# The Reaction Energies of $Ne^{21}(d, \alpha)F^{19}$ and $Ne^{21}(d, p)Ne^{22}$ from Magnetic Analysis*

CURT MILEIKOWSKY† AND WARD WHALING
*Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California*
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Separated isotopic targets of $Ne^{21}$, which were produced at the Nobel Institute of Physics, have been used to measure the $Q$-values of the reactions (1) $Ne^{21}(d, \alpha)F^{19}$, and (2) $Ne^{21}(d, p)Ne^{22}$. A double focusing magnetic spectrograph was used to compare the energy of the protons and alpha-particles from these reactions with the alpha-particles from ThC and ThC′. The angle of observation and the deuteron bombarding energy were chosen so that the particles being studied and the alpha-line used for energy calibration lay nearly side by side on the photographic plate used as a detector. The $Q$-values measured are $6.432\pm0.010$ Mev for reaction (1) and $8.137\pm0.011$ Mev for reaction (2). From these $Q$-values and the mass of $F^{19}$ the atomic masses of $Ne^{21}$ and $Ne^{22}$ are obtained. Other alpha-groups from reaction (1) correspond to transitions to states in $F^{19}$ at $0.113\pm0.008$ Mev and $0.192\pm0.012$ Mev above the ground state. Additional particle groups from N and Na contamination on the targets have been observed: The $Q$-values measured are $8.613\pm0.011$ Mev for $N^{14}(d, p)N^{15}$ and $4.723\pm0.008$ for $Na^{23}(d, p)Na^{24}$.

## I. INTRODUCTION

THE $Q$-values measured with the precision afforded by magnetic analysis provide a very accurate measure of mass differences. A sufficient number of mass differences have been measured to determine the masses of most of the light nuclei up through $F^{19}$ directly in terms of $O^{16}$. In the past year these accurate $Q$-values measurements have been extended by Buechner's group at the Massachusetts Institute of Technology to include many of the nuclei between Ne and P. However, there has not yet been reported any precise measurement of the mass difference between F and Ne which would make it possible to relate the masses of these heavier nuclei to $O^{16}$. This paper describes a measurement of the $Ne^{21}(d, p)Ne^{22}$ and $Ne^{21}(d, \alpha)F^{19}$ $Q$-values which determine the masses of $Ne^{21}$ and $Ne^{22}$ in terms of $O^{16}$. Together with the measurements of the MIT group, these $Q$-values may be used to determine the masses of many of the heavier nuclei by means of nuclear transmutation energies.

## II. APPARATUS

The isotopic targets of $Ne^{21}$ were prepared in the 1.6-meter isotope separator of the Nobel Institute[1] by bombarding silver disks, 0.8 inch in diameter by 0.125-inch thick, with $Ne^{21}$ ions at an energy of about 50 kev. These targets are thus very thin for protons, deuterons, and alpha-particles of a few Mev. The $Ne^{21}$ bombardments were sufficient to saturate the targets. Since the neon is absorbed in the silver surface and escapes readily if the silver is heated,[2] the target was mounted in close thermal contact with a block of copper which was maintained at room temperature during the deuteron bombardment, and the deuteron beam on the target was kept below 0.3 microampere to prevent local heating.

TABLE I. Sources of experimental error and their contribution to the probable error in the $Ne^{21}(d, \alpha)F^{19}$ $Q$-value.

| Source of error | Probable error in $Q$ kev |
|---|---|
| Statistical error in $E_2$ ($\pm\frac{1}{6}$ width at half-maximum) | 7 |
| Energy of ThC alpha-particles | 4 |
| Surface layer correction ($\pm\frac{1}{4}$ layer thickness) | 1 |
| Displacement of beam spot relative to ThC source ($\pm0.5$ mm) | 5 |
| Deuteron bombarding energy ($\pm0.2$ percent) | 3.5 |
| Angle of observation ($\pm0.2°$) | 2 |
| Net probable error in $Q=10$ kev | |

The energy of the incident deuterons from the 3.0-Mev Van de Graaff generator of the Kellogg Radiation Laboratory was measured with a 90° electrostatic analyzer. The analyzer was calibrated against the $Al^{27}(p, \gamma)Si^{28}$ resonance at 0.9933 Mev,[3] and the linearity of the analyzer was checked by observing this same resonance with the $H^+$ and $HH^+$ ions. The electrostatic analyzer calibration was checked frequently during the course of the experiment. At each run the target was bombarded with 1000–1600 microcoulombs of $D^+$ ions.

The energy of the emitted particles was measured with the 16-inch double focusing magnetic spectrograph. The full solid angle of 0.007 steradian was utilized. Ilford emulsions, 100 microns thick, were placed in the focal plane of the spectrograph to detect the particle groups. A weak ThC−ThC′ alpha-source was placed 6 mm from the target spot as measured along the axial direction of the spectrograph so that the spectrum of particles from the alpha-source appeared on the photographic plate displaced axially 5 mm from the spectrum of particles emitted from the target. The angle of observation, $150.2\pm0.2°$, and the bombarding energies were chosen so that the alpha-calibration line lay very near the line whose energy was to be measured. The plate was exposed simultaneously to the calibration alphas and the reaction products, and thus any drift in

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† On leave from the Nobel Institute of Physics, Stockholm, Sweden.
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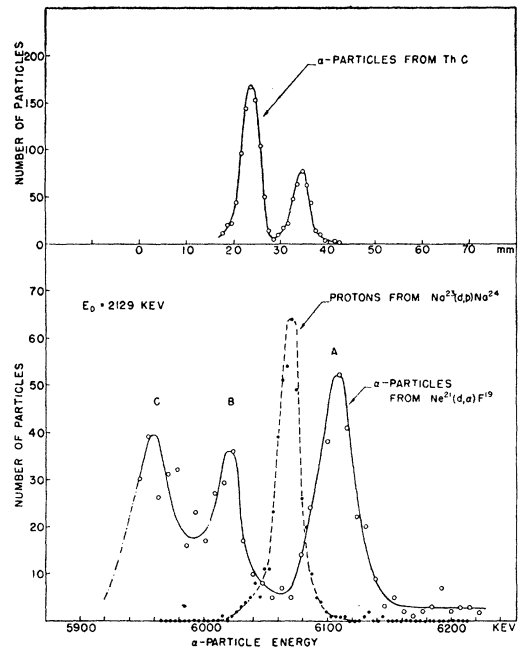


FIG. 1. Alpha-spectrum from $Ne^{21}(d, \alpha)F^{19}$. The group marked $A$ corresponds to transitions to the ground state of $F^{19}$; groups $B$ and $C$ are attributed to transitions to states in $F^{19}$ at $113\pm8$ kev and $192\pm12$ kev above the ground state. The dot-dashed part of peak $C$ is obtained from plates exposed at a lower magnetic field. The ThC lines which were used to calibrate the energy scale are shown in the upper figure, plotted against the radial displacement from the end of the photographic plate. The energy scale is different for protons and alphas; $E_{proton}=0.9931E_{\alpha}$. The dotted curve shows the protons from the reaction $Na^{23}(d, p)Na^{24}$.

the magnetic field during an exposure would appear in the width of the calibration alpha-line. The magnetic field was monitored continuously during an exposure with a fluxmeter of the type that has been described previously.[4] The method of preparing the alpha-sources and the method of measuring the angle of observation have also been described.[5]

## III. RESULTS

### A. $Ne^{21}(d, \alpha)F^{19}$

The spectrum observed at a bombarding energy of 2.129 Mev is shown in Fig. 1. The upper curve shows the two alpha-calibration lines from ThC. The energies assigned to these two alpha-lines are $6.038\pm0.003$ Mev and $6.078\pm0.003$ Mev calculated from Briggs'[6] measurement of $H\rho$ for RaC and the Cavendish measurements[7] of the ratios of the velocity of the thorium alpha-particles to the velocity of the RaC alpha-particles. A 4-kev correction in this calculated energy has been included for the penetration of the recoil ThB nucleus into the target backing. The group of alpha-particles marked $A$ is from the $Ne^{21}(d, \alpha)F^{19}$ reaction and has an energy of 6.106 Mev which is obtained by a linear extrapolation of the momentum scale set by the calibration alpha-lines.

The target surfaces were slightly discolored, and it would appear that during the course of the $Ne^{21}$ bombardment carbon also was deposited on the surface. Thus the observed energy must be corrected for the energy loss of the alpha-particles in this contamination layer on the surface of the target. The thickness of this layer was measured by observing the energy of deuterons scattered from the face of the target and comparing this energy with the energy of deuterons scattered from a clean evaporated silver surface. In this measurement the photographic plate was replaced by collecting slits and a scintillation counter, and the magnetic field was varied to observe the spectrum. Figure 2 shows these two spectra, from which it appears that the layer on the surface is 3.6 kev thick, for deuterons of 873 kev. The two steps are displaced by twice this amount since the deuterons pass through the layer twice. The 6-Mev alpha-particles would lose 5.9 kev in passing through this layer. Two $Ne^{21}$ targets were used in the present work, one with a contamination layer of 3.6 kev for 873-kev deuterons, one with a layer of 11 kev. By comparing the energy of the $Ne^{21}(d, \alpha)F^{19}$ alpha-particles from the two targets, it was found that the $Ne^{21}$ was distributed throughout the contamination layer, as would be expected if the contamination were laid down during the $Ne^{21}$ bombardment in the isotope separator. Hence the energy of the emitted alpha-particles has been corrected for penetration through only one-half of the surface layer. Four measurements of this alpha-particle energy were made, and the corresponding $Q$-value is $6.432\pm0.010$ Mev; relativistic effects have been included in the calculation of the $Q$-value, and nuclear masses have been used. The contributions to the probable error are summarized in Table I.

Two other lines marked $B$ and $C$ appear in our ex-

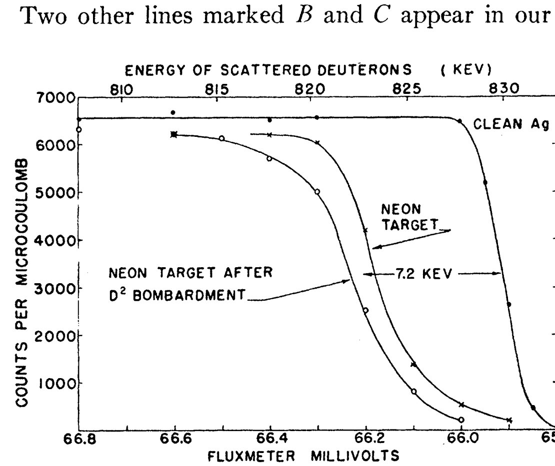


FIG. 2 Spectrum of deuterons scattered from clean silver and from the neon target before and after 1000-microcoulomb deuteron bombardment. The incident deuteron energy is 873 kev.

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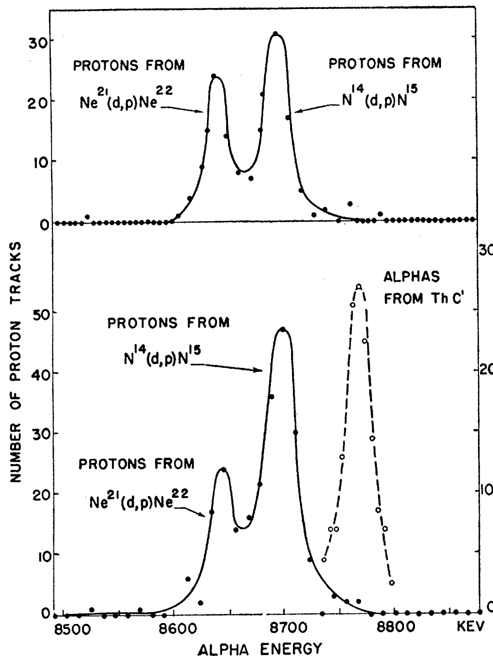


FIG. 3. The proton spectrum from $Ne^{21}(d, p)Ne^{22}$ and $N^{14}(d, p)N^{15}$, at a deuteron bombarding energy of 1.354 Mev. The upper and lower curves were obtained with two different targets. The dotted curve shows the alpha-line from ThC′ used to calibrate the energy scale for the lower curve. The energy scale is different for proton and alphas, $E_{\text{proton}}=0.9931E_{\alpha}$.

posures. The variation of their energy with changes in the deuteron bombarding energy indicates a target nucleus of mass 21±4, and we attribute these lines to the $Ne^{21}(d, \alpha)F^{19}$ reaction leading to states in $F^{19}$ at 113±8 kev and 192±12 kev above the ground state. These levels have not been reported earlier.

### B. $Ne^{21}(d, p)Ne^{22}$

The spectrum of protons observed at a bombarding energy of 1.354 Mev is shown in Fig. 3. The protons from the $Ne^{21}(d, p)Ne^{22}$ reaction have very nearly the same energy as the protons from the $N^{14}(d, p)N^{15}$ reaction. In a plate exposed at 1.850-Mev deuteron energy, the two proton groups were not resolved, but the variation of the proton energy with changes in the incident deuteron energy makes possible the resolution and identification of the proton groups. Taking the energy of the ThC′ calibration alpha-line to be 8.772±0.003 Mev, we find for the $Q$-value of the $Ne^{21}(d, p)Ne^{22}$ reaction 8.137±0.011 Mev. This value is lower than the value 8.34 Mev found from range measurements.[8]

### C. $N^{14}(d, p)N^{15}$ and $Na^{23}(d, p)Na^{24}$

The proton line from $N^{14}(d, p)N^{15}$ shown in Fig. 3 has been used to calculate the $Q$-value for this reaction, yielding 8.613±0.011 Mev. This value is in good agreement with an earlier measurement by the MIT group[9] of 8.615±0.009 Mev. The proton line in Fig. 1 has been identified as coming from the reaction $Na^{23}(d, p)Na^{24}$ and yields a $Q$-value for this reaction of 4.723±0.008 Mev, again in good agreement with the MIT value, 4.731±0.009 Mev.[9]

## IV. MASSES OF THE NEON ISOTOPES

From our $Q$-values for the $Ne^{21}(d, \alpha)F^{19}$ and $Ne^{21}(d, p)Ne^{22}$ reactions we can calculate the atomic masses of $Ne^{21}$ and $Ne^{22}$ using the atomic masses of $H^1$, $D^2$, $He^4$, and $F^{19}$ obtained from nuclear reaction energies,[10] and $Ne^{20}$ mass can then be obtained from the MIT measurement[11] of the $Ne^{20}(d, p)Ne^{21}$ $Q$-value. We assume that the $Q$-values can be used directly to calculate the *atomic* masses. These mass values are listed in Table II together with recent mass spectroscopic values based on Ewald's[12] measurements of the $D_2O^{16}-Ne^{20}$, $D_2HO^{16}-Ne^{21}$, and $D_3O^{16}-Ne^{22}$ doublets; the first doublet has also been measured by Nier[13] who finds a value in agreement with Ewald's. It is evident from Table II that there is good agreement between the nuclear and mass spectroscopic measurements of the masses of $Ne^{20}$ and $Ne^{22}$; for $Ne^{21}$, however, there is a discrepancy of 109 $\mu$MU. The agreement between the nuclear and mass spectroscopic values for $Ne^{20}$ and $Ne^{22}$ may be interpreted as lending mass spectroscopic support to our mass of $Ne^{21}$, since the nuclear transmutation mass values for $Ne^{20}$ and $Ne^{22}$ are obtained directly from the nuclear transmutation mass of $Ne^{21}$.

With the value of the $Ne^{21}(d, p)Ne^{22}$ $Q$-value we are able to check the consistency of the following cycle of nuclear reactions: $Ne^{21}(d, p)Ne^{22}$, $Ne^{22}(d, p)Ne^{23}$, $Q=2.964\pm0.007$ Mev;[9] $Ne^{23}(\beta)Na^{23}$, $Q=4.21\pm0.015$ Mev;[14] and $Na^{23}(d, \alpha)Ne^{21}$, $Q=6.902\pm0.010$ Mev.[9] The cycle so formed fails to close by 178 kev, which is far more than the quoted errors would allow. If all the measurements are correct, it would appear that one of the measured transitions may not go to the ground state. In view of the fact that the earlier range measurement of the $Ne^{21}(d, p)Ne^{22}$ $Q$-value gave a result which would close the cycle, we emphasize that we have examined the region of the spectrum where the protons corresponding to the higher $Q$-value would fall and find none. Further evidence that the protons we observe correspond to the ground state transition lies in the agreement with

TABLE II. Masses of the neon isotopes, in atomic mass units.

| | | | |
|---|---|---|---|
| From nuclear data | 19.998 773±27 | 21.000 502±25 | 21.998 356±28 |
| From mass spectroscopy | 19.998 771±12 | 21.000 393±22 | 21.998 329±19 |

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Ewald's value for the mass of $Ne^{22}$, and in the agreement with Middleton's range measurement[15] of the energy of the alpha-particles from $Ne^{22}(d, \alpha)F^{20}$.

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# The Beta-Decay of $F^{20}$†

David E. Alburger
*Brookhaven National Laboratory, Upton, New York*
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The beta-decay of $F^{10}$ has been investigated with a lens spectrometer using sources activated by the $F^{19}$-$(d, p)F^{20}$ reaction. A simple beta-ray spectrum of allowed shape is observed having an end-point energy of 5.406±0.017 Mev. Beta-emission is followed by a 1.631±0.006 Mev gamma-ray from an excited state of $Ne^{20}$. The gamma-ray energy was checked by comparing with the $Sb^{124}$ gamma-ray, measured as 1.692±0.005 Mev, and by failure to observe photoneutrons from Be. Beta-ray branching to the ground state of $Ne^{20}$, if present, has a relative intensity of less than 1 percent. The total $F^{20}$ disintegration energy, 7.038±0.018 Mev, is used together with other nuclear data to derive a $Ne^{20}$ mass which is independent of mass spectrographic measurements. The result, $Ne^{20}$ = 19.998794±0.000026 amu, is in agreement with mass spectrographic values.

## INTRODUCTION

Up to the present the scale of accurate atomic mass values[1,2] based solely on nuclear measurements has extended only up to $F^{20}$. Isotopes in the mass region from $Ne^{20}$ to sulfur are interconnected by beta-decay energies and reaction $Q$-values which have errors of less than 20 kev. However, this group of elements has been linked to $O^{16}$ only through mass spectrographic work owing to the lack of accurate nuclear data connecting the isotopes of fluorine and neon.

Several ways of bridging this gap by means of nuclear measurements are apparent. One such method is the determination of the ground state $Q$-value of the $Ne^{21}$ $(d,\alpha)F^{19}$ reaction, a problem which might not be expected to be easy because of the relatively low abundance of $Ne^{21}$ in ordinary neon and the difficulty of making a suitable target.

A second possibility consists of determining the total disintegration energy of $F^{20}$. It is known[3] that this isotope decays to $Ne^{20}$ by emission of hard beta-rays with a half-life of 12 seconds and that most of the beta-rays are in coincidence with 1.6-Mev gamma-rays corresponding to a level in $Ne^{20}$. Evidence has been found for complexity of the beta- and gamma-ray spectra. Jelley has reported[3] a single beta-ray group of endpoint energy 5.03±0.05 Mev and two gamma-rays of 1.63±0.02 Mev and 2.45±0.06 Mev having an intensity ratio of 8.4 to 1. On the other hand, Littauer has found[4] a weak gamma of 1.0±0.1 Mev in addition to the one of 1.63 Mev. He also reports that the main beta-component has a 5.33±0.05 Mev end point and that 3.5 percent of the beta-decays proceed to the ground state of $Ne^{20}$ and have an end-point energy of 6.74±0.1 Mev. The value 6.66±0.05 Mev given by Jelley as the total $F^{20}$ disintegration energy disagrees beyond the stated errors with 6.96±0.05 Mev obtained from Littauer's data. In either case the probable error is too large to use the result in establishing a mass scale involving only measurements having errors of less than 20 kev.

Because of the desire to obtain a more accurate total disintegration energy and at the same time to examine the possible complexities in the beta- and gamma-ray spectra it was felt that an investigation of the $F^{20}$ beta-decay should be made.

## GAMMA-RAY MEASUREMENTS

A lens spectrometer employing ring focus was used to study the gamma-ray spectrum from sources of $F^{20}$ produced by the $F^{19}(d,p)F^{20}$ reaction. A 1.8-Mev deuteron beam at a current of 5 $\mu$amp was furnished by the Brookhaven electrostatic accelerator and was allowed to strike a thick $CaF_2$ target located in a brass cup at the normal source position of the spectrometer. Photoelectric converters consisting of uranium foil were attached to the cup whose walls were thick enough to stop the energetic beta-rays. The spectrometer was located 17 feet from the magnetic analyzer of the accelerator and the beam was brought through an extension tube.

In the first tests in which the spectrometer and accelerator vacuum systems were connected together it was found that $N^{13}$ activity, produced by deuteron bom-

† Under contract with the AEC.
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