and are shown in Fig. 2. The calculations gave good qualitative agreement with experiment for $l=0$ and $l=4$ (dotted curves) and very good agreement for $l=2$, without the use of cutoffs or finite-range corrections. This agreement is taken as an affirmation of the empirical choice of three typical curves ($l=0$, 2, and 4), which are then used unchanged (solid lines) to identify the dominant l value and a possible l admixture for the transitions shown. Transitions with $l=0$ contributions can only go to $J^\pi=1^+$ states, and the corresponding assignments are considered very reliable. The pure $l=2$ transitions are tentatively assigned as leading to 2^+ states, but ($1^+, 3^+$) are not firmly excluded. The one 4^+ assignment seems well justified, and the 3^+ assignments are considered reliable on the basis of significant $l=2, 4$ mixing, and the good agreement with $J_{d,p}$ limits.

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PARTICLE-CORE COUPLING IN THE LEAD NUCLEI*

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The particle-core weak-coupling model has been used to describe certain states of odd-mass nuclei by relating them to excited states of adjacent even-even nuclei.[1] According to this model, the extra particle or hole in an odd-mass nucleus may couple to excitations of the even core to form multiplets at about the same energy as the excitation in the even nucleus, and with very similar properties. This description is expected to be valid provided that the coupling does not alter significantly the nature of the core state. A good example of such a state is the collective electric octupole excitation in the lead region, occurring as single states in Pb^{206} and Pb^{208}, a doublet in Pb^{207}, and a complex multiplet in Bi^{209}, all in the vicinity of 2.6 MeV.[2] Among the interesting questions relevant to this model are (1) the extent to which it is valid as the excitation energies of both the particle and core increase, (2) the nature of the core states to which it may be applied, and (3) the nature of the particle-core interaction. In addition, information pertaining to these questions is also important for the "doorway theory" of nuclear reactions because particle-plus-core excitations may occupy the crucial position of doorway states, and hence constitute the first step toward bridging the gap between broad single-particle excitations and narrow states in the compound nucleus.[3] The purpose of this Letter is to present experimental results which indicate the existence, at intermediate energies in the lead nuclei, of particles in excited states coupled to various excitations of the core, and to show how the isobaric analogs of these states are selectively excited by proton scattering. The experiments are part of a study of isobaric analog resonances currently in progress at this laboratory using the Emperor tandem accelerator.

The experimental data to be discussed here consist of proton elastic- and inelastic-scattering excitation functions from targets of Pb^{208} and Pb^{206}. Figure 1 shows the 165° differential cross sections for the Pb^{208} ground state and for the 3^- state at 2.615 MeV for incident proton energies betwen 14 and 22 MeV. The data are in good agreement with previous measurements which extend only to 18 MeV.[4] Of primary interest for the present discussion are the Pb^{208} results above 18 MeV; however, to emphasize the important distinction between the two regions the lower energy results have been included. The strong resonance behavior in the elastic and inelastic scattering between 14 and 18 MeV corresponds to the population of the isobaric analogs,[4,5] in the Bi^{209} compound system, of the single-particle states of Pb^{209} up to 2.51 MeV of excitation, which are known from the reaction $Pb^{208}(d,p)$.[6,7] Between 18 and 22 MeV new resonance structure is observed in the 3^- inelastic scattering, but unlike the lower energy region, there are no corresponding strong resonances in the elastic scattering. Data obtained for both channels at 125° and 150° agree with these results. The decrease near 19 MeV in the elastic cross section may not be related to the sharp rise in the 3^- scattering at that energy, but may arise from coupling of the (p,p) with the direct (p,n) channel leading to the isobaric analog of the target ground state since the threshold for the (p,n) process is at this energy. This would be similar to the coupling that has been observed between analogous (d,p) and (d,n) channels.[8] The absence of isolated resonances in the elastic scattering is consistent with $Pb^{208}(d,p)$ measurements which show no strong single-particle states above 2.51 MeV.[6,7] Rather, the stripping measurements indicate a gap between 2.51 and 3.9 MeV in Pb^{209} in which there is a negligibly small cross section, while above 3.9 MeV many closely spaced levels with small (d,p) cross sections are populated.

According to the results of Fig. 1, if the resonances in the scattering to the Pb^{208} 3^- state, between 19 and 21 MeV, are interpreted as isobaric analogs, they correspond to levels in Pb^{209} between 4 and 6 MeV, and very little information concerning the structure in this energy region is available. Since the states excited there by the (d,p) reaction are about 50 keV apart, and since neutron-absorption measurements[9] indicate a maximum average spacing for all levels of about 15 keV, it is probable that the (p,p') resonances reflect the overlapping effects of many isobaric analog states. An attractive simple interpretation of these results is that a number of levels are present in Pb^{209} in this energy region, whose structure is largely described as a Pb^{208} core, excited to its 3^- state, coupled to the odd neutron in one of its single-particle states. The isobaric analogs of such levels would be expected to decay strongly to the 3^- state of Pb^{208}. In its simplest form, without particle-core interaction, the particle-core coupling model would predict seven multiplets of levels, one for each low-lying single-particle state, at the combined energies of the particle plus core excitations. The location of each multiplet, obtained simply by adding 2.62 MeV to each single-particle state, is indicated by an arrow in Fig. 1. The five multiplets above 19 MeV agree quite well with the location of the resonances in the 3^- excitation function.

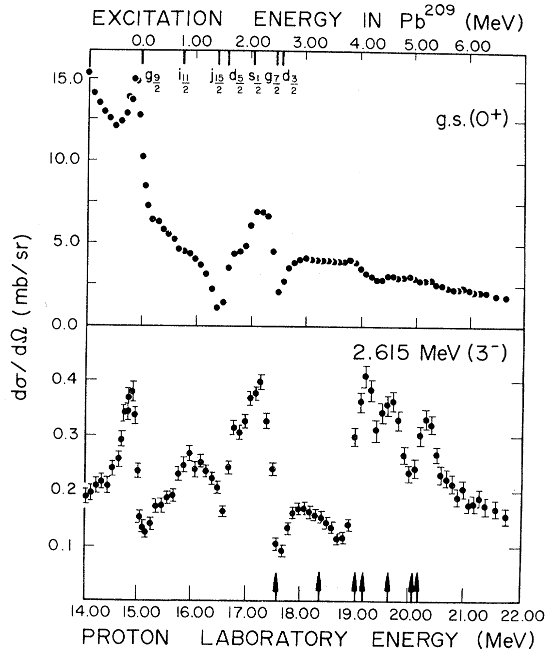

FIG. 1. Proton-scattering excitation functions for the ground state and first excited state of Pb^{208} at a laboratory angle of 165°. The single-neutron states of Pb^{209} are shown along the upper energy scale which has been positioned to correspond to the location of isobaric-analog states in the Bi^{209} compound system. The arrows along the lower axis identify the calculated energies of unperturbed particle-plus-core multiplets obtained by coupling single neutrons with the 3^- core excitation.

While it is apparent that the isobaric analogs of the multiplets should decay strongly to the 3^- state, it is not obvious how they are formed by proton bombardment. A possible mechanism is the existence of small single-particle admixtures in the particle-core states which create nonzero entrance channels for their formation. The (d,p), (p,p), and neutron data imply considerable mixing of the single-particle strength into a large number of states in this region of Pb^{209} and included among these may be the particle-core coupled states in question. It is noteworthy, in this connection, that the abrupt onset of (d,p) strength[6] at 3.9 MeV corresponds to the equally abrupt onset of the analog structure in the 3^- excitation function near 19 MeV. The gap between 2.51- and 3.9-MeV excitation in $Pb^{208}(d,p)$ spectrum has been interpreted as the separation between the positive-parity $126 < N < 184$ shell and the negative-parity $N > 184$ shell,[7] and therefore starting just at 3.9 MeV (and at the analogous proton energy of 18.9 MeV) the proper spins and parity exist for mixing with the predominantly negative-parity particle-core coupled states that we predict.[10]

Inelastic-scattering excitation functions for the next three states above the 3^- state in Pb^{208} are shown in Fig. 2. The scattering to all three states resonates at the $g_{9/2}$ single-particle isobaric analog state at 14.95 MeV, and the 3.20- and 3.48-MeV states are thought to have large $(g_{9/2}, p_{1/2}{}^{-1})$ particle-hole components in their wave functions.[4,5,11] At the higher energies of interest here, the calculated unperturbed positions of the isobaric analogs of multiplets based on the 3.20-MeV (5^-) core excitation are in good agreement with the general location of observed resonances in the inelastic scattering to that state. In sharp contrast to these results are the data for the 3.48-MeV (4^-) state which provide no evidence for the excitation of analogs of particle-core coupled states based on the 4^- Pb^{208} core. However, the scattering to the next state at 3.71 MeV (5^-) does show definite, although weak, resonance structure in the general region where analogs of states based on that core excitation are predicted.

A comparison of the excitation functions leading to the first four excited states of Pb^{208} suggests a possible correlation between the intensities of isobaric-analog resonances which fit the particle-core coupling scheme and the

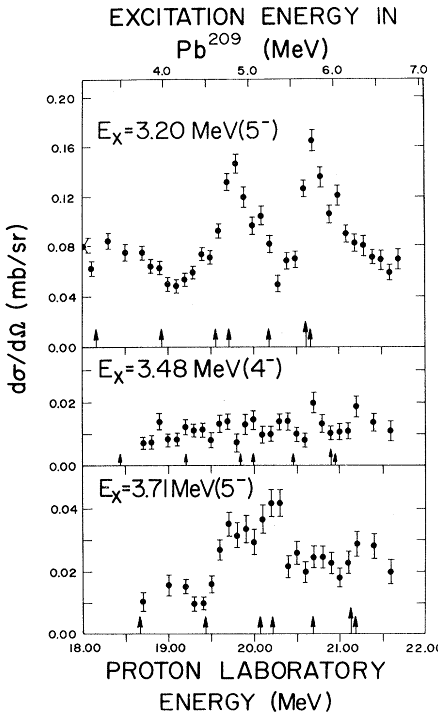

FIG. 2. Proton-scattering excitation functions at 165° for the second, third, and fourth excited states of Pb^{208}. The arrows show the location of <u>unperturbed</u> particle-plus-core multiplets based on each of the Pb^{208} states considered as a core. The region from 14 to 18 MeV has been studied previously (see Refs. 4, 5, and 11).

strengths for exciting the corresponding core states by direct inelastic scattering. In terms of Weisskopf units, the strengths that have been determined from direct (p,p') measurements[12] are 19.5 for the 3^- state, 8.1 and 1.85 for the first and second 5^- states, respectively, and 0.4 for the 4^- state; and the same quantitative trend is indicated by the strengths of the isobaric-analog resonances in the scattering to these states. It should be emphasized that this correlation is not found for resonances corresponding to analogs of single-particle states. For example, at the $g_{9/2}$ isobaric analog at 14.95 MeV, scattering to all the above states shows fairly strong resonances and the 4^- resonance is among the largest.

The conclusions suggested by the data presented thus far are strongly supported by recent measurements[13] of proton scattering from Pb^{206}. A preliminary analysis shows prominent resonances corresponding to particle-plus-core states in Pb^{207} based on collective 2^+, 4^+, and 3^- states in Pb^{206}, while similar strong effects based on noncollective low-lying states do not appear in the data. A graphic illustration of these results is the inelastic-scattering excitation functions for the first and second 2^+ states shown in Fig. 3. The first state is collective with 6.2 Weisskopf units for the transition strength, and the second is only very weakly excited by direct inelastic scattering.[14] The data up to 16 MeV have appeared previously, and the resonances between 12 and 13.5 MeV have been explained in terms of the two-neutron-hole wave functions for these states.[5] Based on a Pb^{206} core excited to each of the 2^+ states, isobaric analogs of particle-plus-core multiplets are predicted in the approximate energy range of 15.8 to 19 MeV. As shown in Fig. 3, only the scattering to the collective first 2^+ state provides strong evidence that these states actually exist.

We may summarize the two main conclusions that are indicated by the data as follows:

(1) There exist in Pb^{207} and Pb^{209} groups of states which are identifiable as particle-plus-core excitations. These states occur at intermediate energies, from about 3 to 8 MeV, where level densities are high and many other modes of excitation are possible, so that the pure particle-plus-core configurations are probably shared by a number of levels.

(2) There exists a correlation between the strength of isobaric-analog resonances corresponding to particle-plus-core states and the probability for exciting the core states themselves by direct proton inelastic scattering.

Other isobaric-analog measurements indicate that the first conclusion may also be applicable to other regions of the periodic table,[15-17] but thus far such results are generally more difficult to interpret than those in the lead region especially as the excitation energy increases. The recently reported measurements[18] for Zr^{91}, which indicate coupling of single-particle states to the 0^+ first excited state of Zr^{90}, would seem initially to be in conflict with the second conclusion. However, the states in Zr^{91} are isolated sharp states at low energies with relatively pure configurations, while in lead the configurations are shared by several states. If the spreading of a particle-plus-core state occurs over a very large energy interval, e.g., several MeV, then it would be difficult to observe in the experiments described here. Thus it might be possible to explain the second conclusion if the configurations based on noncollective cores are dissipated over wide energy regions, while the coupling to collective cores

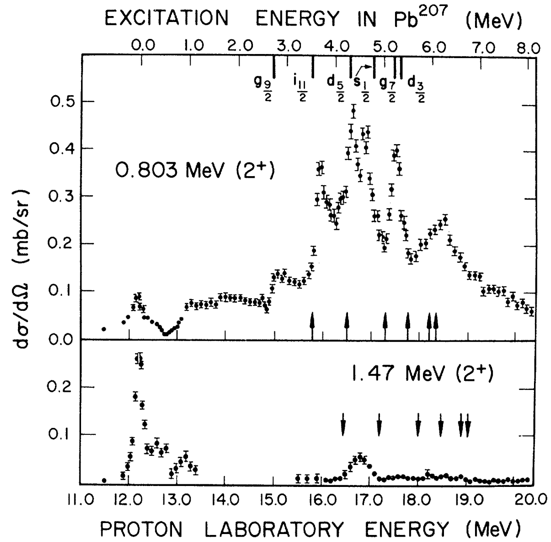

FIG. 3. Proton-scattering excitation functions at 165° for the first two 2^+ states of Pb^{206}. The unperturbed positive-parity single-neutron states in Pb^{207} are indicated on the upper energy scale which has been positioned to correspond to isobaric-analog states in Bi^{207}. (Note that these states are taken to have the same binding energy in Pb^{207} as in Pb^{209}.) The arrows correspond to the unperturbed positive-parity particle-plus-core multiplets based on the 2^+ core excitations. The actual levels in Pb^{207} are expected to contain combinations of these single-particle and particle-plus-core configurations.

results in the concentration of particle-plus-core "strength" into narrow intervals. Another possibility is that a large (p,p') direct-reaction amplitude may be necessary in the excitation mechanism of these isobaric-analog states as exit-channel resonances. On the other hand, we have already commented concerning the admixture of single-particle with particle-plus-core configurations as the mechanism for exciting them in the lead nuclei. This type of explanation seems to be favored by the present data and is also more consistent with the Zr^{91} results.

Particle-plus-core states are examples of two-particle, one-hole states which have been of special interest because of their assumed role as doorway states in nuclear reactions.[3,19] Within this context, particular emphasis has been placed on the possible importance of coupling to collective cores.[3,20] The present results suggest that in the lead nuclei, at intermediate energies, the only doorway states that either exist, or are narrow enough to be observed, are indeed those containing particle-plus-collective core structure.[21] Simpler two-particle, one-hole states could have emerged, for example, from the coupling of a particle to the relatively pure $(g_{9/2}, p_{1/2}^{-1})$ noncollective 4^- state of Pb^{208}, but no evidence for them was observed in the inelastic scattering to that state.

There is a simple plausible interpretation of the present (p,p') results that appears to be in striking accord with the doorway concept. Following the capture of a nucleon into a single-particle state, the interaction with the core excites a collective mode and to conserve energy the nucleon drops to a lower single-particle state. The resulting particle-plus-collective core constitutes the doorway state, and in the (p,p') reaction through the isobaric analog, the proton is observed to escape from it. If the particle-core interaction leading to the doorway state is similar to the interaction governing direct inelastic scattering, the correlation between the collective strength of the core and the probability for exciting particle-core coupled states would follow naturally. More information concerning both the structure of particle-plus-core states (e.g., their width), and the mechanism for reaching them, is necessary to determine the extent to which this simple picture of the dissolution of single-particle strength via collective modes of the core is valid.

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