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Magnetic Analysis Study of Energy Levels of S^{33}

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The energy of protons from the reaction S^{32} (*d,p*) S^{33} has been analyzed magnetically. A total of 21 proton groups have been observed corresponding to the ground state and 20 excited levels of S^{33}. The region of excitation energies up to 9.2 mev was investigated. Besides 12 already known levels 8 new ones have been found in the region of high excitation.

THE nuclide S^{32} which has a natural abundance of 95% has a number of peculiarities. It is an even-even nucleus and has an equal number of protons and neutrons. According to the shell model it has a closed shell configuration and so its shape must be very closely spherical and it should have zero spin and even parity. One can surmise that the excitation probability of such nuclei is smaller than that of odd asymmetric nuclei. In a S^{32} (*d,p*) S^{33} reaction which yields information on S^{33} , one would expect at low excitation energies to reach mostly ''one particle'' states, i.e., such configurations where just the last odd particle is excited, leaving the core in essentially the ground state of S^{32}.

In view of the small yield of the above reaction, the spectrum of the levels of S^{33} is insufficiently known. The review article by Endt and Kluyver[1] gives data from three papers which report studies of the reaction S^{32} (*d,p*) S^{33} in several regions of excitation energy.

In 1941 Smith and Pollard[2] found 6 proton groups corresponding to the ground state and 5 excited states of S^{33}. They used 3.1 mev deuterons. Davison[3] studied the same reaction in 1949 with greater intensity and resolution and reported 13 proton groups, one for the ground state and 12 for excited states of S^{33}. The last paper as of the time of the writing of the present paper seems to be the paper by Holt and Marsham.[4] They used a deuteron energy of 8 mev and so could reach a large range of excitation energies. However, according to the authors, the accuracy and the resolution in this work were inferior to those of Davison. Of their 13 proton groups only 6 can be said to be well established. These are listed in Ref. 1 and are due to levels of S^{33} at the following energies: 0.85, 2.90, 3.26, 4.21, 4.89, and 5.72 mev. The other levels which they found are less trustworthy. Holt and Marsham did not determine the energy of the S^{32} (*d,p*) S^{33} reaction but used the *Q*-value as given by Strait et al.[5]

For some of the proton gruups Holt and Marsham determined the angular distributions. Therefore they could give probable spins and parities of the compound states in addition to the energy. A compilation of the data on S^{33} in the literature is given in Table 1.

In all cited investigations the proton energy was determined by absorption in calibrated Al foils. Clearly this method does not allow high accuracy and resolution. In the present work the energy of the reaction products was measured by means of a magnetic spectrometer which allows a better determination of the energy of the excited states. The method used was described earlier.[6,7,8] In short it consists of a combined plate-and sample-holder (Fig. 1). A sample of the material to be studied is placed at *A*. It is irradiated with a collimated beam of deuterons of an energy up to 4.7 mev. The holder is placed in a magnetic field perpendicular to the plane of the drawing. The charged particles which are emitted in a nuclear reaction are bent by the magnetic field and fall on a thin emulsion plate after passing through a narrow slit at *B*. Discrete proton groups show up as lines C_1, C_2, . . . parallel to the slit. By determining the location of a line and knowing the magnetic field strength *H* one can obtain the energy of a particular particle group if its e/m is known. Thus one can determine the excitation energy of the corresponding level of the nucleus under investigation. On top of the plate there was located a filter of variable thickness. It covered the plate fully lengthwise but only half of the plate across. Its thickness increased along the plate in such a way as to absorb fully deuterons and particles of still shorter range but to transmit protons. The use of this modified wedge-filter[9] allowed us to separate the proton groups originating in the (*d,p*) reaction from all other charged particles.

The high intensity of the available deuteron beam allowed us to obtain exposures which showed visually observable lines on the plates.

TABLE 1.

Excited levels of S^{33}, energies in mev

·Level	Results of the present work	Results of other authors: Smith and Pollard	Davison	Holt and Marsham
0	0	0	0	0
1	0,78$_6$	1.05	0,79	0,85
2	1,86$_9$	—	1,90	1,86
3	2,22$_8$	2,17	2,17	2.28
4	2,95$_6$	—	2,85	2,90
5	3,32$_9$	3.22	3,15	3,26
6	4,02$_3$	—	3.88	3.91
7	4.27$_9$	4.33	4,15	4.21
—	—	—	4,42	—
8	4,77$_0$	—	4,70	4.89
9	5,04$_3$	—	5.11	—
10	5,46$_8$	5,32	5,63	5,72
11	5,90	—	—	—
12	6,10$_2$	—	—	—
13	6,62$_2$	—	6.30	6,48
14	6,91$_6$	—	—	—
15	7,22$_5$	—	—	—
16	7,45$_2$	—	—	7.44
—	—	—	—	7,83
17	8,04$_7$	—	—	—
18	8,28$_9$	—	—	—
19	8,85$_8$	—	—	—
20	9,11$_8$	—	—	—

Therefore the counting of tracks under the microscope could be replaced by an analysis with a microphotometer. The high concentration of tracks necessary to obtain visual lines insured a very high statistical accuracy in the observation of particle groups.

The sample consisted of a thin layer of finely ground ZnS powder on a silver foil. As in the quoted earlier papers the results were interpreted as being due to the isotope S^{32} only. An investigation of the level schemes of Mg, Si and other elements has shown that under the conditions of the present work the influence of reactions from the low abundance isotopes on the results is unimportant. This seems to be borne out also by the comparison of our results on the spectrum of S^{33} with the data in the literature.

Figure 2 is a reproduction of one of the plates with a spectrum from sulfur. The microphotogram of this plate is shown in Fig. 3. The upper curve has been obtained from the uncovered portion of the plate, i.e., it gives the spectrum of all charged particles emerging from the sample under bombardment with deuterons. The lower curve is the microphotogram of the filtered part of the plate and contains the spectrum of protons only. The unfiltered curve shows prominently deuterons scattered from the nuclei of Ag, Zn, and S, making up the target. The energy of the primary deuterons was obtained from these groups. These intense peaks

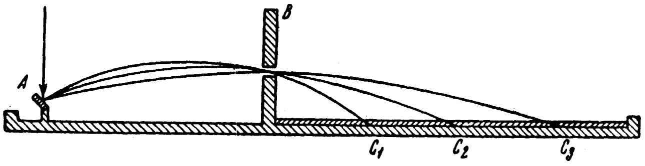

FIG. 1. Schematic diagram of the plateholder.

FIG. 2. Energy spectrum of the nucleus of S^{33}.

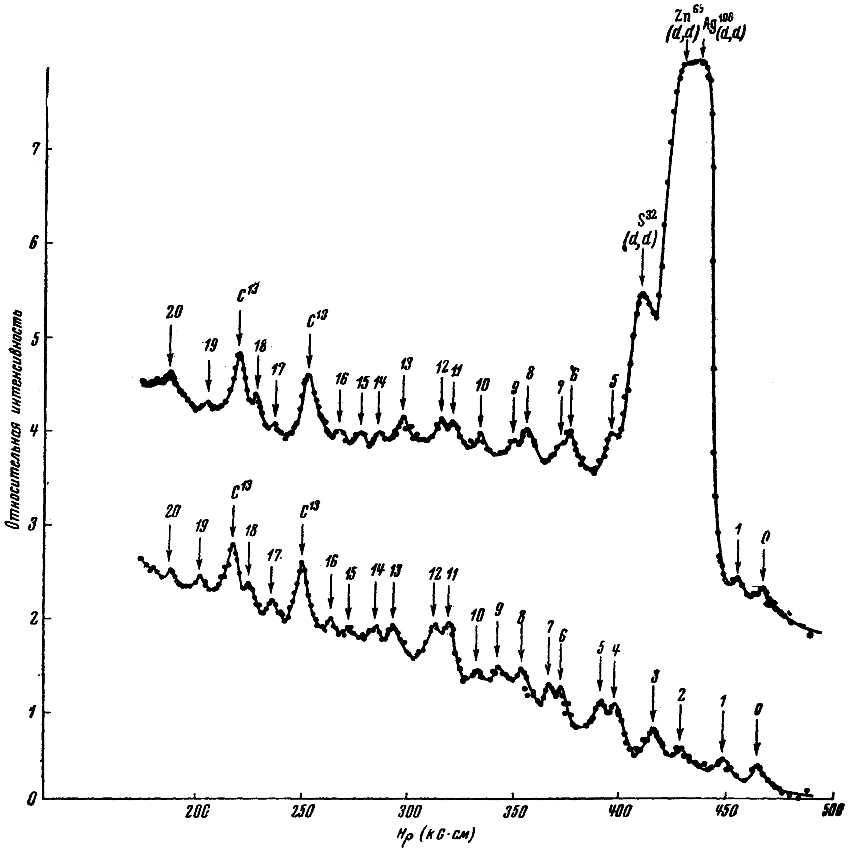

FIG. 3. Microphotogram of a plate showing the energy spectrum of S^{33}. The proton groups corresponding to states in S^{33} are marked by number only. The numbers correspond to those of Table 1. The remaining groups are identified by the reaction. The deuteron energy $E_d = 4.68$ mev. The lower curve is obtained from the filtered part, the upper from the unfiltered part of the plate.

are completely absent in the lower curve of Fig. 3 Besides the deuteron groups the curves show a large number of proton groups. These come from the (d,p) reaction on sulfur, numbered from 0 to 20, and from carbon contaminants.

A total of 5 plates were exposed. A control experiment with a PbS sample showed that the obtained proton groups did not originate in a (d,p) reaction on Zn. The data given in Table 1 are averages from all 5 plates. In order to check on the correctness of the interpretation of the proton groups, 2 primary deuteron energies were used: 3 plates were obtained at a deuteron energy of about 4.7 mev, 2 at about 3.8 mev.

In the present experiment a Q-value for the reaction S^{32} (d,p) S^{33} has been obtained:

$Q_0 = 6.633 \pm 0.020$ mev; Smith and Pollard give $Q_0 = 6.62$ mev, Davison gives $Q_0 = 6.48 \pm 0.11$ mev, Strait et al. give $Q = 6.422 \pm 0.011$ mev.

The analysis of the results, as summarized in Table 1 shows that from the 23 proton groups found in the present work only 2 are due to the reaction $C^{12}(d,p)C^{13}$. All the other groups are due to the (d,p) reaction on sulfur. A comparison with the data of the other workers confirms the identity of almost all levels observed earlier, except for the level of S^{33} at E=4.42 mev. This level was found only by Davison and is absent in the present work as well as in the other cited papers. We do not believe that the identity of this level is sufficiently well established.

The excitation energies of the levels at 3.32_9, 5.46_8, and 6.62_2 mev as obtained in the present study differ considerably from those obtained by the earlier workers. This difference is larger than the experimental errors. In the present experiments they were for the majority of the levels on the order of 20 kev; in a few cases where the corresponding peaks were not too pronounced they reached up to 40 kev.

We found (besides the already published levels of S^{33}) eight new ones; these are the levels 11, 12, 14, 15, 17, 18, 19, 20 of Table 1. The level at 7.83 mev found by Davison was hidden in our work by a rather strong proton group from the reaction $C^{12}(d,p)C^{13}$. Another proton group from the carbon reaction masked the energy region corresponding to an excitation energy of around 8.5 mev, between the levels 18 and 19.

It is also interesting to compare the level scheme of S^{33} as obtained from the (d,p) reaction with the data from γ-spectroscopy. The thermal neutron capture γ-rays obtained by Kinsey, Bartholomew and Walker[10] are listed in Table 2. The γ-rays C,D,E,F,G,H,I,M,O are sufficiently close in energy to the excitation energies of the levels 16, 15, 13, 11, 10, 9, 8, 5 and 4 respectively of Table 1 to suppose that they represent the ground state transitions from the respective levels of S^{33}.

TABLE. 2.

Thermal neutron capture γ-rays in sulfur[10]

Level	γ-ray energy in mev	Level	γ-ray energy in mev	Level	γ-ray energy in mev
A	8.64 ± 0,02	*F*	5,97 ± 0,06	*K*	4,38 ± 0,03
B	7,78 ± 0.03	*G*	5,43 ± 0.02	*L*	3,69 ± 0,05
C	7,42 ± 0.03	*H*	5.03 ± 0,06	*M*	3.36 ± 0.05
D	7,19 ± 0.03	*I*	4,84 ± 0,06	*N*	3,21 ± 0,03
E	6,64 ± 0,03	*J*	4.60 ± 0,06	*O*	2.94 ± 0.05

The γ-rays B,J,K,L and N maybe associated with transitions from the highest level to the levels corresponding to the groups 1, 6, 7, 9, and 10 respectively of Table 1. This interpretation is at variance with the level scheme proposed in Ref.10 on the basis of their results and the data of Davison. It therefore needs further confirmation.

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