# Isobaric Analog Resonances in Elastic and Inelastic Scattering of Protons on $^{208}$Pb†

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Excitation functions for proton elastic scattering and inelastic scattering to the 2.615-MeV ($3^-$), 3.198-MeV ($5^-$), 3.475-MeV ($4^-$), 3.709-MeV ($5^-$), 4.36-MeV, 4.48-MeV, and 4.69-MeV states in $^{208}$Pb were measured at laboratory angles of 90°, 125°, 150°, and 170°. The beam energy was varied in 25-keV steps between 14.2 and 18.2 MeV. In this range of bombarding energies, the isobaric analogs of the $g_{9/2}$, $i_{11/2}$, $d_{5/2}$, $s_{1/2}$, $g_{7/2}$, and $d_{3/2}$ single-neutron states of $^{209}$Pb were observed. The elastic-scattering cross sections have been analyzed to yield the parameters of the $g_{9/2}$, $d_{5/2}$, $s_{1/2}$, $g_{7/2}$, and $d_{3/2}$ resonances. A simple interpretation of the decay of these resonances into the inelastic proton channels is offered, and the particle-hole structure of the excited states of $^{208}$Pb is discussed.

## I. INTRODUCTION

THE discovery of isobaric analog states in heavy nuclei as resonances in highly excited compound systems[1] has attracted considerable attention. A number of both experimental and theoretical investigations have been devoted to their study. It has been shown that the observed anomalies in the excitation functions are due to giant resonances, and that their existence in heavy nuclei is a general phenomenon.[2–7] A systematic study of the spreading widths associated with these resonances in various nuclei is of considerable interest. This quantity is a measure of the mixing of the isobaric analog state into the numerous states of lower isospin that surround it. Apart from being a very interesting phenomenon, the isobaric analog resonances offer a useful tool for the study of nuclear structure. Valuable spectroscopic and nuclear structure information pertaining to the corresponding parent analog state can be obtained from a knowledge of the spin and parity of an isobaric analog resonance and its various partial widths. The partial widths for decay into the inelastic proton channels are of particular importance.[8–10] From these partial widths one expects to be able to extract nuclear structure information, some of which is not accessible from $(d,p)$ or $(d,t)$ reactions.

The elastic and inelastic scattering of protons from $^{208}$Pb at bombarding energies corresponding to the excitation of isobaric analog resonances in $^{209}$Bi is in many ways unique. The target nucleus $^{208}$Pb is the only one in the heavy-element region with both the proton and the neutron shells closed. The large energy gap between the last filled shell and the first unfilled shell (3.4 MeV) leads one to expect a closed-shell configuration for the ground state of $^{208}$Pb,[11] and simple particle-hole configurations for some of its low-lying states. Also, the ground state and the low-lying states in $^{209}$Pb have been shown to be very pure single-neutron states.[12,13] Consequently, their analogs in $^{209}$Bi should cause prominent resonances in the excitation function for elastic scattering of protons from $^{208}$Pb. Further, if it is true that some of the excited states in $^{208}$Pb are predominantly simple neutron–neutron-hole configurations, then one would expect a large overlap between the wave function of an excited state in $^{208}$Pb and that component of an analog state wave function which has the same neutron configuration. Thus, for instance, the $(g_{9/2})_n(p_{1/2})_n^{-1}$ configuration of the $4^-$ state in $^{208}$Pb at 3.47 MeV is contained in the wave function for the isobaric analog of the ground state of $^{209}$Pb:

$$T^-(^{209}\text{Pb g.s.})=(1/45)^{1/2}(g_{9/2})_p(^{208}\text{Pb g.s.})+(2/45)^{1/2} \times(p_{1/2})_p(g_{9/2})_n(p_{1/2})_n^{-1}(^{208}\text{Pb g.s.})+\cdots.$$

In this manner isobaric analog resonances can be used to probe the particle-hole structure of excited states. In all cases discussed in this work, the energies of the protons emitted in the decay of the isobaric analog resonances to excited states in $^{208}$Pb are comparable with the Coulomb barrier. These decays are therefore not expected to be greatly hindered by barrier-

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penetration effects. A level diagram of the low-lying states in $^{209}$Pb, their isobaric analogs in $^{209}$Bi, and some excited states in $^{208}$Pb is shown in Fig. 1. The study of isobaric analog states in $^{209}$Bi requires the measurement of excitation functions with incident proton energies larger than 15 MeV. These experiments thus awaited the operation of corresponding two- or three-state Van de Graaff accelerators. This work describes measurements of excitation functions of elastic and inelastic scattering of protons from $^{208}$Pb with the incident energy ranging between 14.2 and 18.2 MeV. Excitation functions for the elastic scattering and the inelastic scattering to seven levels in $^{208}$Pb measured simultaneously at four scattering angles are presented in Sec. III.

## II. EXPERIMENT

The experiment was performed using The University of Texas Van de Graaff accelerators in three-stage operation. A 5.2-MeV $H^-$ beam obtained from the single-stage CN Van de Graaff was injected into the EN tandem accelerator. By carefully focusing the $H^-$ beam we obtain a proton beam of 0.5 $\mu$A on the target. The beam energy was determined using the 90° analyzing magnet in conjunction with the nuclear magnetic resonance probe. Energy calibration was achieved by using the $^{27}$Al$(p,n)$ threshold at 5.803 MeV.

To measure the excitation functions for the inelastic scattering of protons to a number of excited states in $^{208}$Pb, we paid particular attention to improvement of the spectra of scattered protons. This consisted in (a) choice of proper scattering geometry, (b) improvement of the intrinsic resolution of the counters, and (c) preparation of large lead targets relatively free of contaminants. The beam was collimated by passing it through a $\frac{5}{8}$-in.-diam aperture before it entered the scattering chamber. After passing through the target the beam entered a long Faraday cup. It was stopped about 3 ft beyond the target chamber on a quartz viewer marked with cross hairs. The beam spot on the viewer was observed by closed-circuit television throughout the experiment. Thus the beam could be centered and focused without its ever striking the collimator. The beam spot on the target was about $\frac{1}{8}$ in. in diameter.

Four 3-mm-thick ORTEC Si-Li detectors were used in this experiment. They were placed at 90°, 125°, 150°, and 170° to the incident beam and cooled to approximately dry-ice temperature. As is well known, at these temperatures the reverse current is greatly reduced and the performance of the counters is very much improved. Another technique used to improve the energy resolution was to prevent the electrons ejected from the target from entering the detectors. This was accomplished by means of permanent magnets placed before each detector.

The targets were made by evaporating lead metal

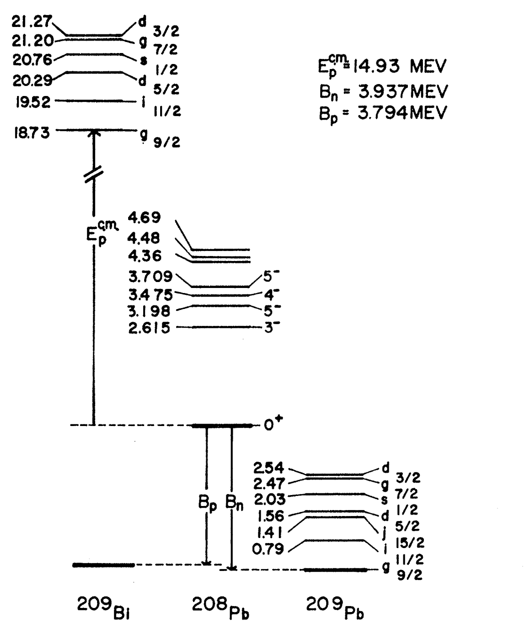


FIG. 1. Level diagram showing the low-lying states in $^{208}$Pb, the low-lying single-particle states in $^{209}$Pb, and their isobaric analog in $^{209}$Bi. For simplicity, the neutron-proton mass difference has been disregarded.

enriched to 99% in $^{208}$Pb from a tungsten boat onto glass slides that were previously coated with a very thin film of a detergent. The target foil was then floated off the glass slide on deionized water in an inert atmosphere. The foil was then lifted off the water using circular aluminum frames $\frac{3}{4}$ in. in diameter. The thickness of the target used in this experiment was determined by punching out a circular section of the target foil and weighing it. It turned out to be 0.71 mg/cm$^2$. This corresponds to an energy loss of about 7.5 keV for 16.0-MeV protons as they penetrate through the target. The actual energy resolution determined from the spectra of the scattered protons was about 35 keV.

A PDP-7 computer was used on line as a 4096-channel analyzer with 1024 channels for each detector. Figure 2 shows a typical spectrum obtained.

## III. DATA

The data obtained in this experiment consist of excitation functions for elastic and inelastic scattering to many states in $^{208}$Pb up to an excitation energy of 7 MeV. The measurements were made for incident proton energy between 14.2 and 18.2 MeV in 25-keV intervals. Differential cross sections for elastic scattering and for inelastic scattering to the 2.615-MeV ($3^-$), 3.148-MeV ($5^-$), 3.475-MeV ($4^-$), 3.709-MeV ($5^-$), 4.36-MeV, 4.48-MeV, and 4.69-MeV states in $^{208}$Pb have been reduced from the data. The elastic-scattering cross sections at 90°, 125°, 150°, and 170° are shown in Fig. 3. A distinction is made between independent measurements to demonstrate the good reproducibility.

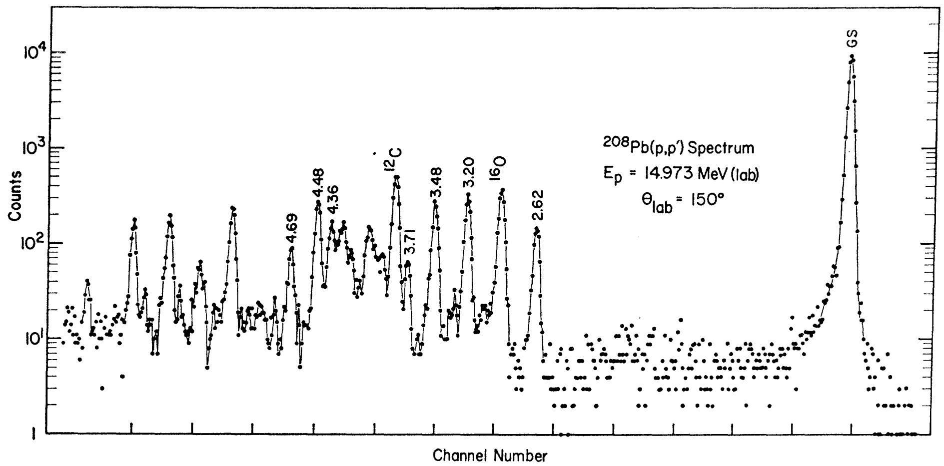


FIG. 2. Spectrum of the scattered protons observed at an incident proton energy close to the resonance energy of the $g_{9/2}$ resonance. The various proton groups are characterized by the excitation energies of the states populated in $^{208}$Pb. Proton peaks labeled in this spectrum are the ones for which excitation functions are presented in this work.

The cross sections display strong anomalies that are due to isobaric analog resonances. These resonances have been identified as the isobaric analogs of the $g_{9/2}$, $i_{11/2}$, $d_{5/2}$, $s_{1/2}$, $g_{7/2}$, and $d_{3/2}$ states in $^{209}$Pb.[14–16] The isobaric analog of $i_{11/2}$ is observed only weakly at $E_p = 15.7$ MeV. This is because of the small penetration factor for $l = 6$ protons. For similar reasons, the isobaric analog of the $j_{15/2}$ state in $^{209}$Pb is not observed. The observed total widths are large compared with those measured for lighter elements. For example, the total widths observed for the tin and barium isotopes are typically of the order of 70 keV. The resonances due to the $d_{5/2}$, $s_{1/2}$, $g_{7/2}$, and $d_{3/2}$ states overlap considerably.

The measured cross sections for inelastic proton scattering to the first excited ($3^-$) state in $^{208}$Pb are shown in Fig. 4. These excitation functions show anomalies at all those energies at which resonances are observed in the elastic-scattering cross sections. In addition, the $i_{11/2}$ resonance which is relatively weak in the elastic-scattering cross section shows up clearly in these excitation functions. The differential cross sections for the inelastic scattering to the $5^-$ level at 3.148 MeV (see Fig. 5), and to the $4^-$ level at 3.475 MeV (see Fig. 6), are striking in that they resonate strongly only at the isobaric analog of the $g_{9/2}$ level. The excitation curves for the inelastic scattering to the $5^-$ level display a weak resonance at the energy corresponding to the excitation of the isobaric analog of the $d_{5/2}$ level. The inelastic scattering to the $5^-$ level contains an appreciable nonresonant component which increases with energy. The excitation curve for inelastic scattering to the $4^-$ level resonates only at the isobaric analog of the $g_{9/2}$ level. It contains also a very small and constant nonresonant component. The excitation curves for the inelastic scattering to the second $5^-$ level at 3.709 MeV are shown in Fig. 7, and those to the levels at 4.36 and 4.48 MeV are shown in Figs. 8 and 9, respectively. These excitation curves show pronounced resonances only at the isobaric analog of the $g_{9/2}$ level in $^{209}$Pb. The nonresonant component of the inelastic scattering to these levels is quite appreciable and increases with energy.

Finally, the excitation curves for the scattering to the

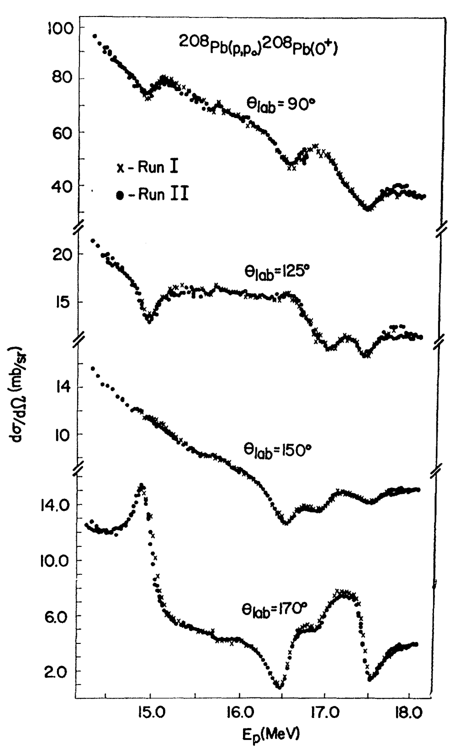


FIG. 3. Excitation functions of the elastic-scattering cross sections measured at four laboratory angles. Two sets of data points corresponding to different measurements are plotted to show the reproducibility of the measurements. In addition to the anomalies that are due to the isobaric analog of the $g_{9/2}$, $d_{5/2}$, $s_{1/2}$, $g_{7/2}$ and $d_{3/2}$ single-particle states in $^{209}$Pb, the 170° curve shows an anomaly at 15.7 MeV. At this energy the isobaric analog of the $i_{11/2}$ is expected to appear.

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4.69-MeV level in $^{208}$Pb (see Fig. 10), resonante both at the isobaric analog of the $g_{9/2}$ level and that of the $d_{5/2}$ level. Energies of the three levels mentioned last were assigned on the basis of studies conducted with the magnetic spectrograph.[17] We observed a number of peaks in our spectra which if assumed to be due to protons would correspond to inelastic scattering to higher excited states. There was, however, some doubt whether the various proton groups were well resolved. In addition, one would expect some deuteron groups from the pick-up reaction $^{208}$Pb$(p,d)^{207}$Pb. The reduction of data to yield inelastic cross sections to higher excited states in $^{208}$Pb was not attempted.

## IV. ANALYSIS AND DISCUSSION

The differential cross section for the elastic scattering of protons on spin-zero targets can be represented in terms of the scattering amplitudes $A$ and $B$ in the following manner:

$$d\sigma/d\Omega = AA^* + BB^* .$$

The two amplitudes are

$$A = -(\eta/2k)\csc^2(\tfrac{1}{2}\theta)\exp\{-i\eta \ln[\sin^2(\tfrac{1}{2}\theta)]\} + \frac{1}{2k}\sum_{L,J}(J+\tfrac{1}{2})iT_{L,J}P_L{}^0(\cos\theta),$$

$$B = \frac{1}{2k}\sum_{L,J}(-1)^{L+J+\frac{1}{2}}T_{L,J}P_L{}^1(\cos\theta),$$

where $T_{L,J}$ is given by $T_{L,J} = \exp 2i\omega_L - U_{L,J}$, where $\omega_L$ is the Coulomb phase shift, and $U_{L,J}$ is the collision matrix defined by Lane and Thomas.[18] Isobaric analog resonances in differential-cross-section measurements for elastic scattering of protons from medium-weight nuclei have been successfully described as Breit-Wigner

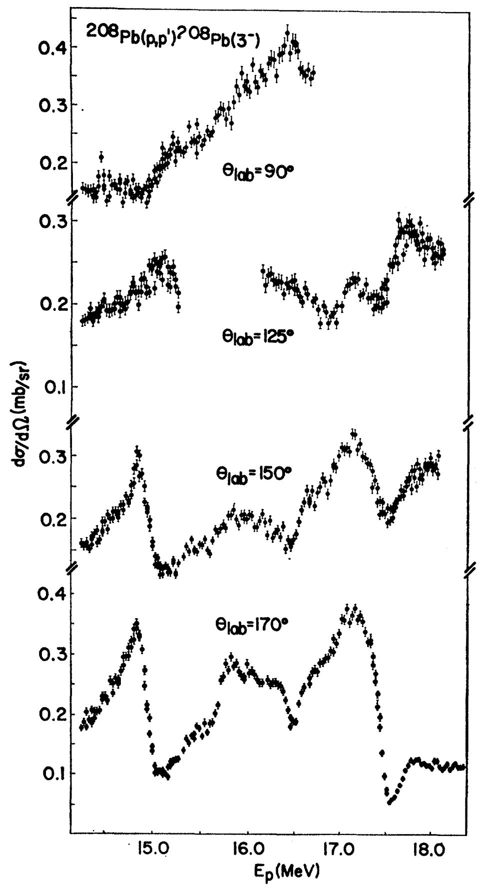


FIG. 4. Excitation functions of the inelastic scattering to the $3^-$ state at 2.615 MeV in $^{208}$Pb. The curves show anomalies at all energies at which isobaric analog resonances are observed in the elastic channel. Gaps in the excitation functions are caused by oxygen or carbon contaminant peaks crossing the $3^-$ peak.

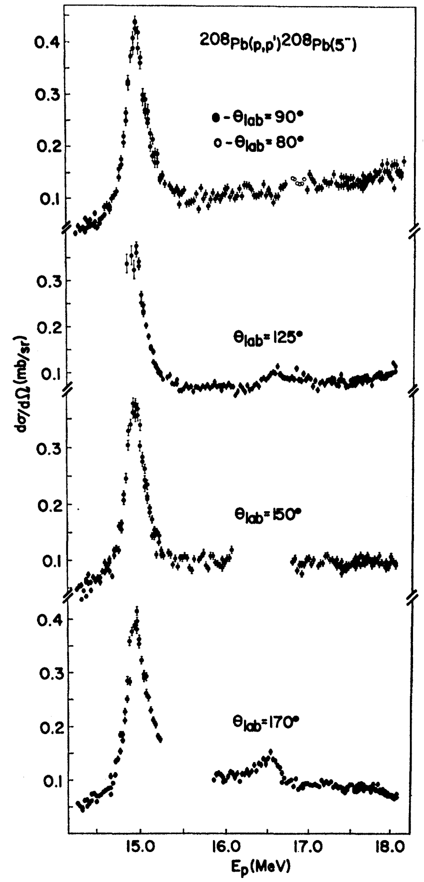


FIG. 5. Excitation functions of the inelastic scattering to the $5^-$ state at 3.198 MeV in $^{208}$Pb. All four excitation functions resonate strongly at the isobaric analog of the $g_{9/2}$ state in $^{209}$Pb. The 170° curve shows an anomaly also at the $d_{5/2}$ resonance. Gaps in the excitation functions are caused by oxygen or carbon contaminant peaks crossing the $5^-$ peak.

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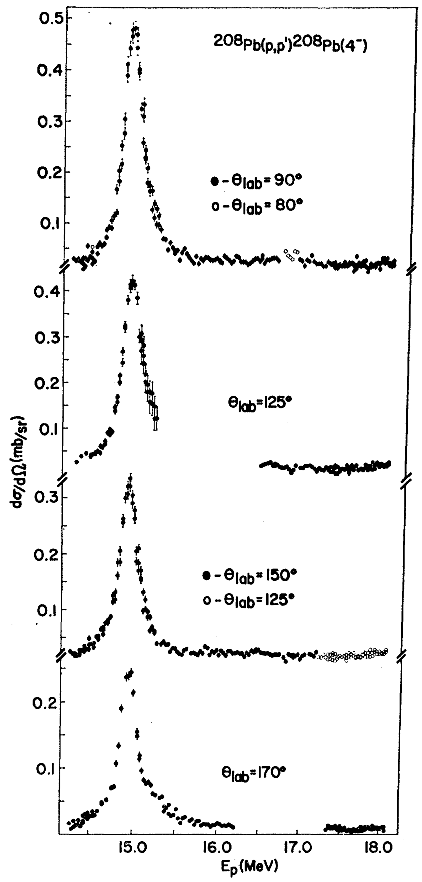


FIG. 6. Excitation functions of the inelastic scattering to the $4^-$ state at 3.475 MeV in $^{208}$Pb. All four excitation functions display a strong resonance at the isobaric analog of the $g_{9/2}$ state followed by a small constant background. Gaps in the excitation functions are caused by oxygen or carbon contaminant peaks crossing the $4^-$ peak.

resonances superimposed on a nonresonant background scattering.[3,4] This means that the collision matrix chosen had the form

$$U_{L,J}=e^{2i\omega_L}\left(e^{2i\xi_{LJ}}+e^{2i\phi_{LJ}}\frac{i\Gamma_{L,J}{}^P}{E_J-E-\frac{1}{2}i\Gamma_{L,J}}\right),$$

where $\phi_L{}^J$ is the background resonance phase and is real. $\xi_L{}^J$ is the optical phase which is complex in general; however, $\xi_L{}^J=\phi_L{}^J$ if $\mathrm{Im}(\xi_L{}^J)=0$. $E_J$ is the resonance energy. Finally, $\Gamma_{L,J}{}^P$ and $\Gamma_{L,J}$ are the partial and the total widths, respectively. This expression for the collision matrix can be obtained from the $R$-matrix theory of the isobaric analog resonances.[2] For the nonresonant scattering we assumed that the spin-flip contribution was negligible so that the phase shifts $\phi_L{}^J$ and $\xi_L{}^J$ could be considered to depend only on $L$. The potential scattering may be expressed in terms of an amplitude dependent on energy and angle. We define

$$\rho e^{i\gamma}=-\frac{\eta}{2k}\csc^2(\tfrac{1}{2}\theta)\exp\{-i\eta\ln[\sin^2(\tfrac{1}{2}\theta)]\}+\frac{1}{2k}\sum_{L,J}(J+\tfrac{1}{2})i(e^{2i\omega_L}-e^{2i\omega_L}e^{2i\phi_L})P_L{}^0(\cos\theta).$$

Then

$$A=\rho e^{i\gamma}-\frac{1}{2k}\sum_{L,J}(J+\tfrac{1}{2})i\times\left(e^{2i\omega_L}e^{2i\phi_L}\frac{i\Gamma_{L,J}{}^P}{E_J-E-\frac{1}{2}i\Gamma_{L,J}}\right)P_L{}^0(\cos\theta),$$

$$B=\frac{-1}{2k}\sum_{L,J}(-1)^{L+J+\frac{1}{2}}\times\left(e^{2i\omega_L}e^{2i\phi_L}\frac{i\Gamma_{L,J}{}^P}{E_J-E-\frac{1}{2}i\Gamma_{L,J}}\right)P_L{}^1(\cos\theta).$$

Now, since the expression for the differential cross section contains only absolute squares of $A$ and $B$,

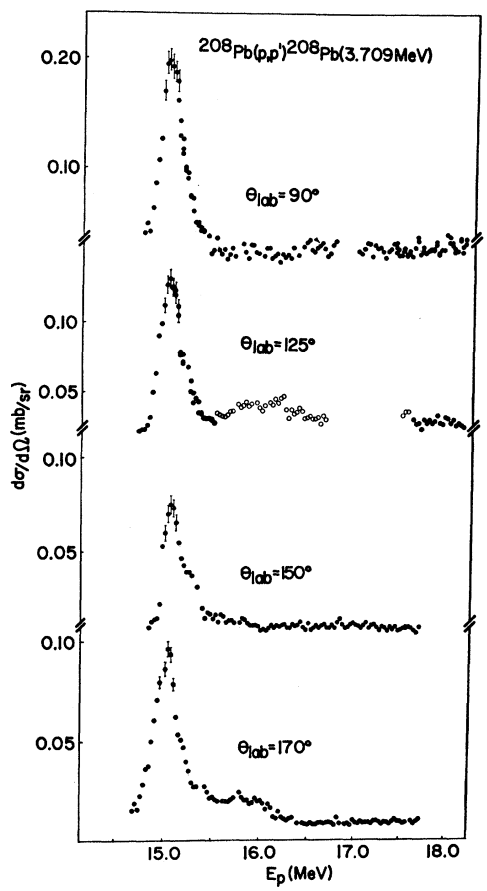


FIG. 7. Excitation functions of the inelastic scattering to the $5^-$ state at 3.709 MeV in $^{208}$Pb. All four excitation functions resonate strongly at the isobaric analog of the $g_{9/2}$ state in $^{209}$Pb. Data points shown as open circles on the 125° curve are obtained after a large background correction.

we may replace these by the following:

$$A'=e^{-i\gamma}A=\rho-\frac{1}{2k}\sum_{L,J}(J+\tfrac{1}{2})ie^{i\alpha_L}\times\frac{i\Gamma_{L,J}{}^{P}}{E_J-E-\frac{1}{2}i\Gamma_{L,J}}P_L{}^0(\cos\theta)\,,$$

$$B'=e^{-i\gamma}B=\frac{-1}{2k}\sum_{L,J}(-1)^{L+J+\frac{1}{2}}e^{i\alpha_L}\times\frac{i\Gamma_{L,J}{}^{P}}{E_J-E-\frac{1}{2}i\Gamma_{L,J}}P_L{}^1(\cos\theta)\,,$$

where

$$\alpha_L=2\omega_L+2\phi_L-\gamma\,.$$

The expression of the cross section in terms of the amplitudes $A'$ and $B'$ is very useful for the analysis of excitation functions. Every observed resonance is represented by a Breit-Wigner term in the expression for $A'$ and $B'$. At a fixed scattering angle the potential scattering is described by the slowly and monotonically changing function of energy $\rho(E)$. The quantity $\alpha$ may be taken to be independent of energy. A computer code BRIGIT[19] was written to fit the measured elastic-scattering cross sections with the theoretical form given above. The quantity $\rho(E)$ was simulated by a polynomial of fourth degree in inverse powers of $E$. The elastic-scattering cross sections at 170°, 150°, 125°, and 90° were fitted using the code BRIGIT, which searches for the best values of the resonance parameters $\Gamma_{L,J}{}^P$, $\Gamma_{L,J}$, $E_J$, and $\alpha_L$. The resonance parameters obtained are given in Table I. No attempt was made to fit the $i_{11/2}$ resonance because of the small effect observed.

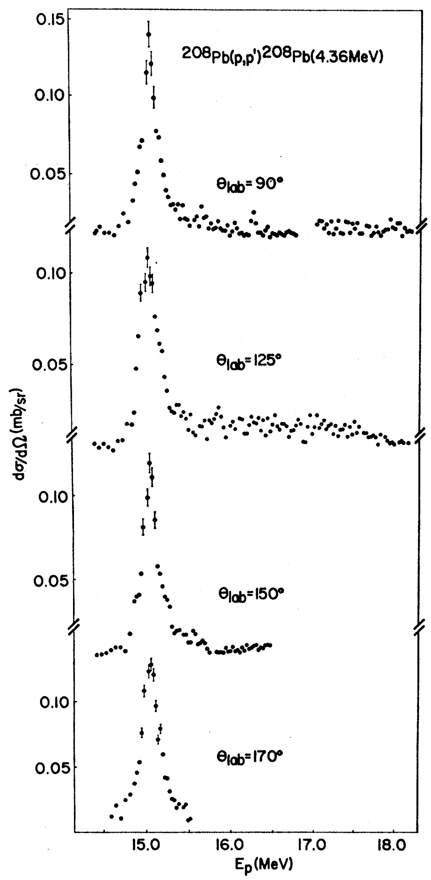


FIG. 8. Excitation functions of the inelastic scattering to the state at 4.36 MeV in $^{208}$Pb.

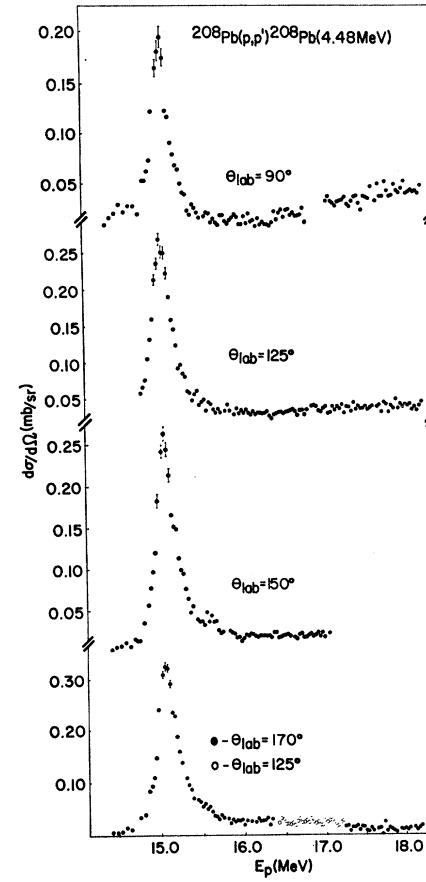


FIG. 9. Excitation functions of the inelastic scattering to the state at 4.48 MeV in $^{208}$Pb.

TABLE I. Resonance parameters obtained from the analysis of elastic-scattering cross sections. $E_J{}^{c.m.}$ is the c.m. resonance energy and $\Gamma_{L,J}$ and $\Gamma_{L,J}{}^P$ are the total and partial widths, respectively.

| $E_J{}^{c.m.}$ (keV) | $L_J$ | $\Gamma_{L,J}$ (keV) | $\Gamma_{L,J}{}^P$ (keV) |
|---|---|---|---|
| 14870±20 | $g_{9/2}$ | 275±15 | 22±3 |
| 16450±20 | $d_{5/2}$ | 225±15 | 30±3 |
| 17000±20 | $s_{1/2}$ | 500±15 | 175±10 |
| 17300±50 | $g_{7/2}$ | 300±30 | 30±6 |
| 17400±50 | $d_{3/2}$ | 350±40 | 40±8 |

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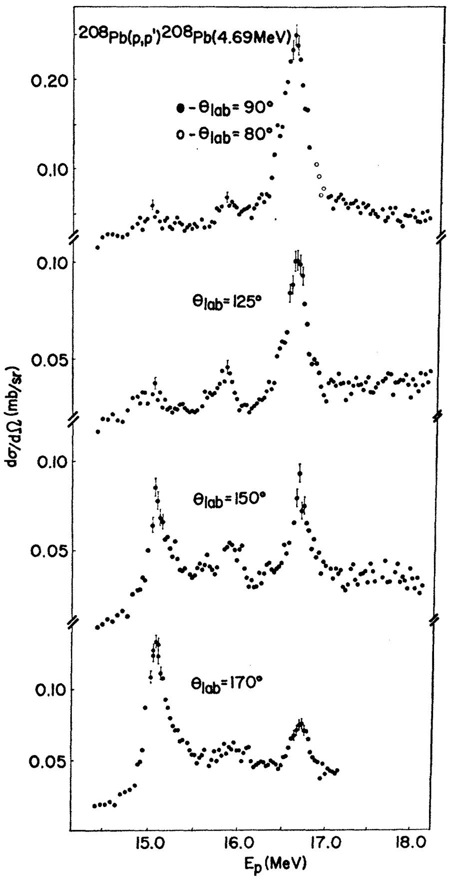


FIG. 10. Excitation functions of the inelastic scattering to the 4.69-MeV state in $Pb^{208}$. These excitation functions resonate at the isobaric analog of both $g_{9/2}$ and $d_{5/2}$ states. The angular distribution of the resonance at 16.5 MeV is peaked towards 90°, whereas the angular distribution of the resonance at 15 MeV is peaked in the backward direction.

The proton decay of an isobaric analog resonance leading to a certain excited state of the final nucleus provides information about the overlap between the wave functions for excited states of the target nucleus and the wave functions of the parent analog states. Investigations of this nature have been conducted on $^{118}$Sb [9] and $^{138}$Ba.[10] For the ground state of the $^{208}$Pb nucleus, the approximation of an inert closed-shell core is expected to be extremely good. Similarly, the low-lying states in $^{209}$Pb are expected to be rather pure single-particle states. Consequently, a study of the inelastic proton decay of the isobaric analog resonances in $^{209}$Bi is particularly interesting since one expects to learn about the various particle-hole configurations occuring in the wave functions of the excited states in $^{208}$Pb.

An outstanding example is given by the excitation function of the $5^-$ and $4^-$ states which are shown in Figs. 5 and 6. These excitation functions show strong resonances at 14.9-MeV proton energy corresponding to the $g_{9/2}$ ground-state resonance, followed by an almost constant cross section where the other major analog resonances occur. This shows that the neutron–neutron-hole configurations contained in these states are almost exclusively of the form $(g_{9/2},j^{-1})$. Since the direct excitation of the $4^-$ state requires a spin-flip transition, it is expected that the cross section for direct inelastic scattering to this state is smaller than the corresponding cross section to the $5^-$ state. This is borne out by the measurements (Figs. 5 and 6).

The angular momentum $j$ of the emitted proton, which is the same as that of the neutron hole, can be determined from the angular distribution of the resonance cross section.

The excitation function for decay to the $3^-$ state has resonances corresponding to all the analog levels observed in this experiment, which indicates that this state contains neutron–neutron-hole configurations for each neutron level from the $2g_{9/2}$ level to the $3d_{3/2}$ level. This is consistent with the theoretical description of this state as a collective state.[20–22] However, previous discussions of this state[21] have considered only the $g_{9/2}$ and $i_{11/2}$ neutron levels along with proton–proton-hole configurations. This work shows that other neutron–neutron-hole configurations are also involved.

## V. SUMMARY AND CONCLUSIONS

The isobaric analogs of the single-particle states in $^{209}$Pb have been studied by elastic and inelastic scattering of protons on $^{208}$Pb. The resonances observed in the elastic channel have been analyzed using a single-level formula. Excitation functions for proton inelastic scattering to seven excited states were measured. A technique for obtaining information about the nuclear structure of excited states is discussed. Excitation functions for the inelastic scattering to 3.198 MeV ($5^-$), 3.475 (MeV) ($4^-$), and 3.709 MeV ($5^-$), as well as those to 4.36 MeV and 4.48 MeV, all resonate strongly at the isobaric analog of the $g_{9/2}$ state. These excitation functions however do not show appreciable anomalies at the other isobaric analog states. This leads us to expect that in the neutron–neutron-hole description of these excited states the $g_{9/2}$ neutron is the dominant contribution. The state at 4.69 MeV resonates both at the isobaric analog of the $g_{9/2}$ state and that of the $d_{5/2}$ state. It seems to have an appreciable admixture of the particle-hole states in which the neutron is in the $d_{5/2}$ state. The $3^-$ state at 2.615 MeV finally must be considered to be a complex superposition of many particle-hole states as it shows anomalies at the isobaric analogs of all the single-particle states studied. The results of this experiment demonstrate the very selective character of the $(p,p')$ reaction proceeding via isobaric analog resonances. It is expected that a quantitative analysis of this data will shed more light on the particle-hole structure of these excited states in $^{208}$Pb.

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