STRUCTURE OF PARTICLE-HOLE STATES IN Ba^{138} †

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Neutron particle-hole states in Ba^{138} have been observed in three different reactions: from the decay of isobaric analog resonances formed by the reaction $Ba^{138}+p$, in the reaction $Ba^{137}(d,p)Ba^{138}$, and as isobaric analog states in proton scattering from Ba^{137}. It is thus possible to make reasonable assignments of spin and parity as well as to determine the shell-model configurations of many of these states.

The work reported in this Letter is part of a larger study of isobaric analog resonances in the barium isotopes. It is being presented now for two reasons: (1) because it is a very effective demonstration of the unique information that can be obtained from such studies and (2) the information relates to particle-hole states, a class of states that is of current interest.

The results are concerned with the structure of the neutron particle-hole states in the closed-neutron-shell ($N=82$) nucleus Ba^{138}. The states have been observed in the decay of isobaric analog resonances formed by the $Ba^{138}+p$ reaction, in the reaction $Ba^{137}(d,p)Ba^{138}$, and as isobaric analog states in proton scattering from Ba^{137}. It has been possible to assign most likely values of J^{π} and infer most probable configurations of many of the states. The information provided about particle-hole states in this mass region is unique since barium is the only $N=82$ nucleus whose isotope with 81 neutrons is stable.

It has previously been observed that populating neutron particle-hole states is a preferred mode of decay of an isobaric analog state.[1] For protons incident on Ba^{138}, the situation is shown schematically in Fig. 1. The resonances in $Ba^{138}+p$ scattering[2,3] are the analogs of

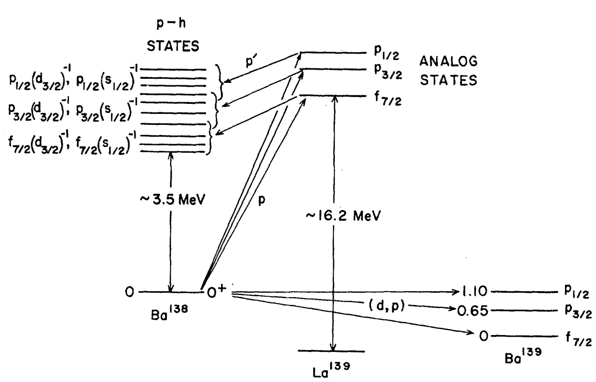

FIG. 1. Schematic diagram showing population of particle-hole states in Ba^{138} from successive analog-state resonances in La^{139}.

the low-lying levels in Ba^{139} observed in the reaction $Ba^{138}(d,p)$.[4] Although these are not pure single-particle states they have the spin sequence expected for neutron single-particle levels above the closed shell $N=82$. In particular, the $p_{1/2}$ nature of the second excited state has been confirmed in a recent polarization measurement.[5] The low-lying neutron particle-hole states in Ba^{138} with which we are concerned will have configurations in which the particles are from levels above $N=82$ ($2f_{7/2}$, $3p_{3/2}$, $3p_{1/2}$) and the holes are from levels below $N=82$ ($2d_{3/2}$, $3s_{1/2}$). They will be populated by the inelastic emission of a $d_{3/2}$ or $s_{1/2}$ proton from the isobaric analog resonance formed in $Ba^{138}+p$. Figure 1 indicates the configurations that result. In some instances the same spin can result from several different configurations.

The spectra of protons scattered from Ba^{138} were taken at several angles with solid-state detectors over an energy region 9.8-11.2 MeV which spans the three resonances shown schematically in Fig. 1. It was found that different groups of states at about 4- to 5-MeV excitation appear strongly and selectively at the three analog resonances. Excitation functions taken over the resonances have a simple Breit-Wigner shape and show little off-resonance yield.

Angular distributions of the inelastic groups associated with the resonances in $Ba^{138}+p$ are found to be symmetric about 90° and to be of the form $1+A_2P_2(\cos\theta)$. If the configurations of the particle-hole states are pure, then the angular distributions of protons leading to $(d_{3/2})^{-1}$ states should have unique A_2 coefficients which can be calculated, and those leading to $(s_{1/2})^{-1}$ states should be isotropic. The fact that no purely isotropic angular distributions are observed at the $f_{7/2}$ resonance indicates mixtures in the hole components. In only one case does the distribution have the shape expected for a particular spin value; the distribution for the state at 3.86 MeV is characteristic of 5^-.

In the scheme described here, the only 5^- state is $f_{7/2}(d_{3/2})^{-1}$; and it may be presumed to be pure.

The particle-hole states described have also been observed in the reaction $Ba^{137}(d,p)Ba^{138}$. The protons from this reaction were analyzed with a magnetic spectrograph. If the ground state of Ba^{137} is assumed to be pure $(d_{3/2})^{-1}$, then one would expect that the only states to be excited would be those whose wave functions include a $(d_{3/2})^{-1}$ component. The (d,p) spectra show all of the states seen in the decay of the analog resonances, and angular distributions of protons leading to these states indicate mainly pure $l_n = 1$ and $l_n = 3$ neutron transfer with some mixed $l_n = 1$ and 3 transitions. Figure 2 compares the excitation of states observed in the (p,p') and (d,p) reactions. The mean excitation energy of the states observed at each resonance increases with increasing resonance energy, as expected from their particle-hole description. However, more levels are observed than would be expected on the basis of spin values alone. Some appear in the decay of both the f- and p-wave resonances and show $l = 3$ and 1 admixtures in the (d,p) measurements, indicating mixtures in the particle components. Mixing in the hole components is exemplified by the small but nonzero cross sections in the

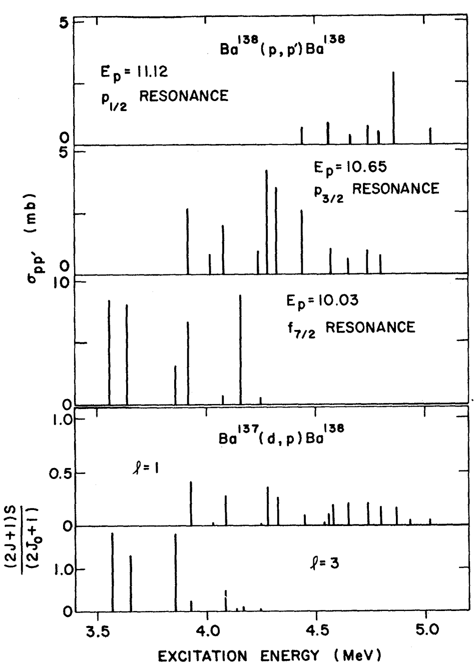

FIG. 2. Location of particle-hole states in Ba^{138} from the reactions $Ba^{138}(p,p')$ and $Ba^{137}(d,p)$.

reactions $Ba^{137}(d,p)$ for states with $(s_{1/2})^{-1}$ hole configurations. Good agreement in excitation energies is observed in both reactions studied.

On the basis of these results one can also obtain information on the structure of some states. For example, the states at 3.92 and 4.16 MeV appear strongly in the decay of the $f_{7/2}$ resonance but only weakly in the $l = 3$ (d,p) reaction. This indicates $f_{7/2}(s_{1/2})^{-1}$ particle-hole structure and $J^\pi = 3^-$ or 4^-. Since the 3.92-MeV level is also observed in the decay of the $p_{3/2}$ resonance and with $l = 1$ transfer in the (d,p) reaction, the additional $p_{3/2}(d_{3/2})^{-1}$ admixture fixes the spin as 3^-. The fact that the 3.56- and 3.64-MeV levels are observed both in the decay of the $f_{7/2}$ resonance and in the (d,p) reaction indicates a predominant $f_{7/2}(d_{3/2})^{-1}$ structure. The values $J^\pi = 3^-$ and 4^- are implied since these members of the $f_{7/2}(d_{3/2})^{-1}$ multiplet should be at least a few hundred keV away from the $f_{7/2}(s_{1/2})^{-1}$ levels to account for the small admixtures observed. This would suggest that the 4.08-MeV state is the remaining 2^- member of the $f_{7/2}(d_{3/2})^{-1}$ multiplet.

Table I shows $\sum\Gamma_{p'}$, the sum of the inelastic proton widths. For each of the three resonances studied, $\Gamma_{p'}$ was derived from the values of Γ and Γ_p extracted from elastic scattering.[3] Since the mean energies of the inelastic protons are closely the same at each resonance, the near equality of the sum reflects the nature of the reaction leading to these states, namely that at each isobaric analog resonance the decay to the particle-hole states involves the emission of the same d and s protons. The particle aspect of these particle-hole states is also demonstrated in the comparison (Table I) of the total strength for the $l = 3$ and 1 transitions in the reaction $Ba^{137}(d,p)$ with the strength observed in the reaction $Ba^{138}(d,p)$ to the individual particle states.

The analogs of the particle-hole states have also been observed[3] as resonances in $Ba^{137} + p$ scattering between 9.5 and 11.0 MeV. Although elastic scattering gives no additional information, the decay of the states to the $(s_{1/2})^{-1}$ level at 0.28 MeV in Ba^{137} can further elucidate their structure. For example, it is found that the analogs of the 4.16- and 3.64-MeV states both weakly decay with comparable intensity to the $(s_{1/2})^{-1}$ level in Ba^{137}. This result can be understood if it is assumed that both states

Table I. Strength of particle-hole excitations in Ba^{138} from (p,p') and (d,p) reactions.

Resonance	(p,p') $(E_R)_{c.m.}$ (MeV)	$(\bar{E}_{p'})_{c.m.}$ (MeV)	$\sum\Gamma_{p'}$ (keV)	(d,p) l	$\sum\frac{2J+1}{2J_0+1}S$ (relative[a])	$(2J+1)S$ for $Ba^{138}(d,p)$[b]
$f_{7/2}$	9.94	~6.0	12.8	3	6.0	6.1
$p_{3/2}$	10.56	~6.2	13.7	1	2.6	2.0
$p_{1/2}$	11.02	~6.3	12.2	1		0.8

[a]Normalization: $[(2J+1)/(2J_0+1)]S=1$ for $Ba^{137}(d,p)Ba^{138}$ (ground state).
[b]Ref. 4.

are $J^\pi=4^-$ and are orthogonal mixtures of predominantly $f_{7/2}(s_{1/2})^{-1}$ and $f_{7/2}(d_{3/2})^{-1}$ components, respectively; the inelastic cross sections, being proportional to the product of their respective squared amplitudes in the wave functions, will then be equal and small. Of the levels based on the $f_{7/2}$ particle, only the analog of the 3.92-MeV level has an appreciable inelastic cross section which is consistent with its large probabilities for formation [via $p_{3/2}(d_{3/2})^{-1}$] and for decay [via $f_{7/2}(s_{1/2})^{-1}$].

In summary, then, our work shows how it is possible to obtain quite detailed information on the structure of the neutron particle-hole states in and around the $N=82$ shell from the composite study described here. Our conclusions with regard to those Ba^{138} states that are based on the $2f_{7/2}$ particle are given in Table II. An extension of this study to the other even-A isotopes of Ba is almost complete.

Table II. Summary of Ba^{138} particle-hole states based on $2f_{7/2}$ particle.

Energy in Ba^{138} (MeV)	J^π	Configuration[a]
3.56	3^-	$fd^{-1}+(fs^{-1})$
3.64	4^-	$fd^{-1}+(fs^{-1})$
3.86	5^-	fd^{-1}
3.92	3^-	$fs^{-1}+pd^{-1}+(fd^{-1})$
4.08	(2^-)	$fd^{-1}+pd^{-1}$
4.16	4^-	$fs^{-1}+(fd^{-1})$

[a]The parentheses indicate small admixtures.

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