THE STUDY OF $^{14}N(\alpha, d)^{16}O$ REACTION AT 21 MeV

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(Received January 12, 1974; Revised version received April 25, 1974)

Angular distributions of deuterons from the $^{14}N(\alpha, d)^{16}O$ reaction were measured. The analysis was made in terms of two-nucleon stripping DWBA theory using shell model wave functions of initial and final nuclei.

1. Introduction

The level scheme of the ^{16}O nucleus has been extensively investigated by many different methods [1]. This nucleus is interesting from different points of view: as a doubly closed-shell nucleus, as a so-called α-nucleus, and also because of the existence of low-lying collective states appearing at the same energy as spherical states. Zuker, Buck, and McGrory [2] have given the unified, microscopic description of the energy spectrum of ^{16}O in the frame of an exact shell model calculation. They have calculated the wave function with a spherical basis of $1p_{1/2}$, $1d_{5/2}$ and $2s_{1/2}$ orbitals. An experimental test for those wave functions is provided by different transfer reactions.

In the present work ^{16}O has been studied by the $^{14}N(\alpha, d)^{16}O$ reaction measured at 21 MeV incident energy. This reaction has been studied at Berkeley, first at 48 MeV [3], with an energy resolution of about 250 keV, and then at 40 MeV [4] with a resolution of 60 keV. The most recent work on this subject is that of Lowe et al. [5] done at 30 MeV. The ground state Q-value of the $^{14}N(\alpha, d)$ ^{16}O reaction is 3.111 MeV.

2. Experimental procedure and results

The Saclay F. N. model tandem Van de Graaff accelerator provided the 21 MeV alpha beam. The target used was made of melamine ($N_6H_6C_3$), containing 30 μg/cm^2 of ^{14}N, evaporated on a 10 μg/cm^2 carbon foil. Particle detection was performed with two solid state counter telescopes (ΔE = 65 μm, E = 2 mm thick) cooled to $-30°C$ by means

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of the Peltier effect thermocouple, and protected against electrons emitted from the target with a transversal 500 Gauss magnetic field. One of these two telescopes was kept at a fixed angle ($0_{lab} = 130^\circ$) and used as a monitor. An analog particle identifier [6] circuit fed with the E and ΔE pulses delivered a signal proportional to log (MZ^2) allowing particle

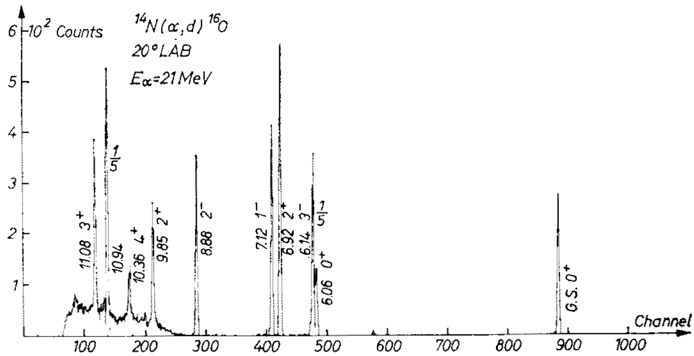
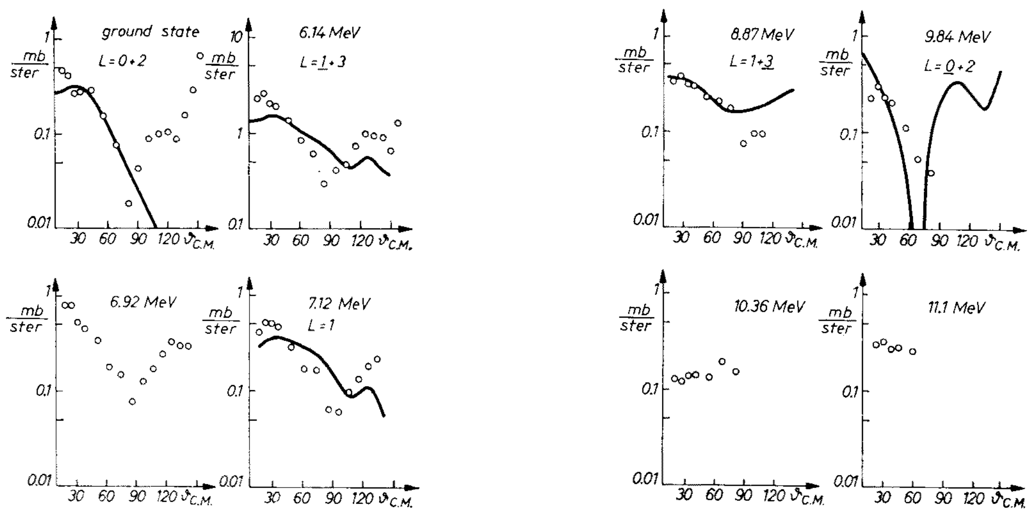


Fig. 1. Spectrum of the $^{14}N(\alpha, d)\,^{16}O$ reaction obtained at an angle of 20° for a beam energy of 21 MeV



a b

Fig. 2. Angular distributions of deuterons from $^{14}N(\alpha, d)\,^{16}O$ reaction. The curves are distorted-wave calculations

selection through digital windows. All particle energy spectra were recorded simultaneously in a 4096 channel analyzer and then fed into a CAE 510 computer for further processing and stored on an IBM compatible magnetic type. Overall energy resolution ranged from 30 to 60 keV depending on the detection angle. The angular distribution of α particles elastically scattered on ^{14}N was also measured over the range 20°–90° (C. M.), and used for absolute normalization of cross sections by comparison with previously published data [7].

An energy spectrum of deuterons from the $^{14}N(\alpha, d)^{16}O$ reaction taken at $\theta_{lab} = 20°$ is shown in Fig. 1. The peaks can be related to the known states [1] of ^{16}O up to 11 MeV excitation energy. The peak corresponding to the 10.94 state contains a large admixture of deuterons from the $^{12}C(\alpha, d)^{14}N$ ground state transition. The weakly excited 6.05 MeV state could be separated from the large 6.13 MeV peak only at forward and backward angles where the energy resolution was the best. At these angles its intensity is only about 1/15 of that of the 6.13 MeV.

The angular distributions of deuterons corresponding to formation of the all observed levels have been obtained and are displayed in Figs 2a and 2b.

3. *Analysis*

As the ^{14}N nucleus has almost pure $(1p_{1/2})^2$ configuration (0p–0h relative to ^{16}O), direct (α, d) reaction ought to populate selectively the ^{16}O states having configurations 0p–0h, 1p–1h, and 2p–2h. The transition to more complicated states is forbidden in a direct two-nucleon transfer because their excitation involves the rearrangement of the $(1p_{1/2})^2$ state of the target. In this light, the strong excitation of 6.92 MeV level, belonging to the rotational band with 4p–4h predominant configuration, may be a hint that, besides the direct two-nucleon transfer, some more complicated process contributes to the reaction. Other members of this band (6.06 MeV and 10.36 MeV) are weakly excited.

It seems, however, that the compound nucleus contribution is small because of the complicated structure and deep minima in the angular distributions.

We have tried the analysis of the angular distributions in the frame of the two-nucleon stripping theory. We have applied the theory given by Glendenning and described in Ref. [8]. The notation from this reference is adapted in the present paper.

The DWBA two-nucleon stripping cross section may be written in the form

$$\frac{d\sigma}{d\Omega} \sim \frac{K_2}{K_1} \frac{2J_z+1}{2J_i+1} \sum_{LSJT} C_{ST}^2 \sum_M \left| \sum_N G_{NLSJT} B_{NL}^M(\vec{K}_1, \vec{K}_2) \right|^2 ,$$

where K_1 and K_2 are incoming and outgoing momenta.

B_{NL}^M are the amplitudes for transferring a pair of nucleons whose center of mass motion is characterized by the quantum numbers N, L, M. Their coherent contributions to the reaction cross-section are weighed by the structure factors G_{NLSJT}.

G_{NLSJT} contain nuclear structure information in the form of the overlap integrals. One of them is the parantage factor connecting the final nucleus with the ground state of target plus two nucleons in the states $|n_1 l_1\rangle$ and $|n_2 l_2\rangle$ coupled to LSJ. In calculations we have used the wave functions of target ^{14}N and final nucleus ^{16}O calculated, as it was mentioned above, by Zuker, Buck, and McGrory [2].

The amplitudes B_{NL}^M can be calculated with any appropriate DWBA computer code, only one has to introduce as a "form factor" the radial wave functions of the center of mass of the transferred pair of nucleons:

$$\sum_N G_{NLSJ} u_{NL}(R).$$

To compute the form factors we have used the code written on the basis of the Glendenning model by Laget [9]. They have been introduced to the DWBA code JULIE [10].

As a preliminary to the DWBA analysis the measured elastic scattering of α particles on ^{14}N differential cross section was fitted to find the optical model parameters. We employed the automatic search code MAGALI [11] using as starting values the parameters published in a survey of McFadden and Sachler [12]. The final potential obtained was very close to that of Sachler's.

The deuteron potentials were extrapolated from the published analysis of deuteron elastic scattering by ^{16}O [14]. The sets of potential parameters are given in Table I.

TABLE I

Optical model parameters used in DWBA analysis of the $^{14}N(\alpha, d)\,^{16}O$ reaction

$$V(r) = -Vf(x) - i\left(W - 4W_D \frac{d}{dx'}\right) f(x') + V_{so} \frac{\hbar^2}{(m_\pi c)^2} r^{-1} \frac{df(x)}{dr} (\vec{L} \cdot \vec{s})$$

$$f(x) = (1+e^x)^{-1},$$

$$x = (r - r_{r0} A^{\frac{1}{3}})/a_r, \quad x' = (r - r_{0i} A^{\frac{1}{3}})/a_i.$$

	E	V	r	r	W	W	r	a	V
ALPHA	21.00	54	1.747	0.565	7.22	0	1.69	0.565	0
DEUTERON	14.87	110	0.97	0.80	0	6.7	1.53	0.70	7.57
	7.96	119	0.94	0.80	0	5.7	1.61	0.70	7.57
	7.00	112	0.93	0.80	0	5.5	1.62	0.70	7.57
	4.90	127	0.91	0.80	0	5.2	1.66	0.70	7.57
	3.80	133	0.89	0.80	0	4.9	1.70	0.70	7.57

$r_{0c} = 1.3$, $r_{so} = r_{0r}$, $a_{so} = a_r$. Units are MeV and fm. In addition a Coulomb potential for a uniform spherical charge distribution of radius $r_{0c}A^{\frac{1}{3}}$ was employed.

Some curves calculated from potentials given in Table I are shown in Figs. 2a and 2b as full lines. It can be seen that the calculations yielded bad fits, especially in the ground state transition case. We have also tried other optical potentials, such as the alpha-particle potential with real part depth of about 200 MeV, or the volume type imaginary potential for deuterons taken from Ref. [13], etc. However, in either case we were not able to reproduce correctly the shapes of the angular distributions. An even more serious problem arose with the normalization. We could not find an overall normalization factor for the calculated distributions and the experimental points. Changes in configuration mixing of the wave functions did not improve the agreement.

Looking for a reason of such a bad fit we realized that it lays in too low incident energy. In fact, elastic scattering of strongly absorbed particles exhibits different anomalies which simple optical model cannot account for. In the case of $\alpha + {}^{14}N$ elastic scattering studied in the energy range 20–23 MeV [7] one observed backward angle enhancement. The most pronounced effect was at 20 MeV and it decreased with energy. It means that the optical model is not sufficient for a description of $\alpha+{}^{14}N$ channel, and one should use l-dependent optical model [15] or resonance description [16].

Another reason for such a bad fit is probably the angular momentum mismatch. It is known [17] that only few partial waves having the reflection coefficients η_L about 1/2 are determined by elastic scattering for strongly absorbed particles. DWBA tend to predict transfer reaction well if the same partial waves give the most important overlap in the stripping integrals. As an example we have checked the case of the transition to 6.13 MeV level, and we have found very important contribution to the cross section from the integrals constructed with partial waves strongly absorbed in α channel. It means that there is a significant contribution from nuclear interior and it may be a reason for the failure of our DWBA calculation. Similar difficulties arose for ${}^{14}N({}^{3}He, p)\,{}^{16}O$ reaction (also deuteron transfer on ${}^{14}N$). In the case of this reaction the angular momentum matching conditions are easier to be fulfilled. However, the author [18] was not able to fit the angular distributions at 7.7 MeV incident energy, while at 18 MeV the fits were good.

Unfortunately, in our case, the measurement at higher energy was not possible as 21 MeV of α particles is very near the highest energy available with tandem accelerator in Saclay.

The authors would like to thank Dr A. Zuker for helpful discussions and for some additional calculations done for us. We are also grateful to Dr J. Laget for use of his two-nucleon transfer formfactor program. One of us (I. M. T.) wishes to aknowledge the hospitality of DPhN/BE — CEN — Saclay.

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