MULTIPARTICLE EXCITATIONS IN THE INTERMEDIATE COMPOUND STATE*

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The following mechanism is offered as a description for the irregularly spaced peaks and valleys seen in scattering cross sections at several MeV.[1,2] These have been interpreted as fluctuations in the cross section by Ericson.[3]

An incident nucleon penetrates the single-particle well of the target nucleus at such an energy that it forms a virtual state. If it were not for the residual interaction between the incident nucleon and the target, the incident nucleon would "live" in this virtual state for a while and then leave the target, making a resonance peak in the cross section. However, when a two-body residual interaction exists, the incident nucleon may be de-excited from this level while exciting one of the target nucleons (see Fig. 1). Such two-particle, one-hole states (denoted as 2p1h states), can, in general, arise from any virtual level. From these, the three-particle, two-hole states (denoted as 3p2h states), and more complex configurations may be reached in like manner. The occurrence of the 2p1h states will split the original virtual-state resonance into a series of narrower resonances.[4] This comes about in the following way: The set of 2p1h states are energy degenerate with respect to the incident virtual state. The residual interaction removes this degeneracy and produces splitting of the virtual-state resonance. Since these 2p1h states have definite phase relations among one another, they will show coherence effects. We have not taken into account the effects of collective states.

In this note we will explore the systematics for the occurrence of 2p1h and 3p2h states for both incident neutrons and protons on sample even nuclei in the region $16 \leqslant A \leqslant 146$. It should be noted that the angular momentum of the incident nucleon inside the well is determined by the virtual level it occupies. Using conservation of angular momentum, parity, and energy (as discussed in reference 1), the results for the systematics are broken into three categories; neutron-neutron, proton-proton, and neutron-proton interactions. It is assumed that the residual interactions are the same in all cases and may be represented by $L = 0$ to 3 multipole components. Green's neutron and proton levels were used.[5]

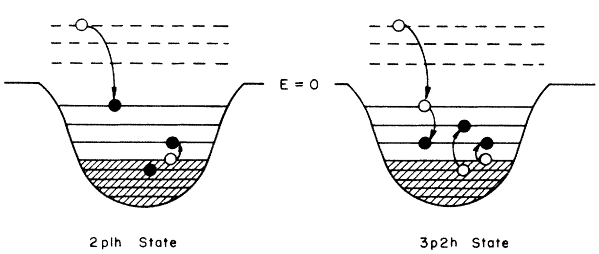

FIG. 1. Neutron (proton) incident at virtual level of neutron (proton) well. Shown are the type of 2p1h and succeeding 3p2h states made up of neutrons (protons) only.

We examined two categories of 2p1h states but present results only for the former: The excited nucleons both end up in bound levels, or one of them ends up in a virtual level. The 2p1h states with at least one particle in a virtual level should be handled on a different basis from the other case. A qualitative argument may be given for this. The lifetime of a 2p1h state with both particles bound is shorter than one with a particle in a virtual level by the lifetime of the virtual level. Similarly, only the 3p2h states in which all particles end up in bound levels have been considered.

Two representative tables are given. Table I shows the number of states reached through a given virtual level by way of the residual interaction multipole components when incident neutrons (below 6 MeV) give rise to $(2n - 1nh)$ and $(3n - 2nh)$ states in the neutron well. Table II shows the number of states reached through a virtual level when incident protons give rise to $(1p, 1n-1nh)$ states followed by either a further $(1n-1nh)$ or $(1p-1ph)$ excitation. Similar results are found in the other cases.

The number of levels reached was determined for values of the energy uncertainty Δ_3E for the (2p1h) states, $\Delta_3E = 1.5$, 1, and 0.5 MeV. The energy uncertainty for the (3p2h) states was taken at $\Delta_5E = 1.5$, 0.75, and 0.38 MeV with $\Delta_3E = 1.5$ MeV and $\Delta_5E = 1.5$ MeV for the other Δ_3E. As suggested by Feshbach, the energy width for the (3p2h) states may be quite different from (2p1h) width.

The qualitative behavior discussed below is independent of the energy uncertainties used, except that the total number of "degenerate" (2p1h) and (3p2h) states is cut down as the various ΔE's are made smaller.

Table I. Incident neutron in $2g_{9/2}$ virtual state. $\Delta_3E = 1.5$ MeV, $\Delta_5E = 1.5$ MeV. L_3 and L_5 refer to the multipole component of the residual potential used to excite, respectively, the 2p1h and 3p2h states. E is the energy of the virtual state.

	Z	N	A	$L_3=0$	$L_3=1$	$L_5=0$	$L_5=1$	$L_5=2$	$L_3=2$	$L_5=0$	$L_5=1$	$L_5=2$	E (MeV)
Sn	50	72	122	0	12	0	0	18	2	0	9	0	5.4
Sn	50	74	124	0	11	0	0	16	2	0	7	0	5.0
Te	52	74	126	0	11	0	0	17	2	0	7	0	4.8
Te	52	76	128	0	7	0	0	0	2	0	0	0	4.6
Te	52	78	130	0	8	0	0	13	2	0	0	2	4.3
Xe	54	78	132	0	9	0	0	15	2	0	0	2	4.1
Xe	54	80	134	0	14	0	0	35	2	0	0	2	3.8
Ba	56	80	136	0	16	0	0	38	2	0	0	2	3.5
Ba	56	82	138	0	17	0	0	0	2	0	0	0	3.1
Ce	58	82	140	0	17	0	0	0	2	0	0	0	2.9
Ce	58	84	142	0	17	0	0	32	2	0	0	2	2.6
Nd	60	84	144	0	17	0	0	32	2	0	0	2	2.4
Nd	60	86	146	0	18	0	0	43	2	0	0	2	2.2

Incident neutron on neutron well.—There are two general features of this situation in the absence of a neutron-proton residual interaction. Excepting a few cases, 3p2h states do not occur below $A \sim 50$. They occur in appreciable numbers above about $A \sim 60$.

At a magic neutron number, there are no 3p2h states possible, even though they occur in large numbers for neighboring nuclei (see Table I). The case of an incident proton on a proton well with no proton-neutron residual interaction shows similar behavior.

Incident proton on neutron well.—The general features of this situation where one allows a proton-neutron residual interaction are somewhat different from the above cases. The major change is that there is no pronounced difference in the number of 3p2h states for magic proton numbers compared to neighboring nuclei (see Table II). This qualitative difference in the behavior at closed shells due to the neutron-proton interaction could provide a tool for examining it.

The occurrence of 3p2h states for increasing A follows a similar pattern to the above neutron case. Finally, if a neutron is incident on a proton well, the results are similar to the case of an incident proton on neutron well.

The effect of shell structure can be seen in the tables, appearing not only through the selection of certain multipole components of the residual

Table II. Incident proton in $2f_{7/2}$ virtual state. $\Delta_3E = 1.5$ MeV, $\Delta_5E = 1.5$ MeV. L_3 and L_5 refer to the multipole component of the residual potential used to excite, respectively, the 2p1h and 3p2h states. E is the energy of the virtual state.

	Z	N	A	$L_3=0$	$L_3=1$	$L_5=0$	$L_5=1$	$L_5=2$	$L_3=2$	$L_5=0$	$L_5=1$	$L_5=2$	E (MeV)
Sn	50	70	120	0	14	0	0	24	2	0	0	0	4.9
Sn	50	72	122	0	13	0	0	23	2	0	0	0	4.7
Sn	50	74	124	0	14	0	0	25	2	0	0	0	4.4
Te	52	74	126	0	15	0	0	49	2	0	0	1	4.3
Te	52	76	128	0	13	0	0	29	2	0	0	2	4.1
Te	52	78	130	0	11	0	0	31	2	0	0	3	3.8
Xe	54	78	132	0	12	0	0	31	2	0	0	3	3.7
Xe	54	80	134	0	13	0	0	41	2	0	0	3	3.4
Ba	56	80	136	0	13	0	0	43	2	0	0	3	3.3
Ba	56	82	138	0	12	0	0	13	2	0	0	1	3.0
Ce	58	82	140	0	9	0	0	3	2	0	0	1	3.2
Ce	58	84	142	0	9	8	0	12	2	2	0	3	2.5
Nd	60	84	144	0	9	9	0	21	2	2	0	4	2.6
Nd	60	86	146	0	9	9	0	18	2	2	0	3	2.1

potential, but also by modulation of the number of each type of state. The number of 2p1h states gives the degeneracy splitting of the virtual level. The effect of the 3p2h states on the 2p1h states is to change their strength. It is therefore necessary to know where the 3p2h states occur before one can estimate the width of the 2p1h "doorway states."

We may summarize by noting that states which require excitations over only one energy gap can be plentiful. When two such excitations are necessary, the number of 3p2h states is severely curtailed. The region of immediate experimental interest for study of the neutron-proton interaction would therefore be at and near the doubly magic nuclei.

This survey gives one some feeling for the complexity and systematics of the compound states that may be built out of particle-hole interactions. It also predicts regions where the "compound nucleus" is simple enough to lend itself to computation.

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[2]A. K. Kerman, L. S. Rodberg, and J. E. Young, Phys. Rev. Letters 11, 422 (1963).

[3]T. Ericson, Ann. Phys. (N.Y.) 23, 390 (1963).

[4]See reference 1, Sec. IV, for a discussion of this point.

[5]A. E. S. Green, Phys. Rev. 104, 1617 (1956).

EVIDENCE FOR A π-ρ INTERACTION PRODUCED IN THE π^+p REACTION AT 3.65 BeV/c†

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In this note we wish to discuss our results on the study of the π^+p reaction at 3.65 BeV/c leading to four charged particles in the final state. In particular, we wish to point out an anomaly we have observed in the mass distribution of the $\pi\rho$ system. This work was carried out in the 20-inch BNL hydrogen bubble chamber[1] exposed in the Yale-Brookhaven beam[2] at the AGS. The analysis[3] of the four-prong events permitted us to identify the three reactions[4]

$$\pi^+p\to\pi^+\pi^-\pi^+p,\quad 1784 \text{ events},$$
$$\sigma=3.85\pm0.30 \text{ mb}, \quad (1)$$

$$\pi^+p\to\pi^+\pi^-\pi^0\pi^+p,\quad 1998 \text{ events},$$
$$\sigma=4.3\pm0.35 \text{ mb}, \quad (2)$$

$$\pi^+p\to\pi^+\pi^+\pi^+\pi^-n,\quad 359 \text{ events},$$
$$\sigma=0.76\pm0.07 \text{ mb}. \quad (3)$$

In what follows we discuss Reaction (1) and, in particular, those events leading to ρ^0 formation. Table I gives the summary of the cross section for all the channels identified in Reaction (1). The result of our analysis of the reaction products indicates that the majority of the events involve

Table I. Partial cross sections for channels leading to ρ^0, f^0, and $N^{*++}(1238)$ formation in the reaction $\pi^+p\to\pi^+\pi^-\pi^+p$ at 3.65 BeV/c.[a]

Channel	Final state	Branching ratio (%)	Cross section (mb)
(1a)	ρ^0N^{*++}	30.5	1.17 ± 0.12
(1b)	$\rho^0\pi^+p$	23.0	0.86 ± 0.09
(1c)	$\pi^+\pi^-N^{*++}$	30.1	1.16 ± 0.12
(1d)	f^0N^{*++}	3.4	0.13 ± 0.04
(1e)	$\pi^+\pi^-\pi^+p$ ("nonresonant")	13.0	0.53 ± 0.1
	Total	100.0	3.85 ± 0.30[b]

[a]This table refers only to the most prominent features. Finer features such as the A^+ effect, $N^{*0}(1238)$ formation, etc., are not explicitly incorporated.

[b]The cross sections were calculated by calibration of the total number of π^+p interactions against the cross-section measurements by M. J. Longo and B. J. Moyer, Phys. Rev. 125, 701 (1962).