a_m^+ | A, 0\rangle|^2 \quad (3)$$

of the $|\alpha\rangle = |\frac{15}{2}^-\rangle$ state at 1.42 MeV in ^{209}Pb. Similar considerations hold for the other single-particle states contributing to the magnetic high-spin states.

We evaluate the single-particle strength $Z_m^{(\alpha)}$ by taking into account explicitly the coupling of phonons in ^{208}Pb to single-particle states, thus obtaining quasiparticle states in the neighbor nuclei. These quasiparticle and quasihole states are used to construct a core-coupling random-phase wave function containing the most relevant 2p-2h configurations. Details are given in Ref. 10. Including as phonons only the 3^- state at 2.61 MeV and the 5^- state at 3.19 MeV, the single-particle strength is reduced to $Z = 0.55$ for the $\nu j_{15/2}\, i_{13/2}^{-1}$ configuration and to $Z = 0.58$ for the $\pi i_{13/2} h_{11/2}^{-1}$ configuration. These single-particle strengths were not further reduced, when more phonons were taken into account. The results of the 2p-2h calculations with a finite-range interaction are given in Table I. The 2p-2h components of the wave function strongly reduce the $B(M,L)$ values as compared to a pure 1p-1h wave function and produce a further decrease of the excitation energy. The fraction of the normalization of the wave function carried by the 2p-2h components is 52.6% for the 14^- state and 47.9% and 48.4% for the 12^- states. The mixing between proton and neutron configurations is found to be negligibly small for the 12^- states.

In Fig. 1, the inelastic electron scattering cross sections at $\vartheta = 90°$ and $\vartheta = 160°$ are shown for the three magnetic high-spin states. The calculations were performed in distorted-wave Born

TABLE I. Excitation energies and $B(M,L)$ values for the magnetic high-spin states in ^{208}Pb obtained with the following models: 1p-1h–a = a single-particle, single-hole configuration; 1p-1h–b = random-phase approximation (RPA) with zero-range interaction; 1p-1h–c = RPA with finite-range interaction; 2p-2h = two-particle, two-hole calculation described in the text. The experimental data are from Ref. 1. The $B(M,L)$ values are divided by the shell-model values (1p-1h–a) $B_1(M,L) = 0.57 \times 10^{23}\ \mu^2 \cdot \mathrm{fm}^{22}$; $B_2(M,L) = 0.68 \times 10^{23}\ \mu^2 \cdot \mathrm{fm}^{22}$; $B_3(M,L) = 1.33 \times 10^{27}\ \mu^2 \cdot \mathrm{fm}^{26}$.

Model	E (MeV)	$B(M,L)/B_1(M,L)$	E (MeV)	$B(M,L)/B_2(M,L)$	E (MeV)	$B(M,L)/B_3(M,L)$
	$J^\pi = 12^-$		$J^\pi = 12^-$		$J^\pi = 14^-$	
1p-1h–a	6.49	1.00	7.18	1.00	6.49	1.00
1p-1h–b	6.77	0.44	7.86	0.91	7.14	0.82
1p-1h–c	6.60	1.18	7.52	0.94	6.68	0.96
2p-2h	6.55	0.60	7.37	0.54	6.65	0.45
expt	6.43		7.06		6.75	

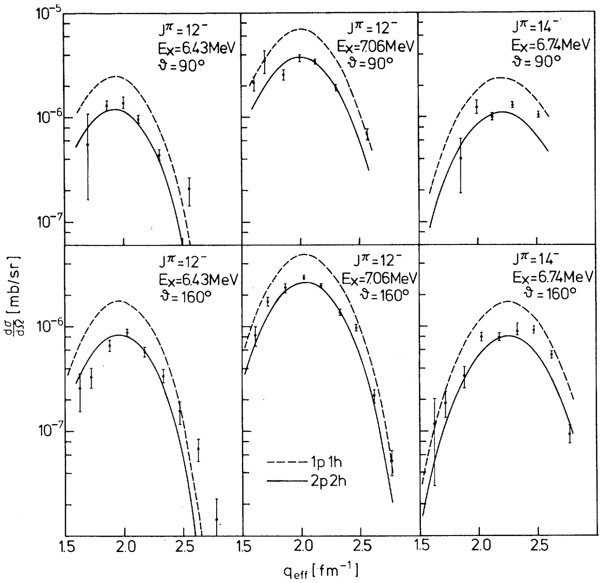

FIG. 1. The experimental cross sections for inelastic electron scattering of Ref. 1 are compared with an RPA calculation (dashed line) and a 2p-2h calculation described in the text (solid line). Both calculations were performed with a finite-range interaction including one-pion and ρ-meson exchange. The cross sections were obtained in DWBA (Ref. 11).

approximation (DWBA), using the code HEIMAG by Heisenberg.[11] The Woods-Saxon functions employed as single-particle wave functions in the present calculation were obtained from the potential of Ref. 12 which was fitted to the neutron rms radius given by Negele's Hartree-Fock calculation.[13] The inclusion of 2p-2h configurations reduces the cross sections, as expected, so that both shapes and absolute magnitudes of the cross sections are now in good though not perfect agreement with the experimental data in the three cases considered.

The single-particle strength missing in the three low-lying states is fragmented into many states at higher energies in this approach. The next 12^- states come at 8.10, 8.23, 8.38, and 8.65 MeV, while 14^- excitations are expected at 8.12, 8.39, and 8.70 MeV, respectively. The maximal inelastic electron scattering cross section of each state is less than 10% of the experimental strength of the known high-spin states, however.

Lindgren *et al.*[14] recently analyzed proton scattering to the high-spin states with a single-particle, single-hole excitation and harmonic-oscillator wave functions.[15] They found that the theoretical (p,p') cross section of the 12^- state at 6.43 MeV had to be reduced by a factor of 0.8 only, in contrast to the inelastic electron scattering analyses.[1] In our calculation, a 13^- state which is almost a pure $\nu j_{15/2} i_{13/2}{}^{-1}$ configuration appears at an excitation energy of 6.56 MeV and has a much smaller inelastic electron scattering cross section at 160° than the first 12^- state. Though the analysis of Lindgren *et al.* should certainly be repeated with more realistic wave functions, it is tempting to conclude that this state might resolve the discrepancy. In fact, Bacher *et al.* resolved two levels at 6.42 and 6.45 MeV in a (p, p') experiment with a preliminary 12^- assignment.[15]

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