[2]Some preliminary results have been reported. B. P. Clayman and A. J. Sievers, Bull. Am. Phys. Soc. 13, 659 (1968).
[3]M. Gomez, S. P. Bowen, and J. A. Krumhansl, Phys. Rev. 153, 1009 (1967).
[4]R. A. Herendeen, Bull. Am. Phys. Soc. 13, 660 (1968); G. Höcherl and H. C. Wolf, Phys. Letters 27A, 133 (1968).
[5]W. Hayes and H. F. Macdonald, Proc. Roy. Soc. (London), Ser. A 297, 503 (1967).
[6]R. D. Kirby and A. J. Sievers, to be published.
[7]Buckbee-Meers Company, Minneapolis, Minnesota.
[8]W. Gebhardt, Phys. Rev. 159, 726 (1967).
[9]D. B. Fitchen, in Physics of Color Centers, edited by W. B. Fowler (Academic Press, Inc., New York, 1968), Chap. 5.
[10]Elliott et al. have used a somewhat similar model to describe the U center in CaF_2; see R. J. Elliott, W. Hayes, G. D. Jones, H. F. Macdonald, and C. T. Sennett, Proc. Roy. Soc. (London), Ser. A 289, 1 (1965).
[11]G. D. Mahan, Phys. Rev. 153, 983 (1967).
[12]I. G. Nolt, R. A. Westwig, R. W. Alexander, Jr., and A. J. Sievers, Phys. Rev. 157, 730 (1967).

ISOBARIC ANALOG RESONANCES IN STRIPPING AND PICKUP REACTIONS*

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Resonance structure is observed in many (d,p) and (p,d) excitation functions in the lead region. The results are compared with previously reported (t,p), (p,t), and (d,p) data, and systematic resonance behavior is found common to all stripping and pickup reactions involving incident or final protons. Resonances occur whenever the proton-channel energies lie between 16 and 18 MeV. This is the energy region where single-particle isobaric analog states occur in the reaction $Pb^{208}(p,p)$.

Isobaric analog states in heavy nuclei have been widely studied by proton elastic and inelastic scattering.[1] Recently, resonances observed in certain (d,p), (p,d), and (t,p) excitation functions from targets in the lead region also have been identified with isobaric analog states.[2-5] However, unlike proton scattering for which many aspects of the analog-resonance phenomenon are reasonably well established and understood, in neutron-transfer reactions neither a clear theoretical understanding nor a firm experimental basis for the occurrence of such resonances has yet been offered. In this Letter results are presented from a study of the reactions $Pb^{208}(p,d)$, $Pb^{207}(d,p)$, and $Pb^{206}(d,p)$ as a function of energy. In the excitation function for almost every transition studied thus far, we find resonance structure that is clearly associated with isobaric analog states. From these results, certain systematic features of analog resonances in transfer reactions in the lead region are readily apparent, and all of the presently available data, including the earlier work mentioned above, can be correlated. The essential feature is the location of the resonance structure in approximately the same region of proton-channel energies for all transitions studied, independent of target nucleus, Q value, final state, or the particular reaction used. These results are important for understanding (1) the isobaric-analog-resonance mechanism, (2) the nature and identity of the isobaric analog states responsible for the resonances, and (3) the relationship between the resonances in the (p,d), (d,p), and (t,p) transfer reactions and the more familiar (p,p) and (p,p') resonances.

The experiments were performed using proton and deuteron beams from the High Voltage Engineering Corporation Model MP tandem accelerator at Yale. The measurements were made with standard solid-state detector systems. Excitation functions measured at 165° for the reaction $Pb^{208}(p,d)$ leading to the first five neutron-hole states of Pb^{207} are presented in Fig. 1. Strong resonance structure can be seen for incident proton energies between 16 and 18 MeV. These are the same incident energies where strong isobaric analog resonances have been observed[6,7] in proton scattering on Pb^{208} corresponding to the $3d_{5/2}$, $4s_{1/2}$, $2g_{7/2}$, and $3d_{3/2}$ single-particle states in Pb^{209}. More detailed measurements[4] near $E_p = 15$ MeV confirm the relatively small resonance effects (~10%), attributed to the $2g_{9/2}$ single-particle analog state, in the first three (p,d) excitation functions.

Excitation functions for the reaction $Pb^{207}(d,p)$

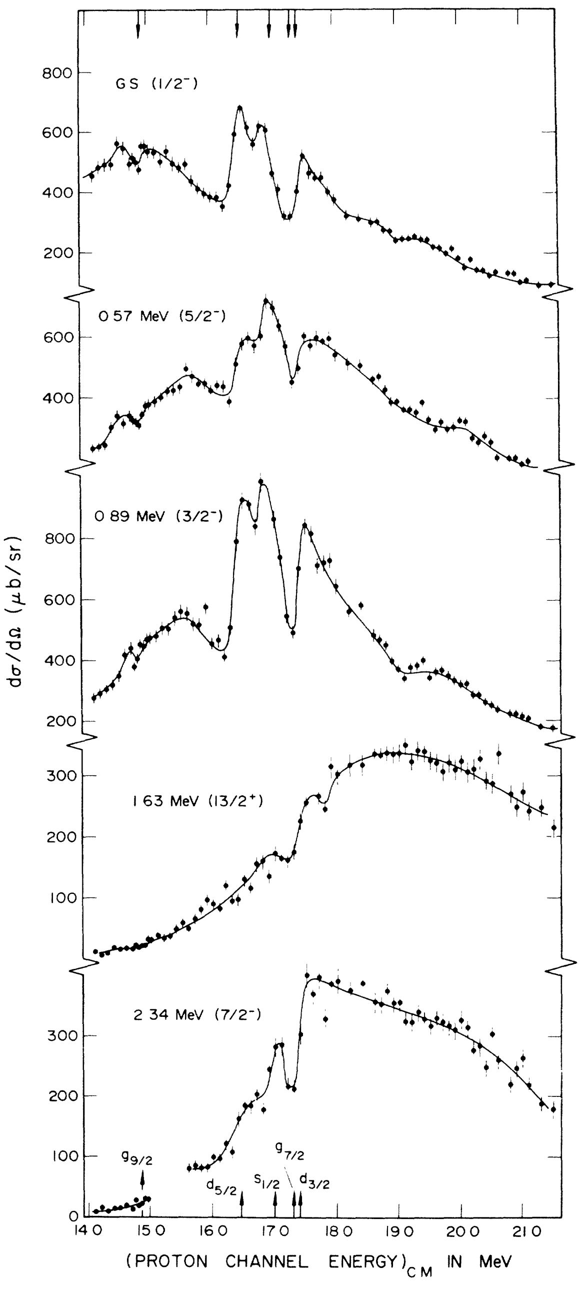

FIG. 1. Excitation functions for the reaction $Pb^{208}(p,d)$ at a laboratory angle of 165° leading to the neutron-hole states of Pb^{207}. The curves in this figure and in Figs. 2 and 3 are drawn as a guide through the experimental points. The proton-channel energies of the isobaric analog resonances in the reaction $Pb^{208}(p,p)$ corresponding to the single-particle states of Pb^{209} are indicated by the arrows in all three figures.

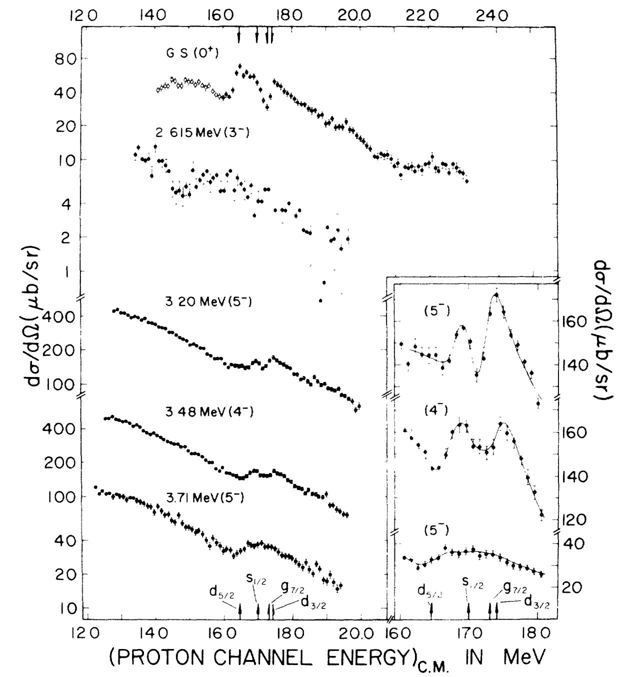

FIG. 2. Excitation functions for the reaction $Pb^{207}(d,p)$ at a laboratory angle of 165° leading to the first five states in Pb^{208}. The open circles in the ground-state transition data were taken from the inverse reaction data in Fig. 1. The insert shows an expansion of the resonance region in the lowest three excitation functions. Note that the horizontal scale refers to the outgoing-proton-channel energy.

at a laboratory angle of 165° were obtained with deuteron energies from 11 to 18 MeV and are shown in Fig. 2. The ground-state transition is in good agreement with the inverse reaction data in Fig. 1 and with the previous (d,p) measurement by Hamburger.[2] The excitation functions for the transitions leading to the excited states at 2.615 MeV (3^-), 3.20 MeV (5^-), 3.48 MeV (4^-), and 3.71 MeV (5^-) of Pb^{208} were not measured previously in this energy region. With the possible exception of the 3^- excitation function for which the cross section is small and the statistics poor, all of the excited-state transitions show significant resonance effects.

An important result from the data in Figs. 1 and 2 is that while the resonance regions in the $Pb^{208}(p,d)$ transitions to different final states all correspond to the same excitation energies in the Bi^{209} compound system, the resonance energies in Bi^{209} for the $Pb^{207}(d,p)$ transitions to various final states are not the same. Of course, the resonances in the (d,p) ground-state transition correspond to those observed in the reaction $Pb^{208}(p,d)$. The factor which is common to all the transitions in the two reactions is that the proton energies, whether in the initial or final channel, in the region of strong resonance behavior are approximately the same, 16 to 18 MeV. To illustrate this fact, the (d,p) excitation functions in Fig. 2 have been plotted as a function of the outgoing-proton-channel energy ϵ_p in the center-of-mass system, which is given by $\epsilon_p = \epsilon_d + Q_{\text{g.s.}} - E_{\text{ex}}$. Here, ϵ_d is the deuteron-channel energy, $Q_{\text{g.s.}}$ is the (d,p) Q value for the ground-state transition, and E_{ex} is the final-state excitation energy.

Behavior similar to that described above is found also in the excitation functions for the reaction $Pb^{206}(d,p)$ leading to the neutron-hole states of Pb^{207}. The results obtained at 165° are shown in Fig. 3, where again the data are plotted as a function of the proton-channel energy. Although the Q value and hence the deuteron incident energies differ from those in the reaction $Pb^{207}(d,p)$ shown in Fig. 2, nevertheless the strongest resonance effects occur for proton-channel energies between 16 and 18 MeV.

Other neutron-transfer excitation functions that have been measured in the lead region are the (t,p), (d,p), and (p,t) reactions[4,5] on Pb^{208} leading to a number of final states. In four of the five transitions reported, strong resonances are observed, and when their proton channel energies are considered, we find that they conform closely to the same pattern indicated in the present results. Thus, based on all the experimental data presently available on neutron-transfer reactions in the lead region involving an incident or final proton, we find in nearly every excitation function studied resonance structure for proton-channel energies between 16 and 18 MeV. The similarity between these energies and the proton resonance energies of the single-particle isobaric analog states observed in the reaction[6,7] $Pb^{208}(p,p)$ strongly suggests that isobaric analog states are also the key to understanding the widespread resonance phenomenon in transfer reactions.

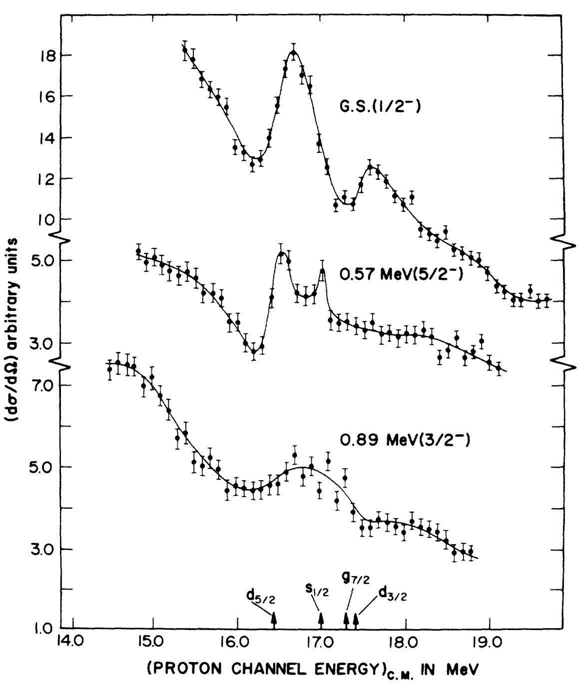

FIG. 3. Excitation functions for the reaction $Pb^{206}(d,p)$ at a laboratory angle of 165° leading to the first three states of Pb^{207}. Note that the horizontal scale refers to the outgoing-proton-channel energy.

The outstanding qualitative features of this resonance behavior are its strong dependence on the proton characteristics and apparent lack of dependence on either the nuclear state in the proton channel or on the properties of the other channel. This suggests the possibility that initial- or final-state resonances will occur in any reaction, not necessarily one involving neutron transfer, as long as incident or final protons with energies corresponding to the single-particle analog states are produced.

Hamberger[2] and Tamura[8] have discussed possible mechanisms for exciting isobaric analog resonances in (d,p) reactions. The general direct-reaction framework given by Tamura is in qualitative accord with the present results. In that approach, the resonance behavior is attributed only to the proton channel, but its effects are carried through into the direct (d,p) reaction amplitude. Such a process would also describe the resonance behavior mentioned above for any direct reaction involving protons in one of the channels. However, a comparison of Tamura's calculations with the $Pb^{207}(d,p)$ ground-state resonances resulted in qualitative but not quantitative reproduction of the effect.[8]

Another interesting aspect of the resonances described here is the nonconservation of isobaric spin which occurs when analog states with $T = T_0 + \frac{1}{2}$ are reached by deuteron bombardment (or $T = T_0 + \frac{3}{2}$ by triton bombardment) on a target with $T = T_0$. This isospin nonconservation is consistant with a direct reaction mechanism occurring on the periphery of the nucleus where the Coulomb interaction is important and isospin need not be conserved.

The nature of the isobaric analog states responsible for the resonances provides some insight into the structure of certain excited states in the lead nuclei. The behavior described above strongly implies that these states contain large components of particle-plus-core structure, with the nuclear state in the proton channel acting as a core coupled to the resonating proton in a single-particle state. Thus, the resonances for each $Pb^{207}(d,p)$ transition in Fig. 2 may be identified with the isobaric analogs of those Pb^{209} states described by coupling single-particle states to the particular core state of Pb^{208} reached in that transition. For the (d,p) ground-state transition and all the $Pb^{208}(p,d)$ transitions, the resonances reflect the usual single-particle states of Pb^{209}. For the (d,p) excited-state transitions, many overlapping isobaric analog states undoubtedly contribute to the observed structure. These states arise from the multiplets produced by the coupling of single-particles to excited-core states, together with the possible mixing of these states with other configurations.[7] Thus, the resonances in the lowest three transitions in Fig. 2 correspond to concentrations of states in Pb^{209} with particle-plus-excited-core configurations based on the 5^-, 4^-, and second 5^- states of Pb^{208}, respectively.

In the reaction $Pb^{206}(d,p)$, the final states observed are the neutron-hole states of Pb^{207}. Therefore, the resonances in Fig. 3 are interpreted as groups of isobaric analog states in Bi^{208} corresponding to particle-hole states of Pb^{208}. Each group of particle-hole states is different in the three excitation functions, since each is based on that hole state reached in the particular transition.

It is of interest to compare the resonances in the stripping and pickup excitation functions with those we reported earlier for proton inelastic scattering.[7] The (p,p') resonances provide evidence for particle-plus-core states built only on collective-core excitations,[7,9] while the present results show that resonance effects can be equally prominent for both collective and noncollective cores. This can be seen in Fig. 2 where the collective 5^- state (3.20 MeV) and noncollective 4^- states have similar resonance behavior in the reaction $Pb^{207}(d,p)$. In the reaction $Pb^{208}(p,p')$, however, only the collective 3^- and 5^- states show particle-plus-core resonances.[7] The ingredient that is essential for the observation of a resonance in the proton-plus-core system for any transition in any reaction is the existence of a non-negligible direct reaction amplitude leading to the core state. For (p,p') these are the collective states; in neutron-transfer reactions they are the states with appreciable spectroscopic factors.

When comparing the particle-plus-core resonances excited in different reactions, it should be noted that for the isospin-forbidden cases, e.g., (d,p) or (t,p), the resonance mechanism most likely involves a direct reaction followed by a final-state resonance, while in the (p,p') reaction where isospin is conserved, the dominant effects can arise from compound inelastic scattering through the analog state.[7,9] Indeed, the (p,p') resonances normally (but not always) show much larger effects than the (d,p) resonances. The present results imply, nevertheless, that direct reaction effects must also be considered in a proper treatment of isobaric analog resonances in the (p,p') reaction. This is not only because of possible interference effects between compound and direct scattering as has been emphasized previously, but also because of the possibility that a resonance can be initiated entirely by the direct (p,p') process with no compound contribution, such as described above for (d,p) and (t,p) reactions.

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[1]See, for example, Isobaric Spin in Nuclear Physics, edited by J. D. Fox and D. Robson (Academic Press, Inc., New York, 1966).

[2]E. W. Hamburger, Phys. Rev. Letters 19, 36 (1967).

[3]N. Stein, Bull. Am. Phys. Soc. 12, 461 (1967); J. P. Coffin, N. Stein, C. A. Whitten, and D. A. Bromley, Bull. Am. Phys. Soc. 13, 656 (1968).

[4]E. M. Bernstein and D. D. Armstrong, Phys. Letters 26B, 365 (1968).

[5]D. D. Armstrong and E. M. Bernstein, Phys. Rev. Letters 20, 936 (1968).

[6]S. A. A. Zaidi, J. L. Parish, J. G. Kulleck, C. F. Moore, and P. von Brentano, Phys. Rev. 165, 1312 (1968).

[7]N. Stein, C. A. Whitten, and D. A. Bromley, Phys. Rev. Letters 20, 113 (1968).

[8]Taro Tamura, J. Phys. Soc. Japan 24, 288 (1968).

[9]A. Auerbach and N. Stein, Phys. Letters 27B, 122 (1968).