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Strong effect of isospin mixing in ^{16}O†

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The intensity ratio of the ground state (2^-) to the 0.30 MeV (3^-) state of ^{16}N as measured in the $^{17}O(d,{}^3He)$ reaction and the intensity ratio of their analog states at 12.97 and 13.26 MeV in ^{16}O as measured in the $^{17}O(d,t)$ and $^{17}O({}^3He,\alpha)$ reactions consistently differ by about 50%. A largely model independent analysis of this isospin mixing effect in ^{16}O suggests $\geq 17\%$ mixing of the 2^- states at 12.97 ($T=1$) and 12.53 MeV ($T=0$) as its dominant source, in which case a lower limit of the isospin mixing matrix element of (155 ± 30) keV is obtained.

NUCLEAR REACTIONS $^{17}O(d,{}^3He)$, $^{17}O(d,t)$, $E=52$ MeV; $^{17}O({}^3He,\alpha)$, $E=36$ MeV. Measured $\sigma(\theta)$ and relative population of the ground state (2^-) and the 0.30 MeV (3^-) state of ^{16}N, and their analog states in ^{16}O at 12.97 and 13.26 MeV, respectively.

NUCLEAR STRUCTURE ^{16}O, deduced isospin mixing of the 2^- states at 12.97 MeV ($T=1$) and 12.53 MeV ($T=0$).

An isospin mixing matrix element of (179 ± 75) keV has been reported[1] in ^{12}C. This has attracted both attention (see Ref. 2 and Refs. given therein) due to the possible far-reaching conclusion of charge dependent nuclear forces, and criticism[3,4] based on the possibility of isospin mixing through the reaction mechanism. This paper reports a strong isospin mixing effect in ^{16}O which has the same magnitude in various isospin allowed reactions. Hence, an isospin violating reaction mechanism may safely be excluded as its origin.

To pursue this effect which we had noticed earlier[5] we performed a simultaneous $(d,{}^3He)$ and (d,t) experiment on ^{17}O with 52 MeV deuterons from the Karlsruhe cyclotron, and a $^{17}O({}^3He,\alpha)$ experiment with 36 MeV ^3He particles from the upgraded Heidelberg MP tandem accelerator. The object was to measure the relative population of the ground ($J^\pi=2^-, T=1$) and 0.30 MeV ($3^-,1$) states in ^{16}N and their analog states in ^{16}O at 12.97 and 13.26 MeV, respectively (see Fig. 1). In the first experiment, in which the $Z=1$ and $Z=2$ reaction products were simultaneously identified in a surface barrier counter telescope, a gas target limited the resolution to about 120 keV. The $({}^3He,\alpha)$ experiment was performed with a resolution of 35 keV using a Quadrupole-dipole-dipole-dipole spectrometer and 60 $\mu g/cm^2$ $Ni^{17}O$ targets. The $Ni({}^3He,\alpha)$ background was subtracted through subsequent runs on pure Ni targets.

The experimental results may be summarized as follows:

(i) In the $(d,{}^3He)$ reaction the ground state and the 0.30 MeV state of ^{16}N are the must strongly excited states[5] and show clear $l=1$ angular distributions. Their intensity ratio in proton pickup (subscript p) averaged over all angles (see Fig. 2) is $I_p(2^-,1)/I_p(3^-,1) \equiv R_p(d,{}^3He)=0.71$. The summed spectroscopic factors[5] of the $2^-,1$ and $3^-,1$ states agree within 15% with the shell model limit for $1p_{1/2}$ pickup and the value of $R_p(d,{}^3He)$ equals 5 : 7 as expected for a $d_{5/2}\times p_{1/2}{}^{-1}$ doublet provided there are no Q-value effects.[6] Microscopic effects as discussed in Ref. 4 should play no role for two close lying states of identical structure.

(ii) In the $({}^3He,\alpha)$ reaction the analog states in ^{16}O are excited with a significantly different intensity ratio $R_n({}^3He,\alpha)=1.19$ which is again angle independent. The statistical errors of both R_p and R_n are $\leq 1\%$. The $({}^3He,\alpha)$ spectra also indicate that the broad ($\Gamma \sim 119$ keV) $3^-,0$ state at 13.13 MeV does not contain more than (14 ± 4)% of the strength of the $3^-,1$ state. At lab angles below 30° the $({}^3He,\alpha)$ spectra in addition exhibit a broad peak below the 13.26 MeV group which we could not attribute to any known state of ^{16}O (nor to any conceivable contaminant).

In the (d,t) experiment this unknown state as well as the 13.13 MeV group are not resolved from the 13.26 MeV state. Evidence for population of the former comes from the width of the 13.26 MeV group which is consistently larger than that of the 12.97 MeV group by an amount not explainable by the natural widths. In fact, if we numerically fold into a forward angle $({}^3He,\alpha)$ spectrum the moderate resolution of the (d,t) experiment then the result (see Fig. 1) is extremely similar to the (d,t) spectra. The seemingly lower $R_n(d,t)$ value

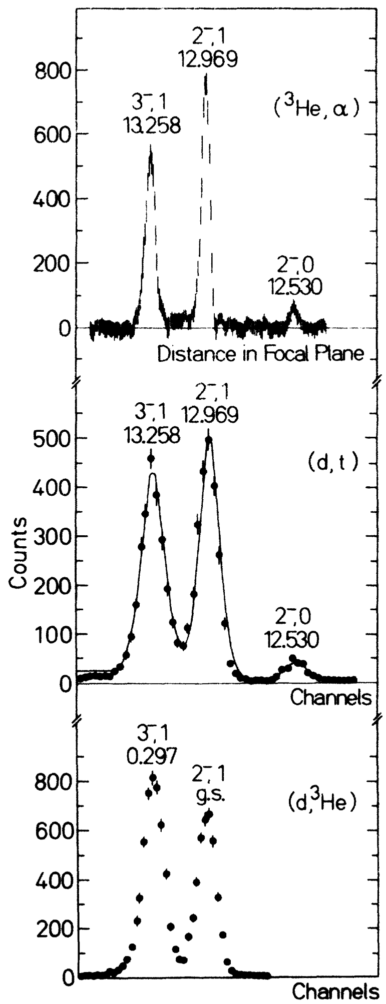

FIG. 1. The relevant part of the spectra measured in (i) the ^{17}O(^{3}He, α)^{16}O reaction at $E_{^3\mathrm{He}}$ = 36 MeV and θ_{lab} = 32° after subtraction of the Ni(^{3}He, α) background (top); (ii) the ^{17}O(d,t)^{16}O reaction (center); and (iii) the ^{17}O(d, ^{3}He)^{16}N reaction (bottom) both at $E_d \triangleq 52$ MeV and θ_{lab} = 10°. The solid line in the (d,t) spectrum represents a smooth curve drawn through a ^{17}O(^{3}He, α) spectrum at θ_{lab} = 20° when folded with the experimental width of the (d,t) experiment.

(see Fig. 2) is thus explained by the insufficient energy resolution of the (d,t) experiment, but at the same time, the compatibility of both neutron pickup experiments is also evident. This holds as well for the intensity ratio $R_n(p,d)$ taken from a published ^{17}O(p,d) spectrum[7] at 31 MeV (see Fig. 2). In the following we shall use the high resolution result $R_n = 1.19$.

The enhancement of R_n over R_p represents a 67% effect due to isospin mixing in ^{16}O, which could result from mixing $T = 0$ states and/or coupling to the continuum with open proton and α and closed neutron channels. The partial widths for p decay are $\Gamma_p(3^-,1) = 4.5$ keV and $\Gamma_p(2^-,1) = 1.2$ keV.[8] Similarly, $\Gamma_\alpha(3^-,1) = 17$ keV exceeds $\Gamma_\alpha(2^-,1) = 1$ keV. Therefore, the $3^-,1$ state appears to be more strongly coupled to the continuum than does the $2^-,1$ state. This lets us exclude continuum mixing as the dominant source of the observed effect since we shall show that this effect is largely due to an isospin impurity of the $2^-,1$ state.

The fact that it is the $2^-,1$ state in ^{16}O which carries relatively too much pickup strength is easily recognized from the ratio of (d,t) and (d, ^{3}He) counting rates leading to the analog states in ^{16}O and their parent states in ^{16}N, respectively. Averaged over all angles these ratios[9] range between 0.49 and 0.52 for states in ^{16}O between 13.26 and 20.45 MeV[5]; the only exception is for the $2^-,1$ state at 12.97 MeV where the ratio is 0.67. We emphasize, however, that these traditionally used experimental $t/^3$He ratios show a slight systematic angular dependence (~±10%) as do the results of distorted-wave Born-approximation (DWBA) calculations. This and the uncertainties in a DWBA treatment required to eliminate reaction induced Coulomb effects from the $t/^3$He cross section ratio, imply that comparing intensity ratios R of two parent states and of their analog states is a more precise means of determining isospin effects.

Thus we are led to assume two-state mixing[10] of the $2^-,1$ state at 12.97 MeV in ^{16}O with the closest known $2^-,0$ state which is at 12.53 MeV:

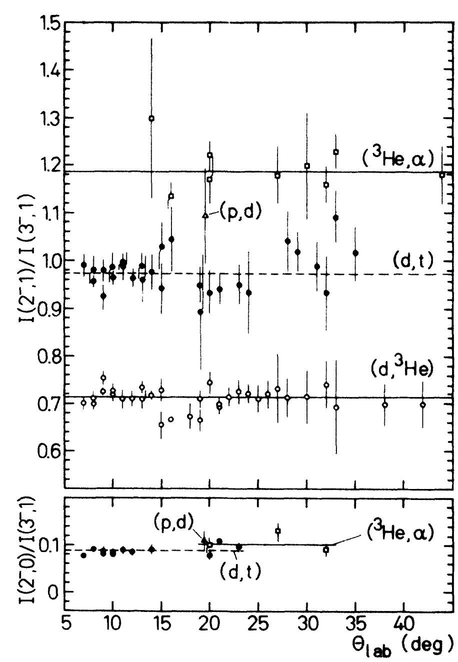

FIG. 2. Angular dependence and average values (horizontal lines) of intensity ratios between groups identified by their spin and isospin J^π, T as in Fig. 1.

$$|12.97\rangle=(1+\epsilon^2)^{-1/2}(|2,1\rangle+\epsilon\,|2,0\rangle),$$
$$|12.53\rangle=(1+\epsilon^2)^{-1/2}(|2,0\rangle-\epsilon\,|2,1\rangle), \quad (1)$$

where $|2,1\rangle$ and $|2,0\rangle$ denote isospin pure basis configurations. The aim is to find the smallest isospin mixing matrix element $\langle H_{cd}\rangle$ compatible with the data. To that end we have also given in Fig. 2 the intensity ratio $I_n(2^-,0)/I_n(3^-,1)\equiv r_n$ of the 12.53 to the 13.26 MeV state. Again the values of r_n from the other neutron pickup reactions agree very well with $r_n(^3\mathrm{He},\alpha)=0.10\pm0.01$. The angular independence of r_n shows the $1p$ character of the 12.53 MeV angular distribution.

Let f_{20}, f_{21}, and f_{31} be the reaction amplitudes for *neutron* pickup leading to the $|2,0\rangle$, $|2,1\rangle$, and $|3,1\rangle$ *basis* configurations. Our basic assumption is $R_p=|f_{21}|^2/|f_{31}|^2$. In addition, we make the following assumptions which we shall drop subsequently: (i) isospin purity of the $3^-,1$ state, so that its intensity $I_n(3^-,1)=|f_{31}|^2$; (ii) pure $p_{1/2}$ pickup leading to a coherent superposition of f_{20} and f_{21}; and (iii) negligible Q-value effects. From the relations

$$R_n=(1+\epsilon^2)^{-1}\,|f_{21}+\epsilon f_{20}|^2/I_n(3^-,1),$$
$$r_n=(1+\epsilon^2)^{-1}\,|f_{20}-\epsilon f_{21}|^2/I_n(3^-,1) \quad (2)$$

we obtain both $|f_{20}|^2/I_n(3^-,1)=r_n+R_n-R_p=0.58$ and $\epsilon^2\geq0.23$ where the equality holds in the case of maximum coherence, i.e., a zero phase angle between f_{20} and f_{21}. This leads[11] to $|\langle H_{cd}\rangle|=(1+\epsilon^2)^{-1}|\epsilon|[E(2^-,1)-E(2^-,0)]\geq(171\pm5)$ keV (statistical error only).

Next we drop assumption (i). The $3^-,1$ state in ^{16}O is known[8] to have $T=0$ admixtures, most probably[12] through mixing with the $3^-,0$ state at 13.13 MeV. The largest possible effect on the extraction of ϵ^2 would result if $f_{30}=0$, i.e., if all of the pickup strength residing in the $3^-,0$ state were of $T=1$ nature. From the (^{3}He, α) value of $I_n(3^-,0)$ we then obtain $I_n(3^-,1)\geq|f_{31}|^2/(1.14\pm0.04)$ which with Eq. (2) leads to $\epsilon^2\geq(0.15\pm0.02)$ and $|\langle H_{cd}\rangle|\geq(149\pm10)$ keV. The used $(14\pm4)\%$ mixing of the 3^- states is close to the maximum value of $(19\pm7)\%$ compatible with the widths[8] of the 3^- states as calculated with the formalism of Shanley[11] supplemented by the unitarity condition[13] $|\langle A|B\rangle|\leq(\Gamma_A\Gamma_B)^{1/2}/|E_A-E_B+i(\Gamma_A+\Gamma_B)/2|$. We note that the isospin mixing of the 3^- states does not show up in the $(d,t)/(d,{}^3\mathrm{He})$ cross section ratios since the $3^-,1$ and $3^-,0$ states are not resolved.

In relaxing condition (ii) we note that a $p_{3/2}$ amplitude would add incoherently. Therefore, one would require much larger mixing to obtain the same effect. In fact, assuming 19% of $|f_{20}|^2$ to be of a $p_{3/2}$ nature would already demand the maximum allowed mixing $\epsilon^2=0.45$ derived from the widths of the states and $|\langle H_{cd}\rangle|=200$ keV. In treating assumption (iii) in standard DWBA we find a slightly increased $\epsilon^2\geq(17\pm7)\%$ and $|\langle H_{cd}\rangle|\geq(155\pm30)$ keV. In the final errors we have included: (a) a conservative 10% estimate for the systematic error of the *relative* spectroscopic factors of the neighboring 2^- and 3^- states; and (b) a 25 keV error accounting for the accuracy to which we can exclude a mixing of other $3^-,0$ states, such as that relatively strongly excited[5] at 15.4 MeV, with the $3^-,1$ state at 13.26 MeV. The "isospin pure" behavior of the (unresolved) 13.26 MeV group was established, within the ~10% accuracy of its measured intensity, by comparing the various $(d,t)/(d,{}^3\mathrm{He})$ intensity ratios.

The assumed two-state mixing implies that the excessive strength of the $2^-,1$ state stems from the relatively weakly populated $2^-,0$ state. The unperturbed $2^-,0$ state at (then) 12.59 MeV would carry 5 times as much strength. As a consequence, the $[d_{5/2}p_{1/2}^{-1}]_{2^-,0}$ antianalog (AA) strength would be shared among the 8.87 (~60%) and 12.59 MeV (~40%) states. This fragmentation moves the centroid AA energy from 8.9 to 10.3 MeV leading to a more reasonable analog (A)-AA splitting of 2.7 MeV. To some extent (66% : 13%) such a fragmentation is also obtained in $3\hbar\omega$ shell model calculations[14] as a result of 1p-1h and 3p-3h configuration mixing. The fragmentation provides a clue to the strong isospin mixing effects since it is responsible for the small energy gap between the $2^-,1$ analog (A) state and the upper AA fragment which for a given mixing matrix element gives rise to a strong effect. Then, of course, due to the larger space-spin overlap this matrix element will be larger between A state and AA fragment than between less related states. In fact, because of the large Coulomb mixing matrix elements which occur between A and AA states in cases of a major shell crossing[15] one has no difficulty in understanding a value for $|\langle H_{cd}\rangle|$ of 150 keV between the A state and a 40% AA fragment from Coulomb forces alone.[16] This also explains the sign of the mixing which as in the previously known cases in ^{8}Be (Ref. 17) and ^{12}C (Ref. 1), is such as to increase the *neutron* particle-hole character of the higher excited state.

A discomforting result is the energy gap between the *unperturbed* $2^-,1$ (12.914 MeV) and $3^-,1$ (13.242 MeV) states[18] of 328 keV compared with 297 keV in ^{16}N and ^{16}F. To obtain a 297 keV gap in ^{16}O a mixing matrix element of 100 keV would be required. This matrix element would demand $R_n\leq0.90$ for $r_n=0.10$, which is beyond our experimental error. This may serve as a warning that more complex effects such as continuum and three-state mixing should not be disregarded. On the other hand it has been noted earlier[19] that the $M2$ ground state transition from the 12.53 MeV state may be understood as an isovector transition resulting from a $(24 \pm 7)\%$ two-state mixing with the 12.97 MeV state.

In conclusion, the strong isospin mixing effect which we have consistently observed in several pickup experiments has been traced back to $\geq(17 \pm 7)\%$ mixing between the $2^-,1$ and $2^-,0$ states at 12.97 and 12.53 MeV in ^{16}O. Apart from the case of complete mixing in ^8Be (Ref. 17) this is the strongest isospin mixture observed so far. The corresponding mixing matrix element of $\geq(155 \pm 30)$ keV may be understood from Coulomb mixing between the A state and a sizable AA component in the $2^-,0$ state. Similar effects might be expected for other particle-hole excitation across a major shell provided that the spreading of the AA strength through configuration mixing is large enough to bridge the A-AA gap.

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