^{60}Ni(n,d) REACTION AT 18.5 MeV

B. MARIANSKI, A. STONERT, A. KORMAN, J. RONDIO

AND

T. CZYZEWSKI

Soltan Institute For Nuclear Studies
Hoża 69, 00-681 Warsaw, Poland

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Deuteron spectra from the ^{60}Ni$(n,d)^{59}$Co reaction has been measured at the reaction angles 0°–70° with an eight-telescope setup. Angular distribution for transitions to the ground state and to groups of excited states were obtained. Distorted wave Born approximation analysis of the angular distributions gives spectroscopic factors of 5.8, 0.71, 3.37, 0.9, 7.4 for the ground and excited states, respectively.

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1. Introduction

Studies of proton pickup via (n,d) reactions are rather sparse, particularly on medium mass nuclei. The direct (n,d) reactions are most often characterized by a pick up of a proton, so they are useful in studying proton hole states. Nickel isotopes have closed proton $1f_{7/2}$ shell and few neutrons outside the $1f_{7/2}$ neutron orbit. Low lying states in Co isotopes excited in proton pickup reaction can be described in terms of a proton hole coupled to the corresponding even mass Ni nuclei [1]. Proton hole states in ^{59}Co have been investigated by the (t,α) and $(d,^3\mathrm{He})$ reactions at projectile energies of 50 and 60 MeV respectively [2, 3]. They indicate that proton is picked up mainly from $1f_{7/2}$, $2s_{1/2}$, $1d_{3/2}$ shell model states. Recently, proton hole states in ^{59}Co have been investigated by ^{60}Ni$(\vec{d},^3\mathrm{He})^{59}$Co reaction using vector polarized deuterons [4]. The use of polarized deuterons allowed a good determination of spectroscopic factors.

Studies of proton hole states by an (n,d) reaction have some advantages over other proton pick-up reactions such as $(d,^3\mathrm{He})$ or (t,α). Neutron

and deuteron optical model potentials and finite range corrections in (n, d) reactions are better understood than those for relatively more complex particles. The spectroscopic factors derived from the ^{27}Al(d,^{3}He) data show an energy dependance which is possibly connected with the uncertainties in the optical potential parameters for complex particles [5]. On the other hand poor energy resolution and greater experimental difficulties are the disadvantages of the (n, d) reaction.

Until now deuterons only at one angle of 14° from the ^{60}Ni(n,d)^{59}Co reaction have been measured by Colli *et al.* [6] at 14.1 MeV neutron energy. On the basis of this measurement spectroscopic factor for the transition to the ground state has been determined.

In this paper we report on results of the ^{60}Ni$(n, d)^{59}$Co reaction investigated at 18.5 MeV neutron energy.

2. Experimental details

The experimental equipment and procedure used in this work have been described in our earlier paper [7]. The eight-telescope setup makes it possible to measure simultaneously eight spectra at eight different angles. A two dimensional analysis is employed to identify the charged particles emitted in the reaction. Deuteron spectra were measured simultaneously with proton spectra. Neutrons of an average energy of 18.5 MeV were produced in the $T(d, n)^4$He reaction, the deuterons being accelerated to 2.3 MeV in the Van de Graaff accelerator. The neutron energy spread was about ±150 keV. The target used was ^{60}Ni (enriched to 93%) electrolytically deposited on a 1 mm tantalum backing. The dimensions of the target were 12×15 mm^2 and its thickness was about 20 mg/cm^2.

3. Data analysis

Deuteron spectra were measured for eight angles from 0° to 70° in 10° steps. Figure 1 shows spectra obtained at three angles 10°, 20°, 30°. The peak corresponding to the transition to the ground state is clearly seen but the transitions to higher excited states are not resolved because the energy resolution is about 0.7 MeV. Angular distributions were obtained for the ground state transition and for the groups of deuterons in the excitation energy range from about 1.0 to 2.3 MeV (group B) and 2.3 to 3.5 MeV (group C). The absolute normalization of the cross section was performed against the (n, p) differential cross section for recoiled protons [8].

We analyse these distributions in the frame of the Distorted Wave Born Approximation (DWBA). Calculations were performed with the code

DWUCK4 [9]. Optical model potential was of the form:

$$V(r) = -V_0 f(r, r_R, a_R) - iW_0 f(r, r_w, a_w) + i4W_d \frac{d}{dr} f(r, r_d, a_d) + V_{s0} \frac{1}{r} \frac{d}{dr} f(r, r_{s0}, a_{s0}) LS + V_c(r),$$

where the Woods–Saxon form-factor of the potential well is given by the formula:

$$f(r, r_i, a_i) = \left(1 + \exp \frac{(r - r_i A^{1/3})}{a_i}\right)^{-1}.$$

The Coulomb potential V_c is approximated by the potential due to a uniformly charged sphere of radius $r_c A^{1/3}$. Parameters used in the calculation are derived from the global parameter sets [10, 11]. They are shown in Table I.

TABLE I

Optical model parameters for the ^{60}Ni$(n,d)^{59}$Co reaction.

	V_0 (MeV)	r_R (fm)	a_R (fm)	W_0 (MeV)	r_w (fm)	a_w (fm)
n	46.81	1.198	0.663	2.73	1.295	0.59
d	106.39	1.050	0.860			
p		1.250	0.650			

	W_d (MeV)	r_d (fm)	a_d (fm)	V_{s0} (MeV)	r_{s0} (fm)	a_{s0} (fm)	r_c (fm)
n	6.01	1.295	0.590	6.20	1.01	0.75	
d	14.38	1.430	0.697	0.75	0.75	0.50	1.3
p							1.3

Well depths were adjusted to give appropriate binding energies. These calculations were performed in the local energy approximation (LEA) which includes corrections both for nonlocality of the potential and for finite range effects. The finite range parameter was 0.667. The parameters to minimize the effects of nonlocality of the potential were set at their usual values of β =0.85 for neutrons and β =0.54 for deuterons [12]. Least squares fits to the experimental cross sections were obtained by minimizing the expression:

$$\chi^2 = \frac{1}{N} \sum \frac{[NC^2 S \sigma(\theta_i)_{DWBA} - \sigma(\theta_i)_{exp}]^2}{(\Delta\sigma(\theta_i))^2_{exp}}.$$

The spectroscopic factors have been extracted by comparison of experimental and theoretical cross sections via the relation:

$$\sigma(\theta) = \frac{3}{2} D_0^2 (C^2 S) \sigma(\theta)_{DWBA},$$

where the value of the overlap integral D_0^2 was taken to be 1.55 from the calculation which included the effect of the d-state admixture in the wave function [11]. The quantity C^2S, where $\langle C \rangle = \langle T_i T_f \frac{1}{2} t_z | T_i T_i z \rangle$, is the isospin Clebsch–Gordon coefficient with T_i and T_f being the isospins of the initial and final nuclei, is the spectroscopic factor.

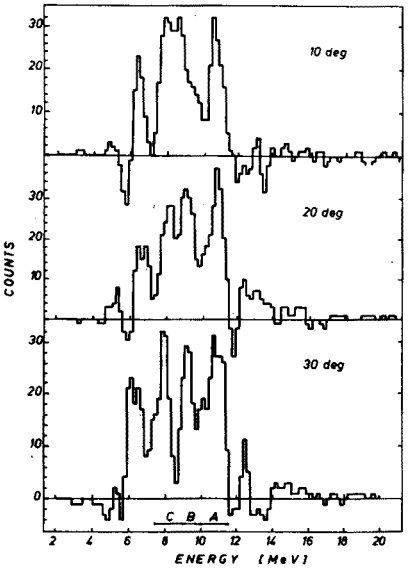

Fig. 1. Deuteron spectra from the ^{60}Ni$(n,d)^{59}$Co reaction obtained at 10, 20, 30 degrees. Peak "A" corresponds to the transition to the ground state.

The ground state peak in the deuteron spectrum (Fig. 1) corresponds to a residual nucleus spin of $J = 7/2^-$. It means that the transition proceeds by a proton pick-up from the $1f_{7/2}$ shell model orbital in ^{60}Ni and implies $l = 3$ transfer. The angular distribution for this transition together with DWBA fits is shown in Fig. 2. Energy resolution of the detector is about 0.7 MeV, so it is probable that "ground state" peak contains some contribution from the transition to the first excited state at 1.093 MeV which proceeds through the pick of a proton in the ^{60}Ni $1p_{3/2}$ orbital. Taking into account this contribution we get a better fit to the experimental points (see Fig. 2). The spectroscopic factors obtained from this fit are $(C^2S)_{l=3} = 5.8 \pm 0.7$ and $(C^2S)_{l=1} = 0.32 \pm 0.09$. The spectroscopic factor is $(C^2S)_{l=3} = 6.9 \pm 1.9$ when the $l = 1$ contribution is neglected and experimental points are fitted with the $l = 3$ angular distribution only. The angular distribution for the second group of deuterons "B" is shown in Fig. 3. We assumed that the most probable transitions in this excitation energy range are to those four states at energies 1.093, 1.291, 1.783 and 2.058 MeV. These states are strongly

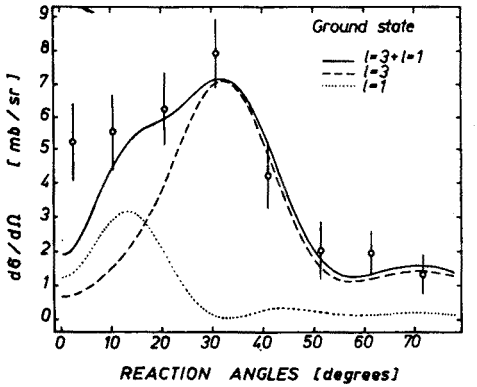

Fig. 2. Angular distribution of deuterons corresponding to the ^{59}Co ground state. The dashed curves represent the distributions for $l = 1$ and $l = 3$ transfer; the solid line represents the summed DWBA fit to the data.

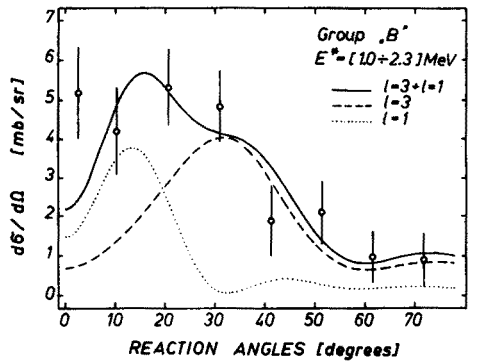

Fig. 3. Angular distribution of deuterons corresponding to the transitions to the 1.093 $(3/2^-)$, 1.293 $(3/2^-)$, 1.783 $(7/2-)$ and 2.058$(7/2^-)$ states in ^{59}Co. The dashed curves represent the distributions for $l = 1$ and $l = 3$ transfer; the solid line represents the summed DWBA fit to the data.

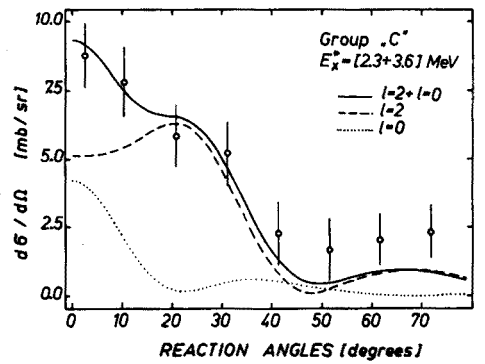

Fig. 4. Angular distribution of deuterons corresponding to transitions to the 2.72(1/2) and 3.16(3/2) states in ^{59}Co. The dashed curves represent the distributions for $l = 0$ and $l = 2$ transfer; the solid line represents the summed DWBA fit to the data.

excited in $(d,^3\mathrm{He})$ and (t,α) reactions which also proceed via a proton pick-up. They have the spins $3/2^-$, $3/2^-$, $7/2^-$, $7/2^-$ respectively, which implies an $l=1$ and $l=3$ transfer. The fitted sum of $l=1$ and $l=3$ distributions is shown in Fig. 3. Spectroscopic factors obtained from this analysis are $(C^2S)_{l=1}=0.39\pm0.20$, $(C^2S)_{l=3}=3.37\pm0.65$. The angular distribution for the third group is shown in Fig. 4 together with the fitted sum of $l=0$ and $l=2$ distribution. We assumed that the dominant transitions should be those to the states at energies 2.72 and 3.16 MeV which have the spins 1/2, 3/2 respectively, what implies $l=0$ and $l=2$ transfers. These states are also excited in (d,^{3}He) and (t,α) reactions. Determined, in this work, spectroscopic factors are $(C^2S)_{l=0}=0.90\pm0.66$ and $(C^2S)_{l=2}=7.4\pm3.8$. The errors in the spectroscopic factors are calculated, taking into account a 10 to 15% experimental error and a 25% error on the Bassel normalization factor.

4. Results and discussion

The spectroscopic factors determined in the present work are shown in Table II and compared with those from previous (n,d), $(d,^3\mathrm{He})$, (t,α) measurements and theoretical calculations. We see that the spectroscopic factor obtained for the $l=3$ transition to the ^{59}Co ground state is in a very good agreement with previous measurements and with model calculations. Exception is the value obtained with polarized deuterons, which is a little bit lower.

TABLE II

Comparison of spectroscopic factors

				C^2S Experimental					Theoretical	
E_x(MeV)	J^π	l	Present work	a (n,d)	b $(d,^3\mathrm{He})$	c $(d,^3\mathrm{He})$	d (t,α)	e $(\vec{d},^3\mathrm{He})$	f	g
0.0	$7/2^-$	3	5.8 ±1.90	5.15	6.38	5.50	6.60	4.38	5.04	5.34
1.09+1.29	$3/2^-$	1	0.71±0.50		0.24	0.51	0.36	0.25		0.44
1.72+2.05	$7/2^-$	3	3.37±1.16		2.29	1.63	1.81	1.24	2.04	
2.72	1/2	0	0.9 ±0.66		1.47		1.66	1.48		
3.16	3/2	2	7.4 ±3.80		2.87		2.39	2.61		

a — Ref. [6], b — Ref. [3], c — Ref. [2], d — Ref. [2], e — Ref. [5] (Values of (C^2S) shown in the table are not renormalized, contrary to data presented in Ref. [5], which were renormalized $(C^2S\times0.87)$), f — Ref. [13], g — Ref. [14].

The calculations of the spectroscopic factors for the proton pickup from ^{60}Ni have been performed in the framework of the unified model [13] and

unified vibrational model including anharmonic and quasiparticle effects [14]. It is assumed that the low energy neutron excitation is described in terms of quadrupole vibrations, and only individual particle excitations are due to the protons outside a closed shell. The structure of the low-lying states of negative parity is described as a mixture of $1f_{7/2}^{-2}2p_{3/2}$, $1f_{7/2}^{-2}1f_{5/2}$, $1f_{7/2}^{-2}2p_{1/2}$ proton configurations coupled to collective quadrupole harmonic surface oscillation. From Table II we see that both models give good results for transitions to the ^{59}Co ground state.

The summed spectroscopic factor for $l = 3$ transitions to 1.72 and 2.05 MeV states is also in a reasonable agreement with the (t,α) measurements of Blair *et al.* [2] and $(d,{}^3\mathrm{He})$ data of Mairle *et al.* [3, 4], in view of uncertainties contained in the data and calculations.

The spectroscopic factor for the $l = 1$ transition is a sum of the $l = 1$ strength extracted from the fit to the angular distribution of group "A" (ground state peak) and $l = 1$ strength obtained from the fit to the group "B" of the proton spectrum. The spectroscopic factor obtained in this way for l=1 transition is in agreement with those obtained in $(d,{}^3\mathrm{He})$ reaction (Ref. 3) and is almost twice as big as obtained by other measurements although still within large error bars.

The states at excitation energies of 2.72 and 3.16 MeV can be formed by a coupling of a positive parity configuration $1d_{3/2}^{-1}$, $2s_{1/2}^{-1}$, $1d_{5/2}^{-1}$ to collective quadrupole vibrations [14]. Determined spectroscopic factors for transitions $l = 0$ and $l = 2$ to 2.72 and 3.16 MeV states are smaller and bigger, respectively, then those determined in $(d,{}^3\mathrm{He})$ and (t,α) reaction. From table II we see that our spectroscopic factors for excited states are rather systematically bigger then those obtained in $(d^3\mathrm{He})$, (t,α) reaction at higher projectile energies. This suggests that at our relatively low neutron energy other reaction mechanism (compound reaction mechanism) has some contribution to the reaction cross section.

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