ELASTIC SCATTERING OF PROTONS BY Mg^{24} NUCLEI

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The Mg^{24} (p, p) Mg^{24} elastic scattering differential cross section was measured for proton energies between 1450 and 4200 keV and c.m.s angles 90, 125, and 141°. Resonances were observed for proton energies of 1495, 1624, 1670, 2015, 2410, 2920, 3140, 3669 and 4022 keV, corresponding to Al^{25} levels with excitation energies 3.725, 3.850, 3.893, 4.224, 4.604, 5.093, 5.304, 5.812, 6.151 MeV, respectively. An analysis of the measurements based on the single-level approximation of dispersion theory shows that the broad resonance at E_p = 3140 keV is caused by proton capture in the l = 0 state and the corresponding Al^{25} level with an excitation energy of 5.304 MeV has spin and parity $1/2^+$. The spin and parity assignment for the 5.812-MeV level is $3/2^+$ or $5/2^+$, while for the 6.151-MeV level it is $3/2^+$. Protons are captured onto these levels in the l = 2 state. The characteristics of the remaining levels of Al^{25} with excitation energies below 5 MeV agree with the results of previous investigations.

INTRODUCTION

THE low-lying levels of Al^{25} have been well investigated experimentally [1] and have been interpreted [2] with considerable success on the basis of the collective model. The most convenient means of studying the excited states of Al^{25} are reactions between protons and Mg^{24} nuclei. The binding energy of a proton in the Al^{25} nucleus is relatively small—2.29 MeV—which, along with the readily available target, makes possible a comparatively simple and reliable determination of the characteristics of the Al^{25} levels. A second source of information on the excited states of this nucleus is the Mg^{24} (d, n) Al^{25} reaction (Q = 0.062 MeV), which has been studied earlier by Goldberg [3]. The study of these reactions has made it possible to determine unambiguously the spins and parities of all Al^{25} levels up to an excitation energy of 4.6 MeV. As regards the excitation energies from 4.6 to 6.2 MeV, the available information is fragmentary and contradictory. There is almost no information for energies above 6.2 MeV. The excitation energy interval between 4.6 and 6.2 MeV has been studied by means of elastic [4,5] and inelastic [6,7] scattering of protons. Data on the Al^{25} levels obtained in [6,7] are shown in Table I. Levels with E_{exc} = 4.90, 5.06, 5.09, and 5.11 MeV do not appear in elastic scattering; the information in the foregoing references is insufficient for an unambiguous determination of the characteristics of these levels. The reliability of the data in the brief account [7] is difficult to assess.

According to [7], the broad resonance at E_p = 3140 keV does not appear in inelastic scattering. The shape of this resonance in elastic scattering of protons at 164° was carefully analyzed by Koester [5]. However, this analysis, based on

Table I

E_{res}, keV	E_{exc}, MeV	Γ, keV	J^π
2720 [6]	4.900 [6]		$\geqslant 5/2$ [6]
2890 [6]	5.060 [6]		
2920 [6]	5.090 [6,7]		$1/2$ ($3/2^+$) [7]
2940 [6]	5.110 [6]; 5,140 [7]	50 [6]	$\geqslant 5/2$ [6]; $5/2^+$ [7]
3140 [4,5]	5.310 [4,5]	200 [5]	$3/2^-$ [5]
	5,750 [7]		$3/2^-$ [7]
3660 [4,5]	5.800 [4,5]		($3/2^+$; $5/2^+$) [5]
	6.140 [7]		$1/2$ ($3/2^+$) [7]

the assumption that the formulas for the elastic scattering differential cross section given by Laubenstain and Laubenstain [8] accurately describe the cross section when used with the experimental data for only one angle, can lead to incorrect conclusions as to the characteristics of the resonances. In this case, the shape of the resonance is qualitatively the same for both the $S_{1/2}$ and $P_{3/2}$ states. The orbital angular momentum with which the proton is captured is more reliably determined from measurements of the excitation function for elastic scattering at several characteristic angles.

Koester [5] did not analyze the resonance at E_p = 3660 keV, since the characteristics of the broad resonance above 3950 keV, whose presence is indicated by the increase in the cross section at these energies, are not known. Lewis and Joyner [7] apparently observed this broad resonance at a proton energy of 4020 keV. It also is not clear how correct is the conclusion of the authors of the survey [1] that the resonance in elastic scattering at E_p = 3660 keV corresponds to the 5.75-MeV level which appears in inelastic scattering.

It would therefore be worth-while to extend the study of elastic and inelastic scattering of protons by Mg^{24} nuclei. In the present experiment we studied the elastic interaction $Mg^{24}(p, p)\,Mg^{24}$ for proton energies from 1450 to 4200 keV.

EXPERIMENTAL METHOD

As a proton source we used the electrostatic accelerator of the Physico-technical Institute of the Ukrainian Academy of Sciences. The target was prepared by the evaporation of Mg^{24} (enriched to 99%) on a polished base consisting of spectrally pure graphite. The number of nuclei in the target was determined from measurements of elastic scattering of low-energy protons at 90°, where the basic contribution to the cross section is due to Coulomb scattering. The target thickness corresponded to a loss of ~ 4 keV for 3-MeV protons. The scattered protons were analyzed with a magnetic spectrometer [9] and were detected by a thin (0.2 mm) CsI(Tl) crystal with FÉU-19 tube. The primary proton current was measured with a Faraday box and current integrator. The errors in the determination of the relative cross section, including the statistical errors, did not exceed 3%.

RESULTS OF THE MEASUREMENTS

The cross sections for the elastic scattering of protons in the energy interval E_p = 1450—2700 keV were measured at 90° in the c.m.s.; in the interval 2700—4200 keV the cross sections were measured at three angles: 90, 125, and 141° c.m.s. The measurements in the interval 1450-2700 keV were made to determine the absolute cross sections. The large thickness of the target made it difficult to study very narrow resonances in this energy interval. However, the peak at 1495 keV observed in our experiment and the weak minima in the cross sections at 1670, 2015, and 2410 keV confirm the correctness of the spin and parity assignments in [5-7] for the corresponding Al^{25} levels. The elastic scattering cross sections close to the broad resonance at E_p = 1624 keV are shown in Fig. 1. Figure 2 shows the elastic scattering cross sections for the scattering of protons by Mg^{24} at energies of 2700—4200 keV for c.m.s. angles 90°, 125, and 141°. The excitation function discloses three rather sharp resonances at proton energies of 3140, 3669, and 4022 keV and a weak resonance at 2920 keV.

Resonance at E_p = 1624 keV. The shape of this resonance at θ_{cms} = 164° in the case of the isolated level is consistent only with the assumption that the proton is captured in the $P_{1/2}$ state [5]. This result is confirmed by our measurements. In fact, the symmetric peak in the elastic scattering cross section at 90° in the c.m.s. can be caused only by odd orbital angular momenta. According to Wigner's relation $\gamma^2 \leq 3\hbar^2/2ma$, this resonance cannot occur with l = 3. Consequently, the spin and parity assignment for the 3.850-MeV level is $\frac{1}{2}^-$. The full width of this resonance is practically equal to the proton width, since the inelastic cross section at this energy is small. The value Γ = 34 keV from our measurements is in good agreement with Koester's data [5] (Γ = 36 keV).

Resonance at E_p = 2920 keV. As is seen from Fig. 2, the cross section for E_p = 2920 keV at 90° has an anomaly exceeding the statistical error in our experiment. This anomaly was also observed by Mooring et al. [4], but was ascribed to impuri-

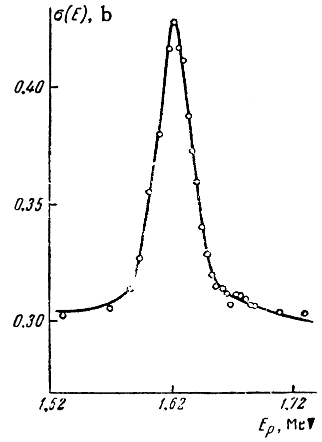

FIG. 1. Resonance at E_p = 1624 keV, θ_{cms} = 90°.

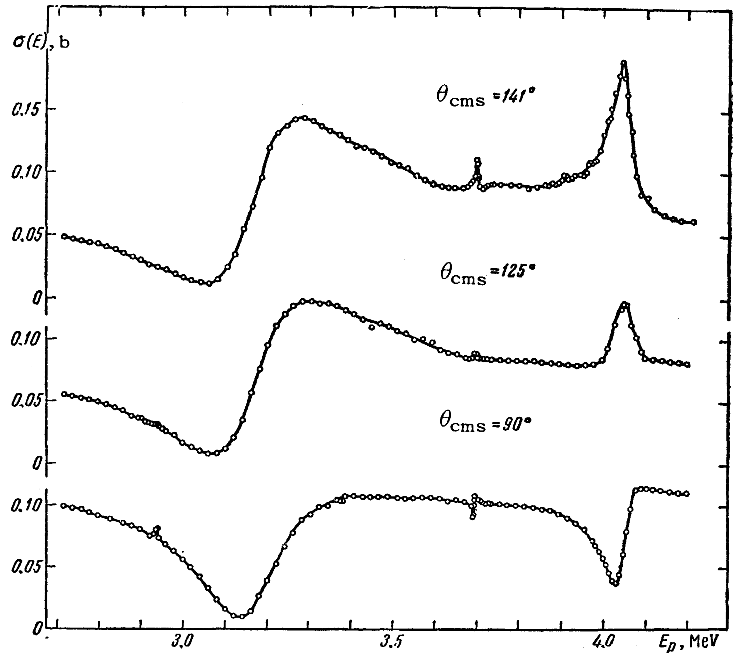

FIG. 2. Differential cross sections of the elastic interactions $Mg^{24}(p, p)Mg^{24}$ for different c.m.s. angles.

ties in the target. The very small width of this resonance does not permit any conclusions on the characteristics of the corresponding Al^{25} level.

Resonance at E_p = 3140 keV. The shape of this resonance at 164° is qualitatively consistent with the assignment $1/2^-$ or $3/2^-$ for the spin and parity of the corresponding Al^{25} level. However, Koester [5] was unable to give a satisfactory description of the cross section in the region of this resonance. Only by a considerable reduction of the interaction radius to the value 5.05×10^{-13} cm can we obtain agreement with the assignment $3/2^-$ for the spin and parity of the 5.304-MeV level. According to our measurements, the cross section at 90° has a minimum, which indicates that the resonance is associated with an even value of the orbital angular momentum. For $l = 2$, the peak at 125° should be almost symmetric, which is not what is observed in the experiment. According to Wigner's relation, higher angular momenta cannot occur. Consequently, the resonance is associated with an S wave and the spin and parity assignment of the 5.304-MeV level is $1/2^+$. A detailed analysis of the shape of this resonance discloses good agreement between the calculated and measured cross sections close to the resonance, but at 141° an appreciable discrepancy is observed in the 3300—3800 keV interval. This discrepancy attains (10—15)% and cannot be removed by a reasonable variation of the interaction radius or potential phase shifts. It is not impossible that this is connected with the existence of the broad resonance between 3140 and 3669 keV which appears weakly in elastic scattering. The 5.75-keV level detected by Lewis and Joyner [7] with spin and parity $3/2^-$ confirms this conclusion to some degree.

Resonance at E_p = 3669 keV. The width of this resonance is much less than the target thickness, and therefore to compare the experimental data with the calculated values, the latter should be averaged over the target thickness; to do this, the proton energy loss in the target must be known. Moreover, for the analysis it is also necessary to have information on the competing processes, i.e., the partial width for inelastic scattering must be known. In view of this, a quantitative comparison between the calculated and experimental values cannot be made. Quantitatively, the shape of this resonance is reproduced very well if it is assumed that $l = 2$ and that the 5.812-MeV corresponding level of the compound nucleus is a $3/2^+$ or $5/2^+$ state. Other channels of the reaction Mg^{24} + p must be studied to determine unambiguously the spin of this level.

Resonance at E_p = 4022 keV. The shape of this resonance is in good agreement with the assumption that $l = 2$. However, a detailed comparison of the theoretical cross section with the measured value discloses an appreciable difference in their absolute values. In this case it is natural to assume that $\Gamma_p \neq \Gamma$ (Γ_p is the proton width) and, consequently, the cross section is not described by the theoretical formulas [8]. The cross section measured at 125° has an almost symmetric peak. For such resonances the value of Γ_p^2/Γ can be determined if we calculate the integral of the

Table II

E_{res}, keV	E_{exc}, MeV	Γ, keV	Γ_p, keV	$\gamma_p^2 / (3\hbar^2/2ma)$	l	J^π
1624	3.850	34	34	0.1	1	$1/2^-$
2920	5.093	< 4				
3140	5.304	200	200	0.06	0	$1/2^+$
3669	5.812	< 4			2	$3/2^+$, $5/2^+$
4022	6.151	45	26	0.02	2	$3/2^+$

resonance scattering (see [10]):

$$R_s = \frac{\pi \sin^4 \theta/2}{B\eta^2 (2I+1)} H \frac{\Gamma_p^2}{\Gamma}, \quad H = \sum_l Z^2 (lJlJ; {}^1/_2 L) P_L(\cos\theta),$$

where B is the ratio of the cross section outside the resonance to the cross section for Rutherford scattering; $\eta = Ze^2/\hbar v$; v is the velocity of the relative motion; I is the spin of the target nucleus; θ is the c.m.s. scattering angle; and J is the spin of the compound nucleus level.

We calculated the value of R_S under the assumption that $J = 3/2^+$ for the angle $\theta = 125°$ and obtained $\Gamma_p^2/\Gamma = 15$ keV, and, using the value of the full width $\Gamma = 45$ keV, we found that $\Gamma_p/\Gamma = 0.6$, while $\Gamma_p = 26$ keV. Then, for the differential cross section for elastic scattering of protons by spin zero nuclei, we used the formula given by Sachs [11], generalized for the case in which $\Gamma_p < \Gamma$. The cross section calculated under the assumption that $\Gamma_p/\Gamma = 0.6$ was in agreement with the experimental value, within the limits of experimental error. Under the assumption that $J = 5/2^+$, the calculated cross section differed appreciably from the measured value. Hence the Al^{25} level with excitation energy 6151 keV has a spin 3/2 and positive parity. Measurements of the angular distributions of protons and γ rays in inelastic scattering [7], yielded of possible spin assignments for this level (1/2 and $3/2^+$) which are not inconsistent with our measurements.

DISCUSSION OF RESULTS

Data on the Al^{25} levels obtained in our experiment are given in Table II. In the determination of the position and widths of the resonances we took into account the energy loss in the target. We took the binding energy of a proton in the Al^{25} nucleus to be 2.29 MeV in the calculation of the excitation energy of the Al^{25} levels.

In the calculation of the reduced widths we used the value 5.63×10^{-13} cm for the interaction radius. Table II shows the ratios of the reduced width to the single-particle width $3\hbar^2/2ma$. It should be noted that the values of the reduced widths strongly depend on the choice of the interaction radius, so that our values could be underestimated.

The density of the Al^{25} levels observed in elastic and inelastic scattering of protons is considerably less than the density of the levels in the Mg^{25} mirror nucleus found in the $Al^{27}(d, \alpha) Mg^{25}$ reaction [12] for the corresponding excitation energy interval. This can be explained by the fact that the Al^{25} levels with larger total angular momenta are not observed in scattering, since these levels should be formed with protons in states of higher orbital angular momenta, and that is why we can expect that the corresponding full and partial widths are very small. The intensity of the groups of α particles from the (d, α) reaction is directly proportional to (2J + 1), and hence the levels with larger angular momenta distinctly appear in this reaction.

The levels analyzed by us do not fall into the previously detected [2] rotational bands for Mg^{25} and Al^{25} with $K = 5/2^+, 1/2^+, 1/2^+$, and $1/2^-$ (Nilsson orbits 5, 9, 11, and 14, respectively). Of special interest is the 5.304-MeV level with spin $1/2^+$ and a considerably reduced width. This level, and also the 5.812- and 6.151-MeV levels form, perhaps, a new rotational band with K = 1/2. It is also possible that these levels are vibrational. Sheline and Harlan [12] suggested the existence of 5.27- and 5.49-MeV levels of Mg^{25} in the $1/2^+$ state. Further study of inelastic scattering and capture of protons by Mg^{24} can give new information on the Al^{25} levels.

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