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Modifications of the tensor and spin-orbit interactions and the stretched states in ^{208}Pb

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We have reanalyzed the (e,e') and (p,p') data at 318 MeV on the stretched, $12^-_{1,2}$ and 14^-, states of ^{208}Pb using the ideas of G. Brown and co-workers on the reduction of meson and nucleon masses in the nuclear medium. The reaction calculations are compared with new, large basis random-phase-approximation calculations using a residual interaction, also modified, in a consistent way. The resulting interaction, based on the one boson exchange $(\pi+\rho)$ model, has reduced tensor and enhanced spin-orbit strengths. Agreement between electron and proton quenching factors is found for effective masses, $m^*/m \simeq 0.79-0.86$. The reduction or enhancement factors for the modified interaction are in qualitative agreement with those found in other analyses.

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I. INTRODUCTION

A. Mass scaling

Evidence has been accumulating [1–13] for the need of "nonstandard" medium modifications in the nucleon-nucleon (NN) interaction used in nuclear structure and intermediate energy nucleon-nucleus scattering calculations. The "standard" medium modifications [14] of the free NN interaction include such effects as Pauli blocking, correlations, and off-shell corrections.

It has been suggested, especially by Brown and co-workers [7–9,13], that scalar and vector mesons, and nucleon masses, obey a universal scaling with nucleon density, ρ, of the form $m^*/m \simeq 1-\lambda\rho/2\rho_0$, where ρ_0 is the nuclear central density and λ is expected to be in the range $\lambda \simeq 0.2-0.4$.

Some of the consequences of this m^* scaling are (1) modifications of the strength and geometry of the kaon- and nucleon-nucleus optical potentials [15,8]; (2) an enhancement of the NN spin-orbit force and a reduction (at large q) of the tensor interaction in the nuclear medium [8,9]; (3) a stiffening of nucleon-nucleus spin-isospin response [9]; (4) a partial explanation of the Okamoto-Nolen-Schiffer anomaly [16,17], based on the reduction, in medium, of the neutron-proton mass difference [18–20]; and (5) enhanced kaon production in relativistic heavy-ion collisions [21]. The first two effects are discussed in more detail below.

In this work we are exploring the consequences of mass scaling ("nonstandard" medium modifications) for proton [22] and electron [23] excitation of the high spin ($12^-_{1,2}$ and 14^-) stretched states of ^{208}Pb. Here we investigate, in a consistent way, the effects of mass scaling on the (p,p') cross sections and on the large basis random-phase-approximation (RPA) structure calculations [24,25].

Some of the consequences of a density-dependent mass scaling which are relevant to this work follow.

1. Elastic optical potential

In the impulse approximation (IA) the central part of the optical potential comes from the central spin-independent part of the NN (or KN) interaction, $t_0(q)$, at fairly low momentum transfer ($q \lesssim 0.5$ fm^{-1}). The real part of t_0 is expected to scale as $(m/m^*)^2$, leading to an enhancement (in the zero-range approximation) by a factor of $\sim(1-\lambda)^{-1}$ and a "shrinking" of the effective real potential radius, $R'=R-\lambda a$, where R and a are the geometry parameters of the unmodified potential [15]. This modification, with $\lambda=0.3\pm0.1$, eliminates the radius discrepancy found in the analysis of proton [8] and K^+-nucleus [15] scattering when densities derived from electron scattering are used in the distorted-wave impulse approximation (DWIA). The radius problem seems to persist even when standard medium modifications are included [26].

The imaginary central part of the optical potential should not be much affected by the mass scaling [8].

2. Spin-orbit interaction

In relativistic mean-field theories the spin-orbit potential scales as $(m/m^*)^3$ [8]. It is reasonable to assume a similar scaling for the NN spin-orbit interaction, t_{LS}. This enhancement in medium will affect elastic and inelastic cross sections and spin observables as well as nuclear structure calculations in which the residual spin-orbit interaction is important.

3. *Tensor and spin-isospin interactions*

In the one boson exchange (OBE) model, with π and ρ mesons, it is predicted [9] that the π part is not much changed but that the ρ contribution should be enhanced by $\sim(m_\rho/m_\rho^*)^2$, leading to an overall reduction of the isovector tensor interaction, $t_{T\tau}$, at high q and an enhancement of the spin-isospin interaction, $t_{\sigma\tau}$. We will see that the modification of $t_{T\tau}$ has consequences for the reaction and structure aspects of the ^{208}Pb stretched states.

B. ^{208}Pb (p,p') and (e,e')

The 12_1^- (6.43 MeV), 12_2^- (7.06 MeV), and 14^- (6.74 MeV) stretched states in ^{208}Pb have been studied in (e,e') [23,27], and in (p,p') at $T_p=135$ [28], 200 [29], and 318 [22] MeV. The 14^- state [at least the one-particle –one-hole (1p-1h) component] is found to be a nearly pure ν $(j_{15/2}i_{13/2}^{-1})$ configuration with a quenching factor, $Q=\sigma_{\text{exp}}/\sigma_{\text{theo}}$ of ~ 0.5 in both (e,e') and (p,p'). (The fact that $Q\neq 1$ presumably reflects the presence in the wave function of 2p-2h and other components not contributing to the inelastic cross sections.) The 12_1^- state is found to be dominated by the (nearly stretched) $\nu(j_{15/2}i_{13/2}^{-1})$ configuration and the 12_2^- by the stretched $\pi(i_{13/2}h_{11/2}^{-1})$ configuration. However, if the (e,e') and (p,p') cross sections are analyzed assuming a single 1p-1h component for each state [22,28], the (e,e') and (p,p') quenching factors, Q_e and Q_p, are found to be in disagreement. It should be noted that the excitation of stretched (or nearly stretched) unnatural parity states is dominated by the same spin density in both (e,e') and (p,p') and so the quenching factors should agree if the analysis is correct.

In an earlier analysis [22] it was found that with a small admixture of the proton (π) component in the 12_1^- state and of the neutron (ν) component in the 12_2^- state one could bring Q_e and Q_p into approximate agreement. In this earlier analysis, the nonrelativistic DWIA with the free Franey-Love interaction [30] was employed for the (p,p') calculations, the DWBA was used for the (e,e'), and the 12^- states were described with a two-component model:

$$\begin{aligned}|12_1^-\rangle &= (1-a^2)^{1/2}|\nu(j_{15/2},i_{13/2}^{-1})\rangle \\ &\quad + a|\pi(i_{13/2},h_{11/2}^{-1})\rangle\,, \\ |12_2^-\rangle &= -a|\nu(j_{15/2},i_{13/2}^{-1})\rangle \\ &\quad + (1-a^2)^{1/2}|\pi(i_{13/2},h_{11/2}^{-1})\rangle \end{aligned} \tag{1}$$

A value of $a=+0.07\pm0.02$ was found to give the best results. It should be noted that the contribution of meson exchange currents (MEC) to the (e,e') cross sections was *not* included in this analysis.

Subsequently, a large basis RPA calculation, including 100 single-particle states in the configuration space, was performed [24] using either a zero-range Landau-Migdal interaction (δ interaction) or the Jülich–Stony Brook interaction [31] ($\delta+\pi+\rho$ interaction), the last one being a Landau-Migdal interaction modified by the inclusion of the π- and ρ-exchange potentials.

The two extremes gave either too much mixing for the 12^- states (δ interaction) or mixing with the wrong sign ($a<0$, for the full $\delta+\pi+\rho$ interaction). This result suggested an intermediate solution, with a reduction of the strength of the π- and ρ-exchange potentials.

Finally, Co' and Lallena [25] studied the spin-dependent and tensor parts of the residual interaction by using the same two interactions. In their work the 12^- states were analyzed together with the two (isoscalar and isovector) 1^+ states of ^{208}Pb, and they found that a reduction of the strength of the tensor interaction was necessary to reasonably describe the experimental data.

In this work we present a new analysis of the 318 MeV (p,p') and the (e,e') data including m^* modifications in the proton calculations and MEC corrections to the electron cross sections. The results will be compared with new RPA calculations using a residual interaction which also includes the m^* modifications. Also, reductions in the full $\delta+\pi+\rho$ interaction as well as in the tensor part are investigated.

In Secs. II A and II B we outline the reaction calculations. In Sec. II C we present results based on a two-component model for the 12^- states and describe the RPA calculations. In Sec. II D we present our final "consistent" reaction and structure calculations and in Sec. II E some comparisons with other work. In Sec. III we give a summary and conclusions.

II. DETAILS OF THE CALCULATIONS AND RESULTS

A. Reaction calculations

The proton calculations employed the nonrelativistic impulse approximation (program DWBA 70) [32] with the (free) Franey-Love (FL) t-matrix $t_{NN}(E,q)$ modified as described in Sec. II B. A phenomenological optical potential [22], which gives an excellent fit to the σ, A_y, and Q data at $\sim$318 MeV, was used for the distorted waves. The results are nearly the same if an IA optical potential calculated with m^* modifications [8] is used instead. The potential parameters for the Woods-Saxon well used for the bound-state wave functions in the (p,p') and (e,e') calculations were the same as in Ref. [22]. In the final RPA calculations the same geometry parameters were used but the well depths were fixed to give the same binding energies for the dominant single-particle states as were used in the reaction calculations. The electron calculations were similar to those described previously [22] using the distorted-wave code HEIMAG [33]. However, the calculated electron cross sections were corrected for MEC effects taking the (q-dependent) percentage corrections ($\sim$10–20 %) to be the same as found in a plane-wave Born approximation (PWBA) calculation [24] in which MEC were explicitly included. MEC contributions to the (p,p') cross sections are expected to be very small and thus were not included here.

B. Modification of tensor and spin-orbit interactions

The OBE ($\pi+\rho$) model [31,34] was used as a guide in modifying the real part of the FL isovector tensor interaction, $\mathrm{Re}t_{T\tau}$. In principle the central $t_{\sigma\tau}$ interaction should also be modified, but this was ignored as it contributes only a few percent to the (p,p') cross sections, which are dominated by the tensor and spin-orbit interactions. For simplicity, we have not included the explicit density dependence of m^*/m but have used constant values. Thus our m^*/m correspond to some average value in the surface region ($\rho\simeq\rho_0/2$) where the transition densities for the high spin states peak. A further simplification was to equate the OBE *potential* to the FL *t matrix* (both in momentum space) which is correct only in the PWIA.

We have *not* modified the imaginary isovector part or the isoscalar parts of the FL t_T as these are small and not given by the OBE model.

The OBE ($\pi+\rho$) isovector tensor interaction can be written as

$$V_{T\tau}(q)=G_\pi\frac{q^2}{q^2+m_\pi^2}-G_\rho\frac{q^2}{q^2+m_\rho^2}\ , \tag{2}$$

where $G_i=(4\pi\hbar c/3)(f_i/m_i)^2$, and $m_\rho=770$ MeV, or 3.9027 fm^{-1}, $m_\pi=138$ MeV, or 0.6994 fm^{-1}. The "free" coupling parameters are

$$G_\pi\simeq 135\ \mathrm{MeV\,fm^3}\ \text{ and }\ G_\rho\simeq(1.5\text{–}2)G_\pi\ .$$

However, the FL $t_{T\tau}(q)$ is only qualitatively similar to the OBE ($\pi+\rho$) potential at 325 MeV so the procedure was first to adjust G_π and G_ρ to fit the *unmodified* FL $\mathrm{Re}t_{T\tau}$, keeping $m_\pi=138$ MeV and $m_\rho=770$ MeV. This resulted in $G'_\pi=80$ MeV fm^3 and $G'_\rho=122$ MeV fm^3. The OBE potential was then modified by scaling G_ρ as $(m/m^*)^2=1.563$, giving $G_\rho=190$ MeV fm^3, corresponding to $m^*/m=0.8$ ($\lambda=0.4$), and replacing m_ρ (in the q-dependent factor) by $m_\rho^*=0.8m_\rho$. The pion contribution is not expected to change much in medium [9], and so was fixed. Finally, to input to DWBA 70, the FL tensor coefficients, V_i^T, were adjusted to fit the modified OBE potential (real isovector parts only). In this way both the direct and exchange parts of $\mathrm{Re}t_{T\tau}$ were modified.

In momentum space, the FL tensor interaction is parametrized as

$$\tilde{V}^T(q)=32\pi\sum_i\frac{V_i^Tq^2R_i^7}{[1+(qR_i)^2]^3}\ . \tag{3}$$

At the first step, G_π and G_ρ were adjusted to fit the unmodified FL $\mathrm{Re}t_{T\tau}$ at $q=1.8$ and 4.3 fm^{-1}, near the peak of the (p,p') cross section (~1.8 fm^{-1}) and the knock-on exchange (~4.3 fm^{-1}) q values. At the final stage the V_i^T were fitted by the modified OBE ($\pi+\rho$) at $q=1.2$, 2.8, and 4.3 fm^{-1} giving essentially a perfect fit. The modified FL coefficients are given in Table I. The steps described above are illustrated in Fig. 1. It can be seen that the modified $\mathrm{Re}t_{T\tau}$ is about half the unmodified one around $q=2$ fm^{-1} and much larger and of opposite sign at the knock-on exchange momentum.

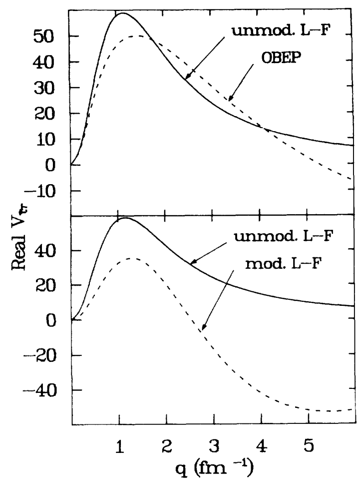

FIG. 1. Upper: Unmodified Franey-Love (FL) $\mathrm{Re}\tilde{V}_\tau^T$ [Eq. (3)] (solid line) and OBE ($\pi+\rho$) potential fit [Eq. (2)] with $G'_\pi=80$ MeV fm^3 and $G'_\rho=122$ MeV fm^3 (dashed line). Lower: Modified (dashed line) and unmodified (solid line) FL interactions. The modified FL is a fit to the modified OBE potential with $G_\pi=80$ MeV fm^3 and $G_\rho=190$ MeV fm^3.

The spin-orbit modification was done more crudely. As mentioned above, in relativistic mean-field theory the spin-orbit potential scales as $(m/m^*)^3$. We simply scaled the real spin-orbit amplitudes in the DWBA 70 calculations by a factor F_{LS} which was adjusted to give the same quenching factor (Q_i) in (e,e') (corrected for MEC) and (p,p') for the nearly pure 14^- neutron state ($Q=0.47$). This resulted (assuming a single neutron configuration for the 14^- state) in $F_{LS}=1.4$ which corresponds to $m^*/m=0.89$ if $(m/m^*)^3$ scaling is

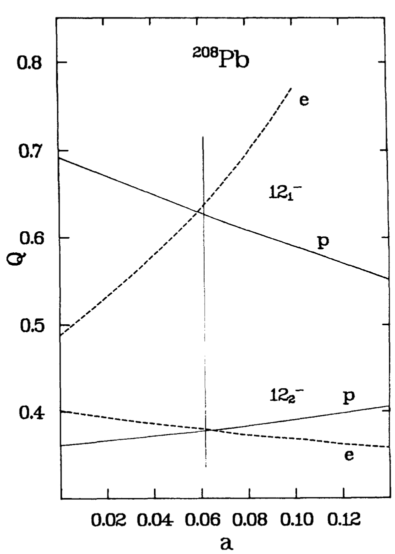

FIG. 2. Quenching factors, $Q=\sigma_{\mathrm{exp}}/\sigma_{\mathrm{theo}}$ for (e,e') (dashed) and (p,p') (solid) vs mixing parameter a [Eq. (1)] in the two-component model. The (p,p') calculations were made with the modified ($\mathrm{Re}t_{T\tau}$) FL interaction with $\mathrm{Re}F_{LS}=1.4$. The (e,e') calculations include MEC contributions.

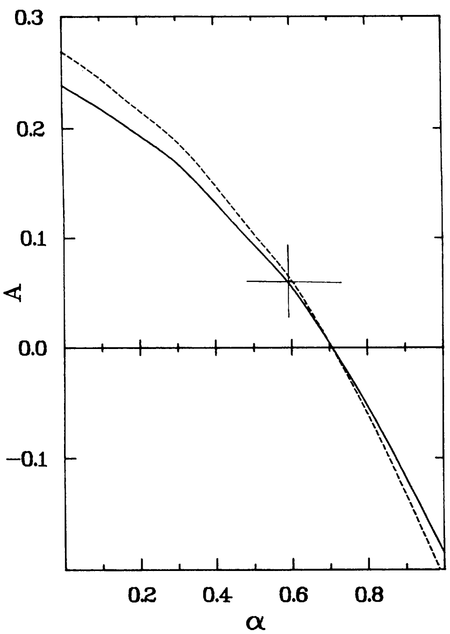

FIG. 3. RPA effective amplitudes, $A=X-Y$ for the 12_1^- states of ^{208}Pb vs OBE ($\pi+\rho$) strength parameter, α [Eq. (10)]. The solid line shows A_π for the $\pi(i_{13/2},h_{11/2}^{-1})$ configuration in the 12_1^- state. The dashed line shows $-A_\nu$ for the $\nu(j_{15/2},i_{13/2}^{-1})$ configuration in the 12_2^- state. The cross shows solution for a two-component model, $A_\pi \simeq -A_\nu \simeq a=0.06$.

assumed—a not unreasonable value in the nuclear surface where the 14^- transition density peaks. In the full RPA calculations described below, slightly different values of F_{LS} were used to fix $Q_p=Q_e$ for the 14^- state.

TABLE I. Modified Franey-Love[a] coefficients, V_i^T, for real parts of tensor interaction at 325 MeV.

R_i	TNE[b]	TNO[b]
0.15	1.713 10(5)	−5.181 85(4)
0.25	−3.595 61(2)	−3.197 66(2)
0.40	−9.121 17(2)	3.014 39(2)
0.70	−1.232 35(1)	2.553 90

[a]The unmodified coefficients are given in Ref. [30]. TNE and TNO are the modified real tensor-even (l) and tensor-odd coefficients in the t-matrix expansion (Eqs. (14) and (15c) of Ref. [41]). The units are MeV fm^{-2}. The ranges are in fm.
[b]Numbers in parentheses indicate powers of 10; note $\tilde{V}_\tau^T=\frac{1}{4}$ (TNO-TNE). TNO and TNE were modified in such a way as to keep $\tilde{V}_0^T$ (isoscalar tensor) unchanged.

C. Two-component (12^-) model calculations and large basis RPA

The (p,p') and (e,e') cross sections and quenching factors were first calculated for the 12^- states in the two-component model [Eq. (1)] using the modified $\mathrm{Re}t_{T\tau}$ interaction, with $F_{LS}=1.4$, and varying the mixing parameter, a. The proton and MEC corrected electron quenching factors are shown in Fig. 2. It can be seen that $a=0.06\pm0.01$ results in agreement between Q_e and Q_p for both 12^- states with $Q(12_1^-)=0.62\pm0.02$, $Q(12_2^-)=0.38\pm0.02$ [and $Q(14^-)=0.47$].

The "experimental" value of the mixing parameter a can now be compared with the mixing of the above π and ν configurations in the 12^- states in the large basis RPA calculations where the same configurations dominate. The unmodified residual interaction used in the RPA cal-

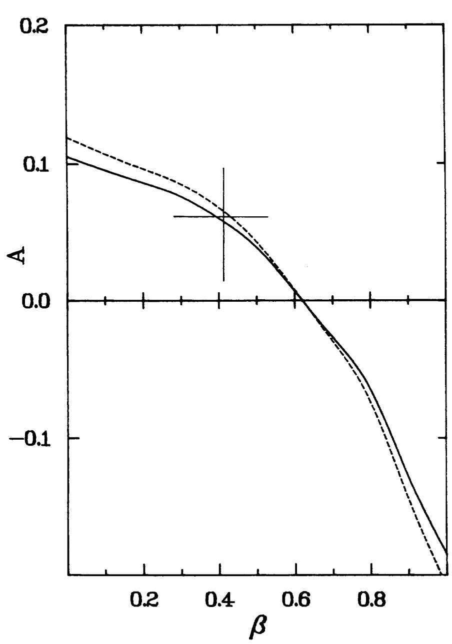

FIG. 4. Same as Fig. 3 but for OBE ($\pi+\rho$) parameter, β [Eq. (11)] for V^T.

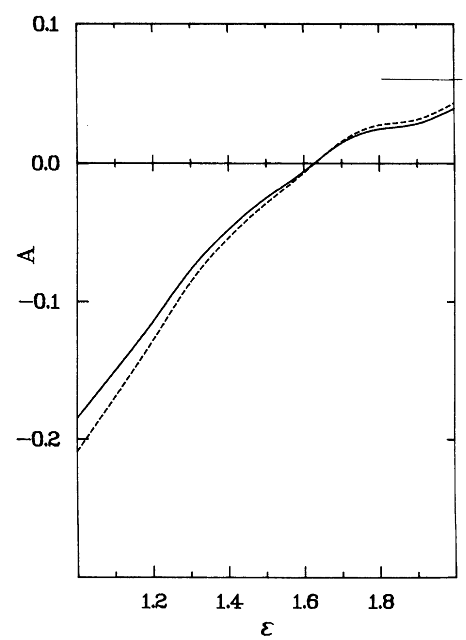

FIG. 5. Same as Fig. 3 but for OBE ($\pi+\rho$) parameter, ϵ [Eq. (12)] for V_ρ. In this calculation, m_ρ (in the range, or q-dependent factors) was kept fixed at the free value.

culation was taken to be the Jülich-Stony Brook interaction [31] which is composed of a long-range part based on the potential generated by the exchange of π and ρ mesons, and a short-range part given by a phenomenological zero-range Landau-Migdal- (LM) type interaction which simulates the short-range correlations. In momentum space this interaction can be written as follows:

$$V_{\rm res}(q)=V_{\rm LM}+V_{\pi}^{\sigma\tau}(q)+V_{\pi}^{T}(q)+V_{\rho}^{\sigma\tau}(q)+V_{\rho}^{T}(q)\ , \qquad (4)$$

where

$$V_{\rm LM}=C_0[g_0\sigma_1\cdot\sigma_2+g_0'\sigma_1\cdot\sigma_2\tau_1\cdot\tau_2] \qquad (5)$$

with $C_0=386.04$ MeV fm^3, and

TABLE II. RPA amplitudes at $\epsilon=1.0$ and 1.6[a] for 12_1^- (6.43 MeV) and 12_2^- (7.06 MeV) states of ^{208}Pb.

	$\epsilon=1.0$ Configuration[b]		$g_0=0.95$ 12_1^-		$g_0'=0.65$ 12_2^-	
	Particle	Hole	X	Y	X	Y
π	167	156	0.2770	−0.0084	0.9571	0.0554
π	178	145	−0.0084	0.0046	0.0700	−0.0288
π	189	134	0.0037	−0.0028	−0.0269	0.0164
π	189	156	−0.0069	0.0039	0.0375	−0.0175
ν	256	167	0.0054	−0.0017	0.0048	−0.0010
ν	267	156	0.0031	−0.0017	−0.0118	0.0061
ν	177	167	−0.0174	−0.0063	0.0213	0.0043
ν	178	145	−0.0256	0.0121	0.0648	−0.0257
ν	178	167	−0.9603	−0.0212	0.2729	0.0299
ν	188	155	−0.0022	0.0016	−0.0022	0.0030
ν	188	156	0.0056	0.0035	−0.0009	0.0001
ν	189	134	0.0099	−0.0067	−0.0236	0.0143
ν	189	234	−0.0216	0.0083	0.0451	−0.0139
ν	189	155	−0.0105	−0.0041	0.0275	0.0092
ν	189	156	−0.0190	0.0095	0.0322	−0.0144
	Calculated energy (MeV)		6.78		8.06	
	Calculated $B(M12)$[c]		0.355(+23)[d]		0.241(+23)	

	$\epsilon=1.6$ Configuration[b]		$g_0=-0.03$ 12_1^-		$g_0'=0.69$ 12_2^-	
	Particle	Hole	X	Y	X	Y
π	167	156	0.0291	−0.0011	0.9994	0.0146
π	178	145	−0.0010	0.0003	0.0168	−0.0073
π	189	134	0.0001	−0.0001	−0.0067	0.0041
π	189	156	−0.0013	0.0006	0.0068	−0.0035
ν	256	167	−0.0026	0.0007	0.0013	−0.0009
ν	267	156	−0.0006	0.0004	−0.0017	0.0012
ν	177	167	0.0081	0.0027	0.0055	0.0002
ν	178	145	0.0085	−0.0041	0.0118	−0.0047
ν	178	167	0.9995	0.0059	−0.0293	−0.0017
ν	188	155	−0.0019	0.0016	0.0089	−0.0027
ν	188	156	−0.0020	−0.0010	0.0013	0.0015
ν	189	134	−0.0035	0.0023	−0.0046	0.0025
ν	189	234	0.0069	−0.0028	0.0040	−0.0014
ν	189	155	0.0059	0.0022	0.0101	0.0037
ν	189	156	0.0052	−0.0027	−0.0016	0.0006
	Calculated energy (MeV)		6.56		7.39	
	Calculated $B(M12)$[c]		0.181(+23)		0.458(+23)	

[a]"Consistent-ϵ" calculation with $m_\rho^*/m_\rho=1/\sqrt{\epsilon}$ in q-dependent denominator in OBE (ρ) interaction. X and Y in the table (rounded off from six figures) are in the convention in which *all* single-particle orbitals are positive near the origin.

[b]Number sequence indicates n, l, $j+\frac{1}{2}$ (π, proton; ν, neutron). Dominant configurations used in the two-component model are underlined.

[c]The units are μ^2 fm^{22}.

[d]Numbers in parentheses indicate powers of 10.

$$V_\pi^{\sigma\tau}(q)=\frac{4\pi\hbar c}{3}\frac{f_\pi^2}{m_\pi^2}\frac{m_\pi^2}{q^2+m_\pi^2}\sigma_1\cdot\sigma_2\tau_1\cdot\tau_2\ , \tag{6}$$

$$V_\pi^T(q)=-\frac{4\pi\hbar c}{3}\frac{f_\pi^2}{m_\pi^2}\frac{q^2}{q^2+m_\pi^2}S_{12}(\hat{q})\tau_1\cdot\tau_2\ , \tag{7}$$

$$V_\rho^{\sigma\tau}(q)=2\frac{4\pi\hbar c}{3}\frac{f_\rho^2}{m_\rho^2}\frac{m_\rho^2}{q^2+m_\rho^2}\sigma_1\cdot\sigma_2\tau_1\cdot\tau_2\ , \tag{8}$$

$$V_\rho^T(q)=\frac{4\pi\hbar c}{3}\frac{f_\rho^2}{m_\rho^2}\frac{q^2}{q^2+m_\rho^2}S_{12}(\hat{q})\tau_1\cdot\tau_2 \tag{9}$$

are the spin-isospin and tensor parts of the π- and ρ-exchange potentials which have been modified as described in Speth *et al.* [31]. The parameters g_0 and g_0' were adjusted to fit the energies of the 1^+ states in ^{208}Pb ($E_{\rm ex}=5.85$ and 7.30 MeV) as in Ref. [25]. The π and ρ coupling constants have been taken as $f_\pi^2=0.08$ and $f_\rho^2=4.85$.

Calculations were made by varying the residual interaction in the following three ways:

$$V_{\rm res}=V_{\rm LM}+\alpha(V_\pi^{\sigma\tau}+V_\pi^T+V_\rho^{\sigma\tau}+V_\rho^T)\ , \tag{10}$$

$$V_{\rm res}=V_{\rm LM}+V_\pi^{\sigma\tau}+V_\rho^{\sigma\tau}+\beta(V_\pi^T+V_\rho^T)\ , \tag{11}$$

$$V_{\rm res}=V_{\rm LM}+V_\pi^{\sigma\tau}+V_\pi^T+\epsilon(V_\rho^{\sigma\tau}+V_\rho^T)\ . \tag{12}$$

In the first case the α-parameter controls the strength of the full ($\pi+\rho$)-exchange potential in the residual interaction which permits us to investigate the intermediate solution suggested by Refs. [22] and [24] and mentioned in the Introduction. The contribution of the tensor piece is modulated by the β parameter of the second type of residual interaction. Its variation allows a detailed investigation of the quantitative contribution of this part of the interaction extending the results found in Ref. [25]. Finally the ϵ parameter of the third version allows us to vary the ρ-exchange contribution. By varying ϵ we investigate the scaling of the ρ-meson mass as suggested by Brown and Rho [9,13].

In the first step the three kinds of calculation were done keeping m_π and m_ρ at the free values. The results show that the two dominant 1p-1h components of the 12^- states are the same as in the two-component model of Eq. (1). The remaining 1p-1h configurations have very small amplitudes ($X,Y<0.02-0.05$). In Figs 3–5 we plot the effective amplitudes, $A=X-Y$ (X and Y being the RPA forward and backward amplitudes) for the two dominant components of the 12^- states. The solid lines correspond to A_π for the $\pi(i_{13/2}h_{11/2}^{-1})$ component of the 12_1^- state, the dashed lines show $-A_\nu$ for the $\nu(j_{15/2}i_{13/2}^{-1})$ component of the 12_2^- state. These amplitudes are approximately equivalent to the "empirical" mixing parameter a of the two-component model [Eq. (1)]. As can be seen, the observed mixing ($a\simeq0.06$) is obtained either for $\alpha=0.6$, or $\beta=0.4$, or $\epsilon>2.1$.

The value of $\beta=0.4$ we find here differs significantly from the 30% reduction proposed in Ref. [25]. In this respect we must point out that the inclusion of (p,p') data in this analysis, which were not taken into account by the authors of Ref. [25], is responsible for the additional reduction. On the other hand, the value of $\epsilon>2.1$ is large in comparison with the value $\frac{16}{9}$ proposed by Brown and Rho [9]. However, in this first step (α, β, ϵ variation with free m_π and m_ρ) the reaction and RPA structure calculations were not completely consistent as slightly different bound-state parameters were used in the (p,p') (from Ref. [22]) and RPA (from Ref. [24]) calculations. Further, the modified FL interaction was derived using $m_\rho^*/m_\rho=0.8$ In the "consistent - ϵ" calculation presented below, the (p,p') and RPA calculations were done in a more consistent way.

TABLE IV. Quenching factors[a] vs ϵ.

ϵ[b]	1.0	1.2	1.4	1.6
ReF_{LS} [c]	1.89	1.61	1.54	1.55
$Q(14^-)$[d]	0.51	0.48	0.47	0.47
$Q_e(12_1^-)$	0.23	0.37	0.54	0.61
$Q_p(12_1^-)$	1.32	0.85	0.66	0.60
$Q_e(12_2^-)$	0.53	0.43	0.39	0.37
$Q_p(12_2^-)$	0.37	0.36	0.38	0.36

[a]$Q=\sigma_{\rm exp}/\sigma_{\rm theo}$, errors in Q are estimated to be ±7% due to normalization uncertainties.
[b]Values of Q are given for the "consistent-ϵ", full RPA calculations as described in the text.
[c]Real spin-orbit amplitude enhancement factor in (p,p') calculations.
[d]ReF_{LS} has been adjusted to give $Q_e=Q_p=Q$ for 14^- state in full RPA calculation.

TABLE III. RPA amplitudes at $\epsilon=1.0$ and 1.6[a] for 14^- (6.74 MeV) state of ^{208}Pb.

	Configuration[b] Particle	Hole	$\epsilon=1.0$ X	Y	$\epsilon=1.6$ X	Y
π	189	156	−0.0512	0.0253	−0.0104	0.0052
ν	178	167	−0.9995	−0.0680	−1.0000	−0.0144
ν	189	156	−0.0674	0.0315	−0.0130	0.0064
	Calculated energy (MeV)		7.44		6.68	
	Calculated $B(M14)$[c]		0.308(+27)[d]		0.336(+27)	

[a]See footnote a, Table II.
[b]See footnote b, Table II.
[c]Units are μ^2 fm^{26}.
[d]Numbers in parentheses indicate powers of 10.

D. "Consistent-ϵ" calculations

The final (p,p') and (e,e') reaction calculations were made including all of the RPA amplitudes for the 12^- and 14^- states. In the (p,p') calculation, the modified FL interaction, as described in Sec. II B, was used with $m_\rho^*/m_\rho=0.8$. The RPA wave functions were obtained with the third type of residual interaction, Eq. (12), but by varying the effective ρ mass [but only in the $q^2+m_\rho^2$ factors of Eqs. (8) and (9)] in a consistent way, i.e., $m_\rho^*/m_\rho=1/\sqrt{\epsilon}$. In addition, the same bound-state potential parameters as in the reaction calculations (Ref. [22]) were employed. As in the first calculations, the parameters g_0 and g_0' were varied to keep the energies of the two 1^+ states fixed. The number of 1p-1h configurations contributing to the RPA wave functions was three for the 14^- state and 15 for the 12^- states. In Tables II and III we give the configurations and amplitudes for $\epsilon=1.0$ and $\epsilon=1.6$ ($m_\rho^*/m_\rho=0.79$), the latter being the value of ϵ for which the best result was obtained. The inclusion of the small RPA amplitudes had little effect on the shape of the cross sections but the magnitudes were changed $\sim 5-15\,\%$ for (e,e') and $20-40\,\%$ for (p,p') near $\epsilon=1$ where the configuration mixing is fairly large. However, near $\epsilon=1.6$ where the mixing is much less the changes were smaller [$<5\%$ for (e,e'), $5-10\,\%$ for (p,p')].

The quenching factors, $Q=\sigma_{\rm exp}/\sigma_{\rm theo}$, for (e,e') and (p,p') are given in Table IV and shown in Fig. 6 for $\epsilon=1.0$, 1.2, 1.4, and 1.6. At each value of ϵ the value of

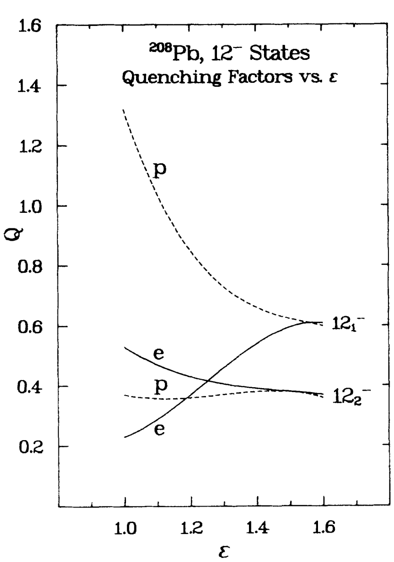

FIG. 6. Calculated quenching factors, $Q=\sigma_{\rm exp}/\sigma_{\rm theo}$ for 12^- states in ^{208}Pb for ρ-coupling parameters, $\epsilon=1.0$ to 1.6 in Eq. (12). Here $m_\rho^*/m_\rho=1/\sqrt{\epsilon}$ in the range factors. Cross sections were calculated in the full RPA space. The calculated (e,e') cross sections were corrected for MEC contributions. The (p,p') cross sections were calculated with the modified FL interaction with ReF_{LS} as given in Table IV. Dashed curves are for proton, and solid curves for electron results. Errors in Q are estimated to be $\pm 7\%$ due to normalization uncertainties.

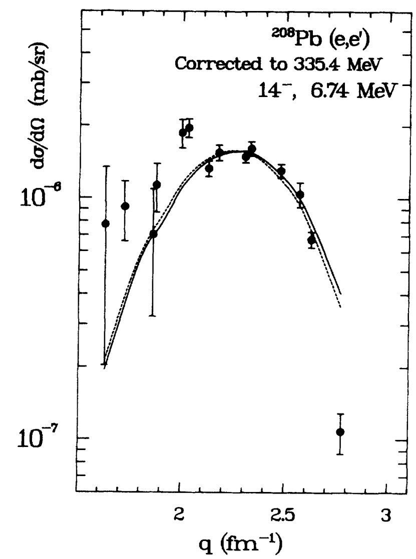

FIG. 7. Cross sections for ^{208}Pb (e,e') to the 14^- state recalculated in program HEIMAG (Ref. [33]) to $E_e=335.4$ MeV vs $q_{\rm eff}$, using the full RPA wave function at $\epsilon=1.6$. Solid curve shows the results with MEC contributions included, normalized to the data with $Q_e=0.47$. Dashed curve shows results without MEC ($Q_e=0.56$). Data are from Ref. [23].

ReF_{LS} was adjusted to give $Q_e=Q_p=Q$ for the 14^- state. It can be seen that there is good agreement between Q_e and Q_p for the 12^- states near $\epsilon=1.6$ ($m_\rho^*/m_\rho=0.79$) with $Q(12_1^-)\simeq 0.61$ and $Q(12_2^-)\simeq 0.37$, close to the values from the two-component model (0.63 and 0.38). The calculated (e,e') and (p,p') cross sections for $\epsilon=1.6$ are shown in Figs. 7–12. The quenching factors for the 12_1^- state are very sensitive to ϵ but for the 12_2^- state are less so. In our final full RPA solution ($\epsilon=1.6$), the effective amplitude of the dominant mixed configuration,

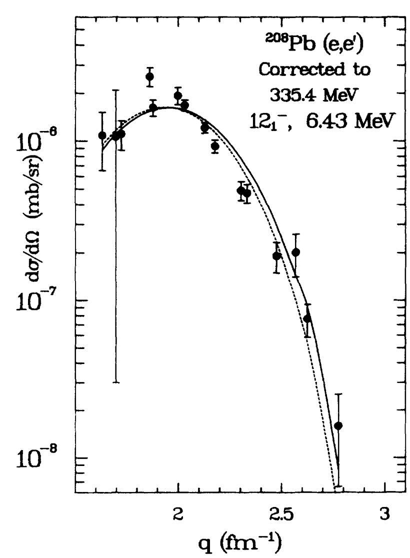

FIG. 8. Same as Fig. 7 but for 12_1^- state with $Q_e=0.61$ (with MEC) and $Q_e=0.73$ (no MEC).

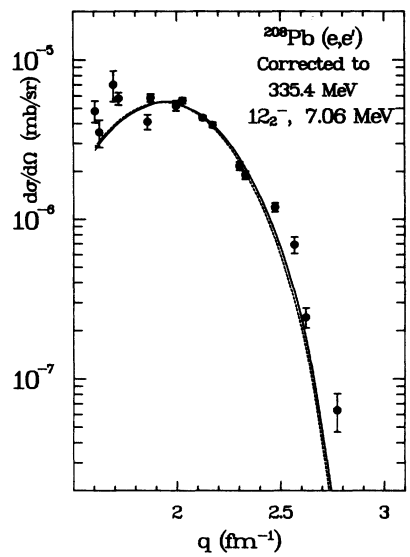

FIG. 9. Same as Fig. 7 but for 12_2^- state with $Q_e=0.37$ (with MEC) and $Q_e=0.44$ (no MEC).

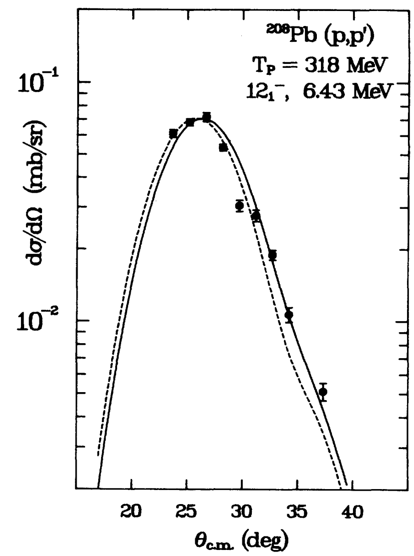

FIG. 11. Same as Fig. 10 but for 12_1^- state and $Q_p=0.60$ (modified FL, full RPA—Table II). Dashed line is for pure $\nu(j_{15/2}i_{13/2}^{-1})$ with $Q_p=0.83$ (unmodified FL).

$A=0.029$, is somewhat smaller than for the best fit with the two-component model ($A=0.06$).

In principle, to be fully consistent, the value of m_p^*/m_p used in the modification of (p,p') interaction should be varied with ϵ, but the constant value used ($m_p^*/m_p=0.8$) is close to that used in the RPA calculation at $\epsilon=1.6$ ($m_p^*/m_p=0.79$). The empirical value of $\mathrm{Re}F_{LS}=1.55$ at $\epsilon=1.6$ corresponds to $m^*/m=0.86$ if $(m/m^*)^3$ scaling is assumed for the NN spin-orbit interaction, but this scaling is expected to be only approximate.

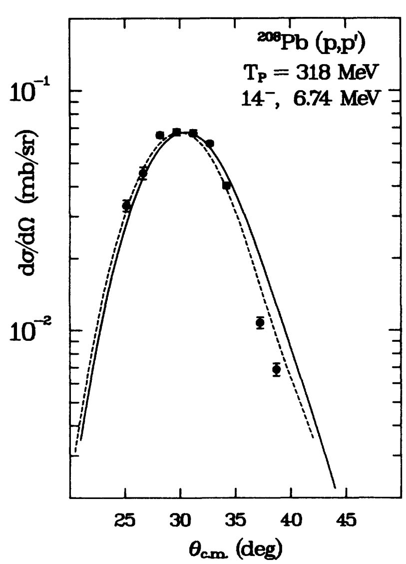

FIG. 10. Cross sections for ^{208}Pb (p,p') to the 14^- state calculated with the modified FL interaction with $\mathrm{Re}F_{LS}=1.55$ using the full RPA wave function (Table III) at $\epsilon=1.6$, and normalized to data with $Q_p=0.47$ (solid line). Dashed line shows calculation with unmodified FL interaction (and $\mathrm{Re}F_{LS}=1.0$) and assuming a pure $\nu(j_{15/2}i_{13/2}^{-1})$ configuration, normalized with $Q_p=0.63$. The data are from Ref. [22].

E. Comparisons

Some comparisons can be made with medium modifications found in other analyses.

(1) "Standard" medium modifications due to Pauli blocking, etc., mainly effect the central-spin-independent interaction, t_0, which plays no role in the excitation of unnatural parity states (except for small exchange terms). The spin-orbit interaction is increased only $\sim 10-15$ % in medium and the tensor interaction is reduced by $\sim 10\%$

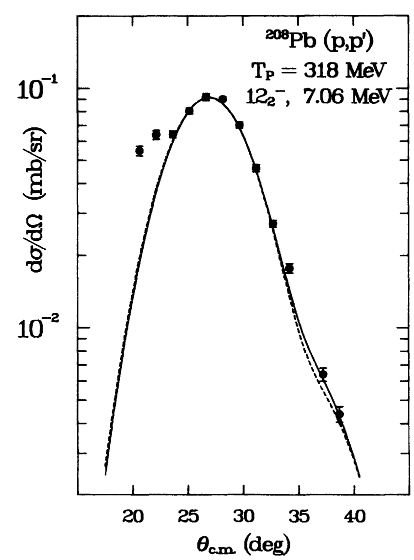

FIG. 12. Same as Fig. 10 but for the 12_2^- state and $Q_p=0.36$ (modified FL, full RPA). Dashed line is for pure $\pi(i_{13/2}, h_{11/2}^{-1})$ with $Q_p=0.39$ (unmodified FL).

[14,26,35].

(2) In the Kelly empirical interaction at 318 MeV [36] (fitted to data) the $\mathrm{Re}t_{LS}$ (isoscalar) interaction increases in medium by ~ 1.3 at $\rho = \rho_0/2$ ($\sim$ surface density) around $q = 2$ fm^{-1}. Our empirical enhancement factor, $\mathrm{Re}F_{LS}$, is slightly larger (~ 1.5).

(3) Zheng and Zamick [11] have done a full 1p-space shell-model calculation using an interaction which simulates the matrix elements of a realistic interaction such as the Kuo-Brown [37] or Bonn [38]. In the calculations they explore the effects of varying separately the strengths of the spin orbit (by a factor X) and tensor (factor Y) interactions. It is found that *either* by increasing the spin-orbit strength ($X \simeq 1.4$) or by decreasing the tensor strength ($Y \simeq 0.5$) they can obtain a nearly zero $^{14}\mathrm{C} \rightarrow {}^{14}\mathrm{N}$ Gamow-Teller matrix element, in agreement with experiment. (They do not try varying both X and Y.) Thus their modifications are similar to ours.

(4) Hosaka and Toki [10] have shown that by using modified meson masses ($m^*/m \sim 0.8$) in a G-matrix calculation, based on the Bonn potential [38], they can significantly improve agreement with the empirical $2s$-$1d$ shell matrix elements determined by Brown *et al.* [39].

(5) Data on proton spin observables (D_{ij}) at $T_p = 500$ MeV for stretched states in ^{28}Si [40] suggest the need for a reduction of the isovector tensor interaction and an increase in the isovector spin-orbit interaction relative to that of the free FL t matrix.

(6) Stephenson and Tostevin [12] have made empirical modifications of the $t_{T\tau}$ and $t_{\sigma\tau}$ components of the FL t matrix to fit cross section, analyzing power (A_y), and spin observable (D_{ij}) data for $^{16}\mathrm{O}(p,p')$ at $T_p = 200$ MeV to the 4^- $T=1$ stretched state at 18.98 MeV. The free FL interaction gives a poor representation of the data, especially A_y, the diagonal D_{ii}, and $D_{LS'}$. Their modified interaction, when compared to the $\pi+\rho$ OBE potential [34] corresponds to a scaling of the ρ-meson coupling constant by $(m/m^*)^2$ with $m^*/m \simeq 0.94$. In their analysis they have *not* modified the ρ mass [in the $q^2 + m_\rho^2$ factor of Eq. (2)] or the spin-orbit interaction, so their results are not directly comparable to ours but are qualitatively similar in that a reduction of $\mathrm{Re}t_{T\tau}$ is required to fit the data.

III. SUMMARY AND CONCLUSIONS

We have reanalyzed the (e,e') and (p,p') data on the stretched ($12^-_{1,2}$ and 14^-) states of ^{208}Pb using the ideas of Brown, Rho, and others on the reduction of meson and nucleon masses in medium. The main consequences, for unnatural parity stretched states, are a reduction of the tensor and enhancement of the spin-orbit NN interactions in reaction and structure calculations. Using the OBE ($\pi+\rho$) model as a guide, we have performed large basis RPA structure calculations and DWIA (p,p') reaction calculations using forces modified in a reasonably consistent manner in both. Agreement between (e,e') and (p,p') quenching factors for the three states can be found for $m^*/m = 0.79$ (for the ϵ scaling) or 0.86 (for the $\mathrm{Re}F_{LS}$ scaling), resulting in a reduction of the real isovector tensor interaction by $\sim \times 0.5$ (at $q \sim 2$ fm^{-1}) and an enhancement of the real isoscalar spin-orbit interaction by $\sim \times 1.5$. These factors are qualitatively similar to those indicated in other analyses.

It should be mentioned that recent high resolution ($\Delta E \sim 30$ keV) (e,e') [27] and (p,p') [29] experiments reveal a "fine structure" in the vicinity of the 12^-_1 (6.43 MeV) and 12^-_2 (7.06 MeV) peaks which were analyzed as single states in Refs. [22] and [23], from which we have taken the data used in this analysis. However, at least in the new (e,e') experiment [27], the summed $J^\pi = 12^-$ intensity agrees with that of the earlier [23] analysis. A final analysis of the new (p,p') data at 200 MeV [29] is not yet available. These new results could alter somewhat our quantitative determinations but are not expected to change our conclusions on the need for a reduction of the tensor and enhancement of the spin-orbit NN interactions in nuclei.

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