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(p, α) reaction on ^{93}Nb and ^{89}Y

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The (p, α) reaction has been studied at 15.2 MeV on ^{93}Nb and ^{89}Y and analyzed using distorted-wave Born-approximation and cluster form factors. The reaction is a direct triton pickup and compound nucleus effects are negligible. In the first case the transferred neutrons are the two extra core neutrons and the reaction behaves like a proton pickup. Positive parity states of ^{90}Zr are populated by the transfer of $g_{9/2}$ protons with strengths in good agreement with a simple model; new levels are excited corresponding to $p_{3/2}$ and $f_{5/2}$ proton holes. In the second case the neutrons are removed from the filled $N = 50$ shell; states corresponding to proton and neutron configurations in ^{86}Sr are excited with comparable strengths and it is difficult to get unambiguous spectroscopic information.

[NUCLEAR REACTIONS ^{93}Nb(p, α), ^{89}Y(p, α), $E_p = 15.2$ MeV; measured $\sigma(E_\alpha, \theta)$, $\theta = 10-160°$, ^{90}Zr levels up to 5.1 MeV, ^{86}Sr levels up to 3 MeV. Reaction mechanism. DWBA analysis.]

I. INTRODUCTION

It has been suggested[1] that, at a high enough energy and in relatively heavy nuclei, the (p, α) reaction results from direct triton pickup and may even behave, in favorable cases, like simple proton pickup. The reaction ^{93}Nb$(p, \alpha)^{90}$Zr appears to be a very favorable case, with a closed $(N = 50)$ neutron shell plus two $d_{5/2}$ neutrons mainly coupled to zero angular momentum,[2] available to be easily picked up as an inert pair. The reaction ^{89}Y(p, α)-^{86}Sr is a much less favorable case where the two neutrons are necessarily picked up from the filled $N = 50$ shell and many different couplings are possible. The very different situation for the pickup of a neutron pair is clearly seen in the (p, t) reactions[3] on ^{92}Zr and ^{90}Zr. A comparative study of the (p, α) reaction on ^{93}Nb and ^{89}Y can therefore help to understand the mechanism of this reaction and to test its possibilities and limitations as a spectroscopic tool. Earlier studies of these reactions[4] resolved only the ground state and, for ^{86}Sr, the first excited state.

If the reaction on ^{93}Nb behaves like proton pickup, it can be used to study states due to excited proton configurations in ^{90}Zr. The states of ^{90}Zr are generally described as two-proton configurations outside of an inert ^{88}Sr core. States corresponding to a proton in the $p_{1/2}$ shell and a proton in other unfilled shells have been observed[5] using the $(^3\text{He}, d)$ reaction on ^{89}Y. States corresponding to a proton in the $g_{9/2}$ shell and a proton in the $p_{1/2}$ shell, or two protons in the $g_{9/2}$ shell, are known from a number of experiments. Three-particle-one-hole configurations, corresponding to $p_{3/2}$ or $f_{5/2}$ proton holes in the ^{88}Sr core, have not been clearly identified although they should appear a few MeV above the ground state. This is mainly due to the fact that, because of the lack of a target, these states cannot be studied using simple proton pickup reactions. The (p, α) reaction appears in this case as a unique way to study these states.

Throughout this paper ^{88}Sr shall be considered as a core and configurations described as holes in, or particles outside, this core.

II. ^{93}Nb$(p, \alpha)^{90}$Zr REACTION

The ^{93}Nb$(p, \alpha)^{90}$Zr reaction has been studied using a 15.2 MeV proton beam from the Orsay MP tandem accelerator (0.1 to 1.5 μA depending on the detection angle) and measuring five angles simultaneously with solid state detectors. For the more forward angles $(\theta_{\text{lab}} \lesssim 25°)$ a telescope consisting of three silicon surface barrier detectors was used to eliminate the scattered protons. The protons scattered at ° were used as a monitor and the beam current measured in a Faraday cup. The electronics included antipileup amplifiers and analog and digital multiplexors to route the data. All dead time and losses of counts due to pileup were measured and the results corrected. The self-supporting targets (100 μg/cm^2) were prepared by evaporating Nb with an electron gun.

An α particle spectrum is presented in Fig. 1. Angular distributions have been obtained for 15 states, every 5° from 10° to 145° and a backward point measured at 160° (see Fig. 2).

The group of states observed between 4.22 and 4.54 MeV has been reexamined with much better energy resolution using a newly installed split pole spectrometer. The beam current through a 1×3 mm slit system was 0.8 μA, the target thickness 43 μg/cm^2, and the solid angle 2 msr. Spectra obtained at 10° and 30° using a 12×50 mm laboratory fabricated solid state position sensitive detector ($\approx$0.3 mm resolution full width at half-maximum for 8.78 MeV α particles) are shown in Fig. 3. The observed resolution is 11 keV. The separation is very good and the state previously observed at 4.47 MeV in the reaction chamber measurement is seen to be a doublet (4.47 and 4.49 MeV).

Reaction mechanism and distorted-wave Born-approximation analysis

It is clear from the very small cross section of the excited 0^+ state at 1.76 MeV ($\approx$2.2% of the 0^+ ground state) and the forward peaked shapes of the angular distributions that compound nuclear effects are negligible and that the reaction is essentially direct.

It is reasonable to suppose that a knockout mechanism should populate relatively strongly the states (among others) observed in the (^{3}He, d) reaction. A comparison of our spectrum with the one obtained[5] using the (^{3}He, d) reaction shows that, except for the two states with the configuration $[(\pi p_{1/2})(\pi g_{9/2})]$, which can be populated in the (^{3}He, d) reaction by $g_{9/2}$ proton stripping and are accessible in the (p, α) reaction by the pickup of a cluster $[(\pi p_{1/2})(\nu)^2{}_0]$, the same states are not populated in the two reactions. This is at least an indication that, under the conditions of our study, the (p, α) reaction proceeds mainly by pickup. The reaction has therefore been analyzed according to this hypothesis and the results for well known levels of ^{90}Zr will first be discussed in order to test its value.

The distorted-wave Born-approximation (DWBA) analysis has been performed assuming direct pickup of a cluster, using a form factor with the principal quantum number determined from conservation of harmonic oscillator energy.[6] The separation energy of the cluster was taken as the triton binding energy. Spin-orbit coupling was not used for the cluster but was included for the proton channel. The optical potentials were taken from a recent study[7] of the ^{96}Mo(p, α)^{93}Nb reaction at 15 MeV and used without modification. The radius of the cluster well was slightly changed in order to obtain better agreement. The parameters are given in Table I. More sophisticated form factors would certainly help in the detailed analysis of the observed strengths. Form factors computed by Suck and Coker[6] have been tried but did not reproduce the shapes of the experimental angular distributions as well as the cluster form factors.

Known proton configuration levels of ^{90}Zr

The well known positive parity levels of ^{90}Zr are populated in the (p, α) reaction. The generally accepted proton configurations of these levels are[8]

$$|^{90}\mathrm{Zr}\rangle_{\mathrm{g.s.}}=a\,|(g_{9/2})^2{}_0\rangle+b\,|(p_{1/2})^2{}_0\rangle\,,$$

$$|^{90}\mathrm{Zr}\rangle_{0_1^+}=b\,|(g_{9/2})^2{}_0\rangle-a\,|(p_{1/2})^2{}_0\rangle\,,$$

and for the 2^+, 4^+, 6^+, and 8^+ members of the $(g_{9/2})^2$ configuration

$$|^{90}\mathrm{Zr}\rangle_J=|(g_{9/2})^2{}_J\rangle\,,$$

the 50 neutrons filling a complete major shell.[8] The $\frac{9}{2}^+$ proton target state can be written, by analogy with ^{90}Zr, as

$$|^{93}\mathrm{Nb}\rangle_{\mathrm{g.s.}}=\alpha\,|(g_{9/2})^3{}_{9/2}\rangle+\beta\,|(p_{1/2})^2{}_0\,g_{9/2}\rangle$$

the two extra core neutrons being mainly $d_{5/2}$ neutrons coupled to zero.[2]

According to this picture the positive parity states of ^{90}Zr should all be reached by the pickup of a cluster consisting of a $g_{9/2}$ proton and a pair

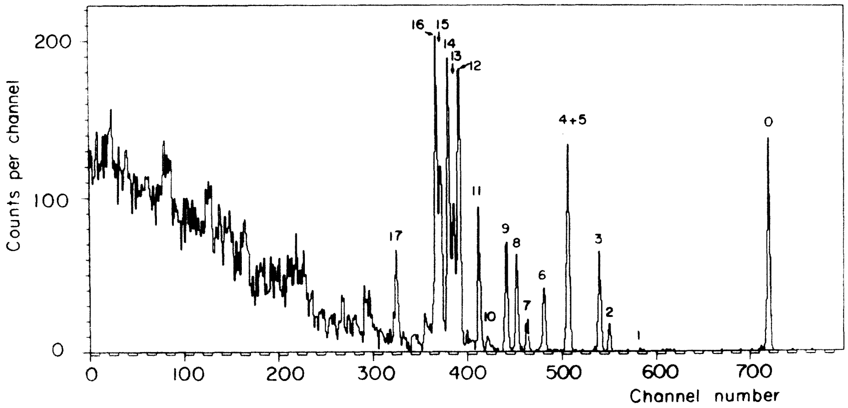

FIG. 1. α particle spectrum of the ^{93}Nb(p, α)^{90}Zr reaction.

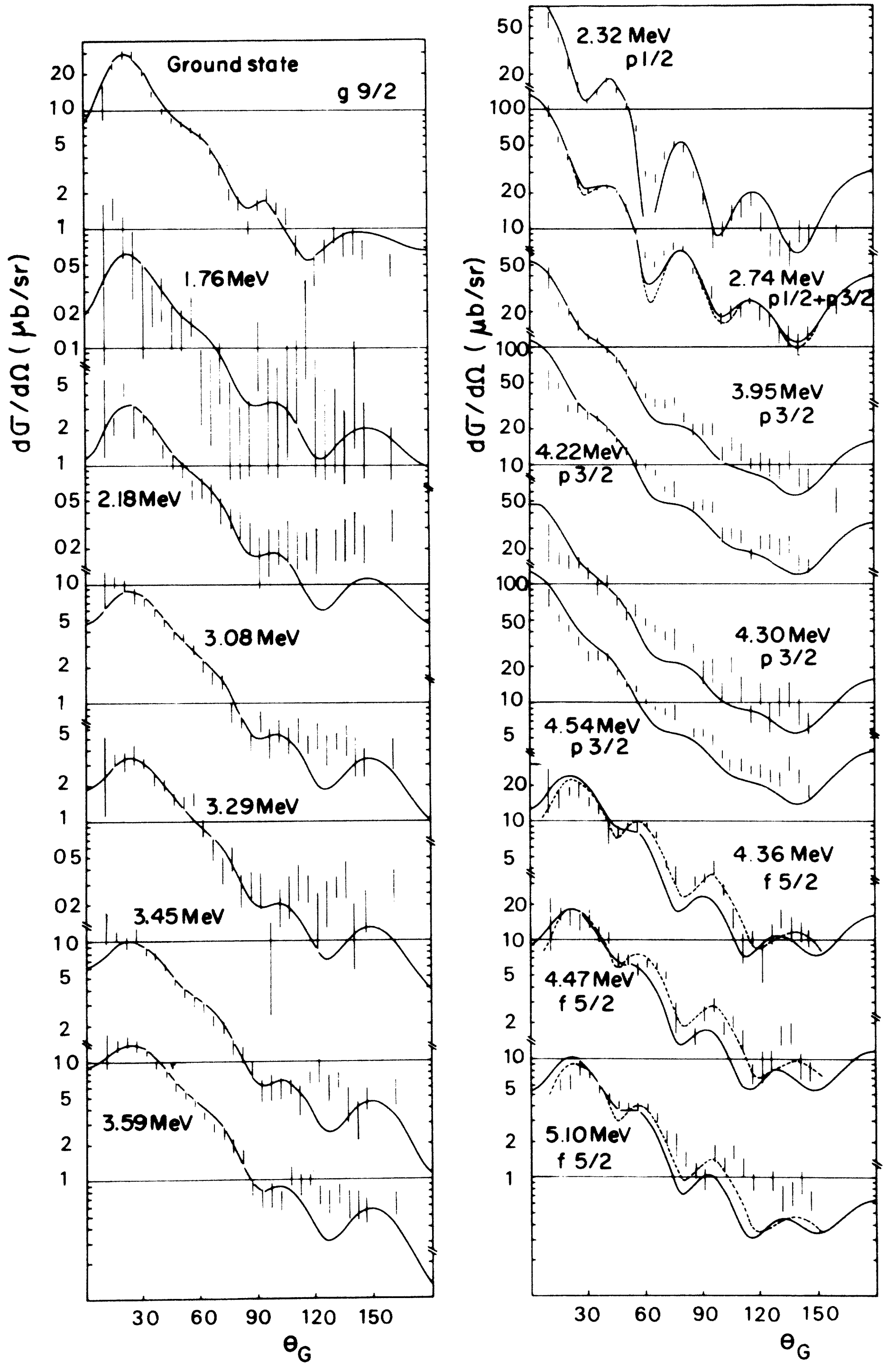

FIG. 2. Angular distributions of the α particles for the ^{93}Nb(p, α)^{90}Zr reaction. Full curves are cluster DWBA calculations. For the level at 2.74 MeV full and dashed curves correspond to the two extreme mixings given in Table II. Dashed curves for other levels correspond to the experimental angular distribution of the level at 1.364 MeV in the ^{96}Mo(p, α)^{93}Nb reaction at 15 MeV. The excitation energies are those measured in the reaction chamber experiment.

TABLE I. Optical-model parameters.

	U (MeV)	r_0 (fm)	a (fm)	λ_{so}	W_s (MeV)	$4W_D$ (MeV)	r' (fm)	a' (fm)
p	50.5	1.251	0.678	28	0	57.52	1.242	0.483
α	180.1	1.528	0.497	0	21.19	0	1.583	0.269
t		1.36	0.32	0				

of zero coupled extra core neutrons. The angular distributions for all of these levels are indeed very well fitted by calculations corresponding to a $g_{9/2}$ cluster transfer, the differences in shapes between the states being due to a Q value effect which is well reproduced by the DWBA calculations. (See Fig. 2.)

The relative magnitudes of the (p, α) cross sections for different levels in the same nucleus, computed with cluster form factors, are generally meaningless. In the particular case, however, where the transferred neutrons are the zero coupled extra core neutrons, the structure of the cluster depends only on the angular momentum transfer. The normalization is then the same for levels with the same angular momentum transfer and relative strengths can be determined from the analysis of the experimental data.

Theoretically these relative strengths are easily computed, since in this particular case they are simply proportional to the spectroscopic factors for a $g_{9/2}$ proton pickup. The values of a and b are already known[8] ($a = 0.6$, $b = 0.8$) and the theoretical values depend only on one parameter, the ratio α/β. The experimental and theoretical relative values are compared in Table II, for $\alpha/\beta = 1.14$. The agreement is quite good although there is a discrepancy for the 2^+ states (whose splitting is not explained in this very simple model).

Courtney and Fortune[9] have recently proposed three component wave functions for the 0^+ states in ^{90}Zr, the third component resulting from core excitation. Using their wave functions for the 0^+ states, still assuming for the 2^+, 4^+, 6^+, and 8^+ states a configuration $(g_{9/2})^2{}_J$, we can deduce for the $^{93}\mathrm{Nb}_{\mathrm{g.s.}}$ a three component wave function, which gives strengths in good agreement with experiment (see Table II); namely,

$$\begin{aligned}|{}^{93}\mathrm{Nb}_{\mathrm{g.s.}}\rangle = 0.565\,|(p_{1/2})^2{}_0 g_{9/2}\rangle \\ +0.744\,|(g_{9/2})^3{}_{9/2}\rangle \\ +0.343\,|(p_{3/2})^{-2}{}_0(p_{1/2})^2{}_0(g_{9/2})^3{}_{9/2}\rangle\,.\end{aligned}$$

We are able to reproduce fairly well the experimental results in either case and the occupation numbers deduced from the proposed $^{93}\mathrm{Nb}_{\mathrm{g.s.}}$ wave functions are rather close to the values one can deduce from the (^{3}He, d) reaction[10] on ^{93}Nb.

The excited state observed at 2.32 MeV is known to be a 5^- state corresponding to a $[(g_{9/2})(p_{1/2})]$ proton configuration. The state strongly excited at ≈2.74 MeV is known to be a close doublet: the level at 2.738 MeV is the 4^- second member of the above configuration, and the level at 2.748 MeV is a 3^- state for which a three-particle-one-hole $[(p_{1/2})^2(g_{9/2})(p_{3/2})^{-1}]$ proton configuration has been proposed.[11] The two members of the

$$[(g_{9/2})(p_{1/2})]$$

proton configuration should be reached with the second component of the $^{93}\mathrm{Nb}_{\mathrm{g.s.}}$ two component wave function by the transfer of a cluster con-

TABLE II. Relative strengths for known ^{90}Zr levels.

N°	E	J^π	Transfer	S_{exp}[a]	S_{model}	
					2 Components	3 Components
0	0.00	0^+	$g_{9/2}$	1	1	1
1	1.76	0^+		0.022	0.023	0.023
2	2.18	2^+		0.117	0.16	0.165
7	3.29	2^+		0.14		
10	3.84	2^+		Weak		
6	3.07	4^+		0.35	0.29	0.30
8	3.45	6^+		0.43	0.42	0.43
9	3.59	8^+		0.56	0.55	0.56
3	2.32	5^-	$p_{1/2}$	1	1	1
4	2.738	4^-	$p_{1/2}$	0.75 to 0.9	0.81	
5	2.748	3^-	$p_{3/2}$	0.64 to 0.57		
11	3.95	5^-	$p_{3/2}$	0.68		

[a] The experimental and theoretical strengths for positive parity levels have been normalized to 1 for the ground state. The experimental and theoretical strengths for negative parity levels have been normalized to 1 for the 5^- level at 2.32 MeV. The normalization has been assumed to be the same for $p_{1/2}$ and $p_{3/2}$ transfers.

sisting of a $p_{1/2}$ proton and a pair of zero coupled extra core neutrons. The angular distribution for the 5^- level is well fitted by a calculation corresponding to a $p_{1/2}$ cluster transfer. The angular distribution of the doublet is less structured. This is to be expected if the 3^- level is excited because it can be reached only by the transfer of a cluster consisting of a $p_{3/2}$ proton and a pair of zero coupled extra core neutrons: the well known j effect in the (p, α) reaction gives an angular distribution much less structured for $p_{3/2}$ than for $p_{1/2}$ transfer. It is possible to fit the experimental angular distribution by a mixture of $p_{1/2}$ and $p_{3/2}$ cluster transfers. Of course this procedure is open to criticism, but the ratio of the $p_{1/2}$ strengths for the 4^- and 5^- levels obtained in this way lies between 0.75 and 0.9, to be compared to a theoretical value of 0.81.

A 5^- level has been observed at 3.95 MeV in several inelastic scattering experiments on ^{90}Zr. A three-particle-one-hole $[(p_{1/2})^2(g_{9/2})(p_{3/2})^{-1}]$ proton configuration has been proposed[11] for this state. This level is strongly excited in the (p, α) reaction and its angular distribution is very well fitted by a $p_{3/2}$ cluster transfer calculation.

In summary, for known levels up to 4 MeV excitation energy, the reaction appears to behave like proton pickup, the extra core neutrons being transferred as a zero coupled pair, and the angular distributions are well fitted by the DWBA calculations using a cluster form factor.

TABLE III. Comparison of the levels observed above 3.9 MeV in the ^{91}Zr$(p,d)^{90}$Zr reaction and in the ^{93}Nb$(p,\alpha)^{90}$Zr reaction.

$N°$	E_{exp}[a]	E_{exp}[b]	E_{exp}[c]	$S(p,d)$[c]	$I(p,\alpha)$[d]
11	3.95	3.955		Absent	1.13
12	4.22	4.225	4.22	0.26	2.4
13	4.30	4.28		Absent	0.85
		4.33	4.32	1.27	0.16
14	4.36	4.37		Absent	1.29
		4.45	4.443	1.85	0.065
15	4.47	4.47		Absent	0.69
		4.49		Absent	0.59
16	4.54	4.54	4.528	2.20	2.20
			4.578	0.96	Absent
			5.05	2.05	Small
17	5.10			Small	≈0.6

[a] Energies obtained in the (p,α) reaction chamber measurement.

[b] Energies obtained in the (p,α) split pole measurement.

[c] Energies and spectroscopic factors obtained in the ^{91}Zr$(p,d)^{90}$Zr experiment (see Ref. 8).

[d] Intensities obtained at 30° in the split pole measurement, arbitrarily normalized to $S(p,d)$ for the level at 4.54 MeV.

Known neutron configuration levels of ^{90}Zr

The fact that the two transferred neutrons appear to be the extra core neutrons coupled to zero can of course be simply due to the particular structure of the final states excited above (closed $N=50$ neutron shell). It is very important to see if levels known to correspond to neutron configurations are also excited in the (p, α) reaction. Such levels (of positive parity) have been observed,[8] between 4.22 and 5.05 MeV, in the ^{91}Zr$(p, d)^{90}$Zr reaction and correspond to a proton structure very similar to that of the ^{90}Zr ground state and a one-particle-one-hole neutron configuration $[(d_{5/2})(g_{9/2})^{-1}]_J$. These levels could be excited in the (p, α) reaction through the transfer of a broken neutron pair $[(d_{5/2})(g_{9/2})]_J$.

Experimentally, strong levels are observed in the (p, α) reaction in the energy region between 4.22 and 5.10 MeV and it was found necessary to determine more precisely their energies using the split pole spectrometer. The energies, spectroscopic factors or intensities for the levels observed between 3.9 and 5.10 MeV in the ^{91}Zr(p, d)-^{90}Zr and ^{93}Nb$(p, \alpha)^{90}$Zr reactions are compared in Table III.

Two of the levels observed in the (p, α) reaction, at 4.22 and 4.54 MeV, have the same energies (within the stated errors) as the levels observed in the ^{91}Zr$(p, d)^{90}$Zr reaction. The strong levels observed in (p, d) at 4.443 and 4.578 MeV, however, are not seen or are very weak in the (p, α) reaction and the 4.32 MeV level is quite small. The strong levels observed in the (p, α) reaction at 4.28, 4.37, 4.47, and 4.49 MeV are not observed at all in the (p, d) experiment. The two spectra

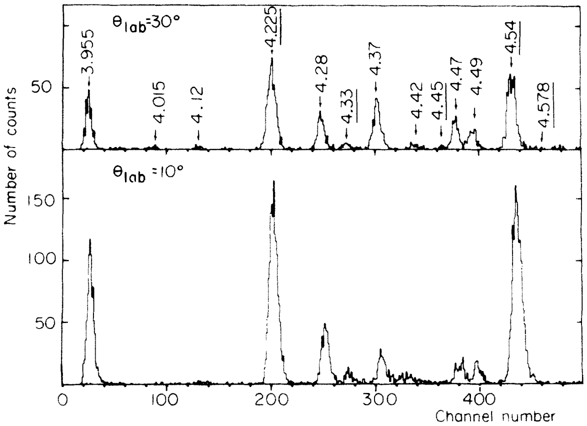

FIG. 3. α particle spectra observed at 10° and 30° using the split pole spectrometer and a position sensitive solid state detector. Error on the excitation energies is ±10 keV. Underlined energies correspond to levels strongly excited in the ^{91}Zr$(p,d)^{90}$Zr reaction.

are in fact completely different, aside from the coincidence in energy of two of the levels. Although these results cannot be considered as absolute proof, we conclude that the neutron configuration levels strongly excited in the (p, d) reaction are weakly excited, if at all, in the (p, α) reaction. Another supporting argument is that the levels observed with the (p, α) reaction are relatively much more strongly populated than those observed in this region with the ^{92}Zr(p, t) reaction. The strongly excited levels observed in the (p, α) reaction are therefore new levels, presumably corresponding to proton configurations.

New levels

The angular distributions given in Fig. 2 for the levels at 4.22, 4.28, and 4.54 MeV have approximately the same shape as that corresponding to the 5^- level at 3.95 MeV. They are all relatively well fitted by a $p_{3/2}$ cluster transfer calculation.

The angular distributions corresponding to the levels at 4.37, 4.47 (4.47 + 4.49), and 5.10 MeV have the same shape, which is different from all of the others. The DWBA fit assuming an $f_{5/2}$ cluster transfer is not very good, but the experimental shape is very similar (see Fig. 2) to that

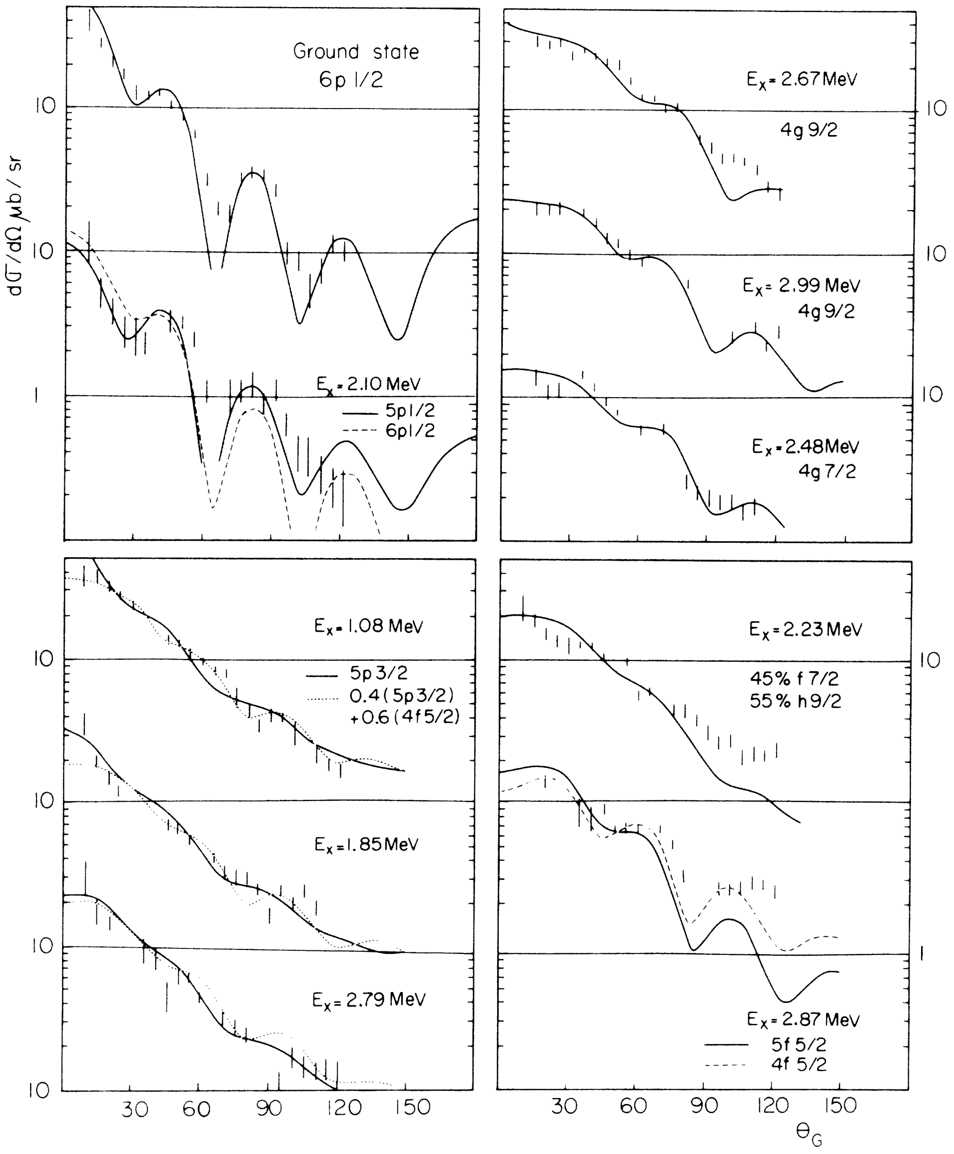

FIG. 4. Angular distributions of the α particles for the ^{89}Y(p, α)^{86}Sr reaction. Full and dashed curves are cluster DWBA calculations. For the 2^+ levels at 1.08, 1.85, and 2.79 MeV they correspond to either pure $p_{3/2}$ or mixed $p_{3/2}$ and $f_{5/2}$ transitions. For the levels at 2.1 and 2.87 MeV they correspond to the two possible different values of the cluster radial quantum number (see Ref. 6).

observed[7] in the ^{96}Mo(p, α)^{93}Nb reaction at 15 MeV, for levels believed to correspond to $l = 3$ transfers. Since the ratio of the strengths for the levels at 4.47 and 4.49 MeV is the same at 10° and 30° (see Fig. 3), we conclude that the two levels correspond to the same transfer.

The simplest explanation of the observed results is that the levels at 4.22, 4.28, and 4.54 MeV correspond mainly to the pickup of a $p_{3/2}$ proton (and a pair of zero coupled extra core neutrons) and that the levels at 4.37, 4.47, 4.49, and 5.10 MeV correspond mainly to the pickup of a $f_{5/2}$ proton (and a pair of zero coupled extra core neutrons). Configuration mixing could be responsible for the observed differences in shape between the almost identical angular distributions of the 3.95 and 4.54 MeV levels and the less forward peaked angular distributions of the 4.22 and 4.28 MeV levels.

The relative positions of the $p_{1/2}$, $p_{3/2}$, and $f_{5/2}$ proton levels are relatively well known in the neighborhood of ^{90}Zr. The reaction ^{90}Zr(d, ^{3}He)^{89}Y locates the $p_{3/2}$ and $f_{5/2}$ levels at 1.51 and 1.75 MeV above the $p_{1/2}$ ground state.[12] It is then easy to deduce that the centroids of the $p_{3/2}$ and $f_{5/2}$ strengths are expected at 4.03 and 4.27 MeV in ^{90}Zr. This compares well with the observed centroids of 4.09 and 4.54 MeV and gives support to the proposed interpretation.

Summary

All of the known positive parity states of ^{90}Zr corresponding to proton configurations have been observed and their strengths are well reproduced by simple calculations. Known negative parity states are observed, populated by the appropriate angular momentum transfers. New negative parity states are observed between 4.22 and 5.10 MeV and it is proposed to identify them as members of the proton three-particle-one-hole multiplets $[(^{93}\mathrm{Nb}_{\mathrm{g.s.}})(p_{3/2})^{-1}]$ and $[(^{93}\mathrm{Nb}_{\mathrm{g.s.}})(f_{5/2})^{-1}]$. The known positive parity levels seen in the ^{91}Zr(p, d) experiment between 4.22 and 5.05 MeV are either not observed here or are very weakly excited.

III. ^{89}Y(p, α)^{86}Sr REACTION

This reaction has been studied in the same conditions and analyzed in the same way as the reaction on ^{93}Nb. The angular distributions for levels up to 3 MeV excitation energy are reproduced in Fig. 4.

In the reaction on ^{93}Nb it appears that, at least up to several MeV excitation energy, we are picking up the two extra core neutrons mainly coupled to zero. In the present case the two neutrons are necessarily picked up from the $N = 50$ closed shell and there is no reason for the pair to be preferentially coupled to zero angular momentum. It is therefore to be expected that the (p, α) reaction will be much more complex and difficult to analyze than in the previous case and that neutron configurations could well be excited.

The target quantum numbers being $J^\pi = \frac{1}{2}^-$ the cluster transfers alllowed by the selection rules are: for 0^+ levels, pure $p_{1/2}$, for 2^+ levels, $p_{3/2}$ and $f_{5/2}$, for 3^- levels, $d_{5/2}$ and $g_{7/2}$, for 5^- levels, $g_{9/2}$ and $i_{11/2}$.... There is at most mixing of two j values and it is therefore relatively easy to see if the DWBA analysis is correct for levels whose quantum numbers and structure are known.

0^+ and 2^+ levels

The angular distributions for the ground state and the level at 2.10 MeV, for which a 0^+ assignment has been proposed[13, 14] on the basis of the (p, t) results, are correctly reproduced by $p_{1/2}$ cluster transfer calculations.

A level is observed at many angles at 3.10 MeV. Its angular distribution, although incomplete and with large error bars, presents around 65° the dip characteristic of the $p_{1/2}$ transfer. This level very tentatively assigned $J^\pi = 0^+$, could correspond to the 0^+ level observed at 3.155 MeV in ^{88}Sr.

Two 2^+ levels are already known in ^{86}Sr. The first at 1.08 MeV is strongly excited in the (p, t) and (p, p') reactions.[14, 15] It corresponds to excited neutron configurations. The second at 1.85 MeV, much less excited in (p, t) and (p, p') reactions (respectively, $\approx\frac{1}{10}$ and $\approx\frac{1}{4}$ of the 1.08 MeV level), must correspond mainly to excited proton configurations. The (p, α) angular distributions for these two levels have about the same shape as that observed for the level at 3.95 MeV in ^{90}Zr, which means that they correspond mainly to a $p_{3/2}$ transfer. This is also true for the level at 2.80 MeV, in agreement with the fact that this level has been observed in (p, t) with an $L = 2$ shape.[13] The observed shapes have indeed weak differences which might be explained by differences in the final level structure, leading to an $f_{5/2}$ admixture for the 1.08 MeV level (see Fig. 4).

3^- and 5^- levels

In the absence of $g_{9/2}$ protons in the $^{89}\mathrm{Y}_{\mathrm{g.s.}}$ the negative parity states necessarily correspond to the transfer of a broken neutron pair (neutrons from two different orbitals). The 3^- states could not anyway be populated by a $[(\pi g_{9/2})(\nu)^2{}_0]$ transfer. Two known 3^- states at 2.48 and 2.99 MeV are strongly populated in (p, α). The shape of the observed angular distributions is well reproduced by a $g_{7/2}$ cluster transfer, in agreement with the $[(\nu g_{9/2})^{-1}(\nu f - p)^{-1}]$ structure of these states. The ratio of the strengths $(I_{2.99}/I_{2.48}\approx 1.5)$ is the same as that in the (p, t) experiment.[14]

The peak observed at 2.67 MeV in (p, α) corresponds to a known doublet (2.642 and 2.673 MeV). The higher member is a 5^- level.[16,18] An acceptable fit is obtained with a $g_{9/2}$ cluster transfer.

Other levels

Positive parity levels with spins 4^+ (2.23 MeV), 6^+ (2.855 MeV), and 8^+ (2.955 MeV), corresponding mainly to a $[(\nu g_{9/2})^{-2}]_J$ configuration, are known[17] from (p, d) results. The 4^+ state is strongly excited in (p, α); it should correspond to $f_{7/2}$ or $h_{9/2}$ transfers. The fit obtained with a mixture of the two angular momentum transfers (45% and 55%) corresponding to a $[(\nu g_{9/2})^{-2}]_{4^+}$ state in ^{86}Sr is better than those obtained with pure angular momentum transfers, but is still not very good.

A state is observed at 2.87 MeV in (p, α). If it is the 6^+ state, the transfer should be $h_{11/2}$ or $j_{13/2}$. No mixing of these transfers can reproduce, even badly, the observed shape. An acceptable fit can only be obtained with an $f_{5/2}$ transfer, leading to $J^\pi = 2^+$ or 3^+. The observed state must then be identified with the $J^\pi = 3^+, 4^+$ state[17] at 2.878 MeV. Only $J^\pi = 3^+$ is consistent with all of the results, including the fact that the level is not observed in (p, t). The 8^+ state at 2.955 MeV is not observed, but could be partly hidden by the strong 2.99 MeV peak.

The spectrum is obscured between 3.25 and 3.60 MeV by a parasite peak due to the 90° scattering of protons in the detectors. States are observed at 3.19, 3.665, 3.92, and 4.26 MeV. The state at 3.92 MeV is strongly excited. The results are not good enough to permit a detailed analysis for these levels.

Summary

The ^{86}Sr levels observed in the (p, α) reaction, with spins and parities known or determined in this experiment, are presented in Fig. 5. They are compared to the proton particle-hole levels of ^{88}Sr observed[19] in the ^{89}Y$(d, {}^3$He$)$ reaction and to a two-neutron hole shell model calculation for ^{86}Sr performed in a $g_{9/2}$, $p_{1/2}$ restricted basis.[15]

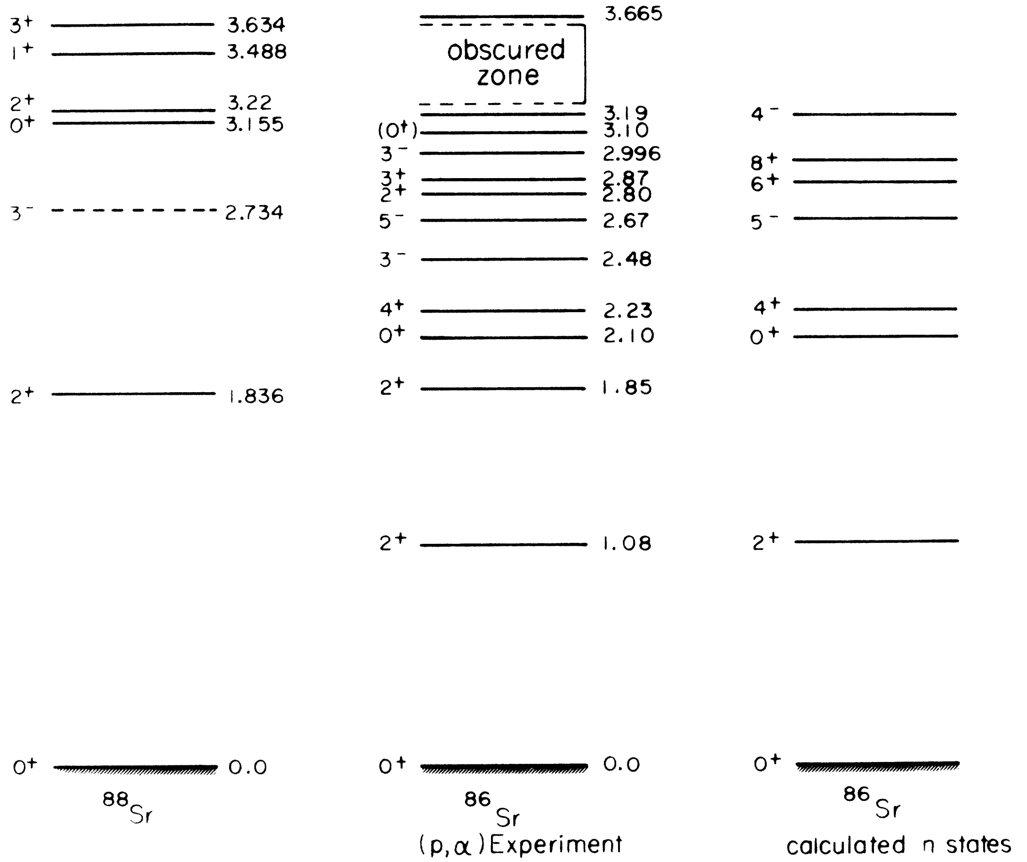

FIG. 5. Comparison of the level schemes of Sr isotopes. On the left: proton configuration levels of ^{88}Sr [seen in the $(d, {}^3$He$)$ reaction with the exception of the 3^- level]. On the right: calculated neutron configuration levels of ^{86}Sr. In the middle: ^{86}Sr levels observed in the (p, α) reaction.

{The 3^- state in ^{88}Sr, shown as a dotted line, is largely a $[(\pi p_{3/2})^{-1}(\pi g_{9/2})]$ state and cannot therefore be observed in the $(d, {}^3\mathrm{He})$ reaction.} This figure shows clearly that both proton particle-hole states, coupled to a zero angular momentum neutron hole pair, and two-neutron hole states, the two neutrons being in the same or in different orbitals, are populated strongly by the (p, α) reaction. For the same final spin and parity the angular distributions have nearly the same shape; weak differences (for example for the two 2^+ states at 1.08 and 1.85 MeV) may indicate a difference in level structure.

In summary, in the ^{89}Y$(p, \alpha)^{86}$Sr reaction the shapes of the angular distributions for levels of known quantum numbers are in agreement with a triton pickup interpretation. The three transferred nucleons can, however, couple in many ways and it is not possible to deduce the precise configuration of the final state from our analysis. Finally, the high spin state 6^+ and 8^+, known from neutron pickup reactions, are not observed in our experiment.

IV. DISCUSSION

The analysis of the experimental results of the (p, α) reaction on ^{89}Y and ^{93}Nb shows very different behavior in the two cases. It is interesting to try to understand this result more precisely.

In the case of ^{89}Y the neutrons are necessarily picked up from the $N=50$ closed shell and there is *a priori* no reason why they should be preferentially coupled to zero. In fact the (p, t) reaction[3] on ^{90}Zr (same $N=50$ closed shell) shows that states corresponding to broken neutron pairs are strongly excited and appear quite low in energy. The neutron states strongly excited in the (p, t) reaction are also strongly excited in the (p, α) reaction. When a comparison is possible (for the two 3^- states, for example) the relative strengths are about the same. The 6^+ and 8^+ members of the $[(g_{9/2})^{-2}{}_J]$ neutron configuration, at 2.855 and 2.955 MeV, are not observed in (p, α); states of the same nature are very weakly excited in the ^{90}Zr$(p, t)^{88}$Zr reaction.[3] One level corresponding mainly to a proton particle-hole state is observed in (p, α) at 1.85 MeV. This level is weakly excited in (p, t).

In the case of ^{93}Nb there are two extra core neutrons mainly coupled to zero.[2] It requires certainly much less energy to remove them than to remove a pair from the closed core and therefore the neutron states corresponding to pickup of pairs from the core should appear rather high in energy. In the (p, t) reaction[3] on ^{92}Zr (about the same neutron configuration) it appears clearly that the ground state transition dominates the whole spectrum and that only very weak transitions are observed up to 4 MeV excitation energy. Among the levels populated between 4 and 5.5 MeV, the strongest are 0^+ states corresponding to the pickup of a zero coupled pair in the $N=50$ core. These states are observed in the (p, α) reaction but weaker than in the (p, t) reaction. States corresponding to the pickup of a broken neutron pair $[(d_{5/2})(g_{9/2})]_J$, which are weakly excited in the (p, t) reaction, are also weakly excited, if at all, in the (p, α) reaction. The states strongly observed in (p, α) are proton three-particle-one-hole states which are practically not excited in the (p, t) reaction.

V. CONCLUSION

At 15 MeV, for nuclei around $A=90$, the (p, α) reaction is a direct triton pickup and the compound nucleus contribution is negligible, at least up to excitation energies of several MeV. For the two studied reactions the angular distributions are characteristic of the transferred angular momentum and can generally be reproduced by simple cluster DWBA calculations. It is therefore possible, if the statistics are good enough, to deduce valuable results concerning spins and parities from such an analysis. This is certainly even more true for even target nuclei where j mixing cannot occur. In the case of the ^{93}Nb$(p, \alpha)^{90}$Zr reaction, the (p, t) results show that the transfer of a zero coupled neutron pair is the dominant process. It follows that the (p, α) reaction behaves like a simple proton pickup and can therefore give precise results about the proton configuration states of ^{90}Zr. This is not the case for the ^{89}Y$(p, \alpha)^{86}$Sr reaction where the transfer of nonzero coupled neutron pairs is important.

In conclusion the (p, α) reaction can be used as a spectroscopic tool, even at 15 MeV, on heavy enough targets. It should give the more precise information when the (p, t) reaction shows that the transfer of zero coupled neutron pairs is the dominant process.

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