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QUASI-ELASTIC SCATTERING OF FAST PROTONS AND THE HOLE EXCITATION SPECTRUM IN THE N^{14} NUCLEUS

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The spectrum of hole excitations induced by fast protons in the N^{14}(p, 2p) reaction is computed. A comparison with experiment confirms the existence of a quasi-elastic collision mechanism in reactions of this kind. Attention is drawn, in connection with a discussion of the properties of hole excitation levels, to the existence of a specific class of anomalously stable above-threshold states in light nuclei.

1. The well known investigations (see [1]) of the (p, 2p) reaction on fast (185 and 440 MeV) protons have uncovered a new source of information on hole excitations in nuclei. Many light nuclei have by now been investigated by this method. The high sensitivity of the method makes it possible not only to distinguish between excitations connected with the knocking out of protons from different shells, but also to exhibit in the forms of the spectra details connected with splitting within a single shell.

Thus, a splitting of the peak of the p-shell was observed in the investigation of the O^{16}(p, 2p)N^{15} reaction. The magnitude of this splitting corresponds exactly to the distance between the ground state $\frac{1}{2}^-$ and the excited state $\frac{3}{2}^-$ in the N^{15} nucleus (ΔE = 6.3 MeV), representing holes in the $p_{1/2}$ and $p_{3/2}$ shells, which are filled in the magic nucleus O^{16}.

2. We know that the spin-orbit interaction constant $a\Sigma l_i s_i$ increases with filling of the shell [the distance $\Delta E(p_{3/2}, p_{1/2})$ amounts to ~ 2.5 MeV in the He^5 nucleus and 6.3 MeV in the N^{15} nucleus]. In this connection, the results obtained by Tyren in the investigation of the reaction on nitrogen are of interest. The splitting of the p peak in the N^{14}(p, 2p)C^{13} reaction[1] turns out to be not smaller than in the case of oxygen, but larger, amounting to ~ 8 MeV, contradicting the jj-coupling scheme. There is no doubt that residual pair interaction between nucleons arises in this case.

Let us turn to the spectroscopic data on the levels of the final C^{13} nucleus[2] (Fig. 1). We are interested only in the $\frac{1}{2}^-$, $\frac{3}{2}^-$, and $\frac{5}{2}^-$ levels, which can be realized in the reaction N^{14}(p, 2p)C^{13} as the protons are knocked out of the p shell. Transitions to the $\frac{1}{2}^-$ ground state and to the $\frac{3}{2}^-$ level

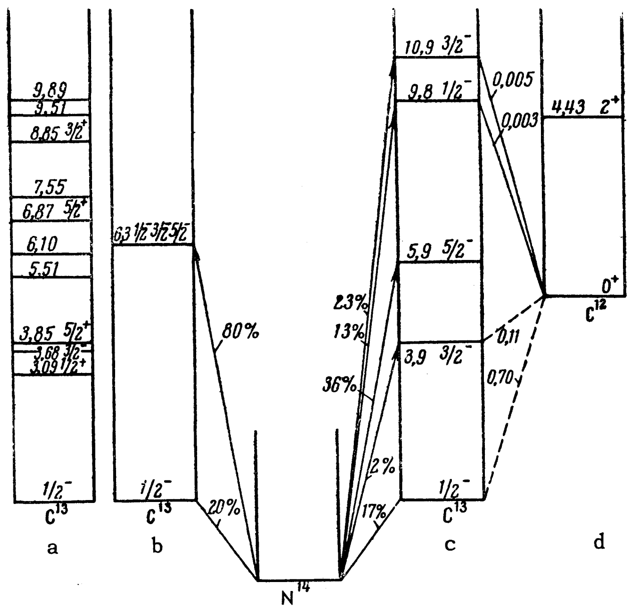

FIG. 1. Level schemes of the nucleus C^{13} and of the transitions $N^{14} \to C^{13}$ and $C^{13} \to C^{12}$: a – levels of C^{13} (experiment [2]); b – levels of C^{13} (jj coupling); c – levels of C^{13} (intermediate coupling). The branching fractions of the $N^{14} \to C^{13}$ transitions are indicated in percent; d – $C^{13} \to C^{12}$ transition scheme (the reduced widths, calculated with the aid of the functions of Tables I–V, are indicated in Wigner units).

at 3.68 MeV cannot explain the experimental data, and some levels strongly coupled to the N^{14} ground state should exist in the 8-MeV excitation energy region. We shall show below that such levels actually exist, and indicate the reasons why they have not been observed hitherto.

3. We have calculated in our work the positions and the characteristics of the low-lying levels, with account of the correlations between the nucleons, within the framework of the intermediate

coupling model. The parameters of the paired central forces (the Rosenfeld exchange variant) and of the spin-orbit forces were taken from Kurath's data[3]: a = −4.2 MeV, L/K = 6, K = −1 MeV. As can be seen from Fig. 1, allowance for the correlations between the nucleons leads to a sharp change in the spectrum, compared with the limiting case of jj-coupling, and makes it possible, in particular, to explain the position of the unknown level $3/2^-$.

Tables I—V list the wave functions obtained by diagonalization for the ground states of C^{12} and N^{14}, and also the excitation energies and the wave functions of all the C^{13} states formed when a proton is knocked out from the p-shell of the N^{14} nucleus. These wave functions were used to calculate the relative excitation probabilities of the individual C^{13} levels (Fig. 1). We used the data obtained, together with the experimental energy resolution, to plot the C^{13} excitation curves in the N^{14}(p, 2p) reaction (Fig. 2). The results of the calculation are in good agreement with the experimental data[1]. We note that the authors of [1] ignore the splitting of the second maximum, so that the accuracy of their measurements is apparently reduced. As follows from the foregoing, splitting itself is not surprising and is due to the residual interaction between nucleons.

TABLE I C^{13} ($1/2^-$)

E, MeV	$[441]^{22} P$	$[432]^{22} P$	$[432]^{24} P$	$[432]^{24} D$	$[333]^{22} S$
0	0.765	0.385	−0.232	0.450	−0.088
9.8	−0.161	0.114	0.765	0.597	0.134
11.6	−0.582	0.133	−0.551	0.560	−0.157
20.2	−0.210	0.855	0.151	−0.351	−0.278
34.5	−0.065	0.297	−0.180	−0.053	0.933

TABLE II C^{13} ($3/2^-$)

E, MeV	$[441]^{22} P$	$[432]^{22} P$	$[432]^{24} P$	$[432]^{22} D$	$[432]^{24} D$
3.9	0.862	−0.019	−0.411	0.213	0.202
10.9	−0.089	0.330	0.121	−0.230	0.902
13.9	0.408	−0.284	0.866	−0.026	0.021
20.0	−0.130	0.359	0.204	0.899	0.057
22.4	0.253	0.824	0.151	−0.303	−0.374

TABLE III C^{13} ($5/2^-$)

E, MeV	$[441]^{22} F$	$[432]^{24} P$	$[432]^{22} D$	$[432]^{24} D$
5.9	0.934	−0.100	0.275	−0.203
14.8	0.281	0.786	−0.365	0.410
15.9	0.117	−0.460	0.082	0.876
25.2	−0.184	0.398	0.885	0.152

TABLE IV C^{12} (0^+)

E, MeV	$[44]^{11} S$	$[431]^{13} P$	$[422]^{11} S$	$[422]^{15} D$	$[332]^{13} P$
0	0.812	0.516	−0.084	0.229	−0.113

TABLE V N^{14} (1^+)

E, MeV	$[442]^{13} S$	$[432]^{11} P$	$[442]^{13} D$
0	−0.190	0.257	0.947

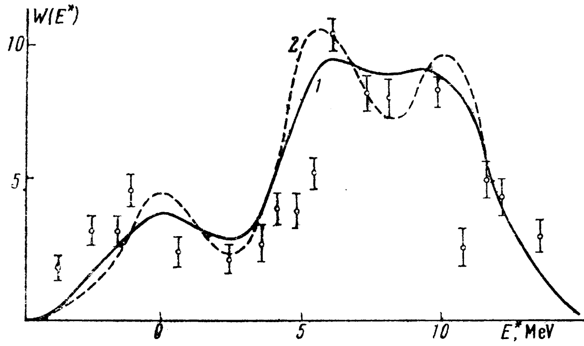

FIG. 2. Calculated curves for the excitation of C^{13} in the N^{14}(p, 2p) reaction: Curve 1 – experimental scatter in the proton energies ΔE = 4.4 MeV[1]; curve 2 – ΔE = 3.8 MeV. The experimental points are from [1].

4. To explain why most of the predicted levels, particularly the $5/2^-$ level corresponding to the most intense $N^{14} \rightarrow C^{13}$ transition, were not observed experimentally in scattering of neutrons on C^{12}, we use the $C^{13} \rightarrow C^{12}$ scheme shown in Fig. 1. The reduced widths of all the unbound C^{13} levels relative to the ground state of C^{12} are very small, three orders of magnitude smaller than the Wigner unit. The decay of the $5/2^-$ level to the ground state of C^{12} is momentum-forbidden, while the decay to the 2^+ excited state is energy-forbidden. These states must thus be investigated in $N^{14} \rightarrow C^{13}$ transitions, for which purpose the "pick-up" reactions (n, d), (p, d), (T, α), and (He^3, α) can be used. One must emphasize, in particular, that the (T, α) and (He^3, α) reactions, in view of their large Q, are the only method of investigating hole excitations of the nuclei, a method which is unfortunately unjustifiably neglected.

5. In connection with the discussion of the properties of the $5/2^-$ level of C^{13}, we must point out that there exists a specific class of light-nuclei states which, being located above the breakup threshold, exhibit anomalous stability. The reason for this stability are the special exclusion rules connected with the shell structure of the nucleus. Thus, in this case, the C^{13} ($5/2^-$) $\rightarrow$ C^{12} (0^+) tran-

sition calls for the emission of an f neutron, something possible only if the shell configurations of the initial (s^4, p^9) or final (s^4, p^8) state are disturbed. The noted exclusion rules are not rigorous and are violated as a result of admixture of higher configurations. The reduced widths of such states can therefore serve as a measure of the purity of the shell structure of the nucleus.

These states should be observed in a large number of light nuclei. We point out the $5/2^-$, $7/2^-$, and $9/2^-$ levels of the Be^9 nucleus[4], which can be investigated in the pick-up reaction on B^{10}. A systematic study of such anomalously stable states would permit an investigation of the nuclear shell structure in excitations occurring in the continuous spectrum region, without involving the existence of open decay channels.

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