The numerical computation for N^+/N^- is carried out for $Z=16$, and for three values of x_0: $x_0=7$, 5, 4.33. The last value of x_0 corresponds to the experiment of Greenberg and Deutsch, and yields

$$N^+/N^-=0.55\times10^{-9}, \quad (21)$$

in good agreement with the experimental value (1). The other values of x_0 do not correspond to any physical case, since they are all calculated for $Z=16$. They are included to show the dependence of N^+/N^- on the energy available. The numerical results may be tabulated as follows:

x_0	$H(x_0)$	$G(x_0)$	N^+/N^-
7	1001.36	2.926	33.9×10^{-9}
5	173.25	0.0461	3.08×10^{-9}
4.33	80.25	0.00380	0.55×10^{-9}

Plots of N^+/N^- and the positron spectrum $F(x_+)$ may be found in the paper of Greenberg and Deutsch[2] and will not be repeated here.

The author wishes to acknowledge the help of the Joint Computing Group of the Laboratory for Nuclear Science, M.I.T. In particular, he wishes to thank Miss Elizabeth Campbell and Mrs. Barbara Levine for carrying out the laborious computations involved. He is also indebted to Dr. J. S. Greenberg and Professor M. Deutsch for providing and discussing their experimental results before publication. Last but not least, thanks are due to Professor S. D. Drell for his interest in this problem and for helpful discussions.

PHYSICAL REVIEW VOLUME 102, NUMBER 2 APRIL 15, 1956

Decay of the New Nuclide Ne^{24}†*

B. J. DROPESKY AND A. W. SCHARDT
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

(Received January 12, 1956)

The nuclide Ne^{24} has been produced by bombarding a neon gas target with 1.5-Mev tritons, the reaction being $Ne^{22}(t,p)Ne^{24}$. Beta and gamma scintillation spectrometers with coincidence circuits were used to study this nuclide. Ne^{24} decays with a half-life of 3.38±0.02 min, emitting negative beta groups of 1.98±0.05 and 1.10±0.05 Mev. This decay is also accompanied by gamma rays of 472±5 and 878±9 kev with relative intensities of 100 to 8, respectively. The excited levels in Na^{24} corresponding to the above transitions are at 0.472 and 1.35 Mev. The 0.472-Mev level is an isomeric state with a half-life of the order of 20 milliseconds. The spins and parities of the Na^{24} ground state, 0.472-Mev, and 1.35-Mev levels are 4+, 1+, and 1+, respectively. The $Ne^{24}-Na^{24}$ energy difference is 2.449±0.035 Mev, and the Ne^{24} mass is 24.001195 ±0.000040 atomic mass units.

INTRODUCTION

THE availability of tritons as bombarding particles has made it possible to add two neutrons to stable nuclides by means of the (t,p) reaction.[1] In the region of light elements several of these isotopes have been observed in this laboratory.[2] The neon activities, Ne^{23} and Ne^{24}, resulting from the (t,p) reaction on neon are relatively easy to study because they can be separated from other activities by passing the gas through a cold charcoal trap. Ne^{24} was of primary interest because it had not been investigated previously, and because its decay scheme was expected to yield information about the levels of the odd-odd nucleus Na^{24}.

Sheline and co-workers,[3] considering the nuclides Si^{32}, Mg^{28}, Ne^{24}, and O^{20}, speculated about the properties of the then unknown Ne^{24}. They estimated the $Ne^{24}-Na^{24}$ mass difference to be 4.4 Mev by extrapolating the mass differences of $Mg^{28}-Al^{28}$ and $S^{36}-Cl^{36}$. Alternately, predictions of mass differences can be made by employing formulas derived from the uniform model of the nucleus.[4] These predictions have been relatively successful in the region of medium-light nuclei. Values of 3.3 and 2.7 Mev are predicted for the $Ne^{24}-Na^{24}$ mass difference, depending on whether the parameters are fixed by the $Mg^{28}-Al^{28}$ or $S^{36}-Cl^{36}$ differences. The discrepancy between these values is typical of shell effects, the magic number 20 being involved in the case of S^{36}. With this amount of energy available, it is to be expected that Ne^{24} would decay to excited levels[5] of Na^{24}, since the ground-state transition would involve a spin change of 4. Spin and parity assignments[6] of 1+ or 2+ have been made to the Na^{24} level at 1.34 Mev and to one of the levels at 0.472 and 0.564 Mev. It

† This work was performed under the auspices of the U. S. Atomic Energy Commission.
* A preliminary report of this work appears in Phys. Rev. **100**, 954 (A) (1955).
[1] D. N. Kundu and M. L. Pool, Phys. Rev. **73**, 22 (1948).
[2] The only previous publication resulting from this work refers to F^{21} [N. Jarmie, Phys. Rev. **99**, 1043 (1955)].
[3] Sheline, Johnson, Bell, Davis, and McGowan, Phys. Rev. **94**, 1642 (1954).
[4] I. G. Weinberg and J. M. Blatt, Am. J. Phys. **21**, 124 (1953).
[5] P. M. Endt and J. C. Kluyver, Revs. Modern Phys. **26**, 95 (1954).
[6] P. Shapiro, Phys. Rev. **93**, 290 (1954). Bretscher, Alderman, Elwyn, and Shull, Phys. Rev. **96**, 103 (1954).

seemed probable, therefore, that the beta decay of the even-even Ne^{24} would be allowed and that a relatively short half-life could be expected.

Triton bombardment of normal neon gas (90.9% Ne^{20}, 0.26% Ne^{21}, and 8.8% Ne^{22}) gives rise to a number of different radionuclides. The following reactions are expected to have appreciable cross sections: $Ne^{20}(t,n)Na^{22}$, 2.6 yr;[7] $Ne^{21}(t,p)Ne^{23}$, 40 sec; $Ne^{21}(t,\alpha)F^{21}$, 10 sec; $Ne^{22}(t,n)Na^{24}$, 15 hr; $Ne^{22}(t,\alpha)F^{21}$, 5 sec; and $Ne^{22}(t,p)Ne^{24}$. In addition, 112-min F^{18} will be produced if any oxygen is present because the $O^{16}(t,n)F^{18}$ reaction has a large cross section.[8] It is apparent that sodium and fluorine activities have to be removed from the irradiated neon before the Ne^{24} decay can be studied.

EXPERIMENTAL METHODS

A relatively simple method was employed for irradiating neon gas with a beam of tritons, purifying the neon of sodium and fluorine activities, and examining the radiations from the neon. Figure 1 shows a schematic arrangement of the components of the gas handling system. The gas target was a conically shaped vessel with an 0-ring-sealed aluminum window 1.4 mg/cm² thick and a beam path length through it of 2 cm. This target was in turn 0-ring-sealed to the beam tube carrying the analyzed tritons of the 2.5-Mev Los Alamos electrostatic accelerator. The trap between the gas target and the counting cell consisted of a small hollow brass cylinder which contained about 1 cc of activated carbon (mesh size 20–35). The counting cell shown in Fig. 1 was used for measuring the gross and coincidence beta spectra. Other counting cells were used, depending upon the particular experiment being carried out; all of them were made of dural and had sample chambers with a diameter of 1.5 in. and lengths of 0.25 to 1.5 in.

Before each irradiation the gas target was evacuated through the $\frac{1}{8}$-in. connecting tubing and then filled with tank neon (Linde, spectroscopic grade, 99.9% pure) to a pressure of about 58 cm Hg. After closing the target valve the rest of the system was again evacuated to 10 to 25μ of Hg. The target was bombarded for 10 min with a 2μa beam of 1.83-Mev tritons. Of this energy, 0.33 Mev was spent in the aluminum foil and 0.40 Mev in the neon gas. At the end of the bombardment the system was sealed from the vacuum pump and the irradiated neon was allowed to expand through the trap into the counting cell. In order to prevent any subsequent change of gas pressure in the counting cell, it was isolated from the rest of the system by closing

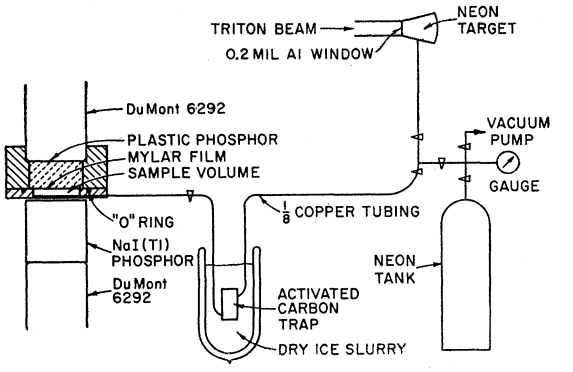

FIG. 1. Apparatus for the production and detection of Ne^{24}. The detector shown at the left was used for beta energy and beta-gamma coincidence measurements.

the appropriate valve. Prior to the run the trap had been evacuated at room temperature and then immersed in a slurry of powdered dry ice and acetone. Since no equilibrium was reached as the gas passed through the trap it was difficult to ascertain the efficiency of the trap. However, one would expect[9] that with the exception of helium and argon all likely impurities were removed from the neon, provided that they were present only in small amounts. An indication of the trapping efficiency was given by the absence of 0.511-Mev annihilation quanta, characteristic of F^{18}, at the counting cell (Fig. 1) although this radiation was quite intense at the trap. Presumably the only activities observed in the counting cell were those of Ne^{23} and Ne^{24}. Argon activities resulting from triton bombardment of impurities should have been negligible because at this energy the reaction cross sections are smaller for higher Z nuclei.

Scintillation spectrometers were used to investigate the radiations. The beta scintillator consisted of a cylinder of Pilot plastic phosphor[10] 1.8 in. in diameter and 0.82 in. high, optically coupled to a DuMont 6292 photomultiplier and held in place by a dural sleeve which was cemented to the tube. Over the face of the plastic phosphor was stretched a film of aluminized Mylar (~0.8 mg/cm²) which served as a window for the beta particles and a cover for the phosphor. To prevent the Mylar window from being pulled away from the phosphor during evacuation of the counting cell, the space surrounding the phosphor was evacuated with an auxiliary pump. Harshaw NaI(Tl) crystals of various sizes coupled to DuMont 6292 photomultipliers served for detection of the gamma rays. The photomultipliers used had been selected so that the shift of pulse height with counting rate[11] was less than 1%.

[7] This reaction was employed by L. G. Cook and K. D. Shafer [Can. J. Chem. **32**, 94 (1954)] for the production of carrier-free Na^{22}. The triton irradiation was carried out in a nuclear reactor using the $Li(n,\alpha)T$ method of Knight, Novey, Cannon, and Turkevich in C. D. Coryell and N. Sugarman, *Radiochemical Studies: The Fission Products* (McGraw-Hill Book Company, Inc., New York, 1951), Paper No. 326, National Nuclear Energy Series, Plutonium Project Record, Vol. 9, Div. IV.

[8] N. Jarmie, Phys. Rev. **98**, 41 (1955).

[9] N. Sugarman in C. D. Coryell and N. Sugarman, *Radiochemical Studies: The Fission Products* (McGraw-Hill Book Company, Inc., New York, 1951), Paper No. 315, National Nuclear Energy Series, Plutonium Project Record, Vol. 9, Div. IV. Also, R. A. Lad and T. F. Young, Paper 317 of the same volume.

[10] Pilot Chemicals, Inc., Felton Street, Waltham, Massachusetts.

[11] Bell, Davis, and Bernstein, Rev. Sci. Instr. **26**, 726 (1955).

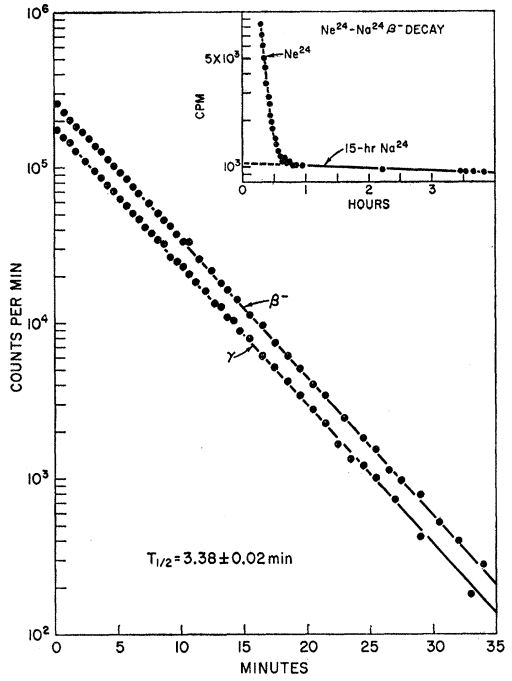

FIG. 2. Ne^{24} beta- and gamma-decay curves. Background and the 15-hr Na^{24} tail have been subtracted. The inset shows the gross $Ne^{24}-Na^{24}$ beta-decay curve from which the Ne^{24} component was resolved.

The electronic units employed in these experiments consisted of Beva high-voltage power supplies,[12] non-overload amplifiers[13] with a rise time of 0.3μsec, a coincidence circuit used with a 0.35μsec resolving time, and a 100-channel analyzer.[14]

BETA AND GAMMA RAY MEASUREMENTS

The half-life of the Ne^{24} activity was determined by following the decay of beta and gamma rays separately; the integral biases of both counters were set at a low pulse height. Treatment of the decay data (Fig. 2) by least squares analysis gave a value of 3.38±0.02 min for the half-life of Ne^{24}. The deviations of the experimental points from the least squares fit were used in arriving at the assigned probable error. In order to check for possible contamination due to a shorter lived activity, such as 40-sec Ne^{23}, an additional analysis of only the decay data between 5 and 35 min was made. No effect attributable to a second half-life component was discernible. The gross gamma decay of a neon sample was followed for 11 hr, and only a 15-hr activity (Na^{24}) was observed after the Ne^{24} had decayed.

Experiments described below showed that the Ne^{24} beta spectrum has an end-point energy of 1.98 Mev (see Fig. 8); however, electron pulses up to 6 Mev were observed. Additional half-life data were taken with the integral bias set to accept only beta pulses above 3 Mev. A complex decay was found which can be fitted with two half-lives. The half-life of the short component is consistent with the 40.2-sec half-life of Ne^{23}, which has 3.95- and 4.40-Mev beta groups.[15] When a least squares analysis of the data was made in which 40.2 sec was used for the short component, the resulting value for the half-life of the long component came out to be 3.25±0.40 min. This half-life would suggest that some high-energy beta rays are associated with the decay of Ne^{24}.

The $Ne^{24}-Na^{24}$ parent-daughter relationship was established by determining the rate of growth of Na^{24} activity during the Ne^{24} decay. This measurement was relatively difficult because of the large ratio of disintegration rates and the interference of the Ne^{24} and Ne^{23} radiations. Only the 2.75-Mev gamma ray of Na^{24} could be used to observe the daughter exclusively, because of the possibility that Ne^{24} emits gamma rays up to 1.4 Mev. In order to avoid difficulties from Ne^{23}, which emits a 1.647-Mev gamma ray,[15] a delay of 3 min was introduced between the end of the triton bombardment and the transfer of the gas to the counting cell. Pulses from the 2×2 in. NaI(Tl) crystal were counted only if they fell into the range from 1.5 to 3.0 Mev. The

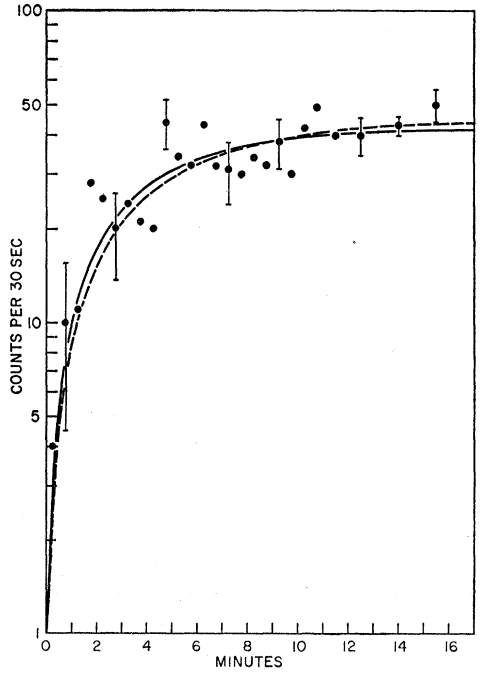

FIG. 3. Growth curve of Na^{24} activity during Ne^{24} decay. The solid line represents the least squares fit to the experimental points ($t_{\frac{1}{2}}$=2.7 min). The dashed curve would be expected on the basis of the 3.38-min half-life of Ne^{24}.

[12] Beva Laboratories, 1640 Olden Ave., Trenton, New Jersey.
[13] Los Alamos, Model 250A, Los Alamos Scientific Laboratory Report LA-1878, 1955 (unpublished).
[14] Los Alamos Model 1 magnetic storage analyzer, P. W. Byington and C. W. Johnstone, Inst. Radio Engrs. Convention Record 3, Part 10, 204 (1955). A commercial version of this instrument is described in Rev. Sci. Instr. **26**, 732 (1955).
[15] J. R. Penning and F. H. Schmidt, Phys. Rev. **100**, 954 (1955)

data of a typical run are shown in Fig. 3. The best value for the half-time of growth from two runs is 2.8 min, consistent with the expected value, 3.38 min. The parent-daughter relationship requires further that the final amount of Na^{24} be equal to the original amount of Ne^{24}. The observed beta counting rates (see Fig. 2) confirm this within a few percent (ratio of counting rates is 257 compared to the expected 266). A small discrepancy is to be expected since the detection efficiencies for the beta groups of the two nuclides were slightly different.

The pulse-height spectrum of the Ne^{24} gamma rays shown in Fig. 4 was observed with a NaI(Tl) crystal 1.5 in. in diameter and 1 in. high. The energy scale was calibrated with the following standard gamma-ray sources: Na^{24}, 1368, 2754 kev; Bi^{207}, 73, 569, 1064 kev;[16] Sc^{46}, 885, 1119 kev;[17] Cs^{137}, 662 kev; Na^{22}, 511 kev; Be^{7}, 479 kev; Au^{198}, 412 kev; and Am^{241}, 59.7 kev. The intensities of the Ne^{24} gamma rays were determined from the areas under the photopeaks corrected by appropriate efficiency factors.[18] The 0.25 in. thick source volume (Fig. 1) was used in this experiment since the relative efficiency is sensitive to the source-to-crystal distance. The results are summarized in Table I. No gamma rays other than those at 472 and 878 kev were found with an energy below 1 Mev. Upper limits are placed on the intensities of possible gamma rays which could occur as transitions between known levels[5] in Na^{24} (see Fig. 8). From an attempt to observe the growth of Na^{24} with a gamma detector biased at about 1.2 Mev, it was concluded that Ne^{24} emits gamma rays above this energy in less than 1% of the disintegrations.

The beta spectrum of Ne^{24} was investigated; both the composite spectrum and the spectrum in coincidence with 878-kev quanta were measured. The plastic scintillator was calibrated with the 976-kev internal conversion electron line of Bi^{207} [16] and the known beta spectra[19] of Au^{198}, Na^{24}, P^{32}, and Y^{90}.[20] Since a considerable time elapsed between the energy calibrations and the final measurements, the gain stability was checked periodically by recording the Compton spectrum of a Bi^{207} gamma-ray source. Fermi plots of the Ne^{24} data are shown in Fig. 5. The raw data have been corrected for scintillator resolution near the end point. Correction factors which were necessary to linearize a Fermi plot of the Au^{198} data were tabulated as a function of energy below the end point. The same correction factors were then applied to the other spectra. A small high-energy tail has been subtracted from the composite neon data; similarly, a small background arising from beta-gamma coincidences in Na^{24} has been subtracted from the coincidence spectrum. The uncertainties introduced by these subtractions limit the accuracy of the end-point determinations to ±50 kev.

The part of the beta spectrum above 3 Mev was investigated separately. As indicated by the complex decay data, several components were to be expected. However, because of limitations imposed by poor statistics of the points in this region and by the distortions characteristic of scintillation spectra the beta analysis was somewhat inconclusive. The data above 4.5 Mev are consistent with a single beta group having an end-point energy of approximately 6 Mev. Indications are that the end point of the next beta group is at 4.4 Mev; however, the Fermi plot is no longer linear

TABLE I. Radiations emitted by Ne^{24}.

Radiation Type	Energy (Mev)	Relative intensity[a] (%)	Coincident radiation (Mev)	Logft	Remarks
γ	0.878±0.009	8±2	β1.10	···	···
γ	0.785	<1	···	···	transition not observed
γ	0.564	<0.5	···	···	transition not observed
γ	0.472±0.005	100	None	···	$M3$, $t_{1/2}=20\pm^{30}_{15}$ msec
γ	0.092	<0.5[a]	···	···	transition not observed
β	1.98±0.05	92±2	···	4.4	$\Delta I=0$, 1 no parity change
β	1.89	<1[b]	···	≥6.3	transition not observed
β	1.10±0.05	8±2	γ0.878[c]	4.4	$\Delta I=0$, 1 no parity change

[a] No corrections have been made for internal conversion because it is at most a few percent. If the 92-kev gamma ray is an $M3$ transition, α_K would be only ~0.3.
[b] Estimated from limits on intensities of the 0.092- and 0.564-Mev gamma rays.
[c] This gamma ray is in coincidence with electron pulses above 0.7 Mev.

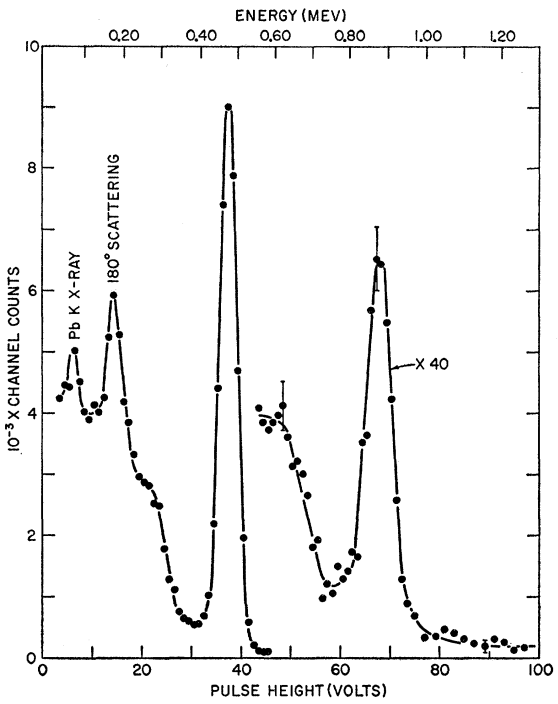

FIG. 4. Gamma-ray pulse-height spectrum from a Ne^{24} source taken with a 1.5-in. diameter by 1-in. high NaI(Tl) crystal.

[16] D. E. Alburger and A. W. Sunyar, Phys. Rev. **99**, 695 (1955).
[17] T. Lindqvist, Arkiv Fysik **6**, 123 (1953).
[18] The authors are indebted to P. R. Bell for making available to them his curves of efficiency *vs* gamma-ray energy for a 1.5-in. diameter by 1 in. high NaI(Tl) crystal.
[19] R. W. King, Revs. Modern Phys. **26**, 327 (1954).
[20] The ($\Delta I=2$, yes) shape factor was applied to the Y^{90} data.

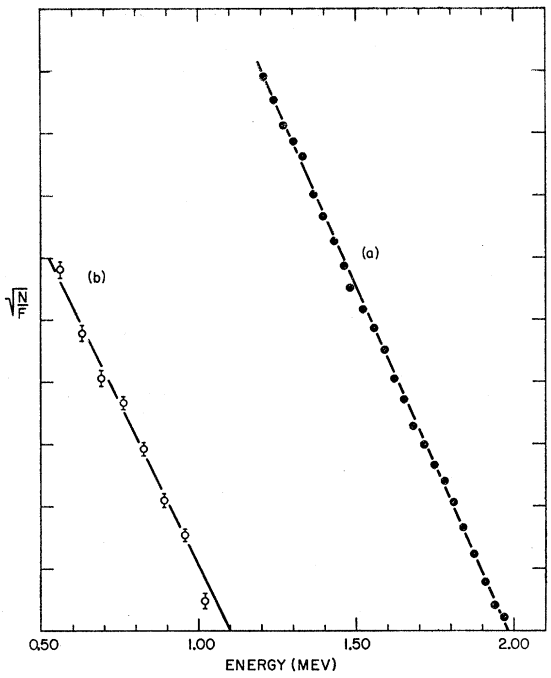

FIG. 5. Corrected Fermi plots of the Ne^{24} beta spectra. (a) Composite beta spectrum. (b) The beta spectrum in coincidence with the 878-kev gamma ray.

below this energy. Since Ne^{23} was present one would expect to find beta groups of 3.95 and 4.40 Mev.[15] The 6-Mev beta group should probably be associated with the Ne^{24} decay, since the only half-lives observed were those of Ne^{23} and Ne^{24} and no 6-Mev beta transition occurs in the Ne^{23} decay.

The spectrum of gamma rays in coincidence with beta particles above 0.7 Mev was investigated. The 878-kev gamma ray was observed but not the 472-kev gamma ray. Subsequent experiments proved conclusively that the 472-kev gamma ray is not in coincidence with either beta or gamma rays. These results would suggest an isomeric transition with a half-life long compared to the coincidence resolving time (0.35μsec). Since the theoretical half-life[21] of a transition with $\Delta I=1$ or 2 is relatively short ($\leqslant 10^{-8}$ sec), one would expect that the 472-kev transition has a half-life in the millisecond range corresponding to a $\Delta I=3$ transition.

STUDY OF Na^{24m}

It is well known[22] that the daughter activities of the rare gases can be collected by applying an electric field across the gas. This technique was applied to the search for the suspected Na^{24} isomer. If the Na^{24m} half-life was longer than the Na^+ ion collection time, the source of 472-kev gamma rays would be at the negative electrode rather than being distributed throughout the gas volume. In that case the gamma-ray counting rate of a detector placed near the collecting electrode would increase upon application of an electric field. A sample of activated neon gas at a pressure of about 3 cm of Hg was counted in a chamber (Fig. 6) having two plate-type electrodes; a scintillation crystal was placed at each electrode. The ratio of gamma-ray counting rates recorded by the two detectors was measured first with the negative voltage applied to the collecting electrode nearest detector No. 1 and then with reversed polarity. The experimental counting rate ratios for the two conditions were 1.80 and 0.38, respectively, for battery voltages over the range of 22.5 to 300 v. However, with a collecting voltage of only 6 v the effect was somewhat smaller. The ion collection time can be estimated by using Tyndall's[23] value for the mobility of Na^+ in neon. The maximum collection time with the 6-v field is about 10 msec. From the above data, a lower limit of 5 milliseconds may be placed on the Na^{24m} half-life.

In order to measure the Na^{24m} half-life more directly, a separation of parent and daughter activities was attempted. This separation may be accomplished by collecting the Na^{24m} on a negative electrode and removing the neon gas from the counting cell. The amount of Ne^{24} parent in the cell at any time can be monitored by recording the beta counting rate because the beta transitions feed the isomeric state (Fig. 8). Similarly, the amount of Na^{24m} on the collection electrode can be monitored by following the 472-kev gamma-ray counting rate. The experimental arrangement consisted of the beta detector shown in Fig. 1 sealed to the left half of the Na^{24m} collection cell with its associated gamma detector (Fig. 6). The total beta and total gamma counts were each scaled by a factor of 40 and recorded simultaneously on a double-pen Brush recorder.[24] After

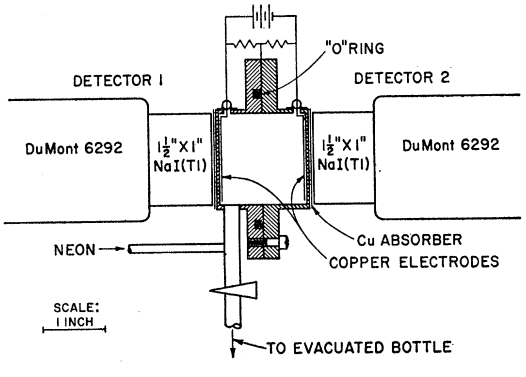

FIG. 6. Counting cell and scintillators which were used for the electrostatic collection and identification of the Na^{24} isomer.

[21] S. A. Moszkowski, in Kai Siegbahn, *Beta- and Gamma-Ray Spectroscopy* (Interscience Publishers, Inc., New York, 1955), Chap. 13; M. Goldhaber and A. W. Sunyar, Chap. 16 of same volume.

[22] R. Overstreet and L. Jacobson, Paper No. 67 of reference 9; Dillard, Adams, Finston, and Turkevich, Paper No. 68 of reference 9.

[23] A. M. Tyndall, *The Mobility of Positive Ions in Gases* (Cambridge University Press, Cambridge, 1938).

[24] A recorder type BL 202 was driven by two amplifiers type BL 905. Both are manufactured by the Brush Development Company, Cleveland, Ohio.

the counting cell was filled with active neon to a pressure of about 5 cm Hg, a collection voltage of 22.5 v was applied between the electrode and the case. The observed increase in counting rate of the gamma detector indicated that Na^{24m} was being collected. After sufficient counts had been recorded to permit an accurate evaluation of the average counting rates, the seat valve was opened rapidly and the gas allowed to expand into an evacuated 5-gal bottle. The data obtained in the best run are shown in Fig. 7; the number of counts have been summed over 40-msec intervals.

The data shown in Fig. 7 prove that the isomeric half-life is shorter than the time taken for the escape of the gas. Nevertheless, the isomeric half-life did have an effect on the gamma-ray counting rate as can be seen from the fact that the ratio of gamma-to-beta counting rates changed from 1.42 before to 1.87 after the valve had been opened. This effect may be used to arrive at an estimate of the isomeric half-life. The following approximations were made in analyzing the data: (a) the collection efficiency for Na^{24m} was taken to be 100%,[25] (b) the collection time for Na^{24m} was neglected (less than 1.2 msec), (c) the contribution of the prompt 878-kev quanta to the gamma-ray counting rate was neglected ($<6\%$), and (d) the amount of neon gas left in the counting cell, as given by the beta-ray counting rate, was approximated by an exponential function of time (this quantity was not calculated theoretically because of turbulent gas flow at the valve).

The isomeric half-life, t_i, is related to the half-life for the escape of gas, t_g, by the expression

$$t_i=(1-\alpha/\alpha')t_g, \quad \text{provided} \quad t_i<t_g,$$

where α and α' are the gamma-to-beta counting rate ratios before and during the removal of the gas, respectively, and α' is measured several isomeric half-lives after the valve was opened. (See Appendix for derivation.) From two runs the average values for t_g and t_i were found to be 90 and 20 msec, respectively. An upper limit of 50 msec can be placed on t_i because the theoretical curve corresponding to this half-life lies outside of the errors associated with the experimental points (see dashed curve, Fig. 7). From the results of the two experiments described in this section, it was concluded that the Na^{24m} half-life falls in the range 5 to 50 msec, with a most probable value of 20 msec.

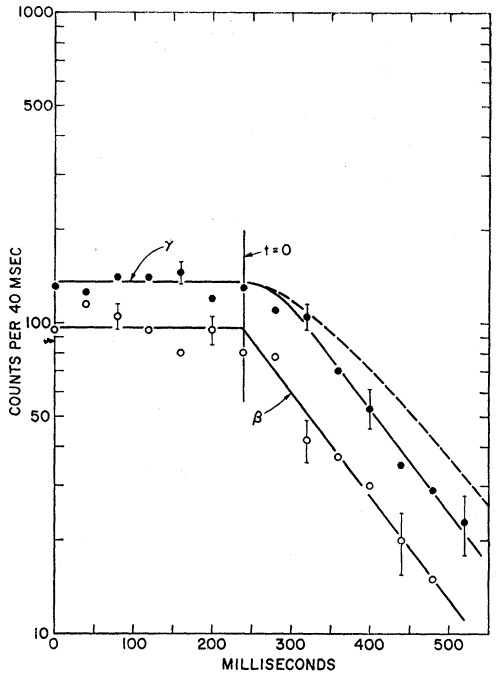

FIG. 7. Beta and gamma counting rates recorded before and during the removal of active neon gas from the counting cell. The dashed curve indicates the expected gamma decay for an isomeric half-life of 50 msec.

DISCUSSION

The following is a brief summary of the evidence supporting the contention that the observed activity is due to Ne^{24}. The high purity of the neon target and the requirements on the physical properties of the gas imposed by the cold charcoal trap severely limit the activities that could have been observed. The residual activity in the counting cell was identified as Na^{24} by its beta and gamma spectra as well as by its half-life. The parent-daughter relation between the neon activity and the residual Na^{24} was demonstrated by the observed growth of Na^{24} high-energy gamma activity. The proper ratio of beta counting rates was obtained between the Ne^{24} and Na^{24}. Finally, the observed activity was accompanied by the emission of gamma rays with energies corresponding to transitions between known levels in Na^{24}. Quanta of the same energies have also been observed in the neutron capture gamma-ray spectrum of Na^{23}.[26]

The decay scheme (Fig. 8) was constructed on the basis of present data and published information on Na^{24}.[5] The spin and parity of the Na^{24} ground state have been measured[27] as 4+. Both Ne^{24} and Mg^{24} are even-even nuclei and thus presumably have 0+ ground states. Since the observed Ne^{24} beta transitions are allowed ($\log ft=4.4$), no Ne^{24} to Na^{24} ground-state transition can be expected. The 1.98-Mev beta group feeds the 472-kev level directly because only the 472-kev gamma ray is of comparable intensity. The position of the other observed level is then fixed at 1.35 Mev by the 1.10-Mev beta group and the coincident 878-kev gamma ray. The allowed $\log ft$ values of both beta groups limit

[25] Measurements have shown that recoil atoms after beta decay have one or several positive charges [S. Wexler and T. H. Davies, Phys. Rev. **88**, 1203 (1952)]. The Na^+ ions cannot be neutralized in collisions with neon atoms because of the difference in ionization potential, therefore Na^+ can be collected quantitatively from neon gas.

[26] H. T. Motz, Phys. Rev. **90**, 355 (1953).

[27] E. H. Bellamy and K. F. Smith, Phil. Mag. **44**, 33 (1953).

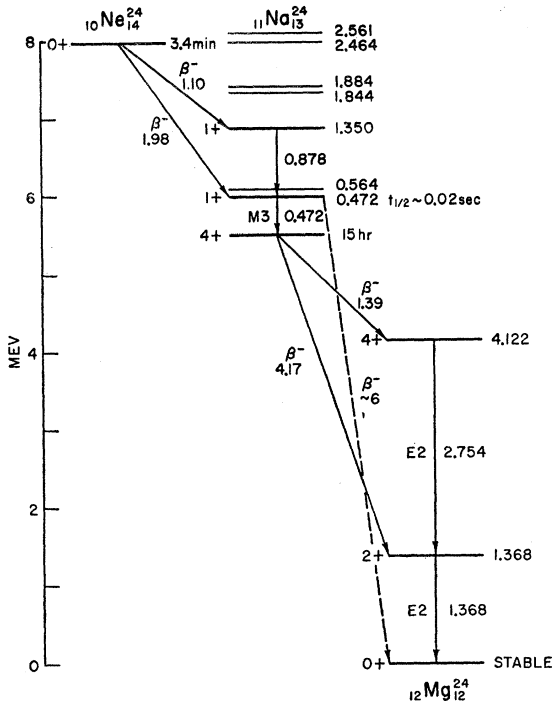

FIG. 8. Decay scheme for the isobaric triplet $Ne^{24}-Na^{24}-Mg^{24}$. Levels in Na^{24} indicated by light lines are not involved in this decay but are known from the $Na^{23}(d,p)Na^{24}$ reaction.

the spin and parity assignments of the two excited levels to 1+ or possibly 0+.[28] The isomeric life-time of 20 msec is consistent only with a spin change of 3 for the 472-kev transition[21]; therefore a unique assignment of 1+ can be made to the first excited state. Angular distribution data[6] of protons from the $Na^{23}(d,p)Na^{24}$ reaction indicate that the 1.35-Mev level can have spins of either 1+ or 2+. By mutual exclusion, one arrives at a 1+ assignment to this level.

Since the Na^{24} isomeric state is a 1+ level, beta transitions to the ground (0+) and first excited (2+) states of Mg^{24} should be allowed. If logft values of 4.4 are assumed for both beta groups the predicted intensities are roughly 1 and $\frac{1}{3}$ percent, respectively, of total Na^{24m} decay. There is experimental evidence for the 6-Mev ground-state transition since a weak beta group of about this energy followed the Ne^{24} half-life. On the other hand, the presence of Ne^{23} activity prevented the identification of a possible 4.6-Mev beta transition to the first excited state of Mg^{24}.

In addition to the two excited states of Na^{24} discussed above, other levels are known. No evidence was found that the 564-kev level is populated by the Ne^{24} decay. Angular distribution measurements[6] have established that the parity of this level is even and limit the possible spin assignments to 0, 1, 2, 3, or 4.[29] A 0+ or 2+ configuration would explain most easily the Ne^{24} beta spectrum (Table I) and the capture gamma-ray data.[26,30,31] Spins of 3 or 4 are improbable since no ground-state transition has been found from this level in the capture gamma-ray work. The two levels of Na^{24} at 1.8 Mev could also be involved in the Ne^{24} decay since there is an energy difference of roughly 0.6 Mev. However, even if the logft values are favorable (4.4), only about 0.5% of the Ne^{24} beta transitions would populate either of these levels. The 1.4-Mev gamma rays, corresponding to the transitions from these levels to the 472-kev isomeric state, would not have been detected in the present work because they would have been masked by the 1.37-Mev transition in Mg^{24}.

The energy levels of odd-odd nuclei are as yet not well understood because of the many possible interactions between the nucleons. De-Shalit[32] has investigated the energy levels which can be formed by the various vector additions of the angular momenta of the odd neutron and odd proton. He has shown that energy differences between levels differing by several units of spin are expected to be small if the spins of the odd neutron and proton are high. This is true especially if the odd nucleons belong to the same Schmidt group. Since the parities of the resultant nuclear states are not affected by a reorientation of the contributing neutron and proton angular momenta, one would expect $M3$ and $E4$ isomers and, indeed, many of the odd-odd isomers fall into this category.[21,33] For nuclides which have an odd $d_{\frac{5}{2}}$ neutron and proton, isomerism with spin changes up to five are possible. Na^{24} and probably Na^{22} [34] exhibit $M3$ transitions while Al^{26} has spins of 5 and 0 for its ground and first excited state,[35] respectively. The half-lives of the known $M3$ transitions in odd-odd isomers are in many cases relatively close to the values predicted on the basis of single proton transition probabilities.[21] In the case of Na^{24m} the predicted half-life is 9 msec as compared to the experimental value of about 20 msec. Similar isomeric states may be expected to exist in other odd-odd nuclei because large spins for the odd proton and odd neutron are known to occur frequently.

The occurrence of analog levels in the mirror nuclei ($T_z=\pm\frac{1}{2}$) Mg^{25} and Al^{25} [5] would indicate that isotopic spin is still a fairly good quantum number in this region of atomic weights. Therefore, Na^{24} and Al^{24}, mirror nuclei with $T_z=\pm1$, would be expected to have similar

[28] The range of logft values of 0+ to 0+ transitions is not well established since only very few such transitions are known (C. S. Wu, Chap. 11 of reference 21). Therefore no reliance is placed on logft evidence for ruling out such a transition.

[29] According to Bretscher *et al.* (reference 6), the spin of the 564-kev level is probably 1 or 2. However, this more restricted assignment depends on the assumption that the spin of the 472-kev level is 3 or 4. Since the spin of the 472-kev level is 1, spin assignments of 0, 1, 2, 3, or 4 are possible for the 564-kev level.

[30] T. H. Braid, Phys. Rev. **90**, 355 (1953).

[31] Kinsey, Bartholomew, and Walker, Phys. Rev. **83**, 519 (1951).

[32] A. de-Shalit, Phys. Rev. **91**, 1479 (1953).

[33] M. Goldhaber and R. D. Hill, Revs. Modern Phys. **24**, 179 (1952).

[34] N. P. Heydenburg and G. M. Temmer, Phys. Rev. **94**, 1252 (1954).

[35] Endt, Kluyver, and Van der Leun, Physica **20**, 1299 (1954).

level schemes. Glass and Richardson[36] concluded from a study of the Al^{24} decay that the Al^{24} ground state is probably the analog of the Na^{24} ground state. If a similar correspondence exists between the first excited states then Al^{24} would exhibit an isomeric transition corresponding to the one found in Na^{24}.

The $Ne^{24}-Na^{24}$ ground-state energy difference from the average of the two beta-gamma energy sums is 2449 ± 35 kev. Beta end-point energies of 1.98 ± 0.05 and 1.10 ± 0.05 Mev were used together with values of 472.0 ± 4.2 and 1345.8 ± 5.7 kev, respectively, for the energies of the excited states in Na^{24}. The latter values are the weighted average of the measurements given by Motz,[26] Sperduto and Buechner,[37] and the present data. Using the known mass of Na^{24},[38] one arrives at 24.001195 ±0.000040 atomic mass units for the mass of Ne^{24}.

ACKNOWLEDGMENTS

The authors are indebted to Arthur Hemmendinger and other members of the 2.5-Mev electrostatic accelerator group for assistance during the course of the experimental work. Thanks are due to Keith Zeigler and Roger Moore for their statistical analysis of the decay data. It is a pleasure to acknowledge many helpful discussions with Jere D. Knight.

APPENDIX. EVALUATION OF DECAY CONSTANTS

Definitions

t = time, $t\leqslant 0$ all gas is in counting volume, $t>0$ valve is open.

$t_i=0.693/\lambda_i$ = half-life of isomeric state.

$t_g=0.693/\lambda_g$ = half-time for exponential escape of gas from counting cell.

$f(t)$ = rate of formation of Na^{24m} in counting chamber due to Ne^{24} decay.

N = number of Na^{24m} nuclei on collection plate at time t.

$N_0=f(0)/\lambda_i$ value of N at time $t\leqslant 0$.

α, α' = ratio of gamma to beta counting rates at time $t\leqslant 0$ and $t>0$, respectively.

Equations

The net rate at which the number of Na^{24m} nuclei changes is equal to the rate of loss due to decay plus the rate of formation of Na^{24m} from the neon still in the chamber,

$$dN/dt=-\lambda_i N+f(t). \tag{1}$$

If the gas leaves the chamber exponentially, then $f(t)=f(0)e^{-\lambda_g t}$. With this substitution for $f(t)$, Eq. (1) can be solved explicitly giving

$$N=\frac{N_0}{(\lambda_i-\lambda_g)}[\lambda_i e^{-\lambda_g t}-\lambda_g e^{-\lambda_i t}]. \tag{2}$$

The constant of integration has been evaluated from the boundary conditions at $t=0$. Equation (2) also holds true for the gamma-ray counting rate since it is proportional to N.

An expression, independent of the specific form of $f(t)$, can be derived for the isomeric half-life. Since $\alpha'=\alpha\lambda_i N/f(t)$, Eq. (1) may be rewritten in the following form:

$$dN/dt=-\lambda_i N(1-\alpha/\alpha'). \tag{1a}$$

This expression can be solved algebraically for λ_i or preferably t_i.

$$t_i=-0.693(1-\alpha/\alpha')(d\ \ln N/dt)^{-1}. \tag{3}$$

According to Eq. (3), the isomeric half-life depends only on the counting rate ratios and the logarithmic derivative of the gamma-ray counting rate. Since only the logarithmic derivative occurs in Eq. (3), $N(t)$ may be approximated by an exponential function. No great error is introduced if the derivative of N is evaluated from Eq. (2). If $t_i<t_g$ and α' is measured at $t\gg t_i$, the following simple expression is obtained:

$$t_i=(1-\alpha/\alpha')t_g. \tag{4}$$

[36] N. W. Glass and J. R. Richardson, Phys. Rev. **98**, 1251 (1955).
[37] A. Sperduto and W. W. Buechner, Phys. Rev. **88**, 574 (1952).
[38] A. H. Wapstra, Physica **21**, 367 (1955).