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Fine Structure of the Magnetic Dipole States in ^{208}Pb

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The splitting of the magnetic dipole states in ^{208}Pb due to the admixture of two-particle, two-hole configurations is calculated. The qualitative structure of a one-particle, one-hole calculation remains but about 30% of the $M1$ strength is distributed over many levels above 8 MeV. The influence of the spin-dependent part of the interaction on the results is critically discussed.

For more than ten years experimentalists and theorists have investigated magnetic dipole states in nuclei. Originally most of the work was done for light nuclei.[1,2] Recently, however, these investigations have been extended also to the heavier ones. From a comparison of the experimental data with the theoretical results one expects information about the spin-dependent part of the interaction.[3] Among all the heavy nuclei, ^{208}Pb is the best example for such a comparison because the assumptions of the theoretical treatment are most reliable here. The structure of the magnetic dipole resonances in ^{208}Pb is mainly given by the two spin-orbit partners $\pi 1h_{9/2}\text{-}\pi 1h_{11/2}^{-1}$ and $\nu 1i_{11/2}\text{-}\nu 1i_{13/2}^{-1}$. Therefore, in a one-particle, one-hole (1p-1h) approximation [Tamm-Dancoff approximation, random-phase approximation (RPA)] one expects to obtain two 1^+ states which practically exhaust the total $M1$ transition strength to the ground state. The relative strengths and the energies of the two states, however, depend sensitively on the particle-hole interaction used.[4,5]

Here the *Ansatz* of Migdal[6] has been used:

$$F^{\mathrm{ph}}(\vec{r}_1, \vec{r}_2) = C\,\delta(\vec{r}_1 - \vec{r}_2)\{f_0 + f_0'\vec{\tau}_1\cdot\vec{\tau}_2 + g_0\vec{\sigma}_1\cdot\vec{\sigma}_2 + g_0'(\vec{\sigma}_1\cdot\vec{\sigma}_2)\vec{\tau}_1\cdot\vec{\tau}_2\}. \tag{1}$$

Only the spin-dependent part of the force contributes to the magnetic properties. From an analysis of magnetic moments and transition probabilities[7] nearly equal values of g_0 and g_0' follow:

$$g_0^{pp} = g_0^{nn} = g_0 + g_0' = 1.3; \quad g_0^{pn} = g_0 - g_0' = -0.15.$$

In this Letter we present the results of a 2p-2h RPA calculation of magnetic dipole states in ^{208}Pb. We have performed this calculation in order to investigate whether the inclusion of 2p-2h correlations changes qualitatively the 1p-1h result of Ref. 5. Such an effect has been reported by Lee and Pittel.[8]

The present calculation has been performed in the core-coupling RPA.[9] Here we take into account the splitting of the single-particle (or single-hole) states due to the admixture of the low-lying states of ^{208}Pb. The wave functions within this approach are written as

$$|\Psi\rangle = \sum_{m,i}(X_{mi}\chi_m{}^{\dagger}\chi_i - Y_{mi}\chi_i{}^{\dagger}\chi_m)|\varphi_0\rangle, \tag{2}$$

with

$$\chi_m{}^{\dagger} = C_m a_m{}^{\dagger} + \sum_{\alpha,\nu} C_{\alpha\nu}{}^{(m)} B_\alpha{}^{\dagger} a_\nu{}^{\dagger}. \tag{3}$$

The amplitudes X and Y are determined from RPA-like equations,[9] and $a_m{}^{\dagger}$ and $B_\alpha{}^{\dagger}$ are shell-model single-particle creation operators and the usual RPA phonon creation operators, respectively.

In a first step, using the methods of Ring and Werner,[10] we determine the coefficients C_m and $C_{\alpha\nu}{}^{(m)}$ of Eq. (3), i.e., the distribution of the single-particle (or hole) strength due to the admixtures of the core states. In this step of the procedure (but not in the following 2p-2h calculation) we neglect the Pauli principle. This is justified since the single-particle states involved are highly degenerate. Experimentally we know that the single-particle (or -hole) strengths in the neighboring odd-mass nuclei of ^{208}Pb deviate only a little from unity, except for those single-particle states which possess the "wrong" parity. This is connected with the fact that these levels (e.g., $\pi h_{11/2}{}^{-1}$ and $\nu i_{13/2}{}^{-1}$) admix easily with the prevailing levels of the opposite parity and the low-lying collective 3^- state of ^{208}Pb. Therefore, in the present approach, we only take into account the splitting of the hole states.

In Fig. 1(a), the 1p-1h RPA results of Ref. 5 are shown. Here an effective magnetic operator was used which reduces the absolute values of the transition probabilities. This operator corrects for mesonic and higher-order (e.g., 2p-2h) contributions.[6,11] For comparison, in Fig. 1(b) the same RPA result is given but without using the effective operator. In the lower half we show the 2p-2h results. In a first approach [Fig. 1(c)] we investigated the influence of only the lowest 3^- state on the spreading of the 1^+ states. The strength of the upper 1^+ level is reduced and we obtain two additional strong 1^+ levels about 1.0 and 1.8 MeV higher in energy. The structure

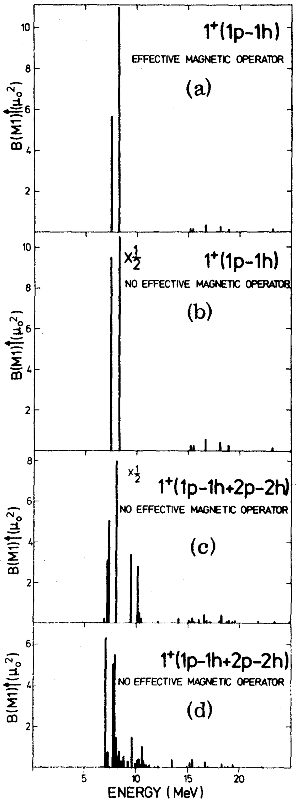

FIG. 1. Different RPA results of the magnetic dipole states in ^{208}Pb. The splitting of the 1^+ states presented in (c) is due to the admixture of only the first excited (3^-) state of ^{208}Pb. In the calculation shown in (d) all the states up to 4.32 MeV (4^+) are included. For comparison in (a) and (b) the 1p-1h RPA results of Ring and Speth (Ref. 5) are shown with and without use of their effective magnetic operator, respectively. The level at 8.30 MeV in (b) and (c) is reduced by one half. In the four calculations the parameters $g^{pp} = 1.30$ and $g^{pn} = -0.15$ are used.

TABLE I. Comparison between the experimental results (Ref. 14) and two different 1p-1h plus 2p-2h RPA calculations of 1^+ states in ^{208}Pb.

Experiment		Theory I ($g^{pn} = -0.15$)		Theory II ($g^{pn} = +0.02$)	
E (MeV)	$B(M1)\uparrow$ (μ_0^2)	E (MeV)	$B(M1)\uparrow$ (μ_0^2)	E (MeV)	$B(M1)\uparrow$ (μ_0^2)
7.06[a]	16.8	7.107	6.33	7.131	9.58
		7.250	0.75	7.256	2.18
		7.475	0.04	7.475	0.17
7.99[b]	10.0	7.853	5.08	7.863	9.10
		7.909	0.01	7.909	0.34
				7.910	0.17
		7.927	0.45	7.927	0.02
		7.933	5.47		
		7.940	0.03		
		8.106	1.49	8.102	0.60
8.228	1.21 ± 0.23	8.303	0.54	8.303	0.45
8.367	0.93 ± 0.04	8.404	0.80	8.402	0.49
8.604	1.35 ± 0.04	8.601	0.33	8.601	0.27
8.694	1.23 ± 0.08	8.771	0.26	8.771	0.21
9.008	1.56 ± 0.07	8.835	0.21	8.835	0.19
9.142	1.39 ± 0.31	8.841	0.55	8.841	0.43
9.299	0.84 ± 0.16	9.281	0.30	9.281	0.29
9.512	0.99 ± 0.21	9.652	1.51	9.651	1.38
		9.983	0.22	9.983	0.22
		10.197	0.41	10.197	0.42
		10.302	0.44	10.302	0.42
		10.481	0.17	10.481	0.17
		10.496	0.11	10.496	0.14
		10.593	1.00	10.593	1.03
		10.768	0.33	10.770	0.71
		10.858	2.89	10.853	1.99

[a] Ref. 12.

[b] Ref. 13.

changes qualitatively if we include all low-lying states of ^{208}Pb up to 4.32 MeV (4^+). Now the strength of the new high-lying 1^+ states in Fig. 1(d) is distributed over many additional 1^+ states and the strong state at around 8 MeV is split into two pieces. If we add these up, then the $M1$-strength distribution between 7 and 8 MeV is very similar to the original one of Ring and Speth; however, we now have used the bare (Schmidt) $M1$ operator. This would only be justified if the main contributions to the effective operator are of 2p-2h character, which is probably not the case. From the meson-exchange currents, however, we might expect even an enhancement of the transition probability.

In Table I we compare these results (theory I) with the present experimental data. The new 1^+ states between 8 and 10 MeV agree at least qualitatively with a most recent experiment.[14] If we make this comparison for the three strongest levels then one notices that the theoretical strength distribution is just reversed. From the 1p-1h RPA investigations of Ref. 11 one knows that this distribution is strongly influenced by the (very weak) spin-dependent proton-neutron interaction g^{pn}. If $g^{pn} < 0$ (theory I) the proton and neutron amplitudes add coherently in the upper state; if one reverses the sign of g^{pn} the lower state is the coherent one. In Fig. 2 and Table I (theory II) we show theoretical results calculated with different, weakly repulsive g^{pn}. The most surprising result here is the disappearance of the splitting of the strong state at around 7.9 MeV. This effect can be understood by looking at the wave functions of the two states. For $g^{pn} = 0$ the 7.85-MeV level is predominantly a 1p-1h neutron state ($i_{11/2} \times i_{13/2}^{-1}$), whereas the dominant structure of the 7.93-MeV state is of the form $[5_1^- \times \pi 3s_{1/2}^{-1}]_{11/2} \times \pi 1h_{9/2}$ plus a $\pi 1h_{9/2} \times \pi 1h_{11/2}^{-1}$ admixture of 0.2 in amplitude. A finite proton-neutron interaction $g^{pn} \neq 0$ gives rise to a mixture of the two states. The 1p-1h $M1$ components of the two states add coherently in the upper state if $g^{pn} < 0$ and destructively for $g^{pn} > 0$. For small positive g^{pn} they

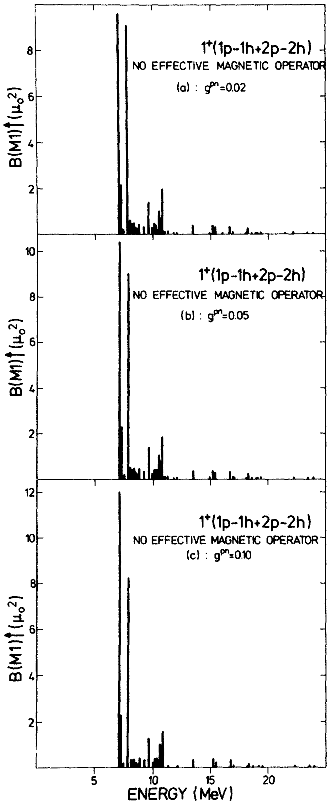

FIG. 2. RPA results of the magnetic dipole states in ^{208}Pb, using different proton-neutron interactions g^{pn}.

nearly cancel each other. The structure of the 7.10-MeV level is predominantly $\pi 1h_{9/2} \times \pi 1h_{11/2}{}^{-1}$, whereas the levels between 8 and 11 MeV are of 2p-2h character with small 1p-1h admixtures. The higher states in Figs. 1 and 2 are due to the $2\hbar\omega$ excitations.[15]

In conclusion, we have calculated the splitting of the low-lying $M1$ resonances due to the admixture of the 2p-2h configurations. Because of this effect about $\frac{1}{3}$ of the $M1$ strength is shifted to higher energies and is distributed over many levels between 8 and 11 MeV. In addition we have shown that the $M1$-strength distribution of the main peaks depends very sensitively on the spin-dependent proton-neutron interaction g^{pn}. The present experimental data seem to favor a small positive g^{pn} value ($g_0' < g_0$). This does not necessarily mean that the originally small negative g^{pn} value ($g_0' > g_0$) which has been deduced from magnetic moments and low-lying $M1$ transitions[7] is incorrect, since we have used a zero-range force. This might indicate a finite-range effect, because this force is determined by the one-π exchange, which reduces the g_0' parameter[16] and from which one expects that it gets more important with increasing transition energy.

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