Energy Levels in Si^{28} Excited by Alpha-Particles on Mg^{24}†

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Alpha-particles produced by the Wisconsin electrostatic generator were used to bombard thin $Mg^{24}F_2$ targets evaporated onto pure graphite backings. The reaction products separated by a 90° magnetic analyzer were observed at a laboratory angle of $164\pm5°$. Excitation curves for the reactions $Mg^{24}(\alpha, \alpha)Mg^{24}$ and $Mg^{24}(\alpha, p)Al^{27}$ were obtained and compared to the excitation curves of the $Al^{27}(p, p)Al^{27}$ and the $Al^{27}(p, \alpha)Mg^{24}$ reactions that had been obtained earlier. Cross sections for the reaction $Mg^{24}(\alpha, p)Al^{27}$ were found to bear a simple qualitative relationship to those of the inverse reaction $Al^{27}(p, \alpha)Mg^{24}$, as suggested by the principle of detailed balance. These two excitation curves could be brought into good correspondence by assuming a Q-value of -1.613 Mev for the reaction $Mg^{24}(\alpha, p)Al^{27}$. Some J-values have been assigned to the levels formed in the compound nucleus Si^{28}.

INTRODUCTION

THE energy levels of Si^{28} excited by protons of energies between 1 and 4 Mev impinging upon Al^{27} have been surveyed recently by Shoemaker, Faulkner, Bouricius, Kaufmann, and Mooring.[1] Their curve giving scattering cross section as a function of proton energy shows a number of resonances, of which only those excited by protons in the low energy region (Fig. 2A) are well enough separated to permit a description in terms of the single level scattering formula. Higher energy regions show increasing density of levels with a consequent loss of definition of each individual level. An interpretation of the high energy data is therefore not possible.

The well-separated resonances in the low energy region of the experimental results of Shoemaker and his associates are superimposed upon a potential scattering background which follows closely the energy dependence of pure Coulomb scattering. A comparison of these resonances with theoretical predictions is possible and has been attempted. The single level resonance formula, taking into account only one partial wave in each resonance, has led to the conclusion that it is likely that most of the resonances analyzed were due to a resonating S-wave in the proton beam. Because of the high spins of the colliding particles, a unique and satisfactory conclusion concerning the J-value of the compound state associated with each resonance analyzed could not be reached. Additional information concerning the J-values was judged to be necessary before J-values could be assigned and the individual resonances be described with more assurance and in greater detail.

On the basis of the energies available from the Wisconsin electrostatic generator, from mass values and the Q-value of the $Al^{27}(p, \alpha)Mg^{24}$ reaction, it was expected that the levels of Si^{28} corresponding to the proton resonances lying in the low energy region of the $Al(p, p)Al$ data could be reached through the bombardment of Mg^{24} by alpha-particles. Such a scattering experiment appeared particularly desirable because neither the alpha-particle nor the Mg^{24} nucleus in its ground state has a spin. Only one partial wave could possibly partake in a resonance, and its orbital momentum L would be equal to the spin J of the compound state of the Si^{28}. For this reason, if the orbital momentum of the partial alpha-particle wave could be inferred from the properties of the resonances observed in the $Mg^{24}(\alpha, \alpha)Mg^{24}$ scattering, the J-value of the Si^{28} nucleus could be definitely assigned, and additional valuable information might be obtained concerning the mechanism of the scattering of protons by Al^{27}.

EXPERIMENTAL ARRANGEMENT

The accelerator used was the Wisconsin electrostatic generator, whose output was separated according to particle momentum by a variable magnetic field. A cylindrical electrostatic analyzer separated the beam according to particle energy and was adjustable to permit beams of predetermined energy and energy spread to pass on to the target assembly. Ions which were not scattered from the target were collected in a Faraday cup and integrated[2] so as to measure the total number of charged particles which had fallen upon the target. Ions that were scattered into a given solid angle, between 159° and 169° in the backward direction, were separated by a magnetic analyzer which is described in reference 1. Those ions that the magnet deflected by 90° were recorded by a proportional counter at the end of their path.

Targets used in the experiment were prepared from $Mg^{24}O$ which was obtained from the Y-12 plant of Oak Ridge National Laboratory. Since the preparation of thin targets is most conveniently done by an evaporation of the target material, and since the evaporation of MgO requires temperatures too high to be practicable, the oxide was converted into the fluoride through mix-

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[1] Shoemaker, Faulkner, Bouricius, Kaufmann, and Mooring, Phys. Rev. **83**, 1011 (1951).

[2] G. M. B. Bouricius and F. C. Shoemaker, Rev. Sci. Instr. **22**, 183 (1951).

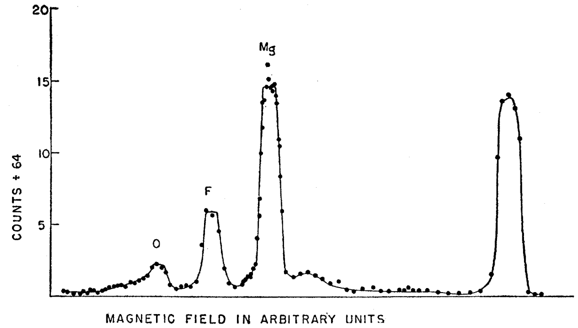

FIG. 1. Momentum analysis of the target. Mg^{24}, F, and O peaks are clearly defined. The peak on the high side of the magnetic field is due to a heavy impurity.

ing it with HF and retaining the precipitate of the reaction. The MgF_2 was evaporated onto polished backings of spectroscopically pure graphite to a thickness equivalent to an energy absorption of 13 kev for 1-Mev alpha-particles. A sample of the momentum distributions of alpha-particles recoiling from the various constituents of this target is shown in Fig. 1. The data have been obtained through a method quite similar to that employed for the corresponding momentum analyses in the paper of Shoemaker *et al.*

Particles were detected in a proportional counter filled with a mixture of 98 percent argon and 2 percent CO_2, sealed from the main vacuum system by a 1/20-mil nickel window. An examination of this window, carried out by permitting alpha-particles of various energies to strike it, showed that the window would not permit alpha-particles of energy below 1.2 Mev to penetrate into the counter with energies sufficient to give usable and well-defined signals.

The $Mg^{24}(\alpha, p)Al^{27}$ reaction was surveyed with a 1/10-mil nickel window in front of the proportional counter. As computations had predicted, this window was thick enough to suppress the alpha-particle background but did permit protons of the reaction to penetrate and to register with large, uniformly sized signals.

EXPERIMENTAL RESULTS

Figure 2 shows the experimental data. A portion of the yield curves of the $Al^{27}(p, p)Al^{27}$ and $Al^{27}(p, \alpha)Mg^{24}$ reactions that are given in the paper of Shoemaker *et al.* is reproduced in Figs. 2A and 2B. The proton scattering curve of Fig. 2A was taken with a target thickness of 1.4 kev,[3] and the proton beam was resolved energetically to have an energy spread at half-maximum intensity of 0.07 percent of its mean energy. The survey of the $Al^{27}(p, \alpha)Mg^{24}$ reaction below 1.3 Mev was made five months after the survey of the region above this energy. The target thicknesses were 13 kev in both surveys, and the energy spread of the beam in the earlier work was 0.07 percent. Because energy calibrations were not made with sufficient frequency over this extended period of time, discrepancies in the energy scales as high as 10 kev were found in some cases. Later difficulties with shifts in the generator energy scale were traced to poor contacts in the Rubicon potentiometer which determines the energy of the generator. It is likely that this was the major cause of the shifts in this experiment. The accuracy of the Q-value given in the next section is directly affected by these discrepancies. The results of the alpha-particle bombardment of Mg^{24} are shown in Figs. 2C and 2D. The $Mg^{24}(\alpha, p)Al^{27}$ curve of Fig. 2C was taken with 13-kev targets and an energy spread of 0.1 percent. The same target and energy spread were used for the curve showing elastic scattering of alpha-particles from Mg^{24} (Fig. 2D). The curves of Figs. 2C and 2D were taken in September 1950.

Q-VALUE AND INVERSE REACTION CROSS SECTIONS

The match of the energy scales in the center-of-mass system of the different experimental curves, as it is shown in Fig. 2, defines a difference in the origin of the energy axes of the $Mg^{24}(\alpha, p)Al^{27}$ and the $Al^{27}(p, \alpha)Mg^{24}$ reaction to be 1.613 Mev. The good correspondence in the curves of the two inverse reactions has been considered sufficient evidence that the difference in the origin of the energy scales as shown in the figure represents the Q-value of the reaction. Corrections have been made for the shift in the peak of each resonance due to target thickness. By bringing each pair of sufficiently defined resonance peaks (those corresponding to alpha-particle energies of 2.755, 2.931, 2.955, 3.002, 3.137, 3.203, 3.280 Mev on the $Mg^{24}(\alpha, p)Al^{27}$ yield curve) of the inverse reaction curves into coincidence in turn, seven values for the Q-value of the reaction were obtained which did not differ by more than 3 kev from their average value of 1.613 Mev. Referring to the shift in energy scales discussed in the previous section, it is assumed that our Q-value may be in error by about 10 kev.

Not only is the level structure reproduced in the two inverse curves, but the intensities of corresponding peaks appear to be in good agreement. Small deviations can be discovered in the detailed structure: a small (α, p) peak at 2.84–Mev alpha-particle energy is not matched by a perceptible rise on the (p, α) curve; the doublets in the neighborhood of 1.51 and 1.6 Mev on the (p, α) curve are opposite to single peaks on the alpha-scale, whose asymmetry suggests that the resolution of the alpha-run was not sufficient to separate the two levels. If such discrepancies find their explanation in terms of resolution differences in the two runs, then the over-all aspect of the two curves may be said to verify qualitatively the principle of detailed balance. The theoretical ratio of the reaction cross sections is

$$\sigma_{\alpha p}/\sigma_{p\alpha} = (2s+1)(2i+1)(mv_p)^2/(mv_\alpha)^2 = 12(mv_p)^2/(mv_\alpha)^2,$$

[3] All target thicknesses are expressed in terms of absorption thickness of incoming particles at 1 Mev.

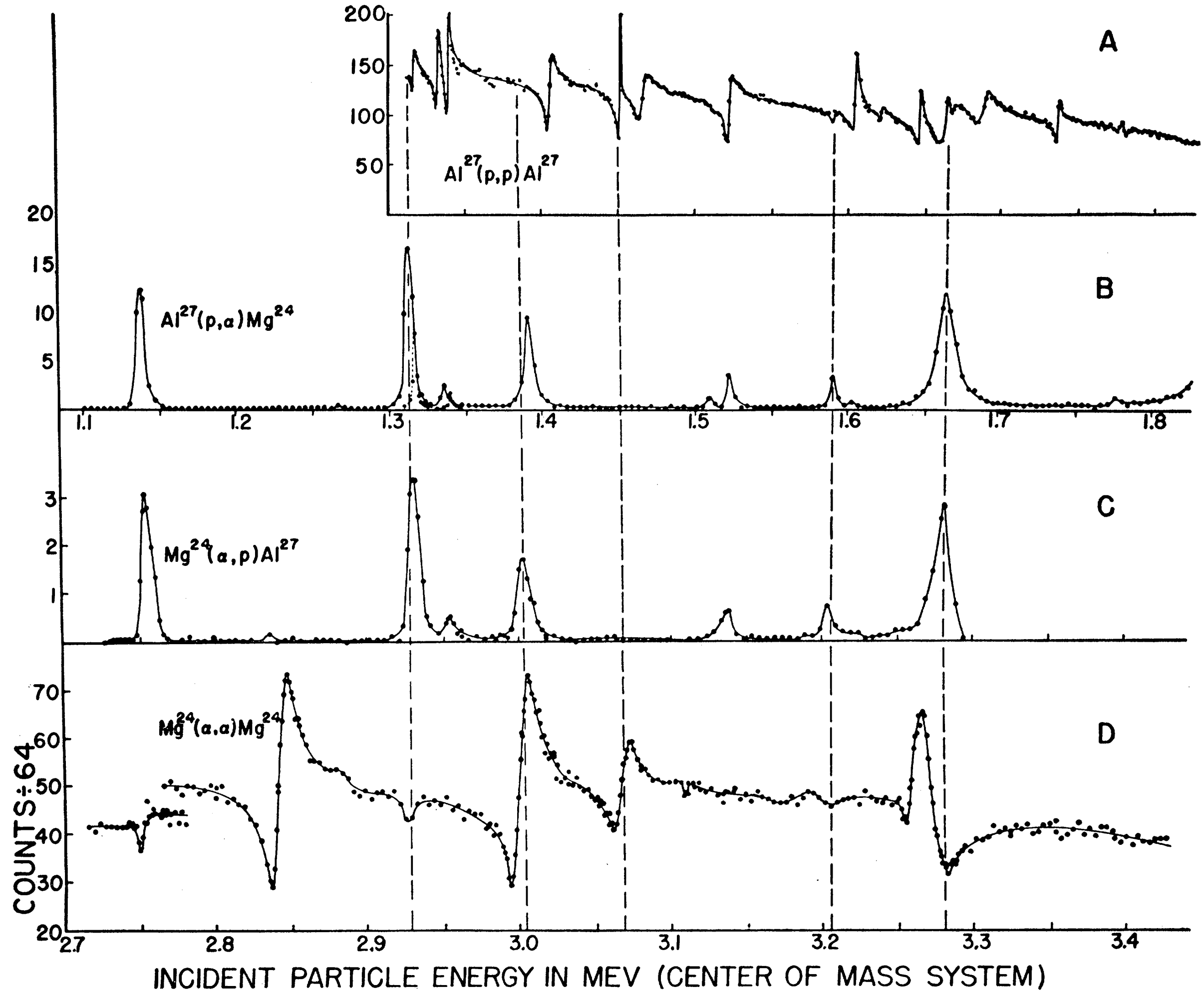

FIG. 2. A. $Al^{27}(p, p)Al^{27}$ curve taken with 1.4-kev targets, beam energy spread 0.07 percent; B. $Al^{27}(p, \alpha)Mg^{24}$ curve taken with 13-kev targets (region below 1.3 Mev), and with 13-kev targets and beam energy spread of 0.07 percent (region above 1.3 Mev). Data shown in curves 2A and 2B are reproduced from reference 1; C. $Mg^{24}(\alpha, p)Al^{27}$ curve taken with 13-kev targets, beam energy spread 0.1 percent; D. $Mg^{24}(\alpha, \alpha)Mg^{24}$ curve taken with 13-kev targets, beam energy spread 0.1 percent.

where mv_p is the momentum of the emitted proton, mv_α is the momentum of the emitted alpha particle, s is the spin of the Al^{27} nucleus in the ground state, and i is the spin of the proton. An attempt has been made to compare this with the experimental value. The computations were handicapped by the uncertainty in target thickness, particularly for the (p, α) curve, which was known only roughly from the geometry used in the preparation of the target. Assuming that the theoretical ratio of cross sections, as given in the principle of detailed balance, is correct, it was computed that the absorption thickness of the magnesium target for alpha-particles must be approximately three times as much as the absorption thickness of the aluminum target for protons. However, in the preparation of the targets, the geometry used had been such that both targets should have had equal absorption thickness for the respective ions with which they were to be bombarded. A discrepancy of a factor of approximately three, therefore, remains between the experimental results and the theoretical prediction, and this discrepancy is probably due to errors in the determination of target thickness.

ESTIMATES OF ORBITAL ANGULAR MOMENTA

A detailed analysis of the data, comparing accurately the energy dependence of the theoretical and observed scattering cross sections in the resonance regions, has not yet been made. A more qualitative interpretation of the resonances, using only the ratio of minimum to maximum scattering cross section belonging to any one resonance, has been attempted through the aid of a diagram reproducing the essentials of the scattering formula in the complex plane. Through some simple, graphical steps, the angle $(\alpha_L-\alpha)$ has been determined,[4] from which the L-value of the resonating partial wave can be determined. This analysis has given the follow-

[4] L. I. Schiff, *Quantum Mechanics* (McGraw-Hill Book Company, Inc., New York, 1949), p. 120, Eq. (20.24).

ing results: The scattering resonances at 2.83 and 3.00 Mev on the $Mg^{24}(\alpha, \alpha)Mg^{24}$ curve have ratios of minimum cross section to Rutherford cross section and maximum cross section to Rutherford cross section, which agree well with the theoretical values for pure *S*-scattering with no competing reactions. The resonance at 2.93 Mev on the alpha-particle energy scale has the qualitative aspect of a *D*-resonance suggesting a *D*-level in the compound nucleus. *S*-, *P*-, and *F*-resonances at this energy are expected to show a peak in the scattering cross section which, in our data, is not perceptible. The corresponding resonance on the proton scattering cross section (Fig. 2A) suggests an *S*-resonance with amplitude less than that predicted for scattering without competing reactions. The proton *S*-resonance is consistent with the *D*-resonance observed in the corresponding alpha-particle curve of Fig. 2D. The alpha-particle resonance at 3.07 Mev on Fig. 2D has a ratio of maximum to minimum cross section suggesting that the *S*-wave resonates here. It is correlated energetically to a sharp and strong resonance in the proton scattering curve at 1.45 Mev proton energy. Analysis of this proton resonance has shown that it, too, suggests *S*-scattering. No *J*-value for the compound nucleus Si^{28} can be found which is consistent with a proton *S*-wave falling upon Al^{27} and an alpha-particle *S*-wave falling upon Mg^{24}. It is assumed that the Si^{28} nucleus formed by 3.07-Mev alpha-particles on Mg^{24} is in a state different from that formed by 1.45-Mev protons impinging upon Al^{27}. The assumption that the angular momenta of these two states in Si^{28} are different seems to be supported by the fact that at this energy no (α, p) nor (p, α) transitions are observed. In the region above 3.1-Mev alpha-particle energy, only one prominent anomaly appears, that at 3.25 Mev. Since the cross section dips to a minimum on both sides of the peak, it is assumed that the anomaly at 3.25 Mev is caused by two overlapping levels in Si^{28}. The appearance of the corresponding region in the proton scattering curve confirms this assumption. A more detailed analysis than that just described might be profitable, but the experimental data, both with regard to absolute cross sections and resolution is somewhat marginal for that purpose.

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