Table IV. Comparison of our results with those previously reported in Refs. 2-4. See Table III for our results.

Institution	Q (e b)
Rutgers-Cal. Tech.	$-0.54 < Q < -0.90$
Aldermaston	-0.49 ± 0.25
Oak Ridge	-0.60 ± 0.14

sults indicate that contributions from this effect must be very small. This is in agreement with theoretical predictions by MacDonald.[8]

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DIRECT-COMPOUND INTERFERENCE AT AN ISOBARIC ANALOG RESONANCE IN DEUTERON STRIPPING

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Isobaric analog resonances are identified in the reaction $Pb^{207}(d,p)Pb^{208}$. A calculation of the cross section based on adding the scattering matrix elements for direct stripping (obtained from distorted-wave Born approximation) and for compound-nucleus formation (from R-matrix theory) fits the data near the $d_{5/2}$ resonance at 11.43 MeV well.

The interference of compound-nucleus formation and direct interactions in rearrangement reactions is not well understood. One of the problems is that the available experimental data have been difficult to analyze: The spins, parities, and widths of the resonances are not known and often there are several overlapping resonances.[1] In this Letter we present data and a successful analysis for a single resonance of known spin, parity, and width which occurs in a predominantly direct reaction. Furthermore, the reaction is on a heavy target nucleus at a much higher bombarding energy than previous work[1]; the direct reaction should therefore be well described by distorted-wave Born approximation (DWBA).

The reaction $Pb^{207}(d,p)Pb^{208}$g.s. was studied as a function of deuteron energy in the range 9.2 to 13 MeV. The yield curves below 10.3 MeV are smooth functions of the energy[2]; the data above 10.3 MeV are shown in Fig. 1.[3] Resonances are apparent near 11.4, 11.9, and 12.4 MeV, and it is clear that there is interference between the resonances and the nonresonant background. These deuteron energies correspond closely to the analog states, in the compound nucleus Bi^{209}, of the following single-particle states of Pb^{209}: $d_{5/2}$, $s_{1/2}$, and $d_{3/2}$-$g_{7/2}$ (unresolved). The same analog states have been studied by means of the reaction $Pb^{208}(p,p)$, and the positions, total widths, and partial elastic-proton widths have been determined.[4]

The presence of the resonances in the (d,p) reaction is of interest also from other points of view. The formation of the analog resonances in the deuteron channel is isospin forbidden because deuterons have isospin $T=0$ and the analog states have T one unit larger than that of the target. Their appearance is then eith-

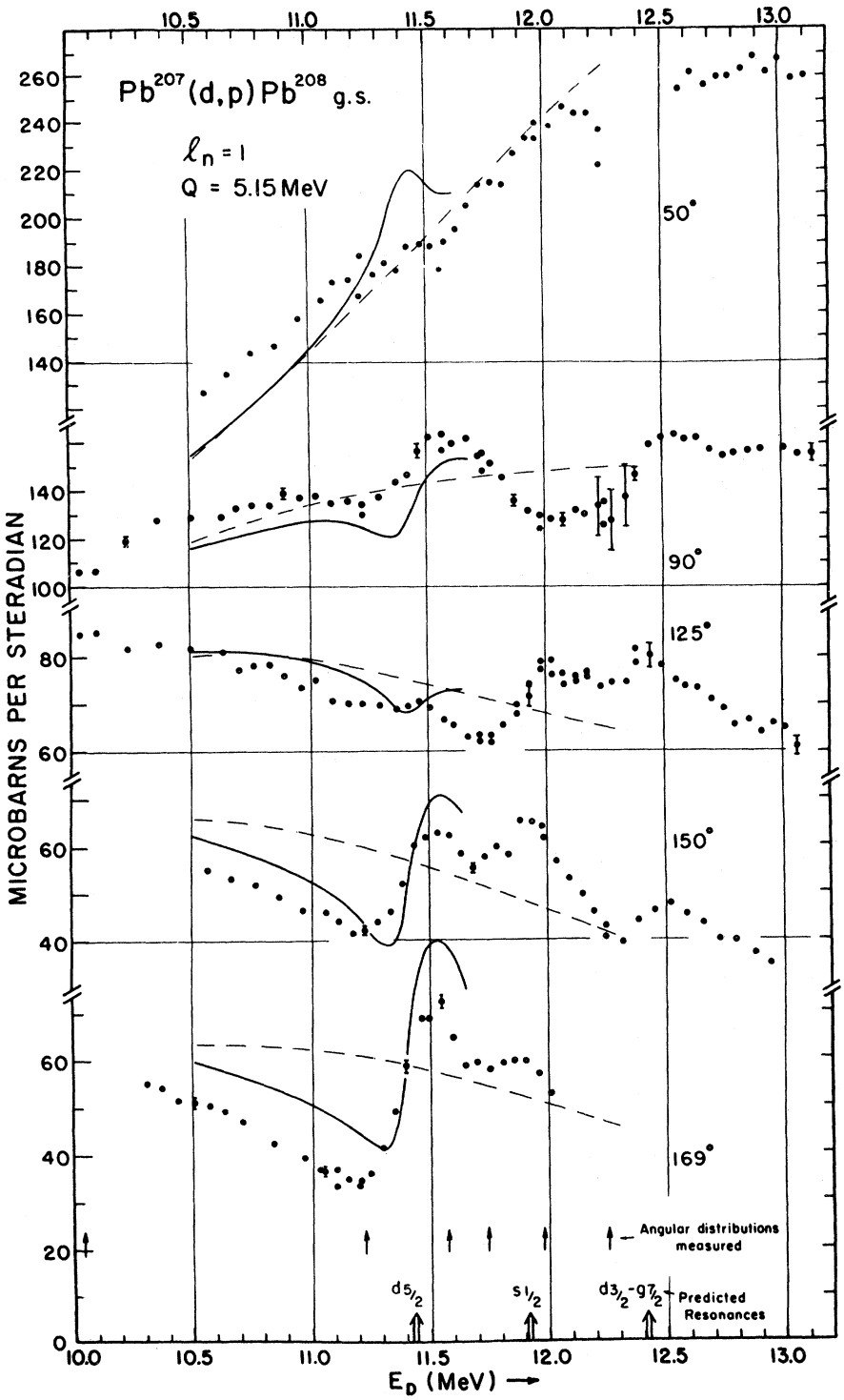

FIG. 1. Yield curve for the reaction $Pb^{207}(d,p)Pb^{208}$g.s. at several angles. Note suppressed zeros and scale change for smaller angles. The double arrows show positions of predicted analog resonances. Single arrows show energies where angular distributions were measured. The full line is the cross section calculated as described in the text and includes direct and compound contributions. The dashed line is calculated DWBA only.

er a consequence of the admixture of $T_<$ states into the analog wave function[5] or an indication of an isospin change during the reaction itself, for example the excitation of the incoming deuteron to a $T=1$ state by the target Coulomb field, as suggested by Drachman[6] and by Griffy.[6]

In this Letter we present an analysis of the lowest, $d_{5/2}$, resonance. The amplitude of the outgoing proton wave in channel c' is proportional to the scattering matrix element $U_{cc'}$.[7] Since the protons come in part from compound-nucleus decay and mostly from the direct reaction, it is natural to try to write the scattering matrix element as the sum of a direct term and a resonance term:

$$U_{cc'}=U_{cc'}^{DI}+U_{cc'}^{R}. \tag{1}$$

As shown by Ratcliff and Austern,[8] Eq. (1) can be a good approximation when, as in the present case, one mechanism predominates over the other.

For the direct term $U_{cc'}^{DI}$ we take the DWBA result as calculated by code JULIE.[9] The neutron transferred in the stripping reaction has $l=1$, $s=\frac{1}{2}$, $j=\frac{1}{2}$. When there is only one value of lsj, the scattering matrix element $U_{cc'}^{DI}$ is proportional to a radial integral of the DWBA, as shown by Satchler[10] in an appendix.

The parameters for the optical-potential wells were taken from recent work on $Pb^{208}(d,p)$ at higher energies.[11] The fit obtained to the angular distributions off resonance (below 10.5 MeV) is quite good; at back angles the calculated cross section is ~20% above the experimental one. The fit is improved by using a cut-off radius of 8 F; however no cutoff is used in the following. The spectroscopic factor extracted off resonance is $S=2$ as expected from the shell model.

The resonance term $U_{cc'}^{R}$ only occurs in three channels c and in one channel c', because of angular-momentum conservation. The spins and parities are the following:

$$Pb^{207}+d \rightarrow Bi^{209*} \rightarrow Pb^{208}+p$$

$$\tfrac{1}{2}^- \quad 1^+ \quad \tfrac{5}{2}^+ \qquad 0^+ \quad \tfrac{1}{2}^+.$$

The allowed angular momenta (l_d,j_d), where $j_d=l_d+s_d$, are (1, 2), (3, 2) and (3, 3). In the exit channel $(l_p,j_p)=(2,\frac{5}{2})$. We try an R-matrix theory[7] expression for $U_{cc'}^{R}$:

$$U_{l_pj_pl_dj_d}^{R}=U_{2\,5/2\,12}^{R}=\exp[i(\omega_p-\varphi_p)]\exp[i(\omega_d-\varphi_d)]i[(\Gamma_{2\,5/2}^{p}\Gamma_{12}^{d})^{1/2}/(E_R-E-i\tfrac{1}{2}\Gamma)]. \tag{2}$$

The other two nonzero matrix elements have similar expressions except that the deuteron partial width Γ_{12}^{d} is replaced by Γ_{32}^{d} or Γ_{33}^{d}. Here ω and φ are the Coulomb and hard-sphere phase shifts, respectively, in the entrance and exit channels.[7] The resonance parameters found from the proton scattering experiments[4] are $E_R=11.43$ MeV, $\Gamma=235$ KeV, and $\Gamma_{2\,5/2}^{p}=32$ keV. The only unknown parameters in Eq. (2) are the deuteron partial widths.

In order to add the direct and resonance matrix elements and calculate the resulting cross sections, we made use of a modified version of the code JULIE, written by Drisko.

Many different combinations of values for the $\Gamma_{l_dj_d}^{d}$ were tried but the experimental yield curves were not even qualitatively reproduced. The hard-sphere phase shifts φ_p,φ_d were then replaced by their optical-model equivalents (which are calculated by JULIE in both entrance and exit channels). Again no fit was found. Finally the phase of U^R was allowed to vary freely; the sum $\omega_p-\varphi_p+\omega_d-\varphi_d$ was replaced by an adjustable parameter ψ. In order to reduce the number of parameters, the $l_d=3$ deuteron widths were assumed to be zero, i.e., only $l_d=1$ was considered. A very reasonable fit was obtained and is shown by the full line in Fig. 1. It should be noted that there is no arbitrary normalization at different angles in the calculation; the cross section at all angles is determined by the spectroscopic factor $S=2$ and by the value of the deuteron partial width $\Gamma_{12}^{d}=1.0$ keV.[12] Also the phase of the resonance term in the scattering matrix element determines the relative phases of the direct and resonance amplitudes at all angles. The value of ψ in the phase factor $e^{i\psi}$ which replaces the two exponentials in Eq. (2) is $\psi=0°$ for the calculated curves in Fig. 1; the hard-sphere value is $\omega_p-\varphi_p+\omega_d-\varphi_d=180°$, while the optical-model phase is +260°.

The good fit obtained shows that the method

of adding resonance and direct-scattering matrix elements as in Eq. (1) is a good parametrization of the data in this case. In order to predict the correct phase for the resonance term, however, a more detailed calculation must be made, for example following the lines of Ratcliff and Austern[8]; the phase may also serve as a test for the deuteron-breakup hypothesis of Drachman and Griffy[6] in this case.

It is clear that several approximations have been made in calculating the curves of Fig. 1, the most important being (a) neglect of the effects of the nearby $s_{1/2}$ resonance in the energy region of the $d_{5/2}$ resonance; (b) assumption that $l_d = 3$ deuteron partial waves do not contribute to the resonance (the $l_d = 1$ and $l_d = 3$ penetrability factors differ by a factor ~2); and (c) nonadjustment of the DWBA parameters to obtain a better fit to the angular distributions off resonance. Better fits to the experimental data can probably be obtained if these approximations are dropped. A more basic assumption is that the analog state is a single resonance having certain widths Γ^p, Γ^d, and Γ; the effects of the mixing with the $T_<$ states are not properly treated.[5]

It is interesting that recent measurements[13] of yield curves for the reactions $Pb^{206}(d,p)$ and $Pb^{208}(d,p)$ do not show any resonances comparable in size with those of Fig. 1. On the other hand, the inverse reaction $Pb^{208}(p,d)Pb^{207}$ does show resonances in several channels.[14]

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