BRIEF REPORTS

Brief Reports are short papers which report on completed research or are addenda to papers previously published in the **Physical Review.** *A Brief Report may be no longer than four printed pages and must be accompanied by an abstract.*

Spectroscopy of ^{21}F with the $(\alpha,{}^2$He$)$ reaction

P. von Neumann-Cosel,[1,2] R. Jahn,[1] U. Fister,[1] T. K. Trelle,[1] and B. A. Brown[3]
[1]*Institut für Strahlen- und Kernphysik, Universität Bonn, D-53115 Bonn, Germany*
[2]*Institut für Kernphysik, Technische Hochschule Darmstadt, D-64289 Darmstadt, Germany*
[3]*National Superconducting Cyclotron Laboratory and Department of Astronomy and Physics, Michigan State University, East Lansing, Michigan 48824*

(Received 26 February 1997)

The ^{19}F$(\alpha,{}^2$He$)^{21}$F reaction was investigated at 55 MeV incident energy. The transferred angular momenta of prominent transitions excited were determined from a distorted wave Born analysis of the angular distributions. Tentative spin assignments for the observed levels are extracted from shell-model calculations with the ''unified'' sd-space interaction based on the very good reproduction of the excitation energies and the predicted large two-neutron transfer spectroscopic factors. [S0556-2813(97)02707-6]

PACS number(s): 25.55.Hp, 27.30.+t, 21.60.Cs, 24.10.Ht

Spectroscopic information about the light neutron-rich isotope ^{21}F is very limited [1]. The available data on levels above 2 MeV result mainly from investigations of β decay [2], the $(d,{}^3$He$)$ proton pickup [3], and the (t,p) two-neutron stripping [4] reactions. In particular, there is no definite information on levels with spins $J>5/2$.

The present work reports on a study of the two-neutron (nn) transfer reaction ^{19}F$(\alpha,{}^2$He$)^{21}$F which might be regarded as a counterpart of (t,p). While the former preferentially populates low-spin states and has been extensively used to study the role of pairing in the ground-state (g.s.) wave function, the latter has been shown [5] to selectively excite stretched nn states coupled to maximum spin. The excitation of stretched configurations involving the largest single-particle spins available is a general phenomenon of α-induced two-nucleon transfer [5–13]. This feature is related to the rather negative Q values which favor the population of large angular momentum transfers.

Systematic studies of the $(\alpha,{}^2$He$)$ reaction have been performed for p-, sd-, and fp-shell nuclei [6,9] and for the doubly magic nucleus ^{208}Pb [14]. With the ^{2}He detection technique described in detail in [9] only limited energy resolution can be achieved. However, the well established selectivity of the reaction should result in new spectroscopic information for ^{21}F. For not too high excitation energies one expects transitions resulting from the coupling of neutron $2s_{1/2}$, $1d_{3/2}$, and $1d_{5/2}$ (sd) single-particle configurations coupled to the highest possible spin $J_{\max}$. With the selection rules of the $(\alpha,{}^2$He$)$ reaction [9] excitations are limited to natural-parity states. Thus, transferred angular momenta $L=0,2,4$ are possible in the present case. Because the ground state (g.s.) wave function of ^{19}F is largely a proton $2s_{1/2}$ particle configuration, population of final states in ^{21}F with a $[\pi 2s_{1/2}\nu(sd,sd)_{J_{\max}}]_{J_{\max}\pm 1/2}$ structure is most likely.

The experiment was performed with a 55-MeV α beam from the Bonn isochronous cyclotron. A self-supporting ^{48}CaF$_2$ target was used where the ^{48}Ca component was isotopically enriched to 97%. The effective thickness of the flourine part of 180 μg/cm^2 was determined by normalizing the elastic scattering cross sections to optical model calculations at forward angles. In order to determine absolute cross sections, the total charge for each run was collected in a Faraday cup. Absolute cross sections are estimated to be accurate within $\pm 25\%$.

The unbound reaction product ^{2}He was detected by measuring the two breakup protons in coincidence. The detector consisted of a double ΔE-E telescope with large area position sensitive 300-μm Si ΔE counters and 5-mm Si(Li) E counters. The setup takes advantage of the kinematic focusing induced by the pp final-state interaction. Details of the telescope, the data analysis, and the method of extraction of differential cross sections in the center-of-mass can be found in [9]. The $(\alpha,{}^2$He$)$ data were taken at five angles between 17.5° and 50° in order to kinematically identify states and extract angular distributions. Beam intensities ranged from 70 nA–1 μA, limited by the electronic dead time of the ^{2}He detection system. By setting electronic gates, the position information of the ΔE detector could be utilized to extract simultaneously three angular distribution points for each detector position. Elastic α scattering was measured separately with the telescope described in [12] over a large angular range of $10°-80°$.

A spectrum taken at $\Theta_{\rm lab}=30°$ is displayed in Fig. 1. A typical energy resolution of about 200 keV (full width at half maximum) is achieved. Seven levels belonging to ^{21}F are unambiguously identified up to $E_x\approx 9$ MeV from the two-body kinematics. Their excitation energies are determined with an uncertainty of about 50 keV. At even higher excitation energies reactions induced by carbon contaminations become too large for a meaningful analysis. Transitions induced by the ^{48}Ca component of the CaF$_2$ target are

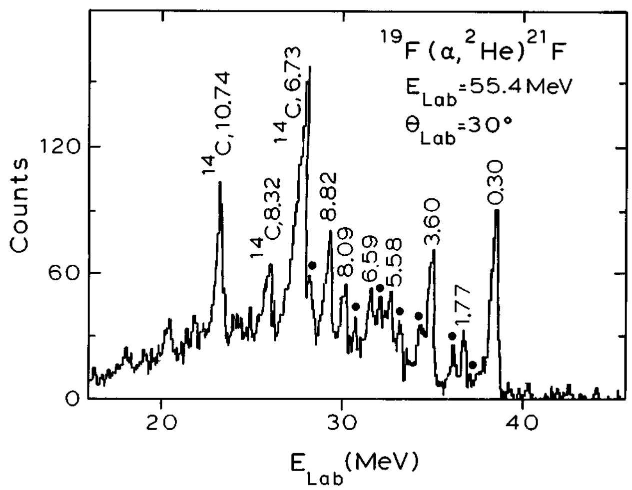

FIG. 1. Spectrum of the ^{19}F(α,^{2}He)^{21}F reaction at $E_{\alpha}=55.4$ MeV and $\Theta_{\mathrm{lab}}=30°$. Transitions marked with a full dot belong to the ^{48}Ca component of the ^{48}CaF$_2$ target.

indicated in the spectrum by full dots. They are well known from a detailed study of the ^{48}Ca(α,^{2}He)^{50}Ca reaction [9].

Because of the different two-body kinematics there is some overlap of transitions from both target components varying with the ^{2}He detection angle. After correction for these underlying background contributions angular distributions were extracted for transitions populating ^{21}F states. These are presented in Fig. 2 and analyzed with zero-range distorted wave Born analysis (DWBA) using the computer code DWUCK4 [15]. A direct stripping process from the incident α particle was assumed where the nn pair is transferred in a relative S state (spin $S=0$ and isospin $T=1$).

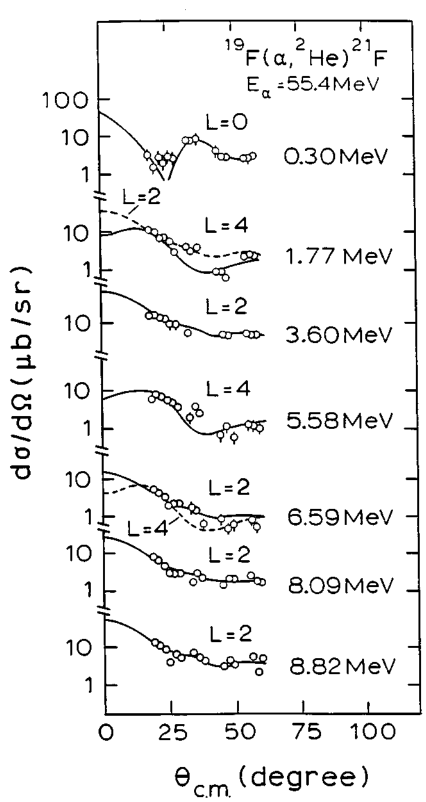

FIG. 2. Angular distributions of transitions to states populated in the ^{19}F(α,^{2}He)^{21}F reaction. The solid and dashed curves are DWBA calculations described in the text.

TABLE I. Optical model potential parameters for the entrance (^{19}F+α) and exit (^{21}F+^{2}He) channels used in the DWBA analysis.

Channel	V (MeV)	r_V (fm)	a_V (fm)	W (MeV)	r_W (fm)	a_W (fm)	r_c (fm)
^{19}F+α	247.2	1.26	0.70	29.2	1.51	0.75	1.3
^{21}F+^{2}He	$93.9-0.35E_{^2\mathrm{He}}$	1.25	0.74	13.0	1.25	0.72	1.3

Optical model parameters for the entrance channel were extracted from an analysis of the simultaneously measured elastic α scattering as described in Refs. [9,12]. The resulting fit parameters assuming a Woods-Saxon shape are given in Table I. The averaged mass-, charge-, and energy-dependent deuteron potential of Hinterberger *et al.* [16] was used for the exit channel (see Table I). Similar to the analysis of the (α,^{2}He) reaction on fp-shell nuclei [9] the real potential depth was increased by 10 MeV in order to account for the smaller effective scattering energy due to the double charge of a ^{2}He system with respect to a deuteron. Such a correction is necessary because of the nonlocality of the optical potential. Bound state wave functions were calculated with a standard Woods-Saxon potential with a radius $R=1.25$ fm, a diffuseness $a=0.65$ fm, and a spin-orbit coupling strength $V_{LS}=6$ MeV. The depths of the potential wells were adjusted to reproduce the binding energies of the neutron single-particle states which were taken from the (d,p) reaction on the neighboring ^{18}O [17].

The calculated angular distributions are displayed in Fig. 2 as solid and dashed lines. For a given L the form exhibits little sensitivity on the assumed binding energy of the single-particle state and on the chosen nn configuration. For example, the $(1d_{5_2})^2$ and $(1d_{5/2},1d_{3/2})$ couplings lead to almost identical shapes for $L=4$ transfer. The data are sensitive enough for most transitions to distinguish between the different possible angular momentum transfer values. The results are summarized in Table II. However, no attempt

TABLE II. DWBA calculations for transitions of the ^{19}F(α,^{2}He)^{21}F reaction, and comparison to other work and shell-model calculations.

Present			Other work [a]		Shell model	
E_x (MeV)	L	J^{π}	E_x (MeV)	J^{π}	E_x (MeV)	J^{π}
0.30	0	$1/2^+$	0.28	$1/2^+$	0.32	$1/2^+$
1.77 [b]	4	$(7/2,9/2)^+$	1.73	$(\geqslant 7/2)$ [c]	1.85	$9/2^+$
	2	$(3/2,5/2)^+$	1.75	$3/2^+$	1.84	$3/2^+$
3.60	2	$(3/2,5/2)^+$			3.68	$5/2^+$
5.58	4	$(7/2,9/2)^+$			5.60	$7/2^+$
6.59	2	$(3/2,5/2)^+$			6.53	$3/2^+$
8.09	2	$(3/2,5/2)^+$				
8.82	2	$(3/2,5/2)^+$				

[a]Reference [1].
[b]Probable doublet.
[c]From Ref. [2].

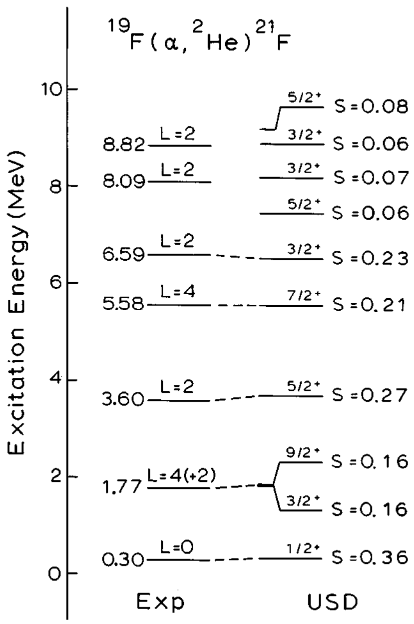

FIG. 3. Comparison of levels excited in the ^{19}F(α,^{2}He)^{21}F reaction with shell-model results using the USD interaction [18]. Only calculated levels with large spectroscopic amplitudes S for dineutron transfer are shown.

was made to compare experiment and DWBA results, which depend upon the assumed single-particle energies, on an absolute scale. It is uncertain whether the single-particle energies of the intermediate nucleus ^{20}F should be taken from the ^{19}O (as assumed here) or from the ^{21}Ne isotone. No data on single-particle energies are available for the latter. One observes rather large structural changes in the isotones of the target nucleus when going from ^{18}O to ^{20}Ne. This is also reflected in the (α,^{2}He) reaction on both nuclei [6].

Further spectroscopic information can be gained from a comparison to shell-model predictions. Calculations for ^{19,21}F allowing the full sd space for the valence particles relative to a ^{16}O core were performed with the "unified" (USD) interaction [18] which is extremely successful in describing a large variety of properties of sd-shell nuclei. Two-nucleon spectroscopic factors S assuming a dineutron cluster transfer with relative angular momentum $l=0$ were extracted from the overlap of the ^{19}F g.s. with final state wave functions in ^{21}F. The spectroscopic factors were calculated in the cluster overlap approximation [19–22]

$$S=G^2\left(\frac{A}{A-k}\right)^{\lambda}|\langle\psi_f|\psi_c\psi_i\rangle|^2, \tag{1}$$

where $k=2$, $\lambda=4$, and $G^2=3/8$ for the dineutron in the sd major shell [22]. Here, ψ_c is a two-neutron cluster wave function in which the internal motion of the two neutrons is in the $1s$ state. It is obtained by diagonalizing an SU(3)-conserving interaction [19,20,23] in the full sd basis. The wave functions and the overlap factors were calculated using the shell-model code OXBASH [24].

Figure 3 displays the shell-model results. For each of the five lowest experimentally observed levels one finds a shell-model state with large S and a total spin consistent with the experimental L transfer. The excitation energies are reproduced within 100 keV. There are two possible candidates for the level at 1.77 MeV, implying either $J^{\pi}=3/2^{+}$ ($L=2$) or $J^{\pi}=9/2^{+}$ ($L=4$). While the experimental angular distribution gives slight preference to $L=4$, an unresolved doublet is also possible. For the two states above 8 MeV, $J^{\pi}=3/2^{+},5/2^{+}$ is likely from experiment, but the correspondence to the calculations is less clear. Possible candidates from the shell-model results are indicated in Fig. 3. While the $J^{\pi}=3/2^{+}$ candidates are found closer to the experimental energies, the predicted two-nucleon spectroscopic factors are comparable for all four calculated levels.

Support for the suggested relation betwen the experimental data and the shell-model results is provided by the absence of well established low-lying ^{21}F levels in the ^{19}F(α,^{2}He) spectra which are either outside the discussed configuration space (negative parity states) or which exhibit small excitation probabilities in the calculations. The transition to the $5/2^{+}$ g.s. in ^{21}F provides a particular example. Excitation of its main configuration $[\pi 1d_{5/2}\nu(sd,sd)_{0^+}]$ is strongly suppressed in direct two-neutron stripping because of the different proton configuration. This is reflected in the calculations by a very small predicted spectroscopic factor $S=0.02$.

It is tempting to extract tentative spin assignments from the shell-model results based on the good correspondence to the experiment (see Table II). For the low-lying 0.30 MeV level the extracted spin $1/2^{+}$ agrees with the findings from other sources [1]. Two known levels could correspond to the 1.77 MeV state within the uncertainty of the experimental energy. One (at 1.730 MeV) has $J^{\pi}=3/2^{+}$ while the spin of the other (at 1.755 MeV) is not established, but should be $J\geqslant 7/2$ from the β-decay properties. Thus, it is quite likely that the level observed in (α,^{2}He) corresponds to a $3/2^{+},9/2^{+}$ doublet. There are several candidates with tentative ($3/2^{+},5/2^{+}$) spin assignments which could be associated with the 3.60 MeV level. However, the limited energy resolution prohibits any further distinction for this and higher-lying states. It must also be noted that more states with large two-neutron transfer amplitudes are predicted than seen in the experiment.

The microscopic predictions allow some insight into the structure underlying the nn transfer. For the experimental levels below 6 MeV dominance of the $(1d_{5/2})^2$ amplitude is found in all cases, but mixing with other allowed couplings is always non-negligible. A complex wave function is found for the $3/2^{+}$ state expected to correspond to the experimental 6.58 MeV level. The largest component in the nn transfer has $(1d_{5/2},2s_{1/2})$, but $(1d_{5/2})^2$, $(1d_{5/2},1d_{3/2})$, and $(1d_{3/2},2s_{1/2})$ must also be taken into account. For the high-lying states above $E_x=8$ MeV the shell-model interpretation differs whether $J^{\pi}=3/2^{+}$ or $5/2^{+}$ is assumed. For the $5/2^{+}$ states, configurations including $1d_{3/2}$ become most important. Assuming $J^{\pi}=3/2^{+}$ all two-neutron amplitudes which can couple to angular momentum $L=2$ contribute with comparable strength.

In summary, excited states in ^{21}F have been identified by means of the nn transfer reaction ^{19}F(α,^{2}He). Because of the selectivity of the reaction and the single-particle nature of the ^{19}F target g.s., levels with a $[\pi 2s_{1/2}\nu(sd,sd)_{J_{\max}}]_{J_{\max}\pm 1/2}$ three-particle structure are preferentially populated. The transferred angular momenta were identified from an analysis of the angular distributions with DWBA calculations. Levels with spins $J > 5/2$ could be uniquely identified for the first time in ^{21}F. A shell-model calculation of spectroscopic two-neutron transfer amplitudes provides tentative spin assignments. For the two lowest observed transitions comparison with other experimental information is possible, and good agreement is found.

This work has been supported by the German Minister of Education, Research and Technology (BMBF) and for B.A.B. by NSF Grant No. PHY 94-03666.

---

[1] P. M. Endt, Nucl. Phys. **A521**, 1 (1990).
[2] D. E. Alburger, C. J. Lister, J. W. Olness, and D. J. Millener, Phys. Rev. C **23**, 2217 (1981).
[3] G. Mairle, L. K. Pao, G. J. Wagner, K. T. Knöpfle, and H. Riedesel, Z. Phys. A **301**, 157 (1981).
[4] P. Horvat, Nucl. Phys. **A52**, 410 (1964).
[5] R. Jahn, G. J. Wozniak, D. P. Stahel, and J. Cerny, Phys. Rev. Lett. **37**, 812 (1976).
[6] R. Jahn, D. P. Stahel, G. J. Wozniak, R. J. de Meijer, and J. Cerny, Phys. Rev. C **18**, 9 (1978).
[7] J. van Driel, R. Kamermans, and R. J. de Meijer, Nucl. Phys. **A350**, 109 (1980).
[8] R. Jahn, U. Wienands, D. Wenzel, and P. von Neumann-Cosel, Phys. Lett. **150B**, 331 (1985).
[9] U. Fister, R. Jahn, P. von Neumann-Cosel, P. Schenk, T. K. Trelle, D. Wenzel, and U. Wienands, Phys. Rev. C **42**, 2375 (1990).
[10] C. C. Lu, M. S. Zisman, and B. G. Harvey, Phys. Rev. **186**, 1086 (1969).
[11] R. M. DelVechhio, R. T. Kouzes, and R. Sherr, Nucl. Phys. **A265**, 200 (1976).
[12] U. Fister, R. Jahn, P. von Neumann-Cosel, P. Schenk, T. K. Trelle, D. Wenzel, and U. Wienands, Nucl. Phys. **A569**, 421 (1994).
[13] P. von Neumann-Cosel, U. Fister, R. Jahn, P. Schenk, T. K. Trelle, D. Wenzel, and U. Wienands, Nucl. Phys. **A569**, 441 (1994).
[14] P. von Neumann-Cosel, P. Schenk, U. Fister, T. K. Trelle, and R. Jahn, Phys. Rev. C **47**, 1027 (1993).
[15] P. D. Kunz, program DWUCK4 (unpublished).
[16] F. Hinterberger, G. Mairle, H. Schmidt-Rohr, G. J. Wagner, and P. Turek, Nucl. Phys. **A111**, 265 (1968).
[17] F. Ajzenberg-Selove, Nucl. Phys. **A300**, 1 (1978).
[18] B. A. Brown and B. H. Wildenthal, Annu. Rev. Nucl. Part. Sci. **38**, 29 (1988).
[19] W. Chung, J. van Hiemen, B. H. Wildenthal, and C. L. Bennett, Phys. Lett. **79B**, 381 (1978).
[20] J. B. McGrory, Phys. Lett. **47B**, 481 (1973).
[21] M. Ichimura, A. Arima, E. C. Halbert, and T. Terasawa, Nucl. Phys. **A204**, 225 (1973).
[22] N. Anyas-Weiss, J. Cornell, P. S. Fisher, P. N. Hudson, A. Menchaka-Rocha, D. J. Millener, A. D. Panagiotou, D. K. Scott, D. Strottman, D. M. Brink, B. Buck, and T. Engeland, Phys. Rep. **12C**, 201 (1974).
[23] M. Harvey, Adv. Nucl. Phys. **1**, 67 (1968).
[24] W. D. M. Rae, A. Etchegoyen, and B. A. Brown, OXBASH, The Oxford-Buenos Aires-MSU shell-model code, Michigan State University Cyclotron Laboratory Report No. 524.