PROTON CAPTURE REACTION ON THE ATOMIC NUCLEI Na^{23}, Mg^{26}, Al^{27} *AND* P^{31}

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The following nuclear reactions were investigated: $Na^{23}(p, \gamma)Mg^{24}$ for E_p = 250 keV, $Mg^{26}(p, \gamma)Al^{27}$ for E_p = 292 keV, $Al^{27}(p, \alpha_0)Mg^{24}$ for E_p = 224 keV, and $P^{31}(p, \alpha_0)Si^{28}$ for E_p = 355 keV. Conclusions concerning the levels and their decay schemes are drawn on the basis of the measured γ spectra. It is deduced from the angular distribution of the radiations that the spin and parity of the 11.933-MeV level in Mg^{24} is 2^+ or 3^+ and the spin and parity of the 8.554-MeV level in Al^{27} is $1/2^{\pm}$ or $3/2^{+}$.

KNOWLEDGE of the nuclear structure in the 1d 2s shell is of interest from the point of view of the study of collective effects. The purpose of our investigation was to obtain further data relative to the structure and decay of Mg^{24}, Al^{27}, Si^{28}, and S^{32} following capture of low-energy protons [1].

1. EXPERIMENTAL METHOD

The proton beam was obtained with a Cockroft-Walton 800 kV generator. The current was 10—200 μA, the γ rays were registered with a NaI(Tl) crystal 7.8 cm in diameter and 7.8 cm in height, with a Dumond-6393 photomultiplier. The α particles were detected with a semi-conductor detector [2] 0.1 cm^2 in area and with a CsI(Tl) scintillation crystal. The amplitude distribution was registered with a 100-channel analyzer.

The targets used were NaCl, MgO, Al_2O_3 and $Ca(PO_3)_2$. A thick target was used, so that the radiation connected with a given resonance was established as a difference of the radiations at energies E_p above and below resonance. The pulse-height spectra were analyzed with the aid of known amplitude distributions [3]. To estimate the intensity ratios, previously published [4] data on internal and peak efficiencies were used. Corrections for the angular resolution, necessitated by the finite counter dimensions, were introduced in the angular distribution coefficients.

2. MEASUREMENT RESULTS

A. Reaction $Na^{23}(p, \gamma)Mg^{24}$ at proton energy E_p = 250 keV. Figure 1a shows the region of high energies of the γ-ray amplitude spectrum, while Fig. 1b shows the low-energy region. The intensities obtained from analysis of the amplitude spectrum are:

E, MeV	1,38	1,5—2,3	2,76	4,24	7,75	10,55	11,99
Relative intensity:	1,26±0,1	0,07—0,1	0,26±0,05	<0,015	0,25±0,05	1	<0,015

On the basis of the energy and intensity ratios of the individual γ lines it can be established that the 11.933-MeV level is de-excited principally via the cascades 11.933 → 1.38 → 0 and 11.933 → 4.14 → 1.38 → 0. As can be seen from Fig. 1, in the 4.5—6 MeV region and also 1.5—2.3 MeV region, there is still an insignificant γ-ray intensity, but we cannot say anything definite concerning its origin and exact energy. During the estimate of the intensity ratios, corrections were made for the summation of pulses due to the cascade processes.

The Legendre coefficients for the measured angular distribution amount to:

$$E_\gamma = 7{,}75\ \text{MeV}: \quad a_2 = -0{,}04 \pm 0{,}06, \quad a_4 = -0{,}05 \pm 0{,}13;$$
$$E_\gamma = 10{,}55\ \text{MeV}: \quad a_2 = -0{,}19 \pm 0{,}02, \quad a_4 = 0{,}14 \pm 0{,}03.$$

On the basis of a comparison of the yield of the reaction when E_p = 250 keV with the reaction yield at 308 keV, it was determined that

$$(2J + 1)\,\Gamma_p\Gamma_\gamma/\Gamma = 0{,}0027\ \text{eV},$$

where J—spin of the intermediate state; Γ_p—half width of the proton line; Γ_γ—half width of the γ line; Γ—total half width of the reaction. This quantity agrees sufficiently well with the value given by Endt and Van der Leun [1].

B. Reaction $Na^{23}(p, \alpha_0)Ne^{20}$ with E_p = 250 keV. The decay from 11.933 MeV to the ground

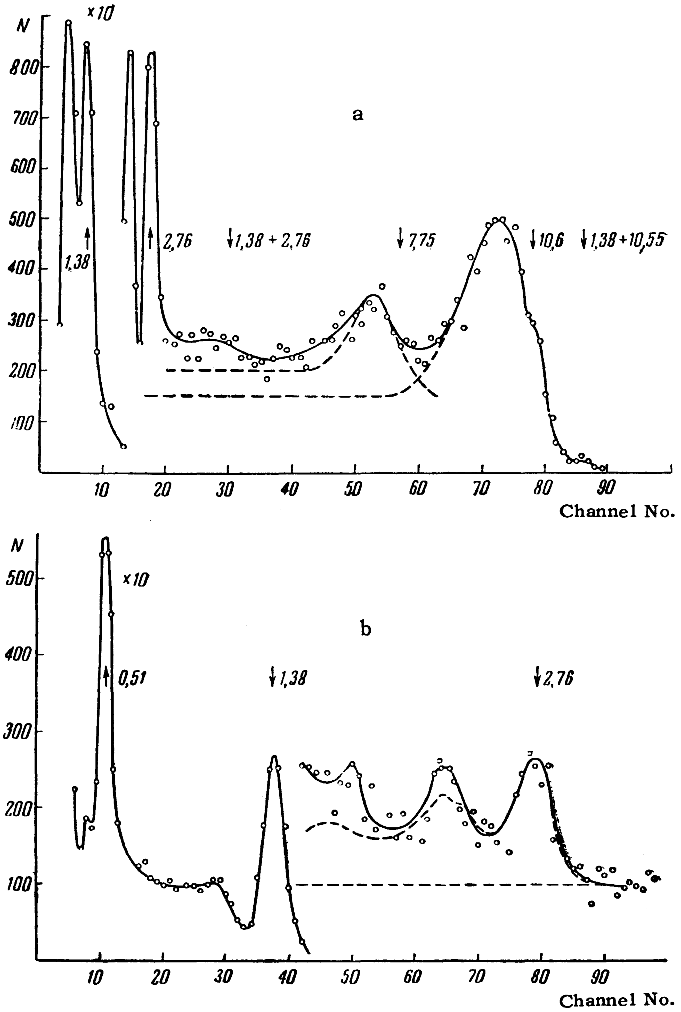

FIG. 1. Amplitude spectrum of γ radiation of the reaction $Na^{23}(p,\gamma)Mg^{24}$ (E_p = 250 keV): a—high-energy region, b—low-energy region. Here, and in the remaining figures, the arrows denote the line energies in MeV. The dashed curve shows the amplitude distributions due to individual lines.

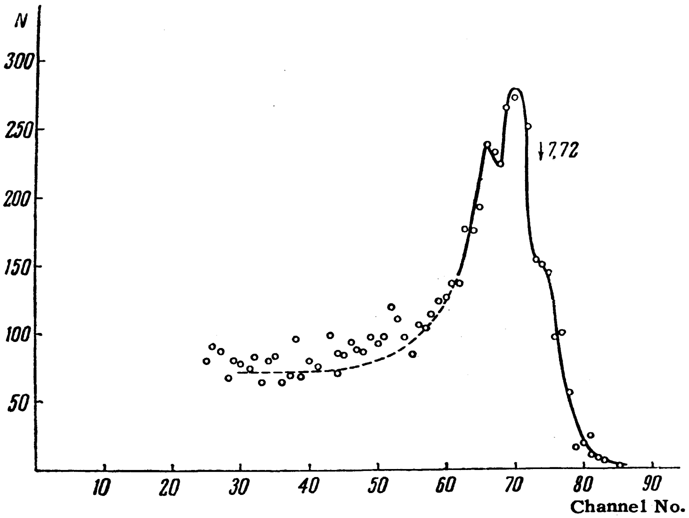

FIG. 2. Amplitude spectrum of γ radiation from the reaction $Mg^{26}(p,\gamma)Al^{27}$ (E_p = 292 keV) in the high-energy region. Dashed curve—amplitude distribution for the 7.72 MeV line.

level of Ne^{20} can proceed with emission of α particles of energy 2.16 MeV. The intensity of the decay was compared with the intensity of the α_0 emission of the resonance at E_p = 287 keV (E_{exc} = 11.97 MeV). The intensity of the α_0 radiation of the 11.93 MeV level was lower than the measurement error; we can therefore give only an upper limit for the α_0-decay probability:

$$(2J + 1)\,\Gamma_\alpha\Gamma_p/\Gamma < 0.01 \text{ eV}.$$

C. Reaction $Mg^{26}(p, \gamma)Al^{27}$ with E_p = 292 keV. The high-energy region of the γ spectrum is shown in Fig. 2, and the low-energy region in Fig. 3. On the basis of a calibration of the counter it was established that the intensive radiation with energy 7.72 MeV is obtained in the γ transition between the 8.56 MeV level and the first excited 0.84 MeV level of Al^{27}. The 840 keV radiation pertaining to this transition is seen in the low energy region of the spectrum.

At the given measurement error, radiation at an energy of 5—6 MeV cannot be seen. This means that the 8.56 MeV level decays via the cascade 8.56 → 0.84 → 0. The intensity of the 8.56 → 0 transition is less than 5 per cent of the intensity of the cascade transition.

The angular distribution of the 7.72 MeV radiation is isotropic:

$$a_2 = -0{,}020 \pm 0{,}038, \qquad a_4 = 0.034 \pm 0.044.$$

Comparing the yield of the reaction $Mg^{26}(p, \gamma)Al^{27}$ with the data for the $Mg^{24}(p,\gamma)Al^{25}$ reaction we obtain

$$(2J + 1)\,\Gamma_\gamma\Gamma_p/\Gamma = 0.048 \text{ eV}.$$

D. Reaction $Al^{27}(p, \alpha_0)Mg^{24}$ at E_p = 224 keV. As in case B, no α radiation could be observed in this reaction.

Comparing with the intensity of γ radiation for the resonance level, we obtain $I_\alpha/I_\gamma < 1$, and consequently

$$(2J + 1)\,\Gamma_\alpha\Gamma_p/\Gamma < 0.01 \text{ eV}.$$

E. Reaction $P^{31}(p, \alpha_0)Si^{28}$ with E_p = 355 keV. We have established elsewhere [6] that the spin of the excited level corresponding to the 355 keV resonance is unity. In order to determine the parity, we considered the intensity of the α_0 transition. We were unable to observe any α_0 transition [7] to the ground state of Si^{28}; in this case $\alpha_0/\Gamma_\gamma < 3$ meaning that $(2J + 1)\Gamma_\alpha\Gamma_p/\Gamma < 0.013$ eV.

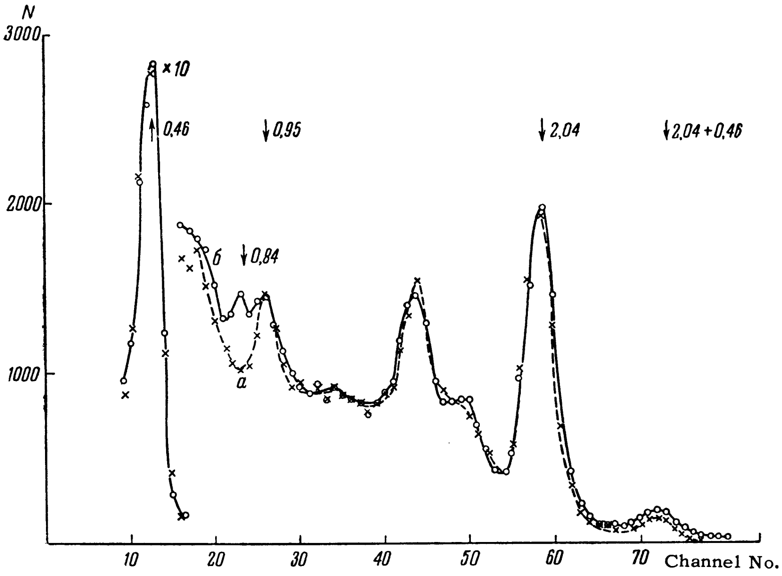

FIG. 3. Amplitude spectra of γ radiation from the reaction $Mg^{26}(p,\gamma)Al^{27}$: a—$E_p < 292$ keV (radiation is from the resonance level $E_p = 224$ keV for the reaction $Mg^{24}(p,\gamma)Al^{25}$; b—$E_p > 292$ keV.

3. DISCUSSION OF RESULTS

A. Reaction $Na^{23} + p$ with $E_p = 250$ keV ($E_{exc} = 11.933$ MeV). The data given in Sec. 2A show that there is no radiation with energy 4.24 MeV. Therefore the 11.933 MeV level, in contrast with the majority of levels above it, decays to a level with energy 4.14 MeV, and not 4.24 MeV.

Prosser et al [8] found, at proton energies $E_p = 989$ and 1419 keV, resonances at which the decay proceeds in most cases via the 4.14 MeV level, while the decay via the first excited 1.38 MeV level proceeds only with low intensity. On the basis of measurements of the angular distributions and the presence of α_0 decay, spin and parity of $3^{\pm}$ or 4^- is assigned to the first level, while 3^-, 4^+, 5^-, or 6^+, is assigned to the second level. On the basis of intensity, an assignment 4^+ is given for both levels. In our case, since the proton energy is low (250 keV), we can assume that the incoming protons can have orbital momentum $l \leq 3$, and there are only types E1, M1, and E2 of γ transitions. The angular distribution coefficients which we presented in Section 2 can be satisfied under the above conditions only by assignments 2^+ and 3^+.

It is interesting that there is a great difference in the decay schemes of the 2^+ level with energy 11.988 MeV and the 2^+ or 3^+ level with energy 11.933 MeV. The 11.988 MeV level decays in 46 per cent of the cases via the 4.24 MeV level with spin and parity 2^+, characterized by a rotational quantum number $K = 2$, and only in 35 per cent does it decay via the first excited state (energy 1.38 MeV, spin and parity 2^+, rotational quantum number $K = 0$). The 11.933 MeV level decays to the first excited level in 80 per cent of the cases and to the 4.14 MeV level (with $K = 0$) in 20 per cent of the cases. Many levels in the energy region > 11.988 MeV have the same character as the 11.988 MeV level. It can be assumed that the 11.933 and 11.988 MeV levels pertain to different rotational bands.

B. Reaction $Mg^{26}(p, \gamma)Al^{27}$ with $E_p = 292$ keV ($E_{exc} = 8.554$ MeV). As indicated above, in the decay of the 8.554 MeV level of Al^{27}, the ratio is $\Gamma_{\gamma 0}/\Gamma_{\gamma 1} < 0.05$ so that it is not probable that the 8.554 MeV level has a spin of $5/2$ or larger. (The spin of the ground state of Al^{27} is $5/2$, and the spin of the first excited state is $1/2$). The isotropic angular distribution eliminates the assignment $3/2^-$, so that the 8.554 MeV level can have an assignment $1/2^{\pm}$ or $3/2^+$.

Reaction	Proton energy in keV	Spin and parity of excited level	$(2J+1)\Gamma_\gamma\Gamma_p/\Gamma$, eV	$(2J+1)\Gamma_\alpha\Gamma_p/\Gamma$, eV
$Na^{23}+p$	250	2^+, 3^+	0,0027	<0.01
$Mg^{26}+p$	292	$1/2^{\pm}$, $3/2^+$	0,048	
$Al^{27}+p$	224			<0.01
$P^{31}+p$	355	$1^{\pm}$	0,0042	<0.02

A summary of the most important results is given in the table.

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