DECAY OF ISOBARIC ANALOG STATES IN THE LEAD REGION*

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Recent experiments[1-5] have shown that isobaric analogs of low-lying states of medium and heavy nuclei can be excited by the (p,n), (p,p), (p,p'), and (p,γ) reactions as resonances in the compound system. The inelastic scattering is of particular interest since the widths for decay from analog states to excited states of the target can yield information about the matrix elements connecting states of the target with bound states of the target-plus-neutron system. Such information is related to the spectroscopic factors that would be obtained if neutron stripping and pick-up experiments could be performed starting with not only the ground state but also excited states of a target nucleus. In this Letter we report new proton-scattering data in the lead region which further demonstrate the usefulness of isobaric analog states for nuclear spectroscopy. More importantly, it is found that many of the (p,p') resonances corresponding to the analog states have shapes quite different from the symmetric Breit-Wigner shapes observed in previous experiments with lighter nuclei at lower incident energies. This indicates the possible importance of another reaction mechanism competing with simple compound inelastic scattering via the analog state, so that the analysis of such data may be more complicated than the Breit-Wigner single-level analysis which has been used up to now.

The University of Washington tandem accelerator was used to measure (p,p) and (p,p') excitation functions for Pb^{206}, Pb^{207}, and Pb^{208} using solid-state detectors. Figure 1 shows the results for Pb^{206} between 11.5 and 14.0 MeV. A p-wave resonance (see Table I) is observed in the elastic scattering at 12.28 MeV, which is the incident energy corresponding to the isobaric analog of the $(3p_{1/2})^{-1}$ ground state of Pb^{207}. Except for a hint of the 0.894 MeV $(3p_{3/2})^{-1}$ state at 13.1 MeV, none of the analogs of the other hole states of Pb^{207} shows an observable effect in elastic scattering. When the penetrabilities for the $l=3$, 5, and 6 protons are taken into account, these observations are consistent with Pb^{206} (d,p) Pb^{207} measurements.[6]

Resonances in (p,p') to three excited states of Pb^{206} were also observed at 12.28 MeV (see Fig. 1). All three resonances display a symmetric shape and were analyzed using a Breit-Wigner single-level formula (see Table I). The results (to be published in more detail elsewhere) are qualitatively consistent with the relative $(p_{1/2}^{-1}, j^{-1})$ mixtures calculated for these states[7] and with the Pb^{207} $(d,t)Pb^{206}$ measurements,[6] in which the states excited most strongly are the three measured here. Above 12.5 MeV, light-element contaminants in the Pb^{206} target prevented observation of inelastic scattering to states other than the 0.804-MeV state and the 2.6-MeV (3^-) state mentioned below [see Figs. 1 and 2(a)].

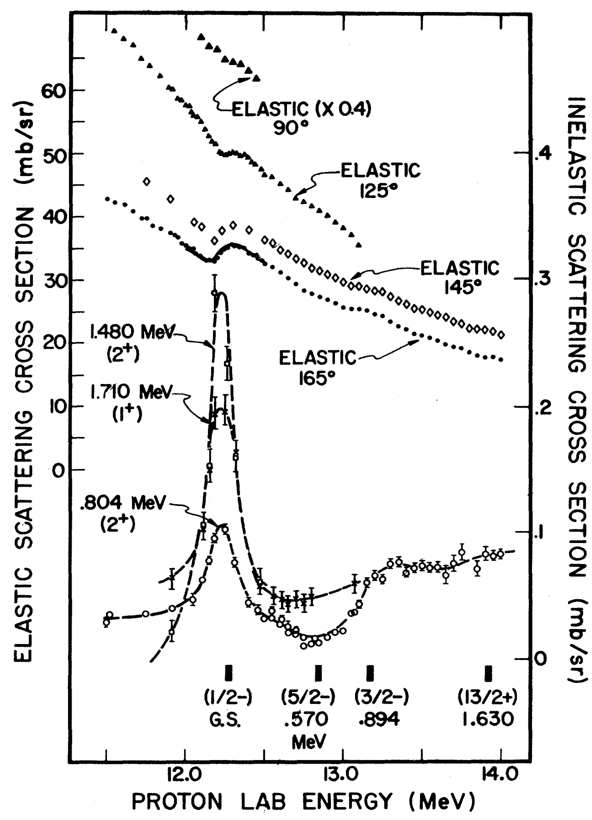

FIG. 1. Pb^{206} (p,p) and (p,p') excitation functions from 11.5 to 14 MeV. The inelastic-scattering data were taken at 165° (lab). The energies and spins indicated by the arrows refer to states in Pb^{206} to which the inelastic scattering was observed. Solid bars at the bottom of the figure show the expected positions of the analogs of the indicated states in Pb^{207}.

Table I. Resonance analysis for elastic[a] and inelastic[b] scattering.[c]

Target nucleus	$E_{\text{res}}^{\text{lab}}$ (MeV)	l	$\Gamma_p{}^{\text{d}}$ (keV)	$\Gamma_{p',\,2^+}(0.804)^{\text{e}}$ (keV)	$\Gamma_{p',\,2^+}(1.48)$ (keV)	$\Gamma_{p',\,1^+}(1.71)$ (keV)	Γ^{f} (keV)	J^π
Pb^{206}	12.28	1	12	12.5	38.5	21	170	$\frac{1}{2}^-$
	14.97	4	23				230	$\frac{9}{2}^+$
Pb^{208}	14.97	4	17	···	···	···	215	$\frac{9}{2}^+$

[a]C. F. Moore and P. Richard, Florida State University Technical Report No. 8, 1965 (unpublished). Equations in this reference were modified (D. Robson, private communication) to include optical model phases.

[b]A single-level Breit-Wigner resonance equation was used to analyze the inelastic resonances.

[c]Errors in resonance parameters are estimated to be less than 20%.

[d]Γ_p is the proton partial width for elastic scattering.

[e]$\Gamma_{p',\,2^+}(0.804)$ is the proton partial width for inelastic scattering to the 2^+ state at 0.804 MeV.

[f]Γ is the total width for the resonance.

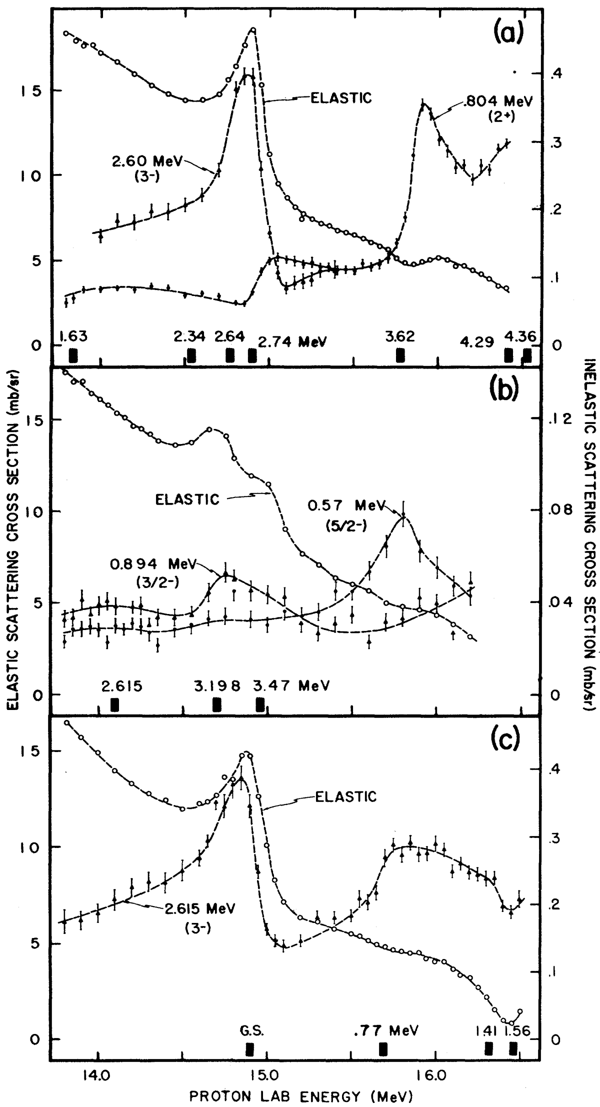

FIG. 2. (p,p) and (p,p') excitation functions at 165° (lab) for (a) Pb^{206}, (b) Pb^{207}, and (c) Pb^{208} between 13.8 and 16.5 MeV. Energies and spins indicated by the arrows refer to states in the target nucleus to which inelastic scattering was observed. Solid bars at the bottom of each figure show the expected positions of the analogs of the indicated states in the target + neutron system.

In Figs. 2(b) and 2(c), Pb^{207} and Pb^{208} data are displayed for comparison with the Pb^{206} results. The resonances at 14.97 MeV in the elastic scattering from Pb^{206} and Pb^{208} are almost identical and correspond to analogs of the $2g_{9/2}$ neutron states in Pb^{207} (2.74 MeV) and Pb^{209} (g.s.).[6] This designation is supported by a resonance analysis consistent with $l=4$. The double peak near 14.9 MeV in $Pb^{207}(p,p)$ is also related to the $g_{9/2}$ neutron state and corresponds to analogs of the 3.198-MeV (5^-) and 3.46-MeV (4^-) states in Pb^{208}, which have the dominant neutron configuration $(2g_{9/2}, 3p_{1/2}{}^{-1})$. The analog of the $1i_{11/2}$ neutron state occurs at 15.8 MeV in $Pb^{206}(p,p)$. Only a hint of this state appears in the elastic scattering from the other targets, although anomalies at the expected energy are seen in the inelastic scattering. Analogs of states in Pb^{207} formed by coupling a $g_{9/2}$ neutron to the first excited (2^+) state of the Pb^{206} core are also expected to lie near this energy. These would enhance the resonance in the exit channel to the 2^+ state and may account for a large fraction of the strong yield seen in the 2^+ excitation function near 15.8 MeV.

In previous analyses[5,8] of (p,p') resonances, the analog states have been treated as isolated compound-nucleus levels. With this assumption each observed resonance must have a symmetric shape characterized by the Breit-Wigner single-level resonance formula. In the present work, striking examples of departure from the single-level resonance shape are seen in the inelastic scattering from Pb^{206} and Pb^{208} at 14.97 MeV. Other examples are the anomalies in the inelastic scattering from Pb^{206} at 13.1 MeV, from Pb^{208} at 15.7 MeV, and possibly from Pb^{206} at 15.8 MeV. It is clear that in these cases complications have to be introduced into the simple picture outlined above and that the single-level analysis will not be applicable.

Among the possible explanations for asymmetric (p,p') resonance shapes are interference between neighboring analog resonances and interference between a resonance and a direct reaction amplitude. However, neither of these mechanisms may be sufficient to explain the anomalous shapes, since in previous experiments the deviations (if any) from simple Breit-Wigner resonances are much smaller than observed here. For example, in a $Ba^{138}(p,p')$ experiment,[5] one might have expected substantial interference effects because both the between-resonance background (assumed to be direct reaction plus level-level interference) and the density of analog states are at least as great as in the present case.

Another possible explanation for the asymmetries is suggested by an examination of the entrance and exit channels for the $g_{9/2}$ analog resonance at 14.97 MeV in Pb^{206} (p,p') to the 2^+ state. The strong effect in the (p,p) excitation function ($\Gamma = 230$ keV, $\Gamma_p = 23$ keV) indicates an entrance-channel resonance. However, the $1i_{13/2}$ neutron-hole state is the only state reasonably consistent with the shell model that is available for coupling with a pure $g_{9/2}$ single-particle state to form 2^+. Direct decay from the $g_{9/2}$ analog to the 2^+ state, therefore, would require an admixture of the $(1i_{13/2}^{-1}, 2g_{9/2})$ particle-hole configuration in that state. In existing theoretical calculations[7] which agree in many details with experimental data, it was not found necessary to include explicitly such configurations in the 2^+ state (these involve promoting a particle across a major shell). Therefore, it is plausible to assume that the channel for direct decay from the analog to the 2^+ state is either closed or very weak.[9] To understand how a strong transition can occur when the exit channel is closed, one may consider the (p,n) reaction via isobaric resonances where the exit channel is also closed. In this case, neutron emission is isospin forbidden, but the decay is explained as proceeding via isospin mixing through the many states of lower T $(T_<)$ in the vicinity of the analog state.[10-12] If this is correct, the same mixing process may account for the observation of resonances in (p,p') when the proton exit channel is closed. In addition, the mechanism may explain the interference shape of such resonances, since interference patterns have shown to be a direct consequence of this mixing and have been observed in the (p,n) reaction.[11]

The above process may be contrasted with the situation in which a (p,p') resonance is observed with no resonance in the elastic channel.[2] In this case, the entrance channel is closed but the exit channel is probably strong. It has been suggested[2] that mixing with $T_<$ states may account for the formation of the analog state and that asymmetric resonance shapes might be expected.[10] However, no clear evidence for these asymmetries has been reported.

The asymmetric resonances in the inelastic scattering to the 3^- states in Pb^{206} and Pb^{208} may be due to interference with a direct process or to mixing with $T_<$ states, even though in this case the entrance and exit channels are probably both open. It is evident that these effects will have to be considered carefully in a detailed analysis of all (p,p') analog resonance data, even where the shapes are apparently symmetric and neither the entrance nor the exit channel is closed.

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PROTON-NUCLEUS INTERACTION AT 20 BeV

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Most experiments with protons in the multi-BeV region have been designed to study interactions in systems with small baryon numbers. Useful additional information may be obtained from coherent scattering by complex nuclei. Such experiments have recently been carried out by Bellettini et al.,[1,2] who measured differential and total cross sections of 19.3-BeV/c protons by copper, lead, uranium, and several light nuclei, using the CERN sonic spark-chamber system. The data show a typical diffraction pattern familiar from nuclear scattering at much lower energies. Because of the large number (many hundreds) of partial waves that participate in the scattering, a direct complex potential model analysis is impracticable. A simple black-sphere model has been used to determine nuclear radii, and the values 5.4, 7.5, and 7.8 fm have been obtained for the interaction radius R of Cu, Pb, and U, respectively.[1,2] More detailed information about the proton-nucleus interaction can be derived from a partial-wave analysis of the differential cross sections. This can be done by means of the generalized strong-absorption model (SAM)[3,4] which is based on a functional parametrization of the scattering function $\eta_l = S(\lambda)$ and gives simple closed expressions for the differential and integrated cross sections. In this Letter we report a SAM analysis of the heavy-target data of Refs. 1 and 2. The results give information about the form of $S(\lambda)$ as a function of $\lambda = l+\frac{1}{2}$ and may be interpreted, semiclassically, in terms of configuration-space properties of the proton-nucleus interaction such as radius, surface diffuseness, real phase shifts, and opacity. From $S(\lambda)$ thus obtained, an optical potential can be derived in high-energy approximation.

In the partial-wave expansion of the scattering amplitude, the black-sphere model corresponds to a sharp cutoff of η_l at the value $\lambda=\Lambda=kR$. It is further assumed that η_l is real so that the scattering amplitude is pure imaginary. In SAM, the sharp cutoff η_l is replaced by a more realistic form, considered as a continuous function $S(\lambda)$. In the simplest case this describes (i) a finite transition region of width Δ in l space, (ii) a finite transparency ϵ for lower-l partial waves, and (iii) an imaginary part of η_l which is centered at the cutoff value Λ. The real and imaginary parts of the scattering function are parametrized in the form[5]

$$\mathrm{Re}\,S(\lambda) = g+\epsilon(1-g), \quad \mathrm{Im}\,S(\lambda)=\mu(dg/d\lambda), \tag{1}$$

where $g = g((\Lambda-\lambda)/\Delta)$ is a smooth approximation of the unit step function at $\lambda = \Lambda$. If Coulomb interaction can be neglected, the differential-scattering cross section is given by[3]

$$\frac{d\sigma}{d\Omega} = \left(\frac{\Lambda}{k}\right)^2 \frac{\theta}{\sin\theta}[F(\Delta\theta)]^2 \times \left\{(1-\epsilon)^2\left[\frac{J_1(\Lambda\theta)}{\theta}\right]^2 + \mu^2[J_0(\Lambda\theta)]^2\right\}, \tag{2}$$

where the form factor $F(\Delta\theta)$ is the Fourier transform of $dg/d\lambda$. For the special shape $g = [1+\exp\{(\Lambda-\lambda)/\Delta\}]^{-1}$, we have $F(\Delta\theta) = \pi\Delta\theta/\sinh(\pi\Delta\theta)$.

The parameter μ, which controls the filling in of the diffraction minima, is a measure of the real nuclear phase shift in the surface of the interaction region. Equation (2) shows that in the absence of Coulomb interaction the differential cross section depends on μ^2 only, so that there is an ambiguity as to the sign of the real part of the scattering amplitude. This ambiguity is resolved when Coulomb interaction is taken into account. For small values of the Coulomb parameter $n = Ze^2/v$, the differential cross section is still approximately