The Decay Scheme of Cl^{39}

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Argon has been irradiated and Cl^{39} produced by the reaction $A^{40}(\gamma, p)Cl^{39}$. The threshold was found to be 14.2 Mev. The Cl^{39} activity was found to have two beta-particles of energies 2.96 and 1.65 Mev, and two gamma-rays of energies 1.31 and 0.35 Mev, the low energy gamma-ray having a conversion coefficient of 0.05. A decay scheme is proposed. Consideration of the results show that A^{39} must have a half-life greater than five years or a decay energy of less than 0.4 Mev.

I. Cl^{39}

ARGON gas has been irradiated in the University of Saskatchewan betatron, and Cl^{39} produced[1] by the reaction $A^{40}(\gamma, p)Cl^{39}$. The half-life of the chlorine isotope was found to be 55.5±0.2 minutes.

This paper describes the measurement of the beta- and gamma-energies and proposes a decay scheme for the Cl^{39} isotope. It also gives the threshold energy for this reaction.

The maximum energies were measured by absorption in aluminum. The absorption curve Fig. 1 shows a very gradual tailing into the background. An analysis of this curve was carried out by a modification of the method previously described in the literature.[2,3] This analysis showed that the curve represented a complex spectrum; this conclusion was confirmed by an analysis in a magnetic field. The power plot[2] of the absorption curve is shown in Fig. 2. The maximum energies and branching ratios of the two beta-spectra were found to be:

2.96±0.04 Mev— 7 percent
1.65±0.03 Mev—93 percent.

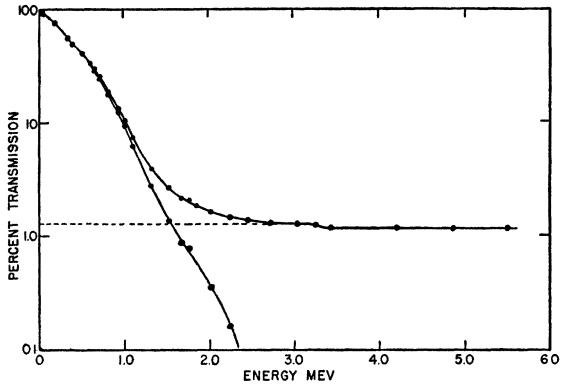

FIG. 1. Absorption of β^--particles from Cl^{39}. The breaks in the curve at 0.35 Mev and 3.2 Mev due to the two conversion peaks are clearly visible.

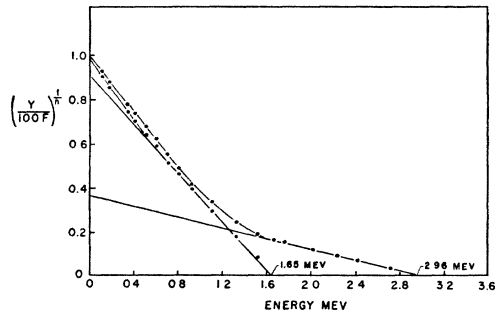

FIG. 2. The power plot of the absorption curve of Cl^{39}.

Two conversion peaks appeared in the absorption curve and were subtracted during the process of analysis. The existence of one of the peaks, near 0.3 Mev, is supported by coincidence measurements. The second conversion peak is at about 3.2 Mev. It is of very low intensity, about 0.11 percent, but appears to be real. It appeared in three absorption curves. However, in only one case was sufficient accuracy obtained to confirm its existence. It is not supported by coincidence measurements, nor can it be explained by any combination of beta- and γ-energies. The conversion peak at 0.3 Mev constitutes about five percent of the total beta-count at zero absorber.

Coincidence measurements were undertaken to determine the decay scheme and to measure the γ-energies.

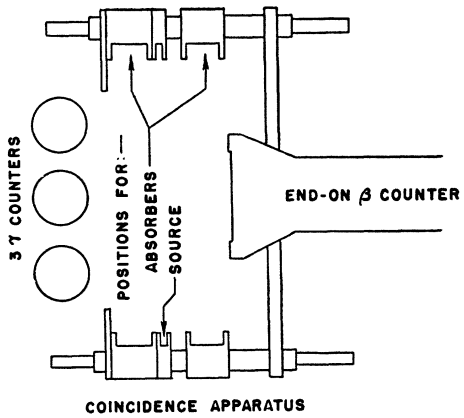

FIG. 3. The experimental arrangement used for the beta-beta and beta-gamma coincidence measurements with Cl^{39}.

[1] Haslam, Katz, Johns, and Moody, Phys. Rev. **76**, 704 (1949).

[2] Katz, Penfold, Moody, Haslam, and Johns, Phys. Rev. **77**, 289 (1950).

[3] A paper now in preparation on this modification will be published shortly.

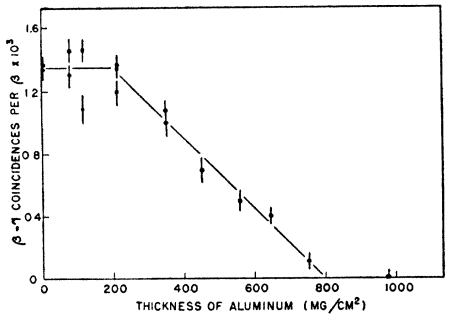

FIG. 4. Beta-gamma coincidences per recorded beta-particle from Cl^{39} plotted against the thickness of aluminum before the beta-counter.

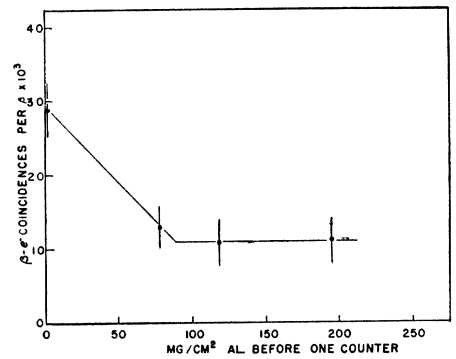

FIG. 5. Beta-beta coincidences per recorded beta-particle from Cl^{39} plotted against the thickness of aluminum before one counter.

The experimental arrangement is shown in Fig. 3. To obtain a high counting rate three cylindrical aluminum walled counters (30 mg/cm²) are connected in parallel and used as a γ-counter. The beta-counter is a mica window end-on counter. The signals from the beta- and gamma-counters are amplified in two preamplifiers and then fed into the coincidence mixer.

Gamma-gamma coincidences were observed, indicating the existence of two or more γ-rays in cascade. Beta-gamma coincidences were then measured. A plot of the number of coincidences per recorded beta-particle *versus* the thickness of aluminum between the source and the beta-counter is shown in Fig. 4. It displays the characteristic shape associated with a complex beta-spectrum. The end point of the coincidence absorption curve is about 1.75 Mev. This is due to the low energy beta-spectrum. The flattening at low energies is evidently due to a low energy beta-particle, presumably a conversion electron. To verify this, $\beta-\beta$ coincidences were measured with absorbers in front of one counter only. The resulting curve is shown in Fig. 5: the end point was determined at 0.35±0.05 Mev.

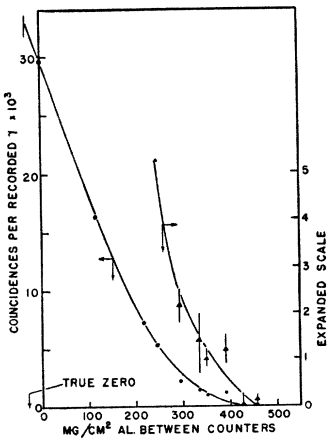

FIG. 6. The coincidence absorption curve of the secondary electrons from Cl^{39}. The lower portion of the curve is shown to an expanded scale with the standard deviation of the experimental points indicated.

Measurements were also made by coincidence absorption of secondary electrons to determine the highest energy γ-ray present. The resulting curve is shown in Fig. 6, with the end point plotted to an enlarged scale. The total range including the counter wall thickness was determined at 460 mg/cm². Using the range-energy curve[4] and the theoretical expression for the energy of the Compton electron ejected in the forward direction, the γ-energy was found to be 1.35±0.05 Mev.

The difference in energy between the 2.96 Mev and 1.65 Mev beta-particles is 1.31 Mev. This obviously corresponds to the 1.35 Mev γ-ray measured by coincidence absorption of secondary electrons. The low energy γ-ray must then follow both beta-particles as shown in Fig. 7. This would mean that the high energy beta-particles should also show β-γ-coincidences. That these coincidences were not observed can be attributed to the low intensity of the high energy beta-particle, the decreased counting efficiency[5] of the 0.3-Mev γ-ray, and the low transmission through 800 mg/cm² of aluminum where these coincidences should have been

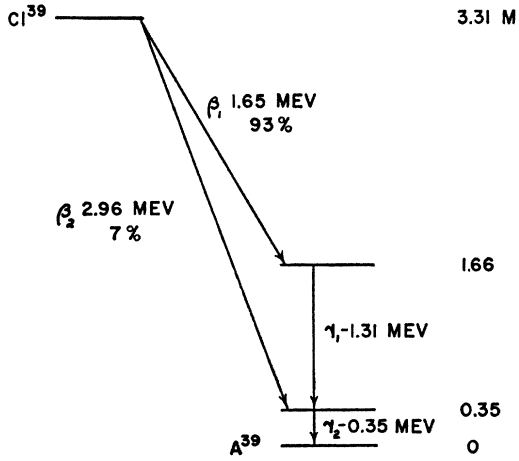

FIG. 7. The proposed decay scheme for Cl^{39}. The energies given do not include the rest mass of the beta-particle.

[4] C. Goodman, ed., *The Science and Engineering of Nuclear Power*, Vol. 1 (Addison-Wesley Press, Cambridge, 1947).

[5] Fowler, Lauritsen, and Lauritsen, Rev. Mod. Phys. **20**, 236 (1948).

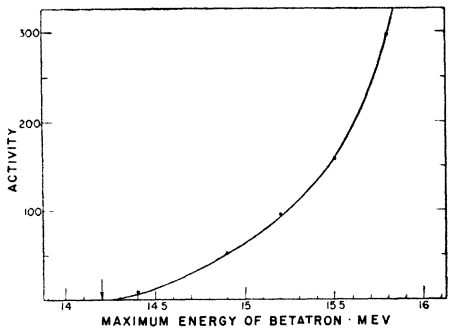

FIG. 8. The Cl^{39} activity curve plotted against the maximum energy of the betatron. The threshold energy for the reaction $A^{40}(\gamma, p)Cl^{39}$ is at 14.2±0.2 Mev.

observed. Assuming appropriate values for these factors one would expect a coincidence rate per recorded beta- of about 0.04×10^{-3}. This is less than the statistical fluctuations of the measurements.

II. A^{39}

Since no activity that could be attributed to A^{39} was observed certain limits can be placed upon the half-life of this isotope.

A^{39} is formed when Cl^{39} disintegrates with the emission of a β^- particle. If the half-life of A^{39} were less than that of Cl^{39} then, when in equilibrium, the disintegration of a chlorine atom would on the average be accompanied by the disintegration of an atom of argon. This would mean that the β-spectra could be divided into two groups of equal intensities. The branching ratio of the two primary β particles is 0.93 and 0.07 with the conversion electrons contributing five percent of the total count. No division into equal parts is possible so it is concluded that the half-life of A^{39} is longer than that of Cl^{39}. An initial recorded chlorine activity of 78,500 counts/min. was obtained which was then allowed to decay to zero and an estimate made of the maximum possible activity remaining. No long-lived activity was observed though two counts per minute would have been readily detectable. A comparison of activities gives an estimated minimum half-life of about five years.* To make sure that the argon gas did not escape as soon as it was formed, the active chlorine was sealed in a thin-windowed glass capsule. The glass window was about 100 mg/cm² thick so that if the β-energy is less than about 0.4 Mev it would not have been observed at all. In a previous article[1] we reported a small residual count. This has not been observed since the procedure for removing the chlorine from the chamber has been altered. It is therefore thought that it may have been due to a slight amount of 12-hour activity from copper dissolved from the walls of the brass irradiation chamber by the dilute hydrochloric acid.

* *Note added in proof:* This value is not in disagreement with a minimum half-life of fifteen years recently reported for an argon isotope, presumably A^{39} formed by $K^{39}(n, p)A^{39}$. [Brosi, Zeldes, and Ketelle, Phys. Rev. **79**, 902 (1950)].

TABLE I.

	Cl^{39}	A^{39}
Beta-energies (Mev)	1.65(93%); 2.96(7%)	—
Gamma-energies (Mev)	1.31 0.35	—
Total disintegration energy (Mev)	3.3	3.8
Conversion coefficient $\alpha=0.05$ for 0.35 Mev gamma		—
Mass	38.9826	38.9790

III. THRESHOLD AND MASS DETERMINATIONS

A series of irradiations was made with the purpose of measuring the gamma-threshold energy for the production of Cl^{39} from A^{40}. Each irradiation was made at a slightly different energy, the energy being determined by the integrator circuit previously described.[6] Extreme care was taken in performing the chemical separation so that conditions might be duplicated from run to run. The observed activity, after being corrected for dosage rate and irradiation time, was plotted against the maximum energy of the betatron. The curve is shown in Fig. 8. The threshold energy is determined at 14.2±0.2 Mev.

From the known mass[7] of the A^{40} isotope, the threshold energy for the production of Cl^{39}, and the total disintegration energy of the Cl^{39} isotope, the masses of Cl^{39} and A^{39} can be calculated. Also using the known mass of the K^{39} isotope the total disintegration energy of A^{39} can be determined. The results of these calculations are given in Table I. It should be noted that the mass of K^{39} is not as well known as that[8] of A^{40} and for that reason the total disintegration energy of A^{39} may be in error by an undetermined amount.

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[6] Katz, McNamara, Forsyth, Haslam, and Johns, Can. J. Research **28**, 113 (1950).

[7] L. Rosenfeld, *Nuclear Forces* (North Holland Publishing Company, Amsterdam, 1948), pp. 501–528.

[8] See reference 7, page 499.