1977-09

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American Physical Society

Isospin of the fine structure between 8 and 12 MeV in ^{208}Pb and its implication for the multipole assignment of the 8.9-MeV resonance*

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(Received 19 April 1977)

The giant-resonance region between 8 and 12 MeV measured by (e,e') in ^{208}Pb is disentangled into narrow lines ($\Gamma_{nat} < 400$ keV) and broad resonances ($\Gamma_{nat} > 1800$ keV). The narrow lines at 10.07, 10.60, and 11.37 MeV have an $E2$ angular distribution, and assumption of $\Delta T = 1$ for them explains controversial experimental results of electromagnetic and hadronic experiments. The new analysis makes an assignment for the 8.9-MeV resonance other than monopole difficult to understand.

[NUCLEAR REACTIONS ^{208}Pb(e,e'), $E_0 = 50$ and 65 MeV, $\theta = 93°$ and 129°; measured $d^2\sigma/d\Omega dE_x$, deduced multipolarity, isospin, sum-rule exhaustion, reduced transition probabilities $B(E\lambda)$; discussion monopole giant resonance (breathing mode).]

The excitation region between 8 and 12 MeV in ^{208}Pb has been subject to an increasing number of investigations in recent years. This has been mainly due to the appearance of fine structure within or on top of the giant isoscalar quadrupole resonance ($\Delta T = 0$, $E2$) which is, for heavy nuclei, unique to ^{208}Pb, and which structure may, therefore, contain important information concerning nuclear dynamics. However, the results have been controversial and apparently contradictory. In this paper we propose a solution based on a new analysis of the (e,e') data of Ref. 1 and a discussion of recently published results from other experiments. The main new point is that the $E2$ fine-structure lines near 10.6 MeV ($\Gamma < 400$ keV) are regarded to have an isospin different from that of the underlying broad $E2$ resonance ($\Gamma = 2600$ keV). Thus, because the lines and resonances differ in the isospin quantum number, it is justified to disentangle the different contributions by a line shape fit. Our evaluation attempts to reconcile existing controversial results. The understanding of the fine structure additionally offers a new basis for a discussion of the nature of the 8.9-MeV resonance. Throughout this paper, the words "line" and "resonance" are used only as defined above.

In the above mentioned (e,e') experiment a triplet of 2^+ or 0^+ states at 10.2, 10.6, and 11.2 MeV was reported.[1] A strength of 35% of the energy-weighted isoscalar sum rule for quadrupole excitations[2] [in the following abbreviated 0.35 EWSR ($E2$, $\Delta T = 0$)] was found in the energy span from 9.7 to 11.7 MeV.[1] The small value of the strength has often been misinterpreted, because it was overlooked that this value corresponded to the cross section in the energy range from 9.7 to 11.7 MeV and not to the total area under the resonance, which exhausts 0.9 EWSR ($E2$, $\Delta T = 0$). Multipolarities other than $E2$ were ruled out by identifying fine structure in (γ,n)[3,4] with this triplet. The total structure was regarded to be the $\Delta T = 0$ giant quadrupole resonance which had just been found in heavy nuclei.[5] A fourth peak at 8.9 MeV with properties similar to the members of the triplet was not evaluated, because it had no counterpart in the (γ,n) cross section. It was stated that the (γ,n) cross section for the fine structure was a factor of 2 to 5 larger than the (e,e') results extrapolated to $q = \omega$, if $E2$ was assumed for both. This deviation was used later by Nagao and Torizuka[6] as an argument against the $E2$ assignment for the (γ,n) fine structure. By evaluating the "peak parts which are manifestly seen"[6] of the (e,e') fine-structure lines they found, however, that the (e,e') form factor had the momentum transfer dependence of an $E2$ transition and included little $E1$ strength. The $E2$ strength extracted for the region of the triplet by these authors was also 0.35 EWSR ($E2$, $\Delta T = 0$); the transition at 8.9 MeV followed an $E2$ or $E0$ form factor and had a strength of 0.08 EWSR ($E2$, $\Delta T = 0$).

A new argument was introduced when, on the basis of new and old (e,e') experiments, it was stated[7] that the narrow 8.9-MeV line should show up in (γ,n) at least as strong as the 10.2-MeV state, if both were $E2$, as reported by Nagao and Torizuka,[6] and that the absence of the former could be explained most easily by a monopole assignment. The width of the 8.9-MeV resonance was found to be 1.8 MeV and, assuming the same multipolarity for both line and resonance structures, the strength [0.50 ± 0.25 EWSR ($E0$, $\Delta T = 0$)] or [0.30 ± 0.15 ($E2$, $\Delta T = 0$)]. Results of a high resolution (e,e') experiment[8] confirmed the strength obtained earlier[7] for the broad 8.9-MeV resonance, but, within the statistical limitations, showed no fine structure in this region. Our new evaluation shows, in contrast to Nagao and Torizuka,[6] that the 8.9-MeV region contains lines of various multipolarities. This may also explain why the high resolution (e,e') spectrum,[8] which had low momentum transfer, revealed no fine structure at this energy within the limits of statistics.

We have dealt above in such detail with the (e,e') experiments, because we will use electroexcitation as the basis with which to compare the results of other experiments. Electron scattering at low momentum transfer excites isoscalar and isovector transitions for $E0$ and $E2$ and the isovector $E1$ transition. High multipolarities are excited only weakly. Experiments using (α,α') are more selective and excite only $E\lambda$, $\Delta T=0$ transitions.[9] In a noncoincidence experiment, (e,e') does not show interference between excitations to states of different multipolarity,[10] in contrast to the (γ,n) reaction for which interference occurs, if the differential cross section is measured by detecting the ejected neutron.

In recent high-resolution (γ,n) investigations by Sherman *et al.*,[11] narrow transitions at 9.034, 9.421, and 10.06 MeV with a natural width of 45, 104, and 134 keV, respectively, were seen, but none of the resonant structure appeared. The lines were assumed, but not independently determined to be $E2$. On this basis, $E2$ strengths of 0.15, 0.25, and 0.48 EWSR ($E2$, $\Delta T=0$), respectively, were extracted.[11] These transitions, if they are $E2$, would result in peaks more than 5 times as high as the strongest visible ones in Fig. 1 of Ref. 8, an apparent contradiction.

A (p,p') and a $(^3He,{}^3He')$ experiment[12] with a resolution equal to the resolution of Ref. 8, 35 keV, reports a monopole transition at 9.1 MeV with a strength of 0.02 EWSR ($E0$, $\Delta T=0$). It was stated by the authors[12] that this result is not in contradiction with the (e,e') spectra of Ref. 8. It has been pointed out by Halbert *et al.*[13] that the extraction of electromagnetic sum-rule strength with inelastic hadron scattering is model dependent. This is especially true for the monopole, where models cannot be tested on low-lying collective states as can be done for other multipolarities.

Inelastic α scattering by Youngblood *et al.*[9] gives a width of 2.6 MeV and a strength of 0.93 EWSR ($E2$, $\Delta T=0$) for the resonance at 10.8 MeV, which is in very good agreement with (e,e'), and shows no monopole contribution is present in this (e,e') region. However, although their resolution, 120 keV, is better than that of Ref. 1, 200 keV, their spectra do not show the triplet structure seen in electron scattering. Inelastic proton scattering by Bertrand and Kocher[14] reports a strength of 0.90 EWSR ($E2$, $\Delta T=0$) for a resonance at 10.6 MeV, but shows neither a resonance nor a line at 8.9 MeV. The fine structure around 10.5 MeV reported earlier[15] was not seen again, but a prominent line of either $E2$ or $E3$ character was found at 9.4 MeV.

The most serious shortcoming of all previous experiments is that the fine structure was never separately evaluated in a way which would establish its multipolarity directly from angular distributions. In the evaluation, the narrow lines were always put together with the underlying resonances or simply assumed to be $E2$. This is a crucial point, because, e.g., an $E1$ ($\Delta T=1$) assignment for the fine structure alone could qualitatively explain why it is seen in (γ,n) and (e,e'), but not in (α,α'), while on the other hand, it would be such a small fraction of the total strength that the $E2$ angular distribution would not be noticeably affected. In order to overcome this shortcoming and to do an analysis which is consistent with (α,α'), we have resolved the strength function into fine structure, referred to as lines, and broad resonances.[16]

In the present analysis the (e,e') spectrum $s(E_x)$, where E_x is the excitation energy, is fitted[17] to a function of the form:

$$f(E_x)=a+bE_x+cR(E_x)+\sum_i g_i(E_x)\,. \tag{1}$$

The first two terms represent the background. $R(E_x)$ is the radiation tail function, which accounts for energy loss by bremsstrahlung in the target, radiation during scattering, energy straggling, and ionization. Both of the radiation terms contain the elastic electron scattering cross section, which is calculated from a phase shift analysis. Each line or resonance is represented by a spectral function $g_i(E_x)$. The strength function $B_i(E\lambda,E_x)$, which determines $g_i(E_x)$, is assumed to have a Breit-Wigner form with appropriate constants for the resonance energy, width and height. In the fitting program, the constants a, b, and c are varied, and the various constants for the resonances may be fixed or varied depending on the information known about the given resonance. Criteria for a good fit are a low value of χ^2, no significant deviation of f from s (which would indicate an omitted resonance), and consistent values for a resonance energy and width when the several spectra for different angles or beam energies are considered together. As a check for reliability it should be noted that a is in agreement with the value expected from the measurement of the constant room background (target-in), that b is a small correction and that c is close to one, indicating that essentially no scaling of the radiation tail is necessary.

For the present analysis of ^{208}Pb, the known excitation energy and width, but not the strength for the $E2$[9] resonance were used as fixed parameters in the fit. Figure 1 shows a fit to a spectrum of Ref. 1 under these assumptions. The angular distributions for the broad resonances at 10.8 and 8.9 MeV are only consistent with $E2$ or $E0$ assignments. The total widths and EWSR fractions are given in Table I. The energy-weighted sum rule for the quadrupole ($\lambda=2$) strength is given by[18]

$$S(E\lambda)=\frac{\hbar^2}{2M_p}\frac{\lambda(2\lambda+1)^2}{4\pi}Z\langle r_p^{2\lambda-2}\rangle_0,$$

with fractions Z/A and N/Z assigned to the isoscalar and isovector modes, respectively. For the isoscalar monopole mode, the sum rule due to Ferrell[19,20] is used:

$$E_x|M_{fi}|^2=\frac{\hbar^2}{M}Z\langle r_p^2\rangle_0.$$

The three lines of the triplet similarly follow an $E2$ ($E0$) angular distribution, but their combined strength is surprisingly small (less than 0.1 EWSR, see Table I). Figure 2 compares the experimental results for the 10.07-MeV line with distorted-wave-Born-approximation calculations based on the the Tassie (Goldhaber-Teller) model.[21] It is di-

TABLE I. Excitation energies, B values, sum-rule fractions, and total widths of the $E2$ or $E0$ states in question. The rms ground-state radius of Friar and Negele [Nucl. Phys. A212, 92 (1973)] was used to calculate the $E2$ and $E0$ sum rules. The widths but not the strengths of the lines depend on the line shape used; a Breit-Wigner form was found to give the best fit. Multiplying the $E2$ sum rule by 1.34 gives the equivalent monopole sum rule for each state; the 8.9-MeV monopole state interpreted as $E2$, thus, corresponds to 0.35 EWSR ($E2$, $\Delta T=0$). Isoscalar and isovector sums differ by the factor (N/Z).

E_x (MeV)	Γ (MeV)	$\lambda^\pi, \Delta T$	R[a]	$B(E\lambda)$ (fm^4)
10.07 ± 0.03	0.20 ± 0.05	2^+, 1	0.013	150 ± 30
10.60 ± 0.04	0.32 ± 0.06	2^+, 1	0.025	280 ± 40
11.37 ± 0.05	0.37 ± 0.05	2^+, 1	0.019	200 ± 40
8.9 ± 0.2	2.0 ± 0.2	0^+, 0	0.47	5300 ± 500
10.8[b]	2.6[b]	2^+, 0	0.86	6200 ± 600

[a] $R=B(E\lambda,\Delta T)E_x/\mathrm{EWSR}(E\lambda,\Delta T)$.
[b] The values from Youngblood *et al.* (Ref. 9) were used in order to achieve a fit compatible with the (α,α') experiments.

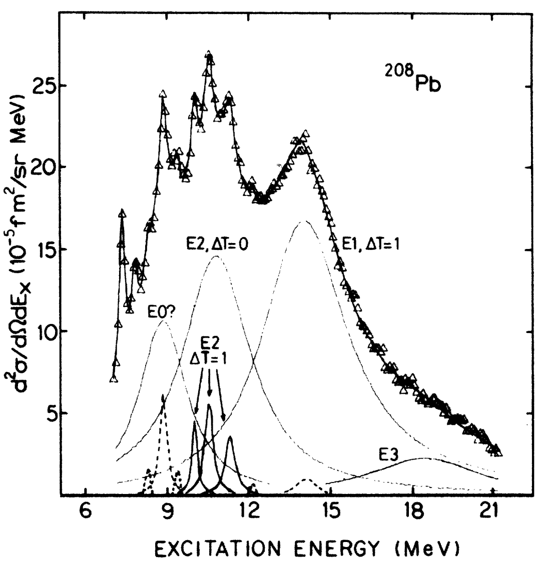

FIG. 1. Reanalysis of a spectrum of 64.6-MeV electrons (Ref. 1), scattered inelastically at 93° from ^{208}Pb with an overall resolution of 190 keV in the giant resonance region. The statistical error is smaller than the size of the experimental points. The triplet around 10.6 MeV is but a small fraction of the cross section. In addition to the states mentioned in the text one has to take into account lines at 7.4, 7.9, 8.4, and 9.4 MeV. More structure is visible at 12 and 14 MeV. The excitation energies of the freely fitted resonances, (8.9 ± 0.2) MeV ($E0$), (13.6 ± 0.2) MeV ($E1$), and (18.5 ± 0.9) MeV ($E3$) denote the maxima of the strength functions, not of the cross sections. It should especially be noted that the strength found for the $E1$ resonance, $B(E1)=60$ fm^2 is in essential agreement with the (γ,n) values of 55 and 75 fm^2 from Refs. 3 and 4, respectively.

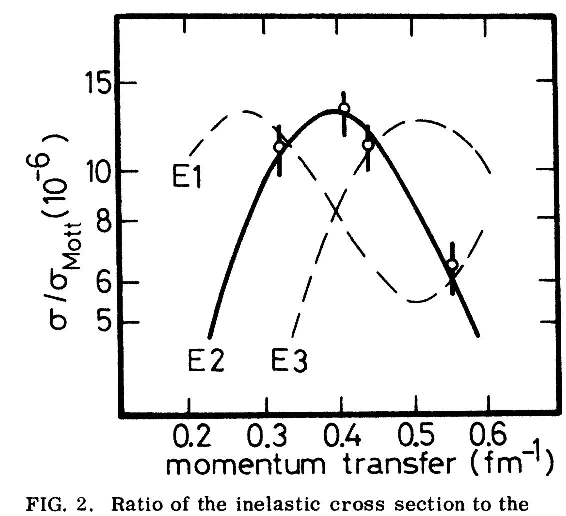

FIG. 2. Ratio of the inelastic cross section to the Mott cross section for the narrow line at 10.07 MeV. The curves show DWBA calculations for a primary energy of 64.6 MeV and an excitation energy of 10.07 MeV. The method of Ziegler and Peterson [Phys. Rev. 165, 1337 (1968)] was used to display points from measurements with different primary energies in the same drawing. Only measurements with scattering angle smaller than 130° were used to avoid transverse contributions.

rectly evident from the figure that the main part of the (e, e') cross section is definitely not of $E1$ character. As an upper limit of the $E1$ strength, a reduced transition probability of $B(E\lambda) = 0.3\ \text{fm}^2$ can be given, which is 30% less than the $E1$ strength seen by Sherman *et al.*[11] at 10.06 MeV. The angular distribution of the 8.91-MeV line on top of the 8.9-MeV resonance indicates a transverse contribution in addition to an $E1$ or $E2$ state.

These contradictory results from various experiments can be reconciled if one assumes an $E2$, $\Delta T = 1$ assignment for the three lines at 10.07, 10.60, and 11.37 MeV, but not for the line at 8.91 MeV, which may even not be $E2$:

1. A $\Delta T = 1$ state will not, or only very weakly, be excited by (α, α)[9] because the α particle has $T = 0$. It could be excited by inelastically scattered particles with $T \neq 0$, as in (p, p'),[14] but the strength is expected to be suppressed by a factor of 10 as compared with isoscalar excitations.[14]

2. If the triplet seen in (γ, n)[3,4] at 10.0, 10.6, and 11.3 MeV does in fact correspond to the (e, e') fine structure, the difference in strength noted earlier[1] would have to be explained. Possibly the (γ, n) fine structure can be enhanced by an interference between the $E2$ lines and the tail of the giant-dipole resonance (GDR). Such interference has recently been observed in measurements of the differential (γ, n) cross section.[22] Thus, one has to assume that $E1$-$E2$ interference in the (γ, n) reactions takes place with the $\Delta T = 1$ part of the $E2$ strength (lines), but not with the $\Delta T = 0$ part (resonance). Since the GDR is isovector in nature, such an assumption seems plausible. The appearance of the lines in the older integrated (γ, n) measurements[4] then would only be possible if the (γ, n) detector did not have a 4π geometry, which is the case.

3. The difference in total width between the 10.8-MeV ($E2$, $\Delta T = 0$) resonance and ($E2$, $\Delta T = 1$) fine structure may be attributed to the different decay channels available to different isospin states.

4. A $\Delta T = 1$ assignment for the lines is consistent with calculations by Ring and Speth,[23] who report on $\Delta T = 1$ contributions to the predominantly $\Delta T = 0$ transitions around 11 MeV.

It is clear from the excitation energy that these lines cannot be analog states. Since $\Delta T = 1$ states at this excitation energy can only decay through admixture of $\Delta T = 0$ impurities, their natural width offers a unique possibility to study this admixture. The $\Delta T = 1$ strength of the three lines together (Table I) is close to the value $[(N - Z)/A]^2$ derived from a simple mass oscillation model for the ratio of isovector and isoscalar sums by Halbert *et al.*,[13] but it falls short by a factor of 4 to their value calculated with microscopic wave functions.

The foregoing explains in a consistent manner the results from various experiments for the $E2$ resonance at 10.6 MeV and the fine structure in this region. The problem of the nature of the resonance at 8.9 MeV must be treated separately, as we do below.

A resonance structure at $53A^{-1/3}$ MeV, compatible with either $E2$ or $E0$ multipolarity, has been seen for several years.[7,8,24,25] An $E0$ assignment is favored over $E2$ by the following arguments:

1. An $E2$ ($\Delta T = 0$) resonance at this energy with 0.35 EWSR ($E2$, $\Delta T = 0$) (Table I) leads to a total strength of 1.48 EWSR ($E2$, $\Delta T = 0$) to which the known states at 4.07, 6.20, and 10.8 MeV contribute 0.17, 0.06, and 0.86 EWSR, respectively. A total strength this large would be difficult to understand for the isoscalar sum, where no exchange terms enter.[2] In addition to the sum-rule argument, an $E2$ resonance of 0.35 EWSR ($E2$, $\Delta T = 0$) should lead to a visible resonance in the hadronic scattering experiments.[9,14] Assumption of $E0$ might explain why it has not been seen.

2. Assumption of $E2$ ($\Delta T = 1$) for the 8.9-MeV resonance would explain why it is suppressed in the hadronic spectrum, but poses the problem of explaining why a broad resonance of $\Delta T = 1$ character should appear several MeV below the narrow $\Delta T = 1$ triplet.

3. The energy for the $E0$ breathing mode, calculated by Überall[26] from optical isotope shifts, agrees with the observed 8.9 MeV. The isotope shift yields a compressibility parameter $K = (81^{+61}_{-25})$ MeV, which is related to the monopole energy by $E = 0.95\sqrt{K}$,[27] giving $(8.6^{+2.7}_{-1.5})$ MeV.

Recently monopole strength >1.0 EWSR ($E0$, $\Delta T = 0$) has been proposed (see Ref. 28 and references therein) from a very weak resonance at about $80A^{-1/3}$ MeV. Such a resonance would be superimposed on the GDR, which in electron scattering would yield a peak almost twice as high as the GDR shown in Figure 1. Thus, there is no possibility to accommodate a monopole state stronger than about 0.1 EWSR ($E0$, $\Delta T = 0$) in the present (e, e') data, especially if one realizes that, for the momentum transfer covered (Fig. 2), the $E2$ relative cross section is at a maximum compared with the $E1$. The arguments of Ref. 28 (and the references quoted therein) are based mainly on the assumption that (α, α') and (d, d') do not excite the isovector GDR measurably. This may not be true. In turn then, the cross section of the resonance at $80A^{-1/3}$ MeV as seen in (α, α') and (d, d'), interpreted as $E1$, might be very suited to investigate the role of isospin impurities. We would also like to point out that the arguments given in favor of $E0$ over $E2$ at 14 MeV in the last paragraph of Ref. 28 apply equally to the assignment of $E0$ vs $E2$ for the 8.9-MeV resonance. Finally, it should be noted that the small structure at 14 MeV in Fig. 1 would be compatible with the 0.2 EWSR ($E4$, $\Delta T=0$) offered as a further alternative assignment in Ref. 28.

It is a pleasure to thank P. Axel, W. Benenson, B. Berman, A. Bohr, B. Mottelson, N. Sherman, and D. Youngblood for critical discussions and helpful remarks. We are especially obliged to Th. Walcher for his many valuable suggestions.

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*Supported in part by the National Science Foundation and the Naval Postgraduate School Research Foundation.

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