Energy Levels of Si^{30}

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The distribution in range of the protons arising when aluminum is bombarded by 22-Mev alpha-particles, produced in the cyclotron, has been investigated. Seven groups of protons, having energies up to 17 Mev, have been measured. The energy levels of the resulting Si^{30} nucleus have been calculated and are found to be 0.0, (2.28), 3.49, 7.18, 8.20, 9.26, 9.87, and 10.86 Mev. Inelastic scattering of protons from aluminum has also been measured.

1. INTRODUCTION

THE study of the energy of the various proton groups, arising when aluminum is bombarded by high energy alpha-particles, shows that, aside from the ground state of the residual Si^{30} nucleus—associated with the longest range particles—several excited states of the Si^{30} nucleus, associated with shorter range proton groups, are formed. The reaction has been studied by Chadwick and Constable[1] who established the existence of several proton groups. They also showed that the number of protons in a given group varied with the energy of the oncoming alpha-particles and that resonance effects existed at certain alpha-particle energies. This reaction was further studied by Duncanson and Miller[2] who established the ground state and three excited states of the Si^{30} nucleus at 0, 2.28, 3.66, and 4.6 Mev. Work of a similar nature was performed by Haxel[3] and Meerhaut,[4] with substantially similar results. All of the above authors used alpha-particles from radioactive sources as the bombarding particle. Benson[5] used alpha-particles of 7.3 Mev, produced in a cyclotron, to investigate the reaction, and found results essentially in agreement with the earlier authors. In addition, by measuring coincidences between protons and gamma-rays, he established that gamma-rays were emitted from the excited states of Si^{30}.

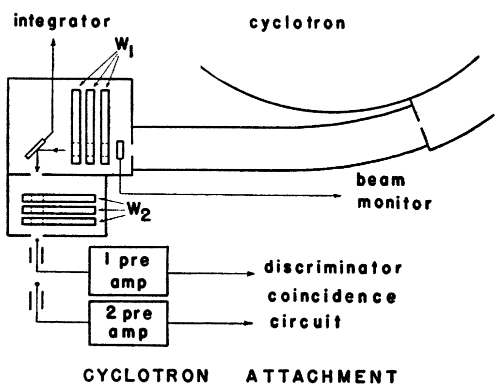

FIG. 1. Cyclotron attachment.

In all of the above investigations, alpha-particles of less than 8.6 Mev were used. Since the Indiana University cyclotron produces a good beam of 22 Mev alpha-particles, the reaction $Al^{27}(\alpha, p)Si^{30}$ was reinvestigated with the purpose of looking for protons from higher energy levels in the Si^{30} nucleus and also to investigate the spacing of these energy levels at higher excitation energy.

2. METHOD AND APPARATUS

The principle of the method is essentially the same as that used by the earlier investigators. An aluminum foil was bombarded in vacuum with 22 Mev alpha-particles from the cyclotron. The protons produced in the reaction, emerging from the aluminum foil at 90° to the incident beam, were counted with the help of two proportional counters in series, arranged for coincidence counting. The range of the various proton groups was determined by allowing the protons to pass through aluminum absorbers into the counting system.

Figure 1 shows the arrangement of the apparatus at the cyclotron. The cyclotron beam was conducted a distance of 43 inches from the gate chamber of the cyclotron by means of a 4-inch i.d. tube. The tube was curved to accommodate the alpha-particle trajectory in the fringing field of the magnet. At the gate end, there were placed a set of stainless steel slits. Upon entering the bombardment chamber the beam passed through an aluminum foil of 1.06 mg/cm² surface density and holes in three wheels W_1, designed to carry absorber foils, and thence to the target. The holes in the absorber wheels, gate slit and fringing magnetic field formed a beam analyzer which tended to monochromatize the beam.

The target was an aluminum foil of 1.06 mg/cm² surface density cemented to a brass ring in such a manner that the beam could not strike the ring. The ring was supported by a brass rod which emerged from the vacuum through a well-insulated Wilson seal. The current to the target was measured by an integrating meter which has been previously described.[6]

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[3] O. Haxel, Zeits. f. Physik **83**, 323 (1933); **88**, 346 (1934); **90**, 373 (1934).
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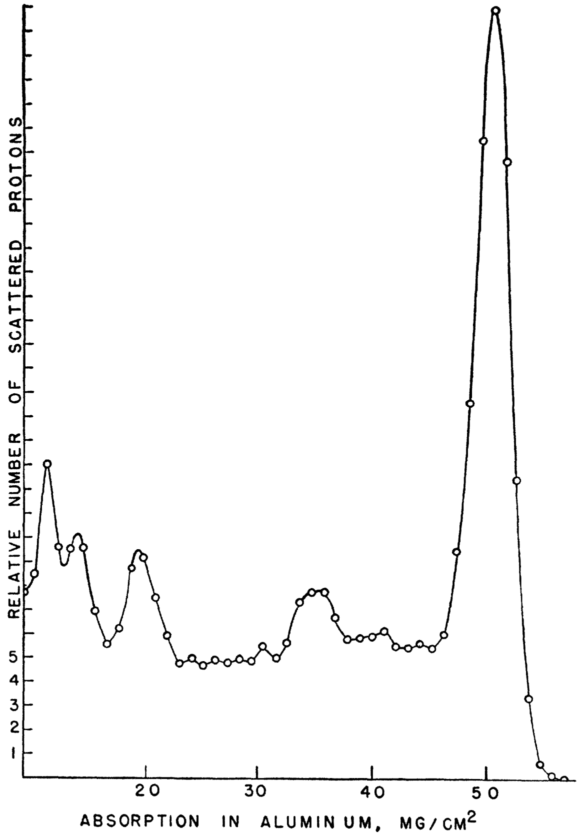

FIG. 2. Protons inelastically scattered from Al.

The protons emerging from the target pass through three wheels, designed to carry a number of absorbers, and into the proportional counters. All absorbers, except one of lead, were laminae of a basic sheet of aluminum of surface density 1.06 mg/cm² and were cemented to the wheels. The wheels could be viewed through windows and rotated to give any desired combination of absorbers.

The counter tubes were $\frac{7}{8}$-inch long and $\frac{1}{2}$-inch inside diameter. The inner wires of tungsten were 0.005-inch in diameter with bronze spheres on the ends. Both tubes were housed in a brass box containing argon at 8 cm Hg pressure. The window was of aluminum alloy, 0.001-inch thick, cemented to the box. The output of the counter tubes was boosted by preamplifiers of the Los Alamos type and fed into a conventional discriminator coincidence circuit. After mixing, the signal was counted on a scale of 128 set which also furnished the high voltage for the counter tubes.

3. EXPERIMENTAL DETAILS AND RESULTS

The apparatus was first tested to see whether sharp peaks could be obtained for protons at the end of their range. Hydrogen molecule ions were accelerated in the cyclotron. These have very nearly the same resonance conditions as deuterons. The beam was then passed through a monitor foil where the ion was stripped of its electron. The protons emerging from the monitor foil were then elastically scattered into the counter tube by the aluminum target. Absorption curves on the scattered protons were taken. The gain of the second channel associated with the last counter tube was varied until optimum peaking was found. The absorption curve is shown in Fig. 2.

The aluminum target was then bombarded with alpha-particles and minor adjustments made to the gain to secure a good compromise between peaking and counting rate. The whole proton absorption curve for alpha-particle bombardment was then run.

In order to calibrate the instrument, the target was replaced with a thin source of thorium C′ alpha-particles. This was prepared by collecting thorium active deposit on a ground stainless steel button from a mesothorium source. Air was used as absorber and the counter adjusted for the best alpha-particle peaks. Since the distance between the source and counter was known, the range spent in the counter was easily obtained. This was found to be 5.79 cm.

The energy of the impinging alpha-particles was obtained by several methods. The direct method consisted of measuring the energy of alpha-particles elastically scattered by a gold foil, of 0.17 mg/cm² surface density, in place of the aluminum target. A value of 21.80 Mev was obtained for alpha-particles entering the bombardment chamber. This quantity could also be computed indirectly from the scattering of protons from the cyclotron by aluminum; a value of 22.00 Mev being obtained.

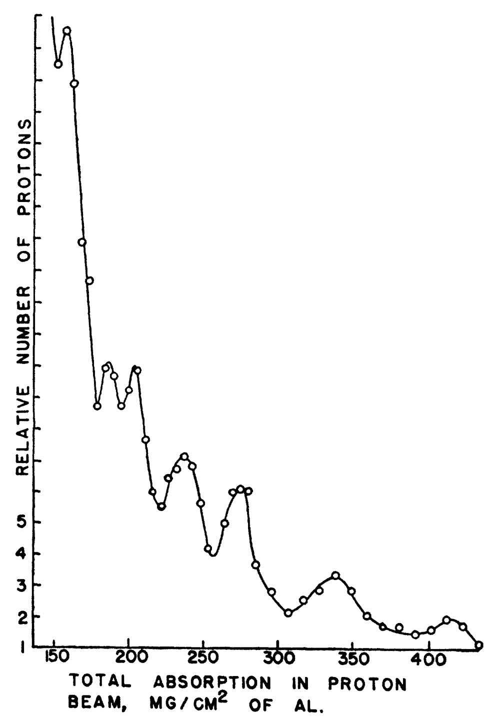

FIG. 3. Protons from Al(α, p)Si^{30}.

TABLE I. Energies and Q-values of proton groups in the reaction $Al^{27}(\alpha, p)Si^{30}$.

Proton energy (Mev)	Q (Mev)
16.85	−1.27
14.96	−3.22
13.28	−4.96
12.29	−5.98
11.27	−7.04
10.68	−7.65
9.72	−8.64

TABLE II. Energy levels of Si^{30} in Mev.

Present work	Benson's
	0
	2.28
3.49	3.66
	about 4.6
5.44	
7.18	
8.20	
9.26	
9.87	
10.86	

The mean of these two measurements 21.90 was taken as the final value. Messrs. R. G. Cochran and A. D. Schelberg, of this laboratory, have measured the energy of the alpha-particle beam, under similar conditions, by magnetic deflection and obtain a value of 21.84 Mev. The half-width of the alpha-particle beam is less than 200 kev.

After these tests, the aluminum target was bombarded with alpha-particles and the distribution in the range of the protons measured. The results of the measurements are shown in Fig. 3 in which the number of protons per unit beam intensity is plotted against the range of the protons.

To obtain the energy of the maxima shown in Fig. 3, the calculations of Smith[7] on the range energy relation for protons in aluminum were used. In Table I these proton energies and associated Q values are compiled. In these calculations, the energy of the alpha-particles striking the foil was taken as 21.54 Mev. This takes into account the absorption in the monitor foil and the mean loss in the target.

There are indications of additional higher energy levels. However, with the present technique, they are difficult to measure in the presence of a background of apparently continuously distributed protons. The proton background rises very rapidly with diminishing energy of the protons. At 2 Mev it is nearly 10,000 times greater than at 17 Mev.

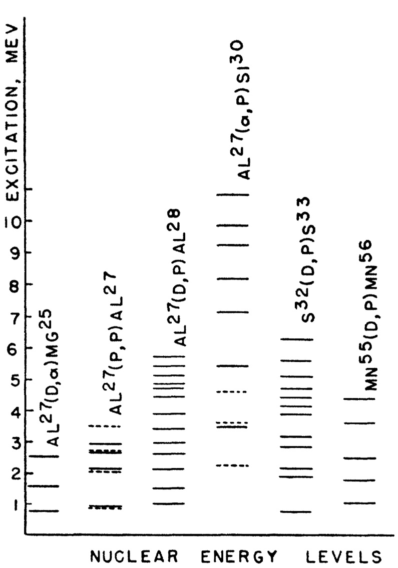

FIG. 4.

[7] J. H. Smith, Phys. Rev. 71, 32 (1947).

The range of the most energetic protons from this reaction could not be well-determined in this experiment. The counting rate in the 17 Mev region was extremely low, only 25 to 50 counts per point being obtained. For this reason the Q-value associated with those protons which go to the ground state was taken from the work of Benson,[5] who gives the value 2.22 Mev. Using this value, the positions of the energy levels of Si^{30} are given in Table II.

TABLE III. Energy levels of Al^{27} in Mev.

Present work	Dicke and Marshall
0.95	0.87
2.14	2.03
2.65	
2.93	2.70
	about 3.5

In the present work, the level reported by Benson at about 4.6 Mev does not appear to be excited. As Benson points out, however, the proton group associated with this level in his experiment comes at almost the same place as that to be expected from hydrogen contamination. Moreover, he finds fewer gamma-rays associated with this group than with the others. Furthermore, he has not resolved the group but obtains it by extrapolation. It is possible that this group is too weak to be observed in the present experiment.

From an inspection of Table II, it will be seen that the level spacing does not appear to decrease significantly with increasing energy. The spacing remains approximately constant at about 1 Mev.

4. INELASTIC SCATTERING OF PROTONS FROM Al^{27}

In the calibration experiments, mentioned earlier, in which protons from the cyclotron were scattered from aluminum, it was possible to observe, in addition to the main group of elastically scattered protons, several groups of protons inelastically scattered from aluminum.

From the results, shown in Fig. 2, a few low lying levels of Al^{28} were calculated.

Table III compares the present results with those of Dicke and Marshall.[8] The first two levels are in fair agreement. It is suggested that the third level reported by Dicke and Marshall as 2.70 Mev may possibly be two at 2.65 and 2.93 Mev. In the present experiment the protons available were not sufficiently energetic to observe the level reported by them at about 3.5 Mev.

5. DISCUSSION OF RESULTS

In the present experiments, evidence has been presented for the existence of excited states of Si^{30} up to about 11 Mev excitation energy. There also appear to be higher levels above 11 Mev, but the proton groups from which the energy levels are derived ride on a continuous background of protons thus making the measurement at this energy difficult. The most striking feature of the results is the large spacing between energy levels and the fact that the spacing does not appear to decrease with increasing excitation energy, at least up to 11 Mev. The results are shown graphically in Fig. 4, along with certain other energy levels to be discussed later.

The liquid drop model and statistical theories predict a much closer spacing and also that the spacing should get closer as the excitation increases. Weisskopf,[9] using a thermodynamical theory of the nucleus, gives the following equation for the level density as a function of energy for nuclei in the neighborhood of Si^{30}.

$$D=10^6 \exp[-2(E)^{\frac{1}{2}}].$$

The values given by this formula for various excitation energies are listed in Table IV. It is interesting to compare this with Fig. 4. There is no apparent agreement.

Table IV.

Excitation energy	Spacing
2 Mev	59 kev
4	18
6	7.5
8	3.5
10	1.5

The wide spacing of the energy levels observed in this and all other experiments of this type is difficult to reconcile with the predictions of the liquid drop and other statistical models. This is especially true when, as in the case here, some of the observed levels lie above the neutron binding energy. The fact that the proton groups appear to ride on a continuous background of protons whose intensity increases as one goes to lower proton energies has led to some speculation on the nature of these groups. It has been suggested that this continuous background of protons may be an unresolved series of proton groups with very small energy level spacing and that the proton groups observed, associated with the higher energy levels, may be an envelope of more closely spaced levels. From the experimental point of view there is no doubt about the existence of the groups, and hence the validity of the energy levels, since the observed spacing of the groups is roughly 1 Mev and the resolving power about 200 kev. The theoretical explanation of the wide level spacing observed is at present not clear from the usual considerations of the liquid drop model. Its solution may lie more in the direction of considering certain other modes of vibration of the nucleus, possibly somewhat similar to the considerations of Goldhaber and Teller.[10]

Figure 4 also shows, for comparison, the energy levels of Mg^{25} obtained from $Al^{27}(d\alpha)$,[11] Al^{27} from inelastic scattering of protons,[12] Al^{28} from $Al^{27}(dp)$,[11] S^{33} from $S^{32}(dp)$,[13] and Mn^{56} from $Mn^{55}(dp)$.[14] The levels drawn in with dashed lines in Al^{28} are those of Dicke and Marshall and those similarly indicated in Si^{30} are those of Benson. It will be noticed at once that the level spacing in the Si^{30} nucleus is greater than in any of its near neighbors. This phenomenon seems to have no very obvious explanation.

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