Beta- and Gamma-Radiation of Al^{28}*

HENRY T. MOTZ AND DAVID E. ALBURGER
Brookhaven National Laboratory, Upton, New York
(Received December 14, 1951)

The beta- and gamma-rays occurring in the decay of Al^{28} have been measured by means of lens spectrometers using sources activated by the (n, γ) and (d, p) reactions on aluminum. The gamma-ray has an energy of 1.782 ± 0.010 Mev and the beta-ray end point is found to be 2.865 ± 0.010 Mev. The total disintegration energy is consistent with nuclear reaction Q-values linking Al^{28} and Si^{28}. It is shown that a discrepancy of 0.4 mMU in the $Si^{28}-Al^{27}$ mass difference exists when reaction data is compared to mass spectroscopic values. A mass for Al^{27} of $26.990\ 140\pm0.000\ 035$ is proposed, based on Si^{28}, P^{31}, and S^{32} as standards.

INTRODUCTION

THE beta- and gamma-rays of 2.30-minute Al^{28} have been studied by several observers during the past ten years. Itoh[1] found one gamma-ray of energy 1.82 ± 0.02 Mev from the distribution of the Compton electrons from a carbon radiator using a 180° magnetic spectrometer. Watase showed[2] that beta-gamma coincidences were present and found no gamma-gamma coincidences. By using a cloud chamber, Eklund and Hole found[3] a simple beta-spectrum with an end point of 2.98 ± 0.18 Mev and a single gamma-ray of energy 2.05 ± 0.15 Mev. Bleuler and Zünti investigated[4] the absorption of the beta- and gamma-rays and obtained a value 2.75 ± 0.10 Mev for the beta end point and 1.80 ± 0.10 Mev for the gamma-ray. These authors also found beta-gamma coincidences. Benes, Hedgran, and Hole found[5] a beta end point of 3.01 Mev and a gamma-ray energy of 1.80 Mev using a thin lens spectrometer. The simple cascade nature of the radiations and their approximate energy values are well established by these investigations.

Recent mass values[6] based on mass spectroscopic and reaction data indicated that the $Al^{28}-Si^{28}$ mass difference was 4.39 ± 0.08 Mev, which is outside the range of the observed values previously quoted. Though this predicted value of 4.39 Mev is now known to be in error, it was thought necessary to have a more accurate experimental value of the total energy in order to reliably check the mass difference of Al^{28} and Si^{28}.

GAMMA-RADIATION

Commercially available 2S aluminum irradiated in the Brookhaven Nuclear Reactor was found to have an initial long-lived activity due to impurities of less than 1 percent for a four minute exposure. This material was considered sufficiently pure for the purposes of this experiment. The externally converted electrons from successive 20- to 30-second exposures of 700 mg samples were studied with a thin lens beta-ray spectrometer. Uranium foil converters of 21- and 42-mg/cm² thickness were used with a resolution of 2 percent in momentum. The electron spectrum was observed over the range of 0.1 to 4.0 Mev, and only one gamma-ray was found in agreement with previous observers. A typical spectrum of the Compton end point and the K and L photoelectron peaks is shown in Fig. 1. In order to integrate the source strength over a counting interval, a monitor counter was used. The spectrometer yield for a fixed number of monitor counts above background was recorded for each setting of the magnet current. Overlapping points were taken for each exposure, and a total of about 15 exposures of each aluminum sample was necessary to complete a run. The spectrometer was calibrated with the internal conversion line of Cs^{137} and the external conversion lines of Na^{24}, ThC″, and Co^{60}. The gamma-ray energy calculated from both the peak and extrapolated momenta of the K photoelectric peak was found to be 1.782 ± 0.010 Mev. The less accurate values obtained from the Compton end point and the L photoelectric peak agree well with this value.

BETA-SPECTRUM

Two independent experiments were carried out to investigate the beta-ray spectrum. The first was done

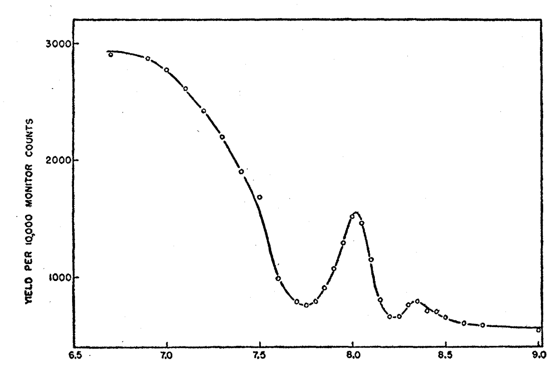

FIG. 1. External conversion electrons from Al^{28} gamma-ray using a 42-mg/cm² uranium converter.

* Research carried on under contract with the AEC.
[1] J. Itoh, Proc. Phys.-Math. Soc. Japan 23, 605 (1941).
[2] Y. Watase, Proc. Phys.-Math. Soc. Japan 23, 618 (1941).
[3] S. Eklund and N. Hole, Arkiv, Mat. Astr. Fys. 29, No. 26 (1943).
[4] E. Bleuler and W. Zünti, Helv. Phys. Acta 20, 195 (1947).
[5] Benes, Hedgran, and Hole, Arkiv Mat. Astr. Fys. 35, No. 12 (1948).
[6] H. T. Motz, Phys. Rev. 81, 1061 (1951).

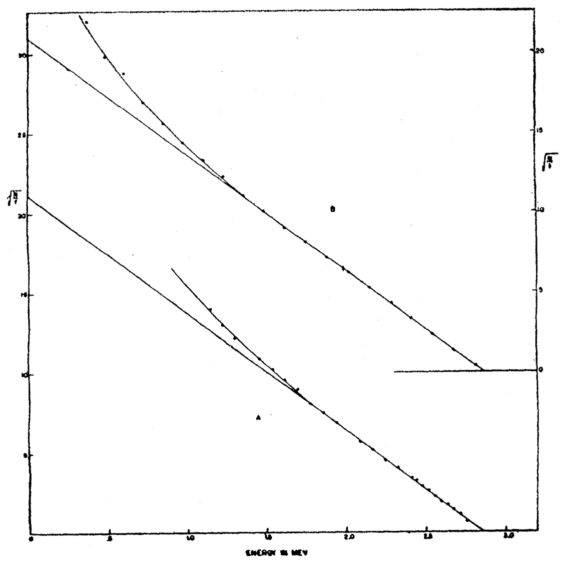

FIG. 2. Kurie plot of Al^{28} beta-spectrum. Curve A, (n, γ) activation; Curve B, (d, p) activation.

with reactor-activated sources and the second with the Brookhaven electrostatic accelerator and a similar but different lens spectrometer. The reactor experiment utilized 2-mg/cm² aluminum foils exposed for two to three minutes. The sources had an initial activity of about 500 microcuries and could be used for four or five momenta settings for a fifteen minute counting period before the background correction became too large. New foils were used for each exposure to avoid the build-up of long-lived activities. The beta-rays entered the spectrometer vacuum chamber through a 10-mg/cm² aluminum port. A thin-window monitor counter was used to determine the average source strength as for the gamma-ray observations. The effect of the aluminum port and source thickness was studied with the use of a source of P^{32} mounted on 2-mg/cm² aluminum foil. The Kurie plot[7] for P^{32} deviated from a straight line below 800 kev and gave an end point of 1.70±0.01 Mev. The Kurie plot obtained from one of the three runs on Al^{28} is shown in Fig. 2, Curve A. The deviation from a straight line is not inconsistent with the results from P^{32}. Some of the scatter in the points is probably due to slight misalignment of the sources and is somewhat greater than the expected statistical variation of yield. By means of a least squares fit, the observed end point is found to be 2.859±0.020 Mev from the reactor-activated samples.

In the second set of experiments, using the electrostatic accelerator, the activity was formed in aluminum foils by the $Al^{27}(d, p)Al^{28}$ reaction using a 2.0-Mev deuteron beam. The foils were 0.22 and 0.9 mg/cm² in thickness, and the corresponding beam currents of 6 and 1.5 microamperes gave similar source strengths. The lens spectrometer was connected to the beam tube of the accelerator in such a way that the foils were located at the normal source position of the spectrometer. A baffle system in the beam tube defined the region of activation to a spot 5 mm in diameter, and the deuteron current passing through the target was collected and measured by means of an insulated Faraday cup attached to the center lead baffle of the spectrometer.

The procedure consisted of irradiating the target for about 2 minutes, turning off the beam, and counting for several minutes. In order to normalize the spectrometer yield to a standard number of disintegrations a gamma-ray monitor was placed near the source, and the data were taken in a manner similar to that described in the reactor experiments.

In initial tests the presence of 10-minute N^{13} positron activity formed by deuteron bombardment of carbon deposits on the target was detected. This caused inconsistency in the data below 1.2 Mev (the positron end point) because of the monitoring technique and resulted in excessive low energy deviations in the Kurie plot. The positrons were finally removed by the installation of a spiral baffle system. The baffles were also found to reduce considerably the background of scattered beta-rays beyond the end point of the spectrum and permit an estimate that not more than 2 percent of the Al^{28} beta-decays go to the ground state of Si^{28}.

The Kurie plot of the beta-ray spectrum is shown in Fig. 2, Curve B, for a 0.22-mg/cm² source. Deviations from linearity occur below 1.2 Mev and vary with the thickness of the source used. From the straight line portion of the curve a least squares analysis gives an end point energy of 2.866±0.010 Mev. The 2.76-Mev Na^{24} gamma-ray was used for calibration. The combined results of all data using both spectrometers gives the value 2.865±0.010 Mev for the Al^{28} beta-ray end point. Using this figure and the measured half-life, the log ft value of the transition is 4.92 as calculated from the graphs given by Moszkowski.[8] This value and the linearity of the Kurie plot show that the beta-decay is of the allowed type.

DISCUSSION

By means of several nuclear reaction Q-values reported by the MIT Group[9] it is possible to calculate the expected total disintegration energy of Al^{28}. Table I lists the observed Q-values and the predicted total disintegration energy as derived from two combinations of the data. The p, d, and α masses given by Li *et al.*[10] were used in these calculations. The observed beta-decay value agrees well with the two calculated from the reaction values and is somewhat more accurate. These data can be used to find the mass difference

[7] The accurate relativistic Fermi functions kindly furnished by the Computation Laboratory of the National Bureau of Standards were used in all of the Kurie plot calculations.

[8] S. A. Moszkowski, Phys. Rev. **82**, 35 (1951).
[9] MIT Progress Report, May 1951.
[10] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. **83**, 512 (1951).

$Si^{28}-Al^{27}$ by combining the Al^{28} decay energy with the other Q-values. The result is a mass difference $Si^{28}-Al^{27}=0.995\ 702\pm0.000\ 018$ MU. The mass of Si^{28} has been reported as $27.985\ 810\pm0.000\ 080$[11] and $27.985\ 792\pm0.000\ 032$ MU.[12] The average of these is $27.985\ 795\pm0.000\ 032$ MU. The mass doublet $C_2H_3-Al^{27}$ has been given as 42.35 ± 0.065 mMU.[13] Using recent values[10] for C and H, a mass of $26.989\ 684\pm0.000\ 070$ is found for Al^{27}. From these mass spectrographic data, one finds $Si^{28}-Al^{27}$ $0.996\ 111\pm0.000\ 080$ MU. The reaction mass difference $0.995\ 702\pm0.000\ 018$ MU is not in agreement with this and indicates that either the absolute value for Al^{27} or that for Si^{28} must be in error by about 0.4 mMU.

The most accurately measured Q-values linking Si^{28} to P^{31} and S^{32} indicate that the Si^{28} mass is consistent with the P^{31} and S^{32} masses[12] to 0.000 04 MU, which is less than the combined probable errors of the observed quantities. Similarly the mass of Si^{28} is consistent with the mass of the Ne^{20} [12] within the same limit. Thus it seems reasonable to accept the Si^{28} mass spectrographic value and reject the Al^{27} value. Using the Si^{28}, P^{31}, and S^{32} masses as standards, one can derive a mass for Al^{27} that is consistent with the known Q-values linking these isotopes.[14] Such a fit gives a value of $26.990\ 140\pm0.000\ 035$ for Al^{27}.

TABLE I. Calculated and observed disintegration energy of Al^{28}.

Disintegration energy (Mev)	Reaction chains and decay energies	Reference
4.657±0.019	$Si^{28}(d, p)Si^{29}$ $Si^{29}(d, \alpha)Al^{27}$ $Al^{27}(d, p)Al^{28}$	a
4.637±0.020	$Si^{28}(d, p)Si^{29}$ $Si^{29}(d, p)Si^{30}$ $Si^{30}(d, \alpha)Al^{28}$	a
4.647±0.014	Beta endpoint 2.865±0.010 Mev Gamma-ray 1.782±0.010 Mev	present work

a See reference 9.

We are indebted to Dr. I. Feister and Miss Irene Stegun of the National Bureau of Standards for supplying the Fermi functions in advance of publication.

11 H. E. Duckworth and R. S. Preston, Phys. Rev. **79**, 402 (1950).
12 H. Ewald, Z. Naturforsch. **6a**, 293 (1951).
13 S. Flügge and J. Mattauch, Physik. Z. **42**, 1 (1941).
14 H. T. Motz, Phys. Rev. **85**, 501 (1952).

PHYSICAL REVIEW VOLUME 86, NUMBER 2 APRIL 15, 1952

Stars Initiated by High Energy Protons and Neutrons

HERBERT FISHMAN AND ALFRED MORRIS PERRY, JR.
Department of Physics, University of Rochester, Rochester, New York
(Received December 20, 1951)

Stars initiated in nuclear emulsions by 240-Mev protons and 180-Mev neutrons have been studied. Size-frequency distributions of the stars and angular distributions of prongs in various energy intervals have been obtained. Comparison with similar results obtained at different energies shows that the star size distribution is more sensitive to incident energy for protons than for neutrons.

I. INTRODUCTION

STARS in photographic emulsions have been studied by several investigators for a variety of incident particles.[1–5] In such experiments, it is hoped, from the average properties of large numbers of stars, to gain insight into the manner in which energetic nucleons interact with nuclei, and to test various nuclear models.

In the present experiment stars initiated by protons of about 240 Mev and neutrons of about 180 Mev have been examined in sensitive emulsions.

II. EXPERIMENTAL PROCEDURE

A. Protons

Ilford G-5 plates, 200, 300, and 600 microns thick were exposed to the proton beam of the 130-in. cyclotron by a method first used by Bernardini, Booth, and Lindenbaum[6] at Columbia. The plates were placed parallel to the median plane of the cyclotron, about $\frac{7}{8}$ in. above and below it, and in the neighborhood of the cyclotron radius at which $-d(\ln H)/d(\ln R)=0.2$. At this radius large vertical oscillations of the proton beam occur, and in the absence of other targets, a parallel beam of protons is spread out over the plates. In azimuth the plates were placed as far as possible from the "up-beam" edge of the dee, to reduce background caused by knock-on neutrons. Exposures were for one to two seconds with arc source and hydrogen supply turned off.

Microscopic scanning for events was done in two ways: by a systematic search over the area of the plate, and by following individual proton tracks which were selected in an unprejudiced manner near the leading edge of the plate. The latter method, while far more tedious, is much more reliable for events with few

1 E. Gardner and V. Peterson, Phys. Rev. **75**, 364 (1949).
2 E. Gardner, Phys. Rev. **75**, 379 (1949).
3 L. S. Germain, Phys. Rev. **82**, 596 (1951).
4 E. W. Titterton, Phil. Mag. **42**, 109 (1951).
5 Bernardini, Booth, and Lindenbaum, Phys. Rev. **80**, 905 (1950); **83**, 669 (1951).
6 S. J. Lindenbaum (private communication).