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THE REACTIONS $^{27}Al(p, p')^{27}Al$ AND $^{27}Al(\alpha,p)^{30}Si$

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THE REACTIONS $^{27}Al(p, p')^{27}Al$ AND $^{27}Al(\alpha, p)^{30}Si$

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ABSTRACT. The reactions $^{27}Al(p, p')^{27}Al$ and $^{27}Al(\alpha, p)^{30}Si$ have been studied at 5 MeV incident energy using a high resolution broad range magnetic spectrograph. Angular distributions of several of the proton groups from each of the reactions were determined and the results suggest that some of the final states are formed by direct processes. The excitations of the first four states of ^{30}Si were found to be 2.258 ± 0.006, 3.518 ± 0.007, 3.798 ± 0.009 and 4.85 ± 0.01 MeV.

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* Now at the University of Manchester, where this work was performed.

§ 1. INTRODUCTION

The spectra of protons from the reactions $^{27}Al(p,p')$ and $^{27}Al(\alpha,p)^{24}Mg$, at approximately 5 MeV bombarding energy, have been investigated at high resolution using a broad range magnetic spectrograph in conjunction with the Manchester University 6 MeV Van de Graaff accelerator. Angular distributions and absolute cross sections of several proton groups were found for both reactions.

Large anisotropies were observed in the angular distributions of some of the proton groups and most of these are asymmetric about the 90° direction in the centre of mass system. This asymmetry may originate from overlapping levels in the compound nucleus but it is also possible that the reactions may proceed, at least in part, by some direct interaction process.

In one such process the incident particle interacts directly with a single particle or small group of particles at the nuclear surface. A detailed discussion of such reactions has been given by Butler (1957) and it is expected that the angular distributions of the reaction products should be characteristic of the net orbital angular momentum $\ell\hbar$ which is transferred to the nucleus.

For strongly deformed nuclei, excitation of rotational levels by direct excitation inelastic scattering may be predicted by the collective model and is particularly likely for quadrupole deformations (Brink 1955, Hayakawa and Yoshida 1955 a,b). The Born approximation method yields angular distributions which are similar to those predicted by the Butler process. Direct excitation inelastic scattering has been reviewed by Devons and Goldfarb (1957). More recently, Sawicki (1958) has applied the unified model to include both rotational and individual particle direct excitations by inelastic scattering.

Investigations of reactions leading to discrete final levels with incident energies of from 10 to 30 MeV have been found to support the direct interaction theory and good agreement has been obtained with the predicted angular distributions (Butler 1957, Silver 1957, Von Herrmann and Pieper 1957). If a nuclear reaction is found to proceed predominantly by a direct surface interaction, measurement of the angular distribution of the resolved groups of outgoing particles can yield information about the spins and parities of the final levels.

At lower bombarding energies than those referred to above, Coulomb effects and interaction of the incident and final particles with the core cannot be neglected but these effects are more important in determining the cross section than the angular distribution, as is also the case for deuteron stripping (Yoccoz 1954). For lower incident energy there should be greater separation of the peaks of the angular distributions corresponding to different ℓ values.

§ 2. EXPERIMENTAL TECHNIQUE

The magnetic spectrograph is of the 90° broad range type, having circular pole edges giving second order spherical aberration correction for symmetrical object and image positions. This instrument is similar to the 20 in. radius, ½ in. field gap, spectrograph described by Browne and Buechner (1956) although the construction of the yoke is simpler. The main differences are that the pole radius is 18 in. but the gap is 1 ½ in. Used as a broad range spectrograph the performance is approximately the same as that of the instrument of Browne and Buechner.

The spectrograph is mounted on a turntable (figure 1) which may be rotated to observe particles in the range - 10° to 115°, though it would be possible to extend observations to 135° with only minor modifications. The beam from the Van de Graaff accelerator is analysed by a 90° magnet and is refocused by magnetic quadrupole lenses. Horizontal and vertical deflections are provided by two pairs of coils, whose currents are determined by signals from two sets of control slits placed close to the target chamber, so that the beam is automatically centred on the final slit. In this way more than 25% of the total analysed beam of the accelerator can be used to irradiate a target area of 0.020 in. high and 0.060 in. long. The system ensures that the beam may readily be regained even after rotation or other disturbance of the beam analyser magnet when the accelerator has been used for other experiments.

Calibration of the spectrograph was made using a thin polonium α-particle source, taking the value $Hr = 3.31644 \times 10^4$ gauss cm, to find the values of r corresponding to different points

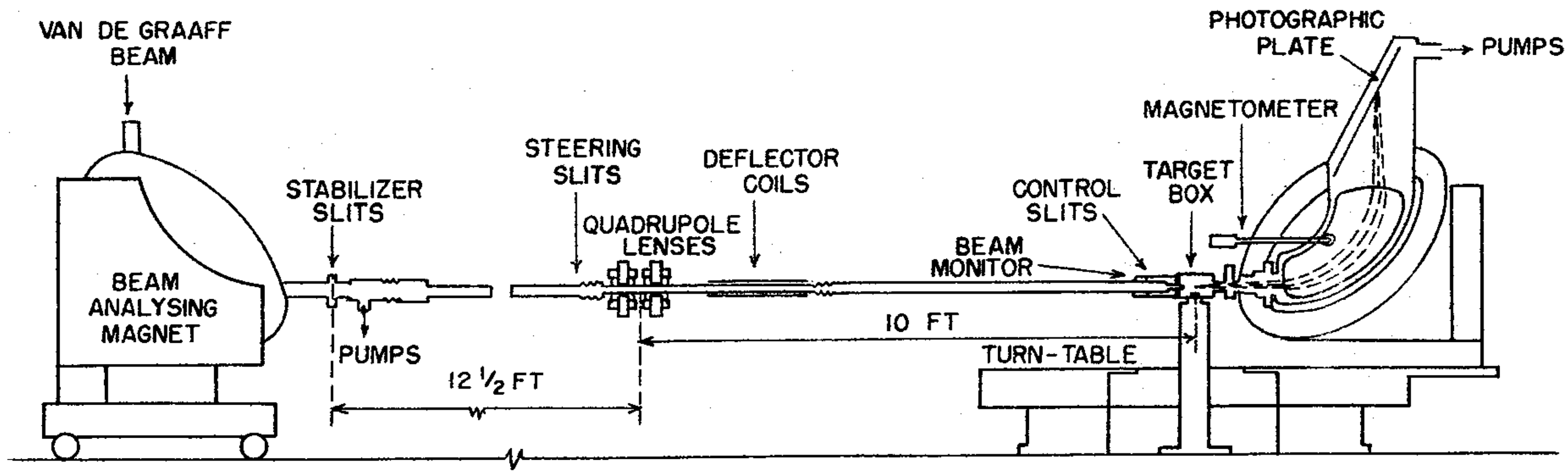

Figure 1. Diagram of the experimental arrangement with the magnetic spectrograph in the 0° position

on the focal surface. Energy resolutions of better than 1 in 1000 were obtained with the polonium source over the whole range.

The magnetic field is measured by the proton and (at the higher fields) lithium nuclear magnetic resonances, the resonant frequency being found on a Hewlett-Packard type 524B frequency meter, which gives a continuous check on the magnetometer oscillator frequency. The spectrograph is excited by a motor generator whose field winding is controlled by the output of a chopper type d.c. amplifier and the field stability is 1 part in 10.000. The spectra were recorded on 50 μ thick C2 nuclear emulsion plates.

Two targets were used: the first a self-supporting aluminium foil 170 $\mu g\ cm^{-2}$ thick giving more than adequate resolution for the investigation of the first three excited states of ^{27}Al by the $^{27}Al(p,p')$ reaction, and for the remaining experiments 70 $\mu g\ cm^{-2}$ Al evaporated on to a VYNS plastic foil of about 10 $\mu g\ cm^{-2}$.

The plane of the target was set along the $-45°$ direction with respect to the incident beam, with the backing, if any, facing, the beam. The beam current was integrated by collection in a Faraday cup fitted with a suppressing electrode and an additional check was provided by monitoring the more energetic protons emitted from the target in the $-135°$ direction with a 0.005 in. thick plastic scintillator.

The target thickness was measured with an α-particle gauge (Enge et al. 1957). The absolute cross sections were calculated directly and also, where possible, by comparison with Rutherford scattering. The absolute values of the cross sections are believed to be accurate to within approximately 15%.

§ 3. RESULTS

The $^{27}Al(p,p')$ reaction was studied in two ranges and typical spectra are shown in figure 2. In each case the beam energy was held constant for all angles. The beam energy was computed from the elastic proton peak for the higher field setting and from the p_3 group for the lower settings. Six excited states of ^{27}Al were observed with the following excitations: 0.840 ± 0.004,

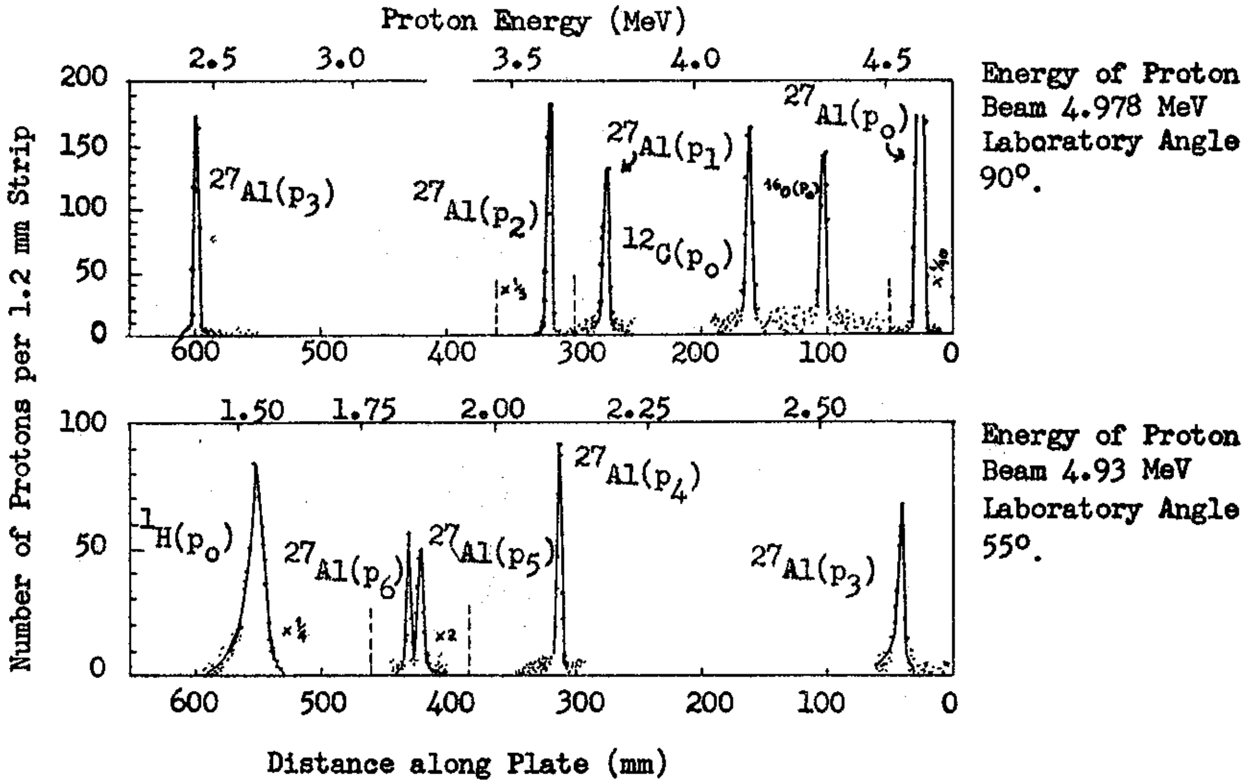

Figure 2. Proton spectra from proton bombardment of ^{27}Al.

1.010 ± 0.004, 2.219 ± 0.004, 2.736 ± 0.006, 2.980 ± 0.006 and 3.002 ± 0.006 MeV. These values are in good agreement with recent data reviewed by Endt and Braams (1957), though the energy of the third excited state was found to be higher than their value of 2.208 MeV by about three times our estimated standard deviation.

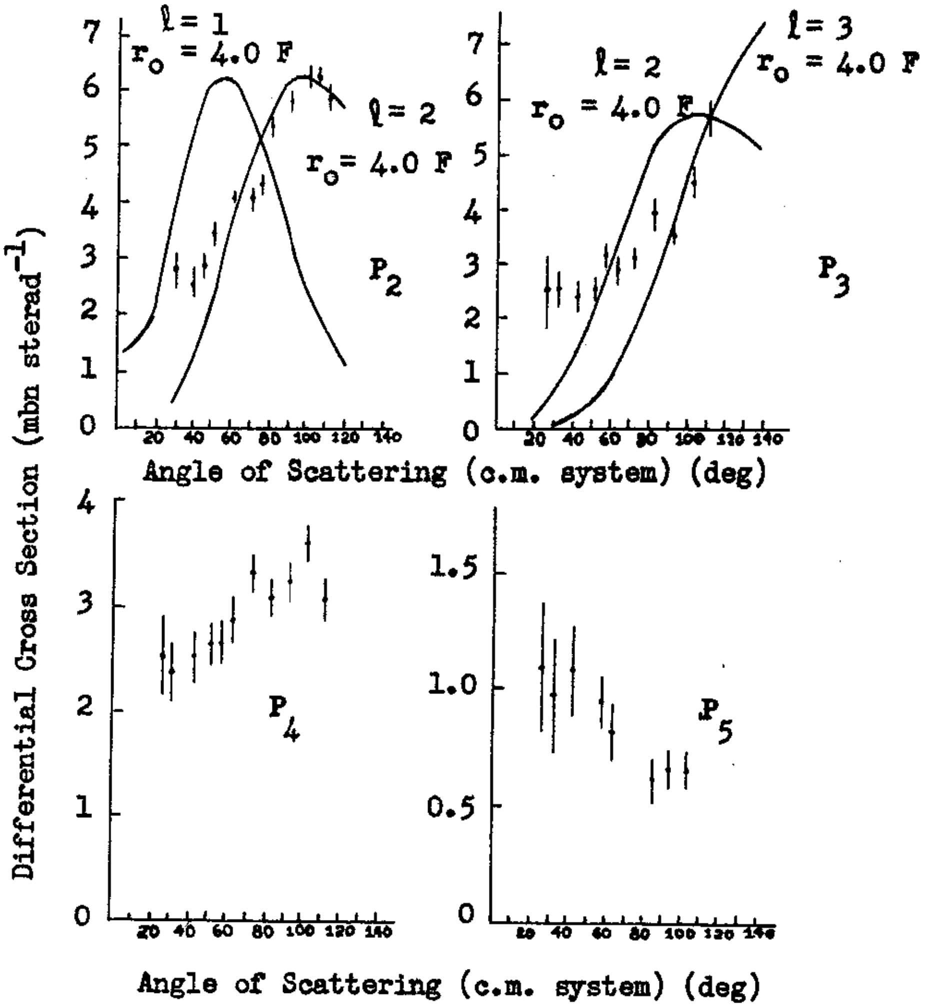

Figure 3. Angular distributions of proton groups from the reaction $^{27}Al(p,p')^{27}Al$

The angular distributions of four of the proton groups are shown in figure 3. The groups p_1 and p_6 yielded distributions which were approximately isotropic with cross sections of 1.3 and 0.8 mbn sterad^{-1} respectively.

The ground and first four excited states of ^{30}Si were investigated by the reaction of $^{27}Al(\alpha,p)^{30}Si$, again using two field settings to cover the range. The Q value leading to the ground state was found as 2.373 ± 0.008 MeV and the excitation of the first four excited states of ^{30}Si as 2.258 ± 0.006, 3.518 ± 0.007, 3.798 ± 0.009 and 4.85 ± 0.01 MeV respectively. These values are somewhat more accurate than previous determinations e.g. Van Patter and Buechner (1952). The angular distributions of the ground and second excited state groups are shown in figure 4. The proton

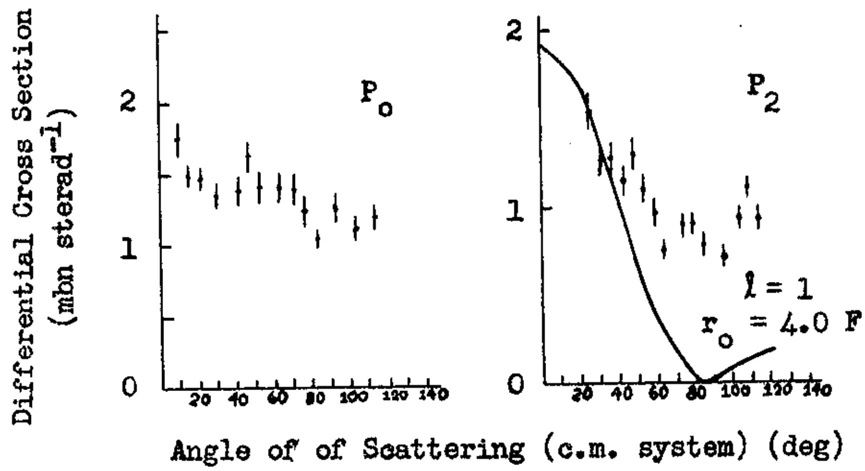

Figure 4. Angular distributions of proton groups from the reaction $^{27}Al(\alpha,p)^{30}Si$ at 5.15 MeV incident energy

group leading to the third excited state was found to be relatively weak with an approximately constant differential cross section of 180 μbn sterad^{-1}. Only incomplete information was obtained about the angular distribution of the p_1 group since at angles below 40^o it was obscured by the peak of elastically scattered α-particles, but no large variation of cross section was found over the angular range of 40^o - 110^o, and a cross section of 0.85 mbn sterad^{-1}

was observed.

§ 4. DISCUSSION

(a) $^{27}Al(p, p')$.

None of the anisotropic proton groups show distributions which are symmetrical about 90^{o} in the centre of mass system. The resonance structure of this reaction has not been investigated above 4.1 MeV but it is unlikely that the reaction is proceeding through a single isolated resonance. It is possible that this asymmetry arises from interference from two or more overlapping compound states, but the degree of anisotropy for the p_2 and p_3 groups is strikingly large. The cross sections for these two groups are notably larger than for any of the others. A comparison of the experimental angular distributions with the Butler theory was made assuming that the binding energy of the last proton in ^{27}Al is 8.2 MeV and the theoretical curves for two different ℓ values are shown in figure 3 for each of these groups. The agreement with the calculated curve for $\ell = 2$ with the p_2 distribution is fairly good and it is thought that the p_3 group corresponds more closely to a higher angular momentum transfer ($\ell = 3$) though this assignment is by no means certain. The agreement could, of course, be considerably improved if an isotropic intensity of some 30%, assumed to arise from compound nucleus formation, was subtracted in each case. The direct interaction amplitude does not change sign over the angular range considered and it would make no difference whether or not the compound nucleus contribution was coherent.

The ground state of ^{27}Al has spin and parity $5/2^+$ and, assuming that spin flip does not occur, $\ell = 2$ is the lowest value allowed by the spin and parity selection rules ($\vec{J}_i + \vec{\ell} = \vec{J}_f$, parity change if ℓ is odd) to form the second excited state ($3/2^+$). The value $\ell = 3$, very tentatively suggested for p_3, would mean that the third excited state has negative parity.

The observed angular distributions indicate that the second and third excited states may be formed predominantly by a direct surface interaction. One explanation for the limitation of a direct interaction to the surface would be that the mean free path for compound nucleus formation is small and that the compound nucleus decays into alternative channels. This is improbable for ^{27}Al(p, p') at 5 MeV since the mean free path of the protons in the nucleus is large and the only competing channels are radiative capture and ^{27}Al(p,α)^{24}Mg. The former is unfavoured at this bombarding energy (Shoemaker et al. 1951) as is also the latter, from our own experience. At low bombarding energies and for high angular momentum transfers, however, there is an alternative reason for expecting a surface interaction. If the momentum transfer is considered on a semi-classical picture, then for the p_2 group at 180° the minimum radius for the direct interaction at 5 MeV incident energy is 2.4 fermis and at 90° it is 3.3 fermis for a transfer of two units of angular momentum. Thus it is considered that for the p_2 and p_3 groups, direct interaction effects would be limited essentially to the nuclear surface and the characteristic angular distributions would be expected. For lower ℓ values, however, this would not be so.

Since ^{27}Al has strong quadrupole deformation, direct excitation of collective rotational states might be expected. The assignment of even the low-lying levels of ^{27}Al to rotational bands has not proved feasible, as it has for the neighbouring nucleus ^{25}Al (Endt and Braams 1957) and although the ground and first two excited states of ^{27}Al have the same spins and parities as the corresponding states in ^{25}Al their spacing is not consistent with a similar assignment (Rakavy 1957). If these are, in fact, rotational levels analogous to those of ^{25}Al the inelastic scattering process leading to the first or second excited states would involve a change of two units in K, the projection of the nuclear angular momentum on the symmetry axis. Such a case is covered by the general relation derived by Sawicki.

(b) ^{27}Al(α, p)^{30}Si.

The angular distributions of the ground and first excited states have been investigated by Von Herrmann and Pieper (1957) at 8.1 and 7.1 MeV who find that the angular distributions varied fairly rapidly with energy; Hunting and Wall (1957) have also investigated the ground state distribution at 30.5 MeV. The most markedly anisotropic group is p_2, but it is not clear whether or not it is symmetrical about 90°. A good fit with the Butler theory could only be obtained if a comparatively large isotropic contribution was deducted (figure 4).

§ 5. CONCLUSION

The results for the reaction $^{27}Al(p, p')$, whilst strongly suggesting the possibility of interpretation in terms of direct interaction effects, may be capable of alternative explanation. In the absence of evidence at other bombarding energies the possibility that the asymmetries about 90° arise from overlapping compound states cannot be eliminated.

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