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Study of Mirror States in $A = 19$ with the (^{6}Li,t) and (^{6}Li,^{3}He) Reactions on ^{16}O†

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The reactions ^{16}O(^{6}Li, ^{3}He)^{19}F and ^{16}O(^{6}Li, t)^{19}Ne have been performed at an incident energy of 24 MeV. The observed strong selectivity of these reactions suggests a predominantly direct-reaction mechanism and allows the identification of several isobaric analogs in ^{19}F and ^{19}Ne.

During the past few years much effort has been devoted to the study of lithium-induced reactions. Most extensively studied have been the α-particle transfer reactions[1-4] (^{6}Li, d) and (^{7}Li, t) and the two-nucleon transfer reaction[2,5-6] (^{6}Li, α). Comparatively few studies have been made of the three-nucleon transfer reactions[2,7] (^{6}Li, ^{3}He) and (^{6}Li, t) until very recently. This lack of interest probably reflected the erroneous belief that the ^{6}Li-induced three-nucleon transfer reactions would be both very weak and unselective. Recent studies,[8] however, have indicated substantial ^{3}He-t clustering in the ^{6}Li ground state. Such clustering is, of course, expected on simple grounds.[9] The present Letter reports preliminary results of a program of (^{6}Li, ^{3}He) and (^{6}Li, t) reactions, demonstrating their use for determining isobaric analogs in mirror nuclei. Ignoring the effects of the Coulomb force, the (^{6}Li, ^{3}He) and the (^{6}Li, t) reactions are expected to be the same. Hence, when these two reactions are studied on self-conjugate targets ($N = Z$), mirror states in the final nuclei would be expected to be populated in a similar manner.

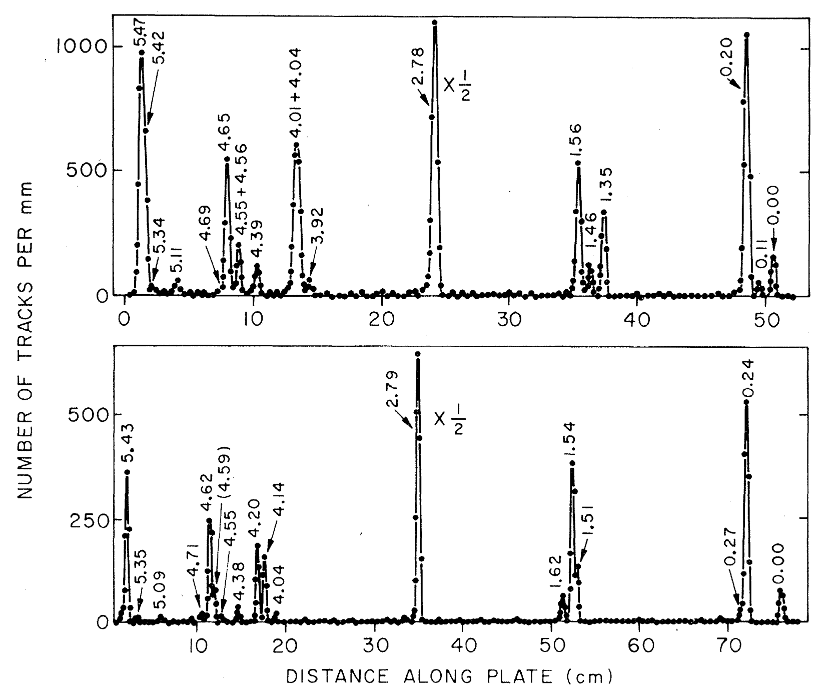

FIG. 1. Energy spectra from the reaction ^{16}O(^{6}Li, ^{3}He)^{19}F (top) and the reaction ^{16}O(^{6}Li, t)^{19}Ne (bottom). Both spectra were obtained at a laboratory angle of 7.5 deg with a 24-MeV incident ^{6}Li beam.

To test this hypothesis the (^{6}Li, ^{3}He) and (^{6}Li, t) reactions were performed on ^{16}O leading to final states in the mirror nuclei ^{19}F and ^{19}Ne. The reactions were induced by a 24-MeV ^{6}Li^{+++} beam from the University of Pennsylvania tandem Van de Graaff accelerator. The reaction products were momentum analyzed in a multiangle magnetic spectrograph and were recorded in nuclear emulsions. The target was natural oxygen gas contained in a gas cell having no entrance window.[1] The ^{3}He and triton spectra were obtained in two separate exposures. Accurate measurement of the gas-cell pressure and the integrated beam current allowed the calculation of the absolute cross sections to an accuracy of ±15%.

Energy spectra from the two reactions measured at a laboratory angle of 7.5° are compared in Fig. 1, and Table I lists the peak differential cross sections of the various groups. The extraction of angular distributions is in progress.

Table I. Excitation energies, spins, parities, and peak differential cross sections for states excited by the reactions ^{16}O(^{6}Li, ^{3}He) and ^{16}O(^{6}Li, t).

^{16}O(^{6}Li, ^{3}He)^{19}F			^{16}O(^{6}Li, t)^{19}Ne		
E_x [a] (MeV)	J^Π [a]	$\sigma_{max}(\Theta)$ (mb/sr)	E_x [a] (MeV)	J^Π [a]	σ_{max} (mb/sr)
0.0*	$1/2^+$	0.106	0.0*	$1/2^+$	0.095
0.11†	$1/2^-$	0.026	0.24*	$5/2^+$	0.612
0.20*	$5/2^+$	0.682	0.27†	$1/2^-$	0.026
1.35†	$5/2^-$	0.173	1.51†	$5/2^-$ [b]	0.082
1.46†	$3/2^-$	0.065	1.54*	$3/2^+$ [b]	0.294
1.56*	$3/2^+$	0.279	1.62	$3/2^-$ [b]	0.052
2.78*	$9/2^+$	1.16	2.79*	$9/2^+$ [b]	0.763
3.92	$3/2^+$ [b]	0.012	4.04	$3/2^+$ [b]	0.008
4.01†	$7/2^-$	} 0.357	4.14†	$7/2^-, (9/2^-)$ [b]	0.072
4.04†	$9/2^-$		4.20†	$9/2^-, (7/2^-)$ [b]	0.083
4.39	$7/2^+$	0.037	4.38	$7/2^+$ [b]	0.016
4.55	$5/2^{(+)}$	} 0.059	4.55	$1/2^-, 3/2^-$	0.006
4.56	$3/2^-, (1/2^-)$		(4.59)		(0.026)
4.65*	$13/2^+$	0.197	4.62*	$13/2^+$ [b]	0.125
4.69	$5/2^-$	c	4.71		0.008
5.11	$(5/2^-, 7/2^-)$	0.012	4.78		0.006
5.34	$1/2^+$ [b]	0.005	5.09	$(5/2^-, 7/2^-)$ [b]	0.011
5.42	$7/2^-$	0.215	5.35	$1/2^+$	0.005
5.47*	$7/2^+$	0.347	5.43*	$7/2^+$ [b]	0.169

[a] Excitation energies and spin and parity assignments from literature as summarized in Ref. 10. An asterisk indicates a member of the $K^\Pi = \frac{1}{2}^+$ rotational band and a dagger a member of the $K^\Pi = \frac{1}{2}^-$ rotational band.

[b] Additional spin and parity assignment from present work based on comparison of relative (^{6}Li, ^{3}He) and (^{6}Li, t) transition strengths and known spin of analog. See Fig. 2 for summary of analog identifications.

[c] Transition masked by strong transition to a neighboring state at 4.65 MeV.

It is evident from Fig. 1 that the two spectra are very similar and that both reactions are highly selective. The latter feature makes the identification of mirror states a relatively simple task, independently of the reaction mechanism.

The states most strongly excited by both reactions correspond to either known or suspected members of the $K^\Pi = \frac{1}{2}^+$(g.s.) rotational band[10] —with the exception of the $\frac{7}{2}^+$ state, which is discussed further below. Cross sections are observed to increase with increasing spin and have a maximum value for the $\frac{9}{2}^+$ state and then appear to decrease. For example, the known $\frac{13}{2}^+$ state[11] in ^{19}F at 4.65 MeV has only about $\frac{1}{5}$ the strength of the $\frac{9}{2}^+$ state. The location of the $\frac{13}{2}^+$ state in ^{19}Ne is not known, but comparison of the energy spectra strongly suggests this to be the level at 4.62 MeV.

The lowest known $\frac{7}{2}^+$ state[12] in ^{19}F at an excitation of 4.39 MeV was not strongly populated by the (^{6}Li, ^{3}He) reaction; however, another $\frac{7}{2}^+$ state[13] at 5.47 MeV was strongly populated. From a comparison of the spectra (Fig. 1) a strongly populated state at 5.43 MeV in ^{19}Ne may be identified as the analog of the 5.47-MeV $\frac{7}{2}^+$ state in ^{19}F. A recent intermediate-coupling calculation[14] predicts the $\frac{7}{2}^+$ state lowest in excitation to have little overlap with the $\frac{7}{2}^+$ member of the ground-state band. This same calculation[14] predicts overlaps of >99% with the ground-state band for the lowest $\frac{1}{2}^+$, $\frac{5}{2}^+$, $\frac{9}{2}^+$, and $\frac{13}{2}^+$ states and an overlap of 97.3% for the lowest $\frac{3}{2}^+$ state. It is then likely that it is the second $\frac{7}{2}^+$ state which should be identified with the $\frac{7}{2}^+$ state of the ground-state rotational band. This second $\frac{7}{2}^+$ state, however, is more weakly populated in both reactions than the $\frac{5}{2}^+$ member of the ground-state band. The reduction in transition strengths for the $\frac{7}{2}^+$ and $\frac{13}{2}^+$ states of this band may be the result of Q dependence of the reaction mechanism or of mixing with higher states of the same spin. (This latter explanation would, however, be contrary to the intermediate-coupling-model prediction[14] for the $\frac{13}{2}^+$ state.)

A second group of states moderately populated by these reactions are the members of a $K^\Pi = \frac{1}{2}^-$ rotational band based largely on a configuration of four s-d-shell particles and a p-shell hole.[1,14] Known members of this band in ^{19}F are denoted by a dagger in Table I. The transition strengths again are observed to increase with increasing spin. A comparison of relative excitation strengths between the (^{6}Li, ^{3}He) and

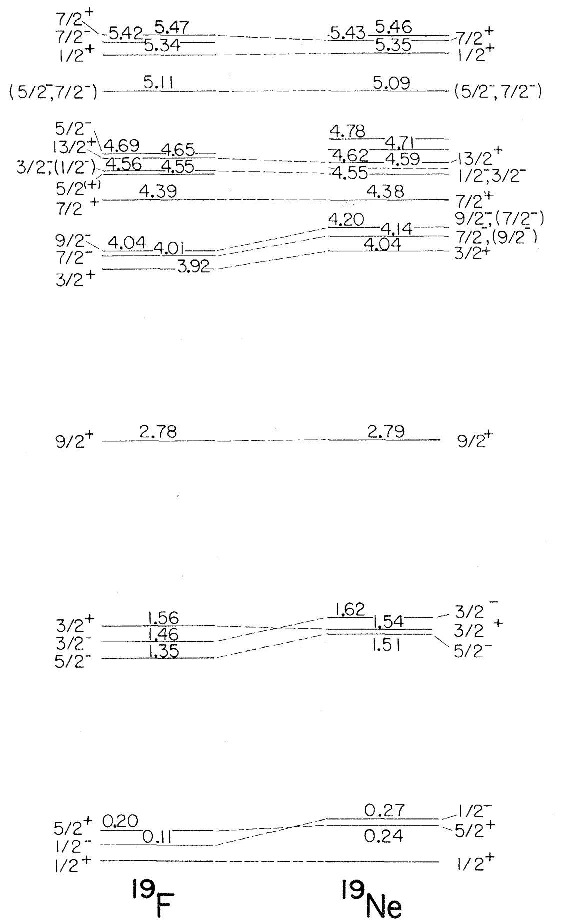

FIG. 2. Energy-level diagram for the experimentally observed states below 5.5 MeV in the mirror nuclei ^{19}F and ^{19}Ne. Isobaric analogs are indicated by the connecting dashed lines. The results are from the literature as summarized in Ref. 10 and the present work. A possible new state at 4.59 MeV in ^{19}Ne (see text) is indicated by a dashed line in the level diagram.

(^{6}Li, t) reactions (Fig. 1 and Table I) is consistent with the suggested[10] negative-parity band in ^{19}Ne and allows the additional spin and parity assignments in ^{19}Ne as summarized in Table I.

The spins and parities of levels of mass 19 below 5.6 MeV are summarized in Fig. 2. Isobaric analog states in the mirror nuclei are indicated by the connecting dashed lines. A "doubtful" state[10,15] at 3.84 MeV in ^{19}Ne was again not observed in the present study. A possible unreported state in ^{19}Ne at 4.59 MeV, however, was observed. Its nearness to a more strongly excited state 30 keV away leaves its identification only tentative, pending further investigation.

The strong selectivity observed in the population of final states (Fig. 1 and Table I) suggests a direct mechanism for the (^{6}Li, ^{3}He) and (^{6}Li, t) reactions. The ground-state rotational bands in ^{19}F and ^{19}Ne would be expected to be populated strongly by such a mechanism, since they are assumed to be based on three $2s$-$1d$-shell particles outside a closed $1s$- and $1p$-shell core (the dominant component of the ^{16}O ground state). In such a model the low-lying negative-parity rotational band in mass 19, 4p-1h (four particle, one-hole), would be excited through 2p-2h and 4p-4h components in the ^{16}O ground state. Such particle-hole configurations are believed[16,17] to be of sufficient magnitude to account for the observed population of the mass-19 negative-parity band in these reactions.

In conclusion it appears that the reactions ^{16}O(^{6}Li, ^{3}He) and ^{16}O(^{6}Li, t) proceed predominantly by means of a direct mechanism. It is further concluded that a comparison of the (^{6}Li, ^{3}He) and (^{6}Li, t) reactions on self-conjugate nuclei represents a powerful tool for determining isobaric analog states in mirror nuclei.

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Upper Limit on High-Energy Neutrinos from Weber Pulses*

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The results from a neutrino experiment deep underground are used to set upper limits on the energy flux of muon neutrinos which might be associated with the gravitational pulses described by Weber.

The results of the solar neutrino experiment of Davis[1] were used by Bahcall and Davis[2] to set an upper limit on the energy in electron neutrinos (ν_e) which could be associated with the Weber gravitational pulses. In this communication, we use the results from our deep underground cosmic-ray neutrino detector[3] to set limits on muon neutrino plus antineutrino ($\nu_\mu+\bar{\nu}_\mu$) which might have such an association. Unlike the radiochemical experiment of Davis, our system enabled us to look for time coincidences between neutrinos and Weber pulses. To a reasonable approximation we can represent the neutrino rate R in our detector by the integral over energy E, as

$$R=\beta\int_E Ef(E)\sigma(E)dE, \tag{1}$$

where $\sigma(E)$ is the interaction cross section, $f(E)$ is the differential neutrino spectrum, and β is a parameter which characterizes the detector geometry and the surrounding rock neutrino target. Since we have no information as to the spectrum of neutrinos which might be associated with Weber pulses, we deduce limits for monoenergetic neutrinos. If we denote R_g as the count rate due to Weber-associated neutrinos of energy E_0, then

$$R_g=(2/\pi)\beta\sigma(E_0)\mathcal{E}, \tag{2}$$

where $\mathcal{E}$ is the energy flux of $\nu_\mu+\bar{\nu}_\mu$ at E_0 and the factor $2/\pi$ arises from the diurnal rotation of the detector relative to the galactic center to which Weber pulses have been attributed. β is obtained by referring to the observed rate of signals from atmospheric cosmic-ray neutrinos,

$$R_a=\beta\int_E Ef_a(E)\sigma(E)dE. \tag{3}$$

Solving for the energy flux ratio,

$$\frac{\mathcal{E}}{\mathcal{E}_g}=\frac{R_g}{R_a}\frac{\pi}{2}\frac{\int_E Ef_a(E)\sigma(E)dE}{\sigma(E_0)\mathcal{E}_g}, \tag{4}$$

where $\mathcal{E}_g=10^5$ ergs cm^{-2} sec^{-1} is the gravitational energy flux attributed to the Weber waves by Gibbons and Hawking[4] and Ruffini and Wheeler.[4] To evaluate (4) we assume that $\sigma(E)=\alpha E$, $f_a(E)=0.6E^{-3}$ ν cm^{-2} sec^{-1} GeV^{-1}, and $E>1$ GeV. The simple expression for $f_a(E)$ gives an integrated atmospheric neutrino flux which is within 20% of the actual value. The result is insensitive as well to the precise value at which $\sigma(E)$ saturates, i.e., a change in saturation energy from 100 to 1000 GeV would imply a change in the limit by at most 30%. Evaluating (4) for a saturation energy of 1000 GeV, we find that

$$\mathcal{E}/\mathcal{E}_g=1.2\times10^{-7}R_g/R_aE_0 \tag{5}$$

where E_0 is in GeV.