explain the large asymmetries in the lead data, and to provide the experimentalist with a reliable estimate of the importance of second Born effects in pair production.[33]

[33] The second Born corrections turn out to be small for the carbon-target experiment of Ref. 14. For example, R is $+0.8\%$ for an electron detected at 30° with energy of 170 MeV, and -0.7% at 15°, 625 MeV: R. Simonds (private communication).

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$N^{14}(\alpha,\gamma)F^{18}$ Reaction*

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The $N^{14}(\alpha,\gamma)F^{18}$ reaction has been studied over the range of bombarding energies from 1.00 to 1.70 MeV. In addition to the well-known resonances at 1.53 and 1.62 MeV, two new resonances have been found at α-particle energies of 1.140 ± 0.005 MeV and 1.395 ± 0.005 MeV, corresponding to excited states in F^{18} at energies of 5.290 and 5.490 MeV, respectively. The branching ratio for the γ decay of the 5.29-MeV state was determined as $5.290 \rightarrow 2.524$ [$(87\pm3)\%$] and $5.290 \rightarrow 0.937$ [$(13\pm3)\%$]. The quantity $(2J+1)\Gamma_\gamma\Gamma_\alpha/\Gamma$ for the total electromagnetic decay of each of these four resonances was determined as 0.084 ± 0.004 eV (1.140 MeV), 0.027 ± 0.003 eV (1.395 MeV), 4.80 ± 0.40 eV (1.53 MeV), and 1.35 ± 0.15 eV (1.62 MeV), respectively. On the basis of the observed lack of nonresonant yield from the $N^{14}(\alpha,\gamma)F^{18}$ reaction in this energy region, it is possible to establish an upper limit on the nonresonant S factor for this reaction, $S\leq1.5\times10^6$ keV b.

INTRODUCTION

The $N^{14}(\alpha,\gamma)F^{18}$ reaction is of interest in nuclear astrophysics as a possible source of energy generation in stars which have exhausted their central hydrogen content via the CNO cycle.[1] In such stars, because of the relatively long life of N^{14} in the CNO cycle, there exists a core containing essentially a mixture of He^4 and N^{14} as the star begins to evolve along the red-giant branch. This stage of evolution will be halted when the central temperature becomes high enough to trigger either the triple-α reaction[2,3] or the $N^{14}(\alpha,\gamma)F^{18}$ reaction, and it therefore is important to know the rates of these two reactions in order to determine how far up the red-giant branch such a star will move. In addition to determining the magnitude and behavior of the nonresonant, low-energy cross section for the $N^{14}(\alpha,\gamma)F^{18}$ reaction, there are a number of excited states in F^{18} which could be important as low-energy resonances in this reaction. Studies of the $F^{19}(He^3,\alpha)F^{18}$ reaction by Hinds and Middleton[4] reveal the existence of nine levels in F^{18} at excitation energies between 4.65 and 5.79 MeV which are accessible as resonances in the $N^{14}+\alpha$ entrance channel at α-particle energies below 2 MeV. Two of these resonances have been observed by Price[5] in the $N^{14}(\alpha,\gamma)F^{18}$ reaction at α-particle energies of 1.53 and 1.62 MeV, and have since been studied through the same reaction by a number of other groups.[6–9] However, although some of this work[8] has searched as low as $E_\alpha=0.64$ MeV, no other resonances were found below 2 MeV. A study of the elastic scattering reaction $N^{14}(\alpha,\alpha)N^{14}$ by Silverstein *et al.*[10] also found only the two resonances at 1.53 and 1.62 MeV in the energy range from $E_\alpha=0.92$ to 2.0 MeV.

The measurements described below were therefore carried out to investigate the nonresonant rate of the $N^{14}(\alpha,\gamma)F^{18}$ reaction at the low energies of interest in

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astrophysics and to search for resonances corresponding to any of the other levels in F^{18} at excitation energies between 4.65 and 5.79 MeV.

PROCEDURE

The nitrogen targets used in this experiment were made by heating titanium, with an rf induction coil, to a temperature of $\sim$1300°C in a nitrogen atmosphere. Thin TiN targets (20 to 40 keV thick to 1.25-MeV α particles) were made by first evaporating the titanium onto a backing of tungsten and then nitriding it. Thicker targets were made by nitriding $\frac{1}{16}$-in.-thick polished titanium disks. When the thick targets made in this way are watercooled, they can be used for several days at beam currents of up to 2μA (1.25-MeV α particles) without any deterioration. The thinner targets with tungsten backings are more stable and can be used for several days without water cooling without deterioration at beam currents (1.25-MeV α particles) of 10 μA for 0.010-in. tungsten backings and at least 20 μA for 0.020-in. tungsten backings.

Measurements were made both by observing the prompt γ radiation from the target directly, using NaI and Ge(Li) detectors, and by measuring the build-up cf F^{18} β^+-activity ($t_{1/2}$=111 min). For the positron measurements the targets were bombarded at constant beam levels ($\pm$3%) for specific lengths of time and for measured charge accumulations; they were then removed to a heavily shielded location and counted for periods of up to 2 h using a 7.62-cm×7.62-cm NaI crystal to detect the 511-keV annihilation radiation. In addition to the advantage of increased sensitivity as a result of counting in a well-shielded location away from the accelerator, this technique has advantages in determining total cross section data independent of angular distributions, and in determining total electromagnetic-decay widths independent of branching ratios, provided there is no significant γ de-excitation to states with appreciable widths for particle decay. By measuring the 511-keV peak intensity as a function of time, checks were made on the half-life of the β^+ activity being observed; the resulting data were always quite consistent with the 111-min F^{18} half-life. For each of these β^+ runs, after background subtraction, the net 511-keV peak was corrected for the residual β^+ activity in the target due to previous bombardments, and then the usual lifetime corrections and NaI photopeak-efficiency calculations were applied in order to determine the number of F^{18} nuclei produced by the particular bombardment.

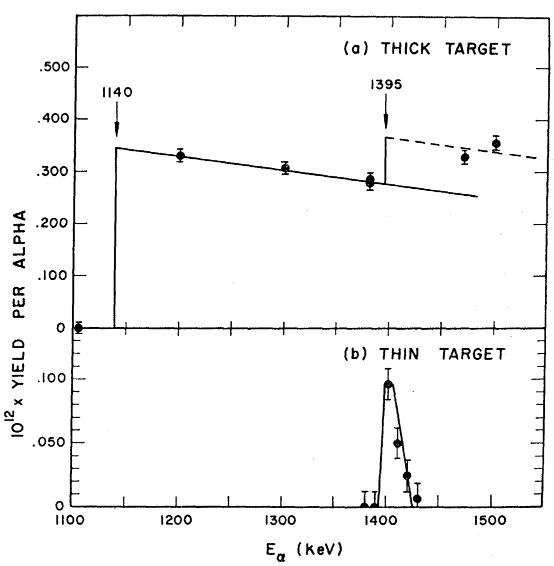

FIG. 1. Excitation functions for the $N^{14}(\alpha,\gamma)F^{18}$ reaction measured using (a) an infinitely thick TiN target and (b) a 20-keV thick target. Data were obtained by observing the positron decay of the F^{18} produced.

Figure 1 shows a plot of this yield of F^{18}, per 10^{12} incident α particles, as a function of α-particle energy. The upper graph is a thick-target excitation function from 1100 to 1500 keV and shows clearly the existence of a resonance between 1100 and 1200 keV and the possible existence of a second resonance between 1380 and 1470 keV. In the latter case, the thick-target data are confused by the continuing contribution from the lower-energy resonance. Therefore, a thinner target was used for a second excitation function covering the region in question in 10-keV steps beginning at 1380 keV. A plot of these results is shown in the lower graph, establishing the existence of a resonance at an energy of 1395$\pm$5 keV. The curve through the data in the lower graph was obtained from a normalization of a more detailed target-thickness measurement made using this same target at the lower-energy resonance. The resonant yield from the thinner target, $(0.096\pm0.012)\times10^{-12}$ per α particle, is consistent with the more uncertain estimate from the upper graph, $(0.085\pm0.040)\times10^{-12}$ per α particle.

Excitation functions taken in 5-keV steps in the neighborhood of the lower resonance indicate a resonant energy of 1139$\pm$5 keV for this resonance which, from the data in Fig. 1(a), gives a resonant yield of $(0.345\pm0.015)\times10^{-12}$ F^{18} per incident α particle. Because of the larger yield at this resonance, spectra were taken of the prompt γ radiation from the target below the resonance and on the resonance in order to study the γ decay of this state. Figure 2 shows the result of an 18-h run on resonance at a beam current of 10 μA, using an 8-cc Ge(Li) detector at 0° to the incident beam and approximately 2 cm from the target. A second-order polynomial for the energy calibration of this spectrum was fitted to the location of six calibration lines from Cs^{137}, Na^{22}, K^{40}, and Tl^{208}, and was then used to extract the energy of the lines due to $N^{14}(\alpha,\gamma)F^{18}$ reaction. Appropriate Doppler-shift corrections were then applied to the extracted F^{18} γ-ray energies to take into account the facts (1) that our measurements were made at 0°

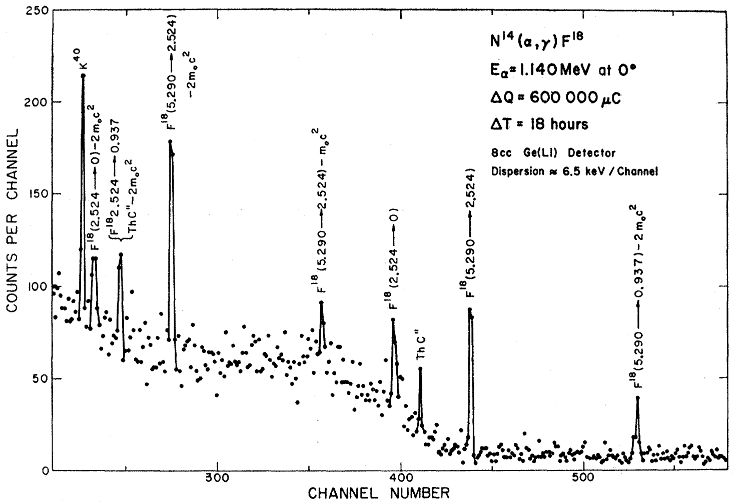

FIG. 2. Partial γ-ray spectrum taken at the 1140-keV resonance in the $N^{14}(\alpha,\gamma)F^{18}$ reaction. Data were obtained using an 8-cc Ge(Li) detector at 0° to the incident beam.

and (2) that in a capture reaction such as this, the recoiling nucleus must travel directly forward. In this particular case, the full Doppler shift amounts to ≈ 5.6 keV/MeV. The accurate transition energies obtained in this way can then be used to precisely determine the excitation energy of this state and hence the resonant energy as well. In particular, as indicated in Fig. 2, transitions were observed from this resonance directly to the 0.937- and 2.524-MeV levels in F^{18}; the energies for these two transitions, as determined from their full-energy and double-escape peaks, yield an excitation for this state of 5.290 ± 0.005 MeV and a corresponding resonant energy of 1.140 ± 0.005 MeV, in excellent agreement with the results of our excitation-function measurements.

RESULTS

Using the relative efficiency curves compiled by Hechtl[11] at Brookhaven National Laboratory for this 8-cc Ge(Li) detector, we normalized the peak areas in the prompt γ-ray spectrum in order to obtain relative transition strengths and branching ratios for the decay of the 5.29-MeV state. The normalized yields from the $(5.290 \to 0.937) - 2m_0c^2$, $(5.290 \to 2.524)$, and $(5.290 \to 2.524) - 2m_0c^2$ lines give a branching ratio at 0° of

$$\frac{[5.290 \to 0.937]}{[5.290 \to 2.524]} = \frac{13 \pm 3}{87 \pm 3}.$$

The normalized yields for each of the other F^{18} γ rays, e.g., $(2.524 \to 0)$, $(2.524 \to 0.937)$, $(0.937 \to 0)$, etc., are all consistent with this ratio and the branching ratios determined by Olness, Warburton and Poletti[12] for the lower-lying levels of F^{18}. A careful search was made for additional lines in this Ge(Li) spectrum which could be attributed to transitions from the 5.29-MeV state to other states in F^{18} or to other transitions between the lower-lying states of F^{18}. No such transitions were found and an upper limit of $\lesssim 3\%$ was established for any additional γ-ray branches from the 5.29-MeV state.

From measurements of the resonant yield at the step in the thick-target excitation function, one can determine the quantity $(2J+1)\Gamma_\gamma\Gamma_\alpha/\Gamma$ as follows:

$$\frac{\Gamma_\gamma\Gamma_\alpha}{\Gamma} = \frac{(2S_0+1)(2S_1+1)}{(2J+1)} \frac{2\epsilon}{\lambda_{\text{c.m.}}^2} y,$$

where S_0, S_1, and J are the spins of the target nucleus, the incident projectile, and the resonant state, respectively; ϵ = the energy loss of the projectile in the target, per target nucleus per cm^2; $\lambda_{\text{c.m.}}$ = (the wavelength of the projectile in the center-of-mass system) $= [(M_1+M_0)/M_0]h/[2M_1E_1(\text{lab})]^{1/2}$; y = the yield at the thick-target step per incident projectile. The stopping cross sections for α particles in TiN were interpolated from the compilations of Whaling[13] and vary slowly over the range of this experiment from 124×10^{-18} keV cm^2 at 1.00 MeV to 107×10^{-18} keV cm^2 at 1.62 MeV.

Using the data from the excitation functions plotted in Fig. 1 and similar data obtained for the higher resonances at 1.53 and 1.62 MeV, we measured the total yield of F^{18} produced per incident α particle and the width, $(2J+1)\Gamma_\gamma\Gamma_\alpha/\Gamma$, for each of these resonances as shown in Table I. It should be emphasized that since

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TABLE I. Summary of data for four resonances in $N^{14}(\alpha,\gamma)F^{18}$.

E_α (keV)	Y [$F^{18}/(10^{12}\alpha$'s)]	$(2J+1)\Gamma_\gamma\Gamma_\alpha/\Gamma$ (eV)
1140	0.345±0.015	0.084±0.004
1395	0.096±0.012	0.027±0.003
1532	16.2 ±1.0	4.80 ±0.40
1619	4.4 ±0.4	1.35 ±0.15

TABLE II. Weisskopf units for transitions from the 5.29-MeV state in F^{18}.

	$5.290\to 2.524(2^+)$	$5.290\to 0.937(3^+)$
$(2J+1)\Gamma_\gamma$	0.130±0.043 eV	0.019±0.006 eV
$\Gamma_{\gamma W}(E1)$	9.9 eV	38 eV
$\Gamma_{\gamma W}(M1)$	0.45 eV	1.73 eV
$\Gamma_{\gamma W}(E2)$	0.00038 eV	0.0036 eV

TABLE III. α-particle and γ-ray widths for the 5.29-MeV state in F^{18}.

	$J=1$	$J=2$	$J=3$
Γ_α (eV)	0.064±0.021	0.038±0.013	0.027±0.009
Γ_γ (eV)	0.050±0.017	0.030±0.010	0.021±0.007
Γ (eV)	0.114±0.038	0.068±0.023	0.048±0.016

the excitation functions were measured in terms of the F^{18} positron activity and since none of these states are known to have significant γ branches to lower-lying states with appreciable widths for particle decay, Γ_γ refers to the *total* electromagnetic width of these states. The results for the two higher resonances are in reasonable agreement with the measurements of Price,[5] who obtained $(2J+1)\Gamma_\gamma\Gamma_\alpha/\Gamma=6\pm2$ and 4 ± 2 eV for the 1.53- and 1.62-MeV resonances, respectively.

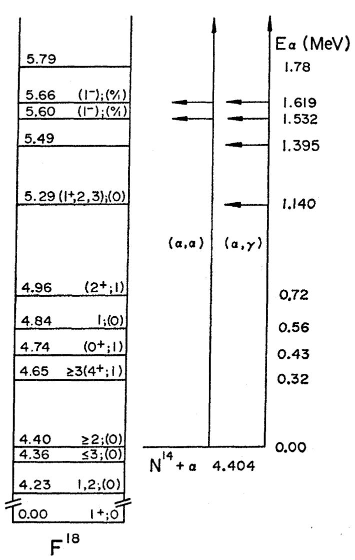

FIG. 3. Abbreviated energy level diagram for F^{18}, indicating the locations of observed and possible resonances in the $N^{14}+\alpha$ entrance channel.

By combining this measurement of $(2J+1)\Gamma_\gamma\Gamma_\alpha/\Gamma$ for the 5.29-MeV state with the recent Strasbourg measurement[14] of

$$\Gamma_\gamma(5.29\to 2.52)/\Gamma=0.38\pm0.12\,,$$

and our measurement of the branching ratio for this state,

$$\Gamma_\gamma(5.29\to 2.52)/\Gamma_\gamma=0.87\pm0.03\,,$$

we obtain the following "widths" for this state:

$$(2J+1)\Gamma_\alpha=0.192\pm0.064\text{ eV}\,,$$
$$(2J+1)\Gamma_\gamma(5.29\to 0.94)=0.019\pm0.006\text{ eV}\,,$$
$$(2J+1)\Gamma_\gamma(5.29\to 2.52)=0.130\pm0.043\text{ eV}.$$

Table II compares these values for $(2J+1)\Gamma_\gamma$ with the Weisskopf units for such transitions. From this comparison it is clear that the $(5.290\to 2.524)$ transition must be either $E1$ or $M1$; an $E2$ multipolarity would require $|M(E2)|^2\geq 38$ which is not likely. For the $(5.290\to 0.937)$ transition $|M(E2)|^2\leq 2$, and therefore $E1$, $M1$, and $E2$ are all possible multipolarities. The $(5.290\to 2.524)$ transition therefore limits the spin of the 5.290-MeV level to $J=1$, 2, 3, while the $(5.290\to 0.937)$ transition limits the spin and parity of this level to $J^\pi=1^+$, $2^\pm$, $3^\pm$, $4^\pm$, 5^+. Between these two transitions we have $J^\pi=1^+$, $2^\pm$, $3^\pm$. In order to see if any further limitations could be set on the spin and parity of this state, α-particle reduced widths were calculated using the values of Γ_α in Table III for $l_\alpha=0$, 1, 2, 3 as required by $J^\pi=1^+$, $2^\pm$, $3^\pm$. However, in all cases these reduced widths were less than 2% of the Wigner single-particle limit. Figure 3 summarizes some of the information derived for these two new resonances, together with the two higher resonances, in an abbreviated level diagram covering this region of F^{18}.

ASTROPHYSICAL RESULTS

The astrophysical interest in the $N^{14}(\alpha,\gamma)F^{18}$ reaction is concerned with its cross section at low energies. This cross section can have contributions from nonresonant direct capture and from low-energy resonances. The energy dependence of the nonresonant cross section is determined primarily by the Coulomb barrier,

$$\sigma=S/E_{\text{c.m.}}\exp[-31.28Z_0Z_1A^{1/2}/E_{\text{c.m.}}{}^{1/2}\text{ (keV)}]\,,$$

where S is very nearly energy-independent.[15] Hence, measurements of the nonresonant cross section at high energies can be used to determine S, and then S can be used to extrapolate cross sections to lower energies in the usual way. The previous estimate of S for the $N^{14}(\alpha,\gamma)F^{18}$ reaction was 8.73×10^9 keV b.[16]

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During the measurements reported in this paper several unsuccessful attempts were made to detect the production of F^{18} via the $N^{14}(\alpha,\gamma)F^{18}$ reaction at energies well removed from known resonances. In particular, at bombarding energies of 1100 and 1390 keV no evidence was found for F^{18} positron activity above the background in the 7.62-cm×7.62-cm NaI detector. On the basis of this lack of F^{18} activity we can set an upper limit on the nonresonant S factor for this reaction,

$$S \leq 1.5 \times 10^{6} \text{ keV b},$$

which is more than 5000 times smaller than the previous estimates. This new limit on S is equivalent to nonresonant cross sections of $\leq 0.1\ \mu$b at 1390 keV and $\leq 0.006\ \mu$b at 1100 keV.

As far as the resonant contributions to the low-energy cross section for the $N^{14}(\alpha,\gamma)F^{18}$ reaction are concerned, the level diagram in Fig. 3 shows that below the resonances at 1.395 and 1.140 MeV there are four more possible resonances, at energies of 0.72, 0.56, 0.43, and 0.32 MeV, corresponding to known excited states in F^{18}, in addition to the 4.40-MeV state right at threshold. For all of the states below 5.00-MeV excitation the α-particle widths are considerably smaller than the γ-ray widths; specifically $\Gamma_\alpha/\Gamma_\gamma \leq 0.2$ for the 4.84-MeV state.[14] The spin-parity and isobaric spin assignments for these levels have been made on the basis of identifications with analog states in O^{18} and on the basis of angular correlation studies at Strasbourg[14] and at Brookhaven.[12] The assignment of $T=1$ to several of these levels need not rule out the possibility of their participation in the $N^{14}(\alpha,\gamma)F^{18}$ reaction, since they might have appreciable $T=0$ impurities. Reeves[17] has suggested that studies of the $Ne^{20}(d,\alpha)F^{18}$ reaction can be used to determine the importance of these states as resonances in the $N^{14}(\alpha,\gamma)F^{18}$ reaction. However, a study of the $Ne^{20}(d,\alpha)F^{18}$ reaction cannot determine the amount of $T=0$ impurities in these states since any population of $T=1$ states in F^{18} via this reaction could also be due to isospin impurities in the Na^{22} compound nucleus. It is also *not* possible for the $Ne^{20}(d,\alpha)F^{18}$ reaction to give any information regarding the α-particle widths of excited states in F^{18}. This information is best obtained either directly via the $N^{14}(\alpha,\gamma)F^{18}$ reaction or via a direct α-transfer reaction[18] such as $N^{14}(Li^7,t)F^{18}$. In view of the small α-particle widths expected for these states, the (Li^7,t) reaction is probably the most feasible way of carrying out these measurements, and it has the added advantage of allowing study of the 4.36- and 4.40-MeV states, which would be inaccessible to the (α,γ) reaction. The role of the $N^{14}(\alpha,\gamma)F^{18}$ reaction as a helium-burning reaction in stars cannot be finally determined until the α-particle widths have been measured for all of these states. Work on the $N^{14}(Li^7,t)F^{18}$ reaction is now in progress at Yale.

ACKNOWLEDGMENTS

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