Radiative Yield of the $E_a = 1.68$ MeV Resonance in the $^{15}$N($\alpha$, $\gamma$)$^{19}$F Reaction\(^1\)

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The radiative yield of the $E_a = 1.68$ MeV resonance in the $^{15}$N($\alpha$, $\gamma$)$^{19}$F reaction has been measured by three different methods. These methods are: (1) a comparison with the $E_a = 1.53$ MeV resonance in the $^{14}$N($\alpha$, $\gamma$)$^{18}$F reaction; (2) a comparison with the $E_a = 0.898$ MeV resonance in the $^{15}$N(p, $\alpha$)$^{12}$C reaction; and (3) an absolute determination based on an efficiency calibration of the detector with a standard radioactive source. The final result is:

$$\omega_Y = \frac{(2J + 1)}{2} \left( \frac{\Gamma_{\gamma}}{\Gamma_{\alpha \gamma}} \right), \text{ c.m.} = 1.64 \pm 0.16 \text{ eV}$$

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1. Introduction

Recently studies of resonances in the $^{15}$N($\alpha$, $\gamma$)$^{19}$F reaction have been carried out at the University of Toronto, and at the National Research Council, Ottawa. In order to compare experimental transition strengths in $^{19}$F with theory, it is desirable to measure the absolute radiative strengths of these resonances. Absolute measurements, however, are very difficult with the solid targets of titanium nitride which have been employed, so that it has been customary to compare the radiative yield of a given resonance to the yield from the resonance at $E_a = 1.68$ MeV. This resonance has been compared by Aitken et al. (1970) to the resonance at $E_a = 1.53$ MeV in the $^{14}$N($\alpha$, $\gamma$)$^{18}$F reaction with a target prepared from a gas mixture of $^{14}$N and $^{15}$N of known composition. The absolute yield of the latter resonance in $^{14}$N had been measured previously by Parker (1968).

In view of the importance of the $E_a = 1.68$ MeV resonance as a standard for $^{19}$F, we have now re-measured its radiative yield by essentially three different methods and found good agreement among them. The first method consisted of repeating Aitken’s comparison between the $^{18}$F and $^{19}$F resonances. The second method consisted of a comparison with the resonance at $E_p = 0.898$ MeV in the $^{15}$N(p, $\alpha$)$^{12}$C reaction for which the radiative yield has been measured by Gorodetzky et al. (1968) using a gas target. The third method has required an absolute efficiency calibration of the gamma-ray detector and a knowledge of the stopping power per $^{15}$N atom in the target. Some subsidiary experiments, to be described below, were performed to determine the N:Ti ratio in the target, and the amount of carbon and oxygen impurities. With estimates of these quantities, the absolute yield was calculated and found to be in reasonable agreement with the results of the intercomparison methods.

The radiative yield $Y$ in photons per alpha particle is

$$Y = \rho \sigma(E) \frac{dE}{E} \frac{S(E)}{S}$$

where $\rho$ is the number of disintegrable nuclei per gram, $\sigma$ is the cross section in cm$^2$ per nucleus for the ($\alpha$, $\gamma$) reaction, and $S$ is the average stopping power for alpha particles in units of energy per g/cm$^2$. We shall denote by $E$ the energy in the laboratory system. In the case of a single narrow Breit–Wigner resonance, and an effectively infinite target, the integration gives

$$Y = \frac{(\rho/2S)\lambda^2}{M_T} \omega_Y$$

where $S$ and $\lambda^2$ are evaluated at the resonant energy,

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\[ \lambda^2 \text{c.m.} = \left( \frac{M_a + M_T}{M_T} \right)^2 \frac{h^2}{2M_aE} \]

(3)

\[ \omega = \frac{2J + 1}{(2I_0 + 1)(2I_0 + 1)} \]

(4)

and

\[ \gamma = \left( \frac{\Gamma_a}{\Gamma} \right) \text{c.m.} \]

(5)

Here $M_a$ and $M_T$ are the masses of the alpha particle and target nucleus respectively, $J$ is the spin of the compound resonant state, $I_0$ is the spin of the ground state of the target nucleus, $I_o = 0$ for alpha particles, $\Gamma_a$ and $\Gamma_r$ are the partial widths for alpha-particle and gamma-ray emission respectively of the compound state, and $\Gamma$ is the total width. The need for inserting the factor $(M_a + M_T)/M_T$ in eq. (2) has recently been emphasized by Snover (1969); it effectively corrects the stopping power to the center-of-mass system. We shall give our results in terms of the quantity $\omega \gamma$ as defined above.

2. Experimental Techniques

(a) Target Preparation

Targets for routine use have been prepared by a method developed by the Toronto group. Titanium is evaporated onto a tantalum strip 6 in. x 1 in. x 0.010 in., nitrogen is allowed into the bell jar to a pressure of about 300 Torr, and a heavy current is passed through the strip until it glows a cherry red ($800-900^\circ$C). This condition is maintained for 2-3 min. Routine precautions here have included polishing the tantalum strip chemically, preheating the boat containing the titanium, preheating the tantalum strip just before the evaporation, and providing water cooling for the electrodes carrying the heavy current. Evaporation is never carried out until the pressure is well below $10^{-6}$ Torr.

According to Ehrlich (1949) this process should be expected to produce titanium nitride with a N:Ti ratio not greater than unity and possibly much less. In order to get a N:Ti ratio closer to 1.0 when absolute yields were to be measured, it was thought desirable to nitride at $1200-1300^\circ$C. Since tantalum itself nitrides at such temperatures, tungsten backings, in the form of squares 1 in. x 1 in. x 0.010 in., were used. Tungsten also has the advantage of being purer than the tantalum used.

One of the main disadvantages of this method of target preparation is that titanium vapor is an excellent getter for residual gas—including hydrocarbons—in the bell jar. Some of the later targets were prepared by operating a titanium sublimation pump just prior to and during the evaporation of the titanium onto the backing. In particular target #141, for which various forms of charged particle analysis have been carried out, was prepared in this way.

(b) Target Assembly

The targets were installed with indium seals in a target holder with provision for direct water cooling. A copper tube surrounding the target, with an aperture to allow the beam through, was kept at liquid nitrogen temperature. With this cold shroud it was not necessary to increase the alpha-particle energy to compensate for carbon buildup on the target during runs of many hours.

(c) Current Integration

The amount of charge deposited on the target was obtained from a current integrator, Elcor model A309B. The integrator calibration has been checked a number of times and never found to be in error by more than 2%. A negative potential of 300 V was applied to the cold shroud to suppress electron emission from the target: no change in the measured target current was observed for suppression voltages between 50 and 500 V.

(d) Ge(Li) Detector

Most of the gamma-ray measurements described in this paper were done with a Canberra Ge(Li) detector of roughly 30 cm$^3$ volume. The manufacturer's description of the detector is as follows: right circular cylinder, drifted coaxially with two open ends; diameter—35 mm; p-core 9 mm diameter, length 36 mm. These dimensions have been checked by radiographing the detector at about 90 kV. The resolution of the detection system was about 2.8 keV at 1.332 MeV. An Ortec 450 amplifier and Northern Scientific pulse-height analyzers of 2048 and 4096 channels were used.

The relative efficiency for the detection of gamma rays in the energy range 1–11 MeV is shown in Fig. 1. In determining these efficiency curves the resonance at $E_r = 1416$ keV in the $^{23}$Na(p, $\gamma$)$^{24}$Mg reaction has played a central role, since it provides gamma rays of energies 8.93, 2.75, and 1.37 MeV with relative intensities...
Fig. 1. Relative efficiency of the Ge(Li) detector for gamma rays originating from the target located in the target chamber. Efficiencies were measured at distances of 4-6 cm from the source to the front surface of the germanium. The detector container was surrounded with a neutron shield composed of 0.098 g/cm² of boron and 0.28 g/cm² of epoxy, and also had a lead shield of 1.015 g/cm² to absorb low-energy gamma rays.

96 ± 2 for the first two gamma rays, and 100 for the 1.37 MeV gamma ray (Baxter et al. 1969). In the region of about 3-8 MeV, however, it is difficult to find gamma-ray decays for which the published branching ratios do not in turn depend on somewhat uncertain efficiency calibrations. In this region we have used the $E_p = 992$ keV resonance in the $^{27}$Al(p, $\gamma$)$^{28}$Si reaction with relative intensities as given by Azuma et al. (1966). The low-energy end was obtained from a radium source with relative intensities as given by Lingeman et al. (1969), and normalized to the $^{23}$Na(p, $\gamma$)$^{24}$Mg points at 1.37 and 2.75 MeV. Since the calibration with reaction gamma rays includes the effect of absorption in the target backing (0.010 in. Ta) and chamber walls, the radium points have been corrected for this absorption also.

(e) Alpha-Particle Stopping Powers

The determination of an $\alpha\gamma$ depends upon a knowledge of $(S/p)$, the stopping power per disintegrable nucleus, so that uncertainties in the atomic stopping powers, as well as in the composition of the target, limit the accuracy attainable. At the present time most stopping power data for alpha particles have uncertainties of at least 5%, and many are uncertain to 20%. A convenient compilation is given by Williamson, Boujot, and Picard (1966), but their alpha-particle stopping powers include a very rough correction for the effective charge of the alpha particle at energies <4 MeV. At such energies it is preferable to use proton stopping powers, for example from the compilation of Janni (1966), with alpha-particle stopping powers being calculated according to...
in a self-evident notation. The square of the effective charge for He ions can be calculated for example from the charge-fraction measurements of Armstrong et al. (1965): 

\[ Z^2_{\text{eff}}(\text{He}) = F_{1\infty} + 4F_{2\infty} \]

where \( F_{1\infty} \) and \( F_{2\infty} \) are the equilibrium fractions of singly and doubly charged He ions respectively. Armstrong et al. measured these fractions together with that for neutrals for He ions emerging from a carbon foil at energies between 0.2 and 6.5 MeV. For \( Z^2_{\text{eff}}(\text{H}) \) one can use the charge fractions for H ions as given by Marion and Young (1968).2

Fortunately alpha-particle stopping powers in titanium have now been measured by Chu and Powers (1969), with an experimental uncertainty of \( \pm 4.1\% \). However, the energy region covered is only between 0.4 and 2 MeV. Above \( E_p = 2.25 \) MeV, Andersen et al. (1968) have measured proton stopping powers with an accuracy of 0.3\%; at the corresponding alpha-particle energies (\( \geq 9 \) MeV) one can apply the Andersen et al. (1969) charge-dependent correction to obtain alpha-particle stopping powers. To interpolate in the region \( 2 < E_p < 9 \) MeV we have used the Janni–Armstrong prescription (eqs. [6] and [7]).

2The use of eqs. [6] and [7] depends upon several assumptions which cannot be fully justified. It is assumed that the ion beam consists of independent components, with no account being taken of the energy losses in the charge exchange processes, and that the only dependence of the stopping power on the charge of the ion is through the factor \( Z^2 \). These assumptions have been discussed, for example, by Meckbach and Allison (1963). There is also a question concerning the applicability of the ion charge fractions measured for carbon to other materials; for heavy ions there is a considerable difference in the charge distribution of the ions emerging from a solid foil and those in a gas, although the internal distributions may be similar (Betz and Grotchins 1970). Still another effect has been shown by Andersen et al. (1969) to exist at energies above the charge-exchange region; the alpha-particle stopping power exceeds four times the proton stopping power at the same velocity. They have measured stopping powers in tantalum and aluminum with an accuracy of 0.3\%, and find values of the ratio \( (S_{\alpha} - 4S_p)/S_p \) of 2.6\% in Ta and 1.3\% in Al at \( E_p = 2.5 \) MeV. Although this ratio appears to vary as \( 1/E_p \) at energies above about \( E_p = 2 \) MeV (\( E_p \approx 8 \) MeV), nothing can really be said about the magnitude of this effect in the charge-exchange region (\( E_p \lesssim 4 \) MeV).

It has been found possible to obtain good agreement with both the Chu–Powers data at low energies, and with the Andersen data at 9–10 MeV, by choosing a normalization factor of 1.0. The estimated accuracy in the stopping powers thus obtained is about 5\%.

Alpha-particle stopping powers for nitrogen have also been calculated according to the Janni–Armstrong prescription and are shown in Fig. 2. The estimated accuracy again is about 5\%. Alpha-particle stopping powers for a TiN target with a N:Ti ratio of 1.0 are also shown in Fig. 2, with the accuracy again about 5\%.

In Section 5 use is made of proton and alpha-particle stopping powers in carbon and oxygen as well as in nitrogen and titanium, at selected energies. The values used are listed in Table 1.

### 3. Comparison of \( ^{15}\text{N}(\alpha, \gamma)^{19}\text{F} \) and \( ^{14}\text{N}(\alpha, \gamma)^{18}\text{F} \) Yields

Aitken et al. (1970) have described a comparison of the radiative yields of the \( E_\gamma = 1.68 \) MeV resonance in the \( ^{15}\text{N}(\alpha, \gamma)^{19}\text{F} \) reaction and the \( E_\gamma = 1.53 \) MeV resonance in the \( ^{14}\text{N}(\alpha, \gamma)^{18}\text{F} \) reaction. Their result is \( \omega_\gamma = 1.30 \pm 0.20 \) eV for the \( ^{19}\text{F} \) resonance, using \( \omega_\gamma = 1.24 \pm 0.10 \) eV for the \( ^{18}\text{F} \) resonance as measured by Parker (1968) and corrected by the factor 14/18. We have repeated this experiment with a new target on a tungsten backing prepared from the same nitrogen gas mixture. The nitrogen gas was analyzed by Mr. D. Priddle of the Department of Chemistry, University of Toronto, and found to have the isotopic ratio \( ^{15}\text{N}/^{14}\text{N} = 0.36 \pm 0.01 \). After the target had been used, the \( ^{15}\text{N}/^{14}\text{N} \) ratio of the surface material was checked with a spark-source mass spectrometer by A. Mykytiuk and D. S. Russell of the Chemistry Division, N.R.C.C., and found to have the value 0.32 \( \pm 0.03 \). It can be concluded that there was little dilution of the \( ^{15}\text{N} \) in the preparation of the target. For the \( \omega_\gamma \) determination we have used the value 0.35 \( \pm 0.02 \) for this ratio.

The target thickness was determined from a gamma-ray yield curve taken with a NaI(Tl) detector, and found to be about 30 keV 10× wide at the energies 1.53 and 1.68 MeV. The Ge(Li) detector was then used to compare the gamma-ray yields. The following transitions were used: in \( ^{19}\text{F} \) (\( \text{R} \rightarrow 1.46 \)), (\( \text{R} \rightarrow 0.110 \)), and (\( \text{R} \rightarrow 0 \)) (\( E_\gamma = 5.34 \) MeV); in \( ^{18}\text{F} \), (\( \text{R} \rightarrow 3.13 \)), (\( \text{R} \rightarrow 3.06 \)), (\( \text{R} \rightarrow 0.35 \)), (\( \text{R} \rightarrow 0.110 \)), and (\( \text{R} \rightarrow 0 \)).
Fig. 2. Alpha-particle stopping powers in Ti, N, and TiN. The experimental points for Ti are from Chu and Powers (1969). The smooth curves are calculated as described in the text.

Table 1. Stopping powers (units of $10^{-15}$ eV cm$^2$ per atom)

<table>
<thead>
<tr>
<th>$E_a$ (MeV)</th>
<th>C</th>
<th>N</th>
<th>O</th>
<th>Ti</th>
<th>Ti$^{18}$N</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.896</td>
<td>4.90$^e$</td>
<td>5.55$^e$</td>
<td>6.31$^e$</td>
<td>12.33$^e$</td>
<td>17.9</td>
<td></td>
</tr>
<tr>
<td>1.36</td>
<td>3.73$^e$</td>
<td>4.19$^e$</td>
<td>4.78$^e$</td>
<td>9.28$^e$</td>
<td>13.5</td>
<td></td>
</tr>
<tr>
<td>1.68</td>
<td>30.6$^e$</td>
<td>33.7$^e$</td>
<td>36.7$^e$</td>
<td>77.9$^e$</td>
<td>111.6</td>
<td></td>
</tr>
<tr>
<td>3.09</td>
<td>21.4$^e$</td>
<td>23.6$^e$</td>
<td>26.6$^e$</td>
<td>55.9$^e$</td>
<td>79.5</td>
<td></td>
</tr>
<tr>
<td>5.30</td>
<td>15.0$^e$</td>
<td>16.8$^e$</td>
<td>19.2$^e$</td>
<td>39.2$^e$</td>
<td>56.0</td>
<td></td>
</tr>
<tr>
<td>5.37</td>
<td>14.8$^e$</td>
<td>16.7$^e$</td>
<td>19.0$^e$</td>
<td>38.9$^e$</td>
<td>55.6</td>
<td></td>
</tr>
</tbody>
</table>

*Ranni-Armstrong prescription for converting proton to alpha-particle stopping powers, eqs. 16 and 17.
*Ranni-Armstrong prescription multiplied by factor 1.05. This fits the experimental data of Chu and Powers (1969) in range 0.4–2.0 MeV and data of Andersen et al. (1968, 1969) at 9–10 MeV.

(R $\rightarrow$ 1.08), (R $\rightarrow$ 1.04), and (R $\rightarrow$ 0) ($E_x = 5.61$ MeV). The detector was used at 55°. Since the resonant state in $^{19}$F has a spin of $\frac{1}{2}$ and the resonant state in $^{18}$F has a spin of $1^-$, there are only terms up to $P_2(\cos \theta)$ in the angular distributions of the gamma rays, and therefore no corrections for the angular distributions were necessary. Since in each case all known primary gamma-ray transitions were used, no corrections for branching ratios were made. The areas under the peaks in the gamma-ray spectra were simply divided by the relative efficiencies (Fig. 1), and summed for each resonance.

The relative yield of the $^{19}$F to the $^{18}$F resonance, after correction for the respective charges, was found to be $0.389 \pm 0.025$, where the error given is statistical only and does not include uncertainties in the relative efficiency factors used. Using eqs. [2] and [3], and stopping powers from Fig. 2, we obtain

$$\omega \gamma^{(19F; 1.68\text{ MeV})} = \omega \gamma^{(18F; 1.53\text{ MeV})} = 1.21 \pm 0.11$$

For the $^{18}$F resonance Parker gives $\omega \gamma = 1.60 \pm 0.13$ eV. We have corrected this by the factor 14/18 and by the larger stopping powers for
titanium nitride which follow from the use of the Chu and Powers (1969) data for titanium. Our modified Parker value is $\omega \gamma = 1.34 \pm 0.11$ eV. The result for the $E_p = 1.68$ MeV resonance in the $^{15}$N($\alpha$, $\gamma$)$^{19}$F reaction therefore is $\omega \gamma = 1.62 \pm 0.20$ eV. A summary of the estimated errors from various causes is given in Table 3.

4. Comparison of $^{15}$N($\alpha$, $\gamma$)$^{19}$F and $^{15}$N(p, $\alpha$)$^{12}$C Yields

The prolific yield of the $^{15}$N(p, $\alpha$)$^{12}$C reaction, leading to emission of a 4.44 MeV gamma ray from $^{12}$C, makes it a suitable standard against which to compare other reaction yields in $^{15}$N. There is a strong resonance at $E_p = 0.898$ MeV with a total width of $\Gamma = 1.5 \pm 0.3$ keV (Bondelid and Butler 1964) for which alpha-particle emission leads exclusively to the 4.4 MeV level in $^{12}$C. Price (1957) has already used this resonance as a standard against which to compare ($\alpha$, $\gamma$) resonance strengths in $^{15}$N and $^{14}$N. He based his work on a measurement by Schardt et al. (1952) which, however, has a large uncertainty arising from the efficiency of the Geiger counter used (see the discussion by Hebbard 1960). There may also be uncertainties arising from the solid KNO$_3$ target used. Gorodetzky et al. (1968) have now re-measured the yield of the 4.4 MeV gamma ray at the $E_p = 0.898$ MeV resonance using a gas target. They obtain $\sigma_0 \Gamma = 1590 \pm 160$ eV b, where $\sigma_0$ is the Breit-Wigner cross section evaluated at the resonant energy. In terms of $\omega \gamma$ we have

$$\omega \gamma = \frac{\pi}{8 \lambda} (\sigma_0 \Gamma)_{\text{e.m.}} = 480 \pm 48 \text{ eV}$$

(It is assumed here that the result of Gorodetzky et al. refers to the center-of-mass system. If not, the value of $\omega \gamma$ given here should be reduced by a factor of 15/16.) It may be noted that eq. [5] becomes $\gamma = (\Gamma_0 \Gamma_{\text{av}}/\Gamma)_{\text{e.m.}}$, but that it is not necessary to know the partial proton and alpha widths for our purposes.

Since the stopping power for 900 keV protons is about 6 times smaller than for 1.68 MeV alpha particles, it was necessary to prepare targets with about 6 times the thickness previously thought adequate, and to ensure uniform if not in fact complete nitriding. Three reasonably satisfactory targets are listed in Table 2. The gamma-ray yield curves for target #141 taken with a NaI(Tl) detector are shown in Figs. 3a and 3b. For the intercomparison the Ge(Li) detector was located at 90° with a small correction being made on the basis of the angular distribution given by Barnes et al. (1952) and of the attenuation coefficients measured for our detector. It was necessary to restrict the target current to about 0.10 $\mu$A in order that the detector could also be used in the same location for the much less prolific $^{15}$N($\alpha$, $\gamma$)$^{19}$F reaction.

The yield of the 4.44 MeV gamma ray from $^{12}$C and the yield of the three resonant gamma rays from $^{19}$F are shown in Table 2, together with the $\omega \gamma$ for the ($\alpha$, $\gamma$) reaction calculated using $\omega \gamma = 480$ eV for the (p, $\alpha$)$\gamma$ resonance. The total spread in the $\omega \gamma$ values is about 10% although the individual yields differ by about 20%. The average $\omega \gamma$ for the three targets is $1.72 \pm 0.20$ eV, in excellent agreement with the result of the comparison with $^{14}$N. In Table 3 estimates are given of the errors in the (p, $\alpha$)$\gamma$ comparison. The major uncertainty arises from the 10% uncertainty in the strength of the ($\alpha$, $\gamma$) resonance.

5. Absolute Strength Determinations

The yields for the $^{15}$N($\alpha$, $\gamma$)$^{19}$F and the $^{15}$N(p, $\alpha$)$^{12}$C resonances given in Table 2 were obtained by making an absolute efficiency calibration of the Ge(Li) detector with a $^{60}$Co source inserted in place of the target. This source was prepared initially on VYNS film for 4n$\beta$-$\gamma$ counting, and was transferred to a tantalum backing similar to those used for our targets after its absolute disintegration rate had been determined.

<table>
<thead>
<tr>
<th>Target number</th>
<th>Backing</th>
<th>Approximate thickness at $E_p = 1.7$ MeV (keV)</th>
<th>$Y(\alpha, \gamma)$ (per a-particle)</th>
<th>$Y(p, \alpha \gamma)$ (per proton)</th>
<th>$\omega \gamma$ ($E_p = 1.68$ MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>134</td>
<td>Ta</td>
<td>60</td>
<td>$1.25 \times 10^{-11}$</td>
<td>$1.00 \times 10^{-7}$</td>
<td>1.66</td>
</tr>
<tr>
<td>139</td>
<td>W</td>
<td>50</td>
<td>1.15</td>
<td>0.83</td>
<td>1.84</td>
</tr>
<tr>
<td>141</td>
<td>W</td>
<td>200</td>
<td>1.33</td>
<td>1.07</td>
<td>1.66</td>
</tr>
</tbody>
</table>
Table 3. Strength ($\sigma$) of the $E_\gamma = 1.68$ MeV resonance in $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$ and estimates of major errors in the three methods

<table>
<thead>
<tr>
<th></th>
<th>Comparison with $^{14}\text{N}(\alpha, \gamma)^{19}\text{F}$</th>
<th>Comparison with $^{15}\text{N}(p, \gamma)^{18}\text{C}$</th>
<th>Absolute (Target #141)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final value (eV)</td>
<td>1.62</td>
<td>1.52</td>
<td>1.5</td>
</tr>
<tr>
<td>Statistical error (%)</td>
<td>6.4</td>
<td>1.5</td>
<td>2.2</td>
</tr>
<tr>
<td>Error in $\gamma$-efficiency (%)</td>
<td>3.0</td>
<td>2.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Error in stopping power, $S$, (%)</td>
<td>—</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Error in target composition, p (%)</td>
<td>5.7</td>
<td>—</td>
<td>17.5</td>
</tr>
<tr>
<td>Error in standard strength (%)</td>
<td>8.3</td>
<td>10.0</td>
<td>20.9</td>
</tr>
<tr>
<td>Total error (%)</td>
<td>12.3</td>
<td>11.5</td>
<td>31.3</td>
</tr>
<tr>
<td>Total error (eV)</td>
<td>0.20</td>
<td>0.20</td>
<td>0.31</td>
</tr>
</tbody>
</table>

The shape of the efficiency curve of our detector (Fig. 1) and the amount of charge delivered to the target were also required to determine the absolute yield. In addition corrections for dead-time losses and for the angular distribution of the reaction gamma rays were made as required.

The stopping power per $^{15}\text{N}$ nucleus is also required for an absolute determination of the radiative strength. A reasonably accurate knowledge of the target composition is therefore required, in contrast to the intercomparison methods where only a ratio of stopping powers is required. If it is assumed that targets #134, 139, and 141 contain only Ti$^{15}\text{N}$ in the ratio N:Ti = 1.0
then the calculated \( \omega \)'s for the \( E_a = 1.68 \) MeV resonance in \( ^{15}\text{N}(\alpha, \gamma)^{19}\text{F} \) turn out to be 1.12, 1.03, and 1.19 eV respectively. Since these values are significantly lower than the intercomparison results, it seems likely that either the N:Ti ratio is significantly less than unity, or there are impurities present, or both.

Let us represent the composition of the target by \( \text{TiN}_x\text{C}_y\text{O}_z \), where \( x \), \( y \), \( z \), .... are the numbers of nitrogen, carbon, oxygen, etc. atoms per titanium atom. The stopping power per "molecule" becomes

\[
\varepsilon = \varepsilon_{\text{Ti}} + x\varepsilon_{\text{N}} + y\varepsilon_{\text{C}} + z\varepsilon_{\text{O}} + ...
\]

where \( \varepsilon_{\text{Ti}}, \varepsilon_{\text{N}}, \varepsilon_{\text{C}}, \varepsilon_{\text{O}} \) ... are the atomic stopping powers of the various elements present. For a yield calculation the relevant quantity is \( (S/p)_\text{Ti} \), the stopping power per nucleus capable of undergoing the particular reaction. It is given by eq. [8] divided by the appropriate atomic factor, e.g. \( x \), and also divided by the isotopic abundance factor.

The rest of this section describes briefly some experiments which were performed on target \#141 in an attempt to determine the atomic composition factors \( x, y, \) and \( z \). The spectrum of alpha particles scattered elastically at 150° from target \#141 for \( E_a = 3.09 \) MeV is shown in Fig. 3d. The elastic scattering was also observed from a target of titanium which had been similarly evaporated onto a tungsten backing, but which had not been nitrided. After correction for the \( Z^2 \) and energy dependence of the cross section, and for the dispersion of the scattered spectra, one obtains from the ratio of the height of the titanium bump to the height from the tungsten interface,

\[
(S/p)_{\text{Ti}} = (0.94 \pm 0.02)(S/p)_\text{w} (\text{target \#141})
\]

\[
(S/p)_{\text{Ti}} = (0.72 \pm 0.03)(S/p)_\text{w} \quad \text{(unnitrided Ti)}
\]

If we now assume that the relative amounts of impurities in the two targets are the same (since they were both prepared in the same evaporator) then we have, by subtraction of [10] from [9],

\[
(x - x')\varepsilon_{\text{N}} = (0.22 \pm 0.03)e_{\text{w}}
\]

where \( x \) is the N:Ti ratio in target \#141, and \( x' \) is the same ratio in the unnitrided target. An unsuccessful search for the \( ^{15}\text{N}(\alpha, \gamma)^{12}\text{C} \) reaction in the unnitrided target showed that \( x < 0.01 \). Thus we obtain, using stopping powers from Table 1,

\[
x = 0.79 \pm 0.13
\]

Incidentally the Rutherford scattering spectrum showed no significant amount of heavy contaminant in the target.

A check on the results of the Rutherford scattering experiment was obtained by comparing the yields of the \( ^{48}\text{Ti}(\alpha, \gamma)^{49}\text{V} \) reaction at the resonance at \( E_a = 1.36 \) MeV. This resonance has been studied by Fodor et al. (1968) and by Klapdor (1969). A gamma-ray yield curve taken with a NaI(Tl) detector for target \#141 is shown in Fig. 3c. Other resonances are clearly visible. However, the characteristic gamma rays are easily separated in a Ge(Li) detector, and the yield is high enough that good statistics can be obtained in a run of a few hours. The ratio of the yields of the \( E_p = 1.36 \) MeV resonance from the unnitrided titanium target and from target \#141 was 1.31 \pm 0.05, in excellent agreement with the ratio of scattering yields at \( E_a = 3.09 \) MeV.

An unsuccessful search was made for the \( E_a = 1.53 \) MeV resonance in the \( ^{14}\text{N}(\alpha, \gamma)^{15}\text{O} \) reaction in target \#141. It showed that the amount of \( ^{14}\text{N} \) present was negligible in comparison to the \( ^{15}\text{N} \).

The next experiment was intended to measure the amount of carbon impurity in target \#141. A resonance in the \( ^{13}\text{C}(\alpha, \gamma)^{16}\text{O} \) reaction at \( E_a = 5.30 \) MeV was selected because of the copious production of the 6.129 MeV gamma ray from \( ^{16}\text{O} \). Yield curves for the double-escape peak of this gamma ray, in the vicinity of \( E_a = 5.3 \) MeV, are shown in Fig. 4. Curve (a) is for a "pure" carbon target of thickness 49 \( \mu \text{g}/\text{cm}^2 \), which corresponds to about 39 keV at \( 5 \) MeV. Curve (c) is for a tungsten blank, and represents the contribution from the beam hitting the shroud as well as the target. This contribution is 3-4% of the yield from the carbon target. Curve (b) shows the yield from target \#141. By the time these runs were made, this target had been extensively used and had a carbon mark on the surface. A peak due to a thin layer of carbon on the surface is clearly visible. Without attempting to interpret the remainder of the yield curve in detail, it is clear that there is also carbon throughout the titanium, which is estimated to be about 100 keV thick at this energy. The yield from the internal carbon was measured at the energy
Fig. 4. Excitation curves for the 6.129 MeV gamma ray produced in the $^{12}$C($\alpha$,\(\gamma\))$^{16}$O reaction as measured with a Ge(Li) detector. (a) Carbon target of thickness 49 µg/cm. (b) Target #141. (c) Tungsten blank. The arrows indicate energies at which longer runs were made.

$E_{\alpha} = 5.346$ MeV with a Ge(Li) detector and compared to the peak yield from the pure carbon target ($E_{\alpha} = 5.32$ MeV), after subtraction of the yield measured with the blank (also at $E_{\alpha} = 5.346$ MeV). This comparison showed that the internal carbon in target #141 gave about 3% of the thick-target yield from a pure carbon target. Using eq. [8], and inserting stopping powers from Table 1, this result can be written as

\[ y = 0.084 + 0.036x + 0.041z + \ldots \]

It is clear that if the amounts of other impurities are small, a sufficiently accurate solution for $y$ can be obtained by using the result [12] already obtained for $x$; this gives

\[ y = 0.11 \pm 0.02 \]

for the carbon:titanium ratio in target #141.

Finally an attempt was made to measure the yield of the $E_{\alpha} = 5.37$ MeV resonance in the $^{16}$O($\alpha$,\(\gamma\))$^{20}$Ne reaction in target #141. However, it was possible only to set an upper limit to the oxygen:titanium ratio:

\[ z < 0.09 \]

The analysis of the amounts of nitrogen, carbon, and oxygen in target #141 can be carried out without reference to the unnitrided titanium target by solving simultaneously three equations obtained respectively from the $^{48}$Ti($p$,\(\gamma\))$^{49}$V or Rutherford scattering experiment, the
The errors in the individual determinations have been combined in quadrature. In comparing the three determinations, however, it should be noted that there may be common systematic errors, particularly in the values of the stopping powers used to deduce the absolute strengths in each case. The final value of $\omega \gamma$ is therefore assigned an error which is slightly larger than the error obtained by quadrature from the individual measurements.

Our value of $\omega \gamma$ is to be compared with the value $\omega \gamma = 1.30 \pm 0.20$ eV given by Aitken et al. (1970) and a value due to Price (1957) and corrected (by us) by the mass factor 15/19 to give $\omega \gamma = 2.6 \pm 0.6$ eV. Price’s value cannot be regarded as well established, however, since it is based on an absolute measurement by Schardt et al. (1952), which as already noted is subject to a major uncertainty in the detector efficiency (Hebbard 1960). The consistency of our relative results can also be regarded to some extent as a confirmation of the absolute measurements of Parker (1968) and of Gorodetzky et al. (1968).

Acknowledgments

The $\omega \gamma$ measurements described here were initiated in cooperation with Dr. J. H. Aitken, who also supplied the gas mixture of $^{15}$N and $^{14}$N. The general program on $^{19}$F is being carried out in collaboration with Dr. A. E. Litherland of the University of Toronto. The targets have all been prepared by Mr. J. D. Stinson of the National Research Council, while Mr. D. Elliott, Mr. G. Smith, and Mr. L. Heistek have kept the experimental equipment in order. We also wish to thank Dr. A. P. Baerg of the radioactivity standards laboratory of N.R.C. for the calibrated $^{60}$Co source, and Drs. W. D. Mackintosh and D. A. Marsden of the Solid State Science Branch, A.E.C.L., Chalk River, for the use of the Rutherford scattering apparatus.

6. Summary

The $\omega \gamma$ values obtained by the three methods are shown in Table 3 together with estimates of the errors in each determination. It is seen that the three methods are in good agreement. The weighted average for the strength of the $^{15}$N($\alpha, \gamma$)$^{19}$F reaction is

$$\omega \gamma = 1.64 \pm 0.16 \text{ eV}$$

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