STRUCTURE OF THE LOW LYING LEVELS OF THE ^{33}S NUCLEUS INVESTIGATED BY THE ^{32}S(d, p)^{33}S REACTION

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An investigation of the ^{32}S(d, p)^{33}S reaction was made at a deuteron bombarding energy of 12.3 MeV. The energy spectra were measured by magnetic analysis and the obtained angular distributions were compared with the predictions of DWBA, using the deuteron optical model parameters obtained from an analysis of the elastic scattering of deuterons on ^{32}S nuclei. The absolute values of spectroscopic factors, extracted on this basis, indicate a significant contribution of higher configurations in the ground state wave function of the ^{32}S nucleus. There are no arguments which permit the identification of the observed states of the ^{33}S nucleus as rotational states.

Introduction

The nucleon transfer reactions have been proved to be a valuable tool for the study of the level structure of the nucleus. Because of the favored transitions to the single particle states we obtain some insight into the details of the wave function as well as the character of the intrinsic interaction in the nucleus.

We have studied the ^{32}S(d,p)^{33}S reaction, performing measurements of differential cross-sections for several proton groups and deriving the absolute values of spectroscopic factors. As the experimental data concerning the ^{33}S nucleus are rather scarce, little is known about the structure of its excited states. Considerable interest arises in the $1/2^+$ (0.84 MeV) state, which appears to be strongly populated in the deuteron stripping reaction, although such a transition is forbidden from the pure shell model point of view. Only a short note [1] has been published concerning the ^{32}S(d, p)^{33}S reaction performed at a deuteron energy larger than 10 MeV and analysed by the DWBA method. Relative values of spectroscopic factors obtained in that work show considerable deviations from those summarized in nuclear tables [2]. The other studies of this reaction were carried out at very low energies and are confined only to the measurements of spectra [3] or to the measurements of angular distributions without determining the absolute values of the cross-section [4, 5, 6].

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Experimental procedure

The measurements were carried out using the 120 cm cyclotron of the Institute of Nuclear Physics in Cracow. A well collimated deuteron beam bombarded the sulphur target placed in the centre of the scattering chamber. Charged reaction products were analysed by means of a broad range magnetic spectrograph and detected in nuclear emulsions.

The thin sulphur target was prepared from spectroscopically pure element by evaporating it on a thin gold backing. To make the target more resistant to heating, the sulphur surface was covered by a thin layer of evaporated gold. The natural sulphur which was used for the target preparation contained 95.06 per cent of ^{32}S, 0.74 per cent of ^{33}S, and 4.18 per cent of ^{34}S isotopes. The thickness of the sulphur layer in the target, determined from measured weight and area, was 1.28 mg/cm^2, and the enclosing gold layers had a total thickness of 0.60 mg/cm^2. During the measurements the thickness of the target was checked continuously by means of a semiconductor detector viewing the target at a fixed scattering angle. It was found that the target thickness diminished in the course of measurement by 18 per cent.

The total charge of deuterons passing through the target was collected in a Faraday cup placed behind the target and measured by a beam integrator.

The energy of the beam was measured by means of a differential method using Al foils as absorber. It was estimated to be 12.3 ± 0.15 MeV.

The final energy resolution of the system observed in the spectra of charged particles was about 250 keV.

Angular distributions of charged particles were measured in 5 degree steps ranging from 50 to 120 degrees (lab.) for elastically scattered deuterons and from 20 to 120 degrees (lab.) for protons from the (d, p) reaction. The inaccuracy in the angle setting was estimated to be 0.2 degree.

Experimental results and analysis of the data

Two energy spectra of protons obtained at angles of $\theta_{lab} = 30$ and $\theta_{lab} = 60$ degrees are shown as examples in Figs 1 and 2. Angular distributions of protons were measured for transitions leading to the ground, 0.84, 2.94 and 3.22 MeV states of the ^{33}S nucleus. The group of protons belonging to the 2.94 MeV state of the ^{33}S nucleus also contains two unresolved groups of protons belonging to the 2.87 and 2.97 MeV transitions. From the high resolution measurement of the spectrum of protons from this reaction, made by Endt *et al.* [3], it is known that these levels are weakly excited. The poorly resolved proton groups corresponding to the 2.94 and 3.22 MeV transitions were decomposed by means of a computer programme which fitted curves of Gaussian shape [7] to the experimental spectrum.

The total error of the absolute value of the cross-section was estimated to be 20 per cent. This value includes the statistical error, the error arising from measurements of the charge and the target thickness and that appearing in scanning reproducibility.

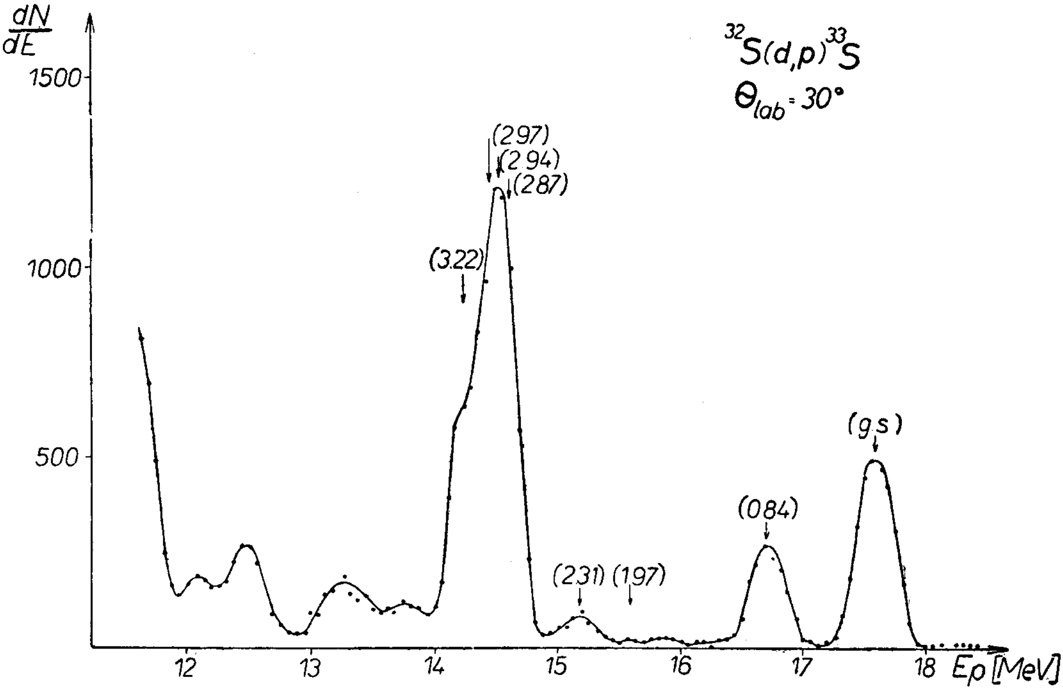

Fig. 1. Energy spectrum of protons from the $^{32}S(d, p)^{33}S$ reaction obtained at an angle of 30 degrees

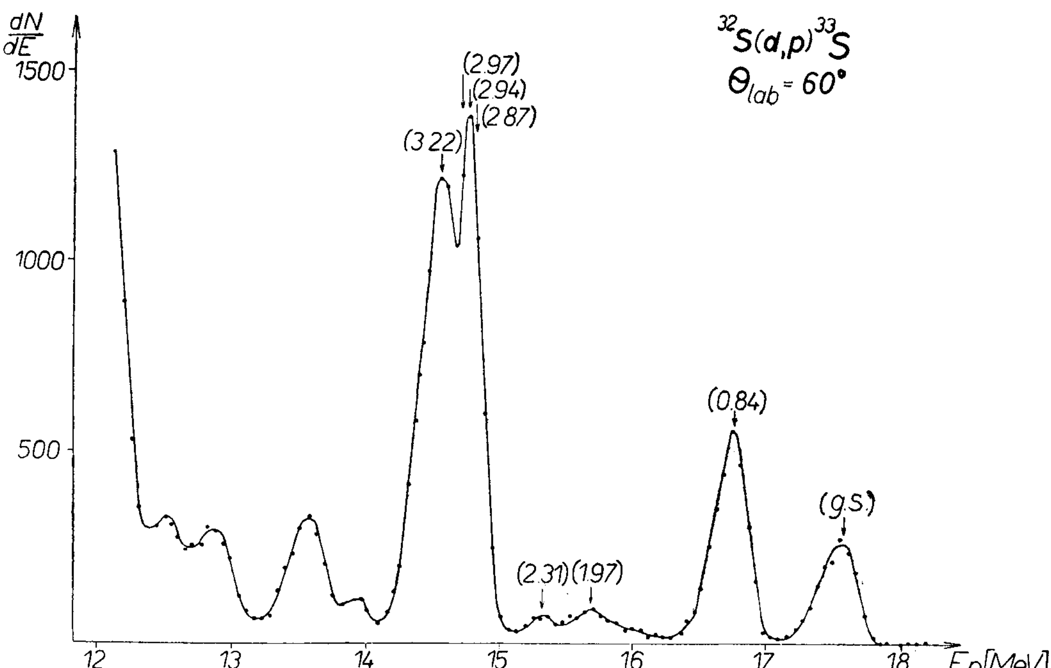

Fig. 2. Energy spectrum of protons from the $^{32}S(d, p)^{33}S$ reaction obtained at an angle of 60 degrees

The angular distributions of deuterons scattered elastically on sulphur nuclei were also measured at the same time as the angular distributions of protons. The angular distributions for the elastic scattering were analysed by means of the optical model using an interaction potential of the form

$$V(r) = V_c(r) + U \cdot f_u(r) + 4iW \frac{df_w(r)}{dr}$$

where $V_c(r)$ is the Coulomb potential taken to be that of a uniformly charged sphere of radius $R_c = r_c \cdot A^{1/3}$, U and W are the real and imaginary depths of the optical potentials, and $f_u(r)$ and $f_w(r)$ are Saxon-Woods form-factors with half value radii $r_u \cdot A^{1/3}$ and $r_w \cdot A^{1/3}$

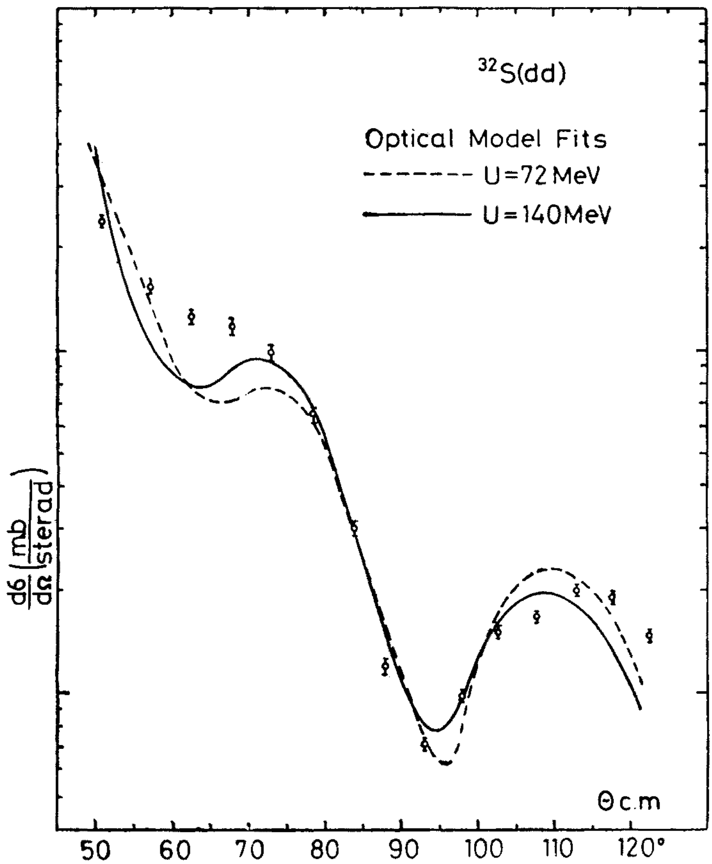

Fig. 3. Angular distributions for elastically scattered deuterons. The curves represent the optical model fits with two sets of deuteron optical model parameters

and diffusenesses a_u and a_w for the real and imaginary parts of the potentials, respectively. The analysis was carried out using the ALA-1 automatic search routine written for the GIER computer [8]. Angular distributions of the elastically scattered deuterons fitted

TABLE I

U (MeV)	$4W$ (MeV)	r_u (fm)	r_w (fm)	a_u (fm)	a_w (fm)
		deuteron parameters			
72.54	98.18	1.405	1.497	0.738	0.499
140.27	102.20	1.179	1.410	0.779	0.627
		proton parameters			
45–47	32.80	1.250	1.250	0.650	0.470

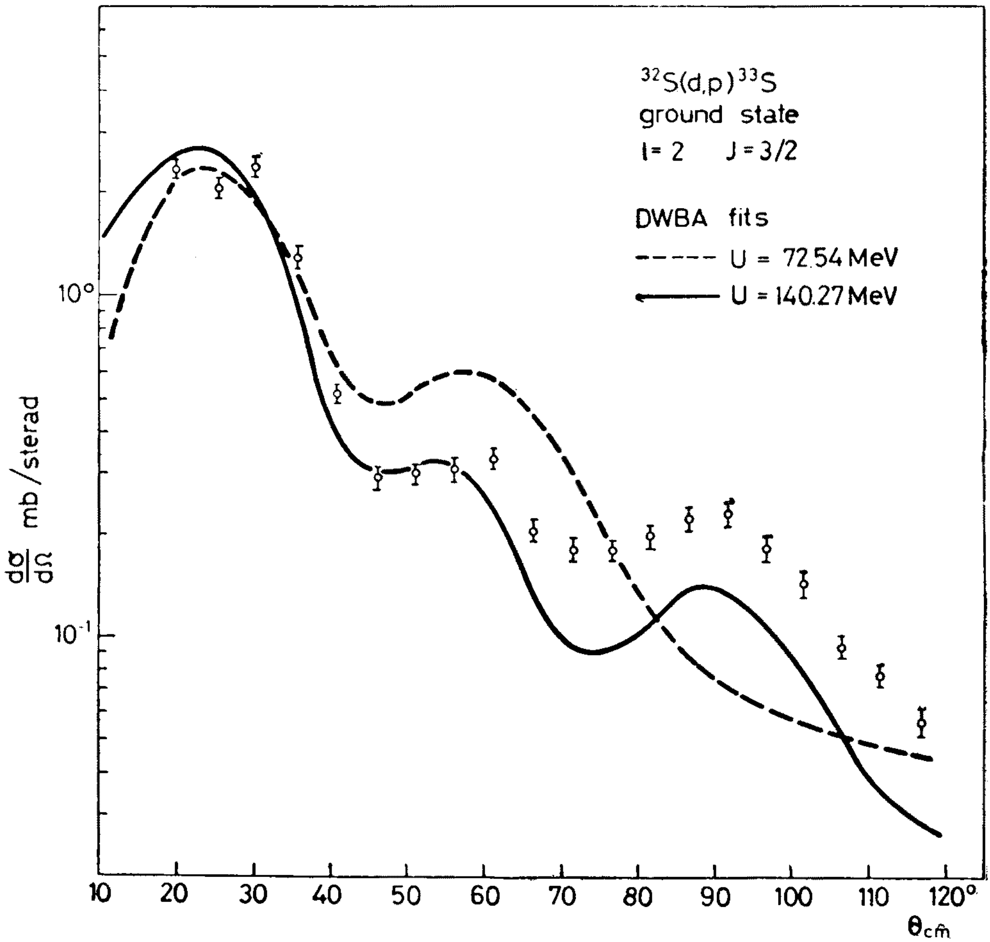

Fig. 4. Angular distributions for the ground state transition in the ^{32}S(d, p)^{33}S reaction. The curves represent the DWBA calculations with two sets of optical model parameters

with this programme are shown in Fig. 3. Two sets of optical model parameters for deuterons found in our analysis are listed in Table I, together with the optical model parameters for protons taken from Perey's work [9].

These parameters were then used for the DWBA calculations performed by means of the GAP-2 programme [10] on the GIER computer. The results of measurements and calculations of the angular distributions of protons from the $^{32}S(d, p)\,^{33}S$ reactions are presented in Figs 4, 5, and 6.

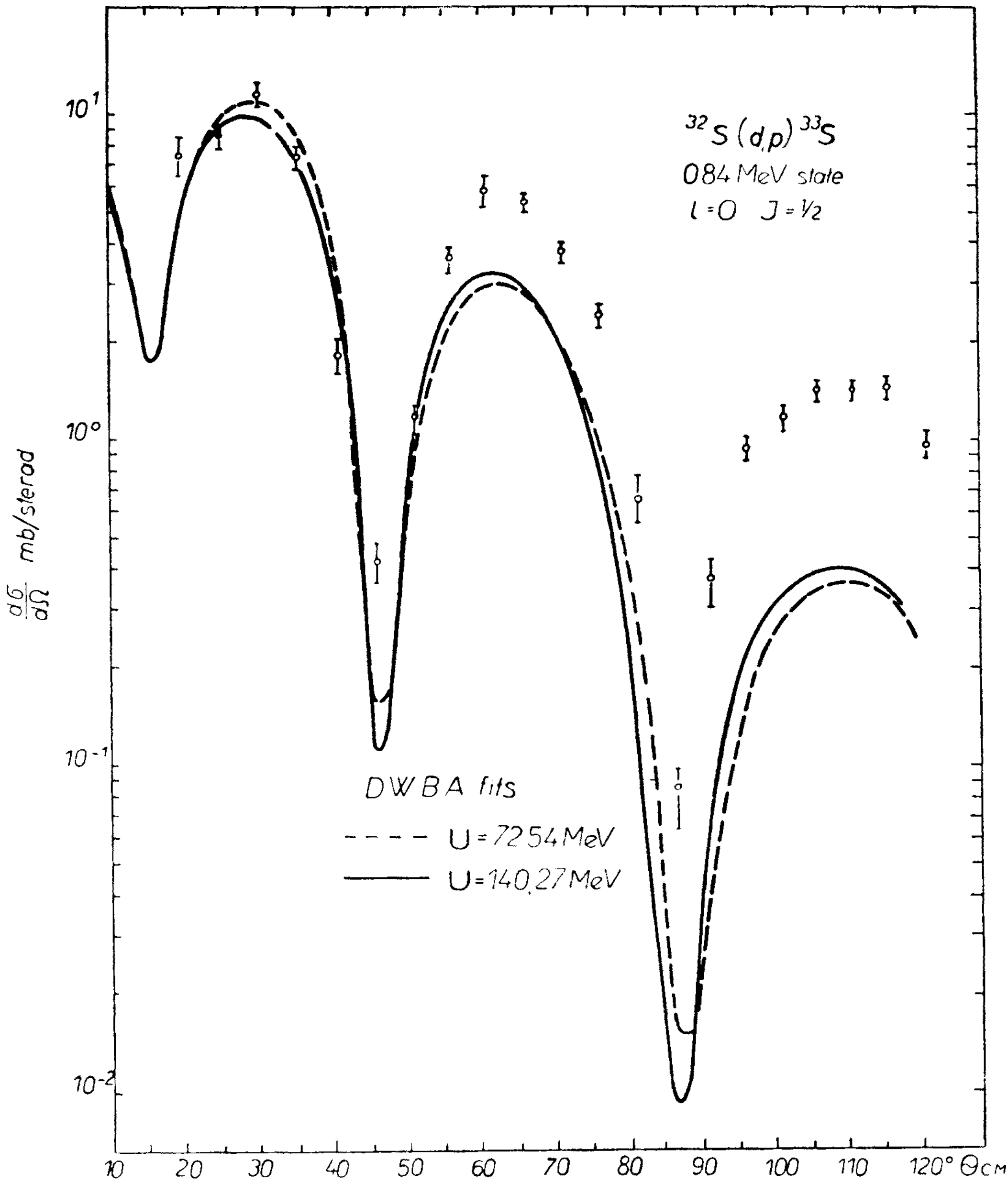

Fig. 5. Angular distributions for the 0.84 MeV state transition in the $^{32}S(d, p)^{33}S$ reaction. The curves represent DWBA calculations with two sets of optical model parameters

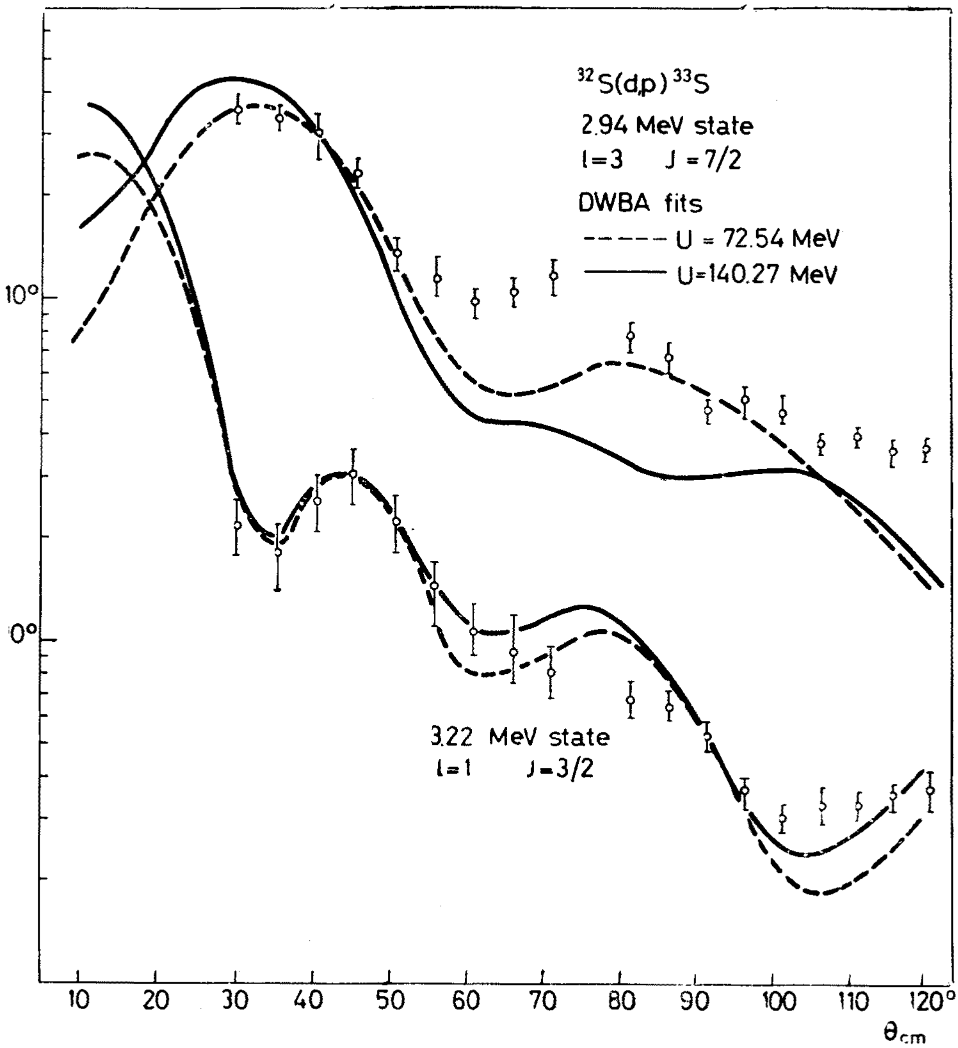

Fig. 6. Angular distributions for the 2.94 MeV and 3.22 MeV state transitions in the ^{32}S(d, p)^{33}S reaction. The curves represent the DWBA calculations with two sets of deuteron optical model parameters

Absolute values of spectroscopic factors S_{lj} were extracted from the differential cross-sections using the relation

$$\sum_{\text{I peak}} \left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} = 1.5 \frac{2J_f+1}{2J_i+1} S_{lj} \sum_{\text{I peak}} \sigma_{lj}(\theta)_{\text{DWBA}}.$$

As is apparent from Fig. 4, the group of deuteron parameters with $U = 140.27$ MeV gives a better overall agreement with the experimental data. Also the values of spectroscopic factors found with the use of these parameters are more acceptable than those found with

TABLE II

States of ^{33}S nucleus (MeV)	J^{π}	l values	Absolute values of S_{lj}		Relative values of S_{lj} taken from nuclear tables [2]	Calculated values of S_{lj}
			present work	Ref. [1]		
0	$\frac{3}{2}^+$	2	0.81	0.69	1.00	0.82
0.84	$\frac{1}{2}^+$	0	0.80	0.27	0.60	0.24
1.97	$\frac{5}{2}^+$	2	weak	—	0.067	0.0004
2.31	$\frac{3}{2}^+$	2	weak	0.05	0.20	0.013
2.87		2	—	—	0.30–0.20	—
2.94	$\frac{7}{2}^-$	3	0.49	0.63	1.00	1.00
2.97						
3.22	$\frac{3}{2}^-$	1	1.26	0.33	2.2	1.00

the use of the other group. The values of spectroscopic factors found in the present experiment using the parameters with $U = 140.27$ MeV are listed in Table II.

For comparison, the values of spectroscopic factors found by other authors are also listed in the same Table.

Discussion

According to the simple shell model with jj-coupling, the target ^{32}S nucleus has doubly closed $1d_{5/2}$ and $2s_{1/2}$ subshells and the neutron transferred in the (d, p) reaction should populate predominantly the $1d_{3/2}$, $1f_{7/2}$, $2p_{3/2}$, and higher single particle states. The results obtained in the study of the ^{32}S(d, p) reaction and presented in Table II indicate that the $3/2^+$ (ground), the $7/2^-$(2.94 MeV), and the $3/2^-$(3.22 MeV) states of ^{33}S have a single particle character. The absolute values of spectroscopic factors of the transitions to the ground and 3.22 MeV states are close to unity. The diminished value of the spectroscopic factor of the transition to the $7/2^-$(2.94 MeV) state indicates an admixture of more than one configuration to the transition strength.

The absolute values of spectroscopic factors found in our experiment are somewhat different from those communicated by the authors of Ref. [1]. The most pronounced differences appear in the cases of the 0.84 and 3.22 MeV transitions.

In order to explain the strong transition to the $1/2^+$ (0.84 MeV) state, it is necessary to assume a considerable admixture of higher configurations in the ground state wave function of the ^{32}S nucleus. We consider the closed $d_{5/2}$(^{28}Si) core and four outer nucleons — two neutrons and two protons — disposed on the $2s_{1/2}$ and $1d_{3/2}$ shells. The wave function of the ground state of the ^{32}S nucleus may thus be expressed in the following way:

$$\Psi(^{32}\mathrm{S})_{T=0\ J=0} = a_1 s_{1/2}^4(00) + a_2 s_{1/2}^2(10) d_{3/2}^2(10) + a_3 s_{1/2}^2(01) d_{3/2}^2(01) + \\ + a_4 s_{1/2}^1(\tfrac{1}{2}\,\tfrac{1}{2}) d_{3/2}^3(\tfrac{1}{2}\,\tfrac{1}{2}) + a_5 d_{3/2}^4(00).$$

All components, except the first, on the right hand side are expected to contribute in the formation of the $1/2^+$(0.84 MeV) and higher states as the $5/2^+$(1.97 MeV) and $3/2^+$(2.31 MeV) states of the ^{33}S nucleus.

Similarly, the wave functions of the states of ^{33}S can be expressed in terms of pure configurations. If we denote the coefficients of this expansion by b_i, the spectroscopic factor of the transition to a given state characterized by l and j may be expressed in terms of partial spectroscopic amplitudes $g_{ij}(l)$ [14].

$$S_{ij} = [\sum_{ij} a_i b_j \sqrt{n_j}\, g_{ij}(l)]^2$$

where n_j is the number of nucleons in the residual nucleus, equivalent to the transferred nucleon. The partial spectroscopic amplitudes $g_{ij}(l)$ in our case are products of fractional parentage coefficients and recoupling Racah coefficients. Using the wave functions obtained by the authors of Ref. [11], the spectroscopic factors for the transitions which were of interest to us were calculated and compared with those extracted from experiment. The experimental and calculated values of spectroscopic factors are presented in Table II. With the exception of the serious inconsistency for the case of the $1/2^+$ (0.84 MeV) transition, the agreement is satisfactory. This indicates that the shell model with mixed configurations may be applied to the description of the states of the ^{32}S and ^{33}S nuclei.

An attempt was made to apply the strong coupling rotational model for the analysis of the spectroscopic factors. Following the suggestions of Bishop [12] and Cox [13], one can assume that the ground state transition is the capture of the neutron to the Nilsson orbit No. 8 ($K = 3/2$) and the first excited state transition is the capture of the neutron to the Nilsson orbit No. 9 ($K = 1/2$) which is formed by the hole state in the target nucleus. In such a case the spectroscopic factors found according to Satchler's formula [16] on assumption of the deformation parameter $\eta = -2$, were an order of magnitude smaller than the experimental values. The $5/2^+$ (1.97 MeV) and $3/2^+$ (2.31 MeV) states can be considered as higher members of the rotational bands built on the intrinsic states with $K = 3/2$ and $K = 1/2$, respectively. Such transitions in the ^{32}S(d, p) ^{33}S reaction are fairly strongly inhibited because the zero value of the spin of the target nucleus makes the Clebsch Gordan coefficients in Satchler's formula equal zero and, consequently, the spectroscopic factors vanish.

The conclusion that the strong coupling rotational model is not applicable to the level structure of the ^{33}S nucleus formed in the stripping reaction on the ^{32}S nucleus is consistent with the results of our previous work [15] on the ^{32}S(d, ^{3}He) ^{31}P reaction. In our treatment the effects of multiple excitation in the entrance and exit channels were not taken into account.

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