It would be expected that the shape of the potential well should be different for these different reaction mechanisms. As long as the absorption is strong, however, it will take place largely at the surface and the calculations will be insensitive to the details of the shape. It seems more likely that useful information about the reaction mechanism could be obtained from the energy and angular distributions of the reaction products, rather than from the elastically scattered particles.

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Direct Radiative Capture of Protons by O^{16} and Ne^{20}*

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A study has been made of the $O^{16}(p,\gamma)F^{17}$ and $Ne^{20}(p,\gamma)Na^{21}$ reactions by counting the positron activities of F^{17} and Na^{21} following proton bombardment of oxygen and neon targets. The $O^{16}(p,\gamma)F^{17}$ cross section was measured at a proton bombarding energy of 616 kev to be 0.29 ± 0.03 microbarn and the $Ne^{20}(p,\gamma)Na^{21}$ cross section was measured at 1100 kev to be 1.3 ± 0.7 microbarns. These cross sections are consistent with the reaction process in each case being one of direct radiative capture. In addition, the energy dependence of the $O^{16}(p,\gamma)F^{17}$ cross section from 275 kev to 616 kev was also consistent with the direct-capture hypothesis.

Both of these reactions are believed to be important at the thermal energies effective in stars. For such energies the cross-section parameter S_0 was estimated to be $S_0=5\pm1$ kev-barns for $O^{16}(p,\gamma)F^{17}$, and $S_0\sim80$ kev-barns for $Ne^{20}(p,\gamma)Na^{21}$.

1. INTRODUCTION

THE $O^{16}(p,\gamma)F^{17}$ reaction is distinguished by a completely smooth yield curve up to a proton bombarding energy of 3 Mev,[1] and by a $\sin^2\theta$ angular distribution[2] for the γ radiation to the first excited state of F^{17}. As Warren *et al.*[2] have suggested, these facts are consistent with the direct radiative capture of p-wave protons. However, the explanation of the ten to one favoring of transitions to the first excited state ($J=\frac{1}{2}^+$)[3] over transitions to the ground state ($J=\frac{5}{2}^+$) is not obvious, since both are electric dipole for incident p-wave protons.

The calculations of Christy and Duck[4] predict both the absolute cross section and intensity ratio with remarkable accuracy. It was noted that the favoring of the excited state transition was a result of the low proton binding energy (100 kev) of this state which leads to a considerable extension of the proton wave function beyond the customary nuclear radius. This suggested that $Ne^{20}(p,\gamma)Na^{21}$ should also have a large direct radiative capture cross section, as Na^{21} has an excited state[5] of $J=\frac{1}{2}^+$ bound by 26 kev with respect to $Ne^{20}+p$. In addition, this state in Na^{21} is believed to have a large proton reduced width,[6] which is undoubtedly a necessary condition for a large cross section.

Both of the reactions $O^{16}(p,\gamma)F^{17}$ and $Ne^{20}(p,\gamma)Na^{21}$ are believed to be important in determining the element abundances in stars.[7] The oxygen reaction is effective in returning any leakage through $N^{15}(p,\gamma)O^{16}$ from the C-N cycle by $O^{16}(p,\gamma)F^{17}(\beta^+\nu)O^{17}$ followed by the fast reaction $O^{17}(p,\alpha)N^{14}$.

The Ne^{20} reaction is the first step of the Ne-Na cycle and is principally interesting as the process for generating Ne^{21}. Ne^{21} owes its importance to the exoergic reaction $Ne^{21}(\alpha,n)Mg^{24}$ which is proposed by Burbidge *et al.*[7] as the main source of neutrons for building heavy elements through neutron capture processes.

2. EXPERIMENTAL

As the cross sections for both reactions are quite small, the yields were observed by delayed counting of

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[1] R. A. Laubenstein and M. J. W. Laubenstein, Phys. Rev. **84**, 18 (1951).

[2] Warren, Laurie, James, and Erdman, Can. J. Phys. **32**, 563 (1954).

[3] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

[4] R. F. Christy and I. M. Duck (to be published).

[5] P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 683 (1957).

[6] J. B. Marion and W. A. Fowler, Astrophys. J. **125**, 221 (1957).

[7] Burbidge, Burbidge, Fowler, and Hoyle, Revs. Modern Phys. **29**, 547 (1957).

the F^{17}($\tau_{\frac{1}{2}}=66$ sec) and Na^{21}($\tau_{\frac{1}{2}}=23$ sec) positron activities after proton bombardment. The apparatus was designed by Pixley[8] for studies of the $N^{14}(p,\gamma)O^{15}$ reaction. It consisted of a target mounted off-axis on a vacuum sealed shaft which could be rotated to move the target out of the proton beam and close to the β counter. For the neon measurements the apparatus was modified to allow the target to be water cooled.

The procedure was to bombard the target with a proton beam, monitored by a current integrator, for a time comparable to one half-life and then to record the decay curve of the β activity. Decay of the activity during bombardment was estimated from the bombarding time, or, more satisfactorily, corrected for automatically by the use of a "leaky integrator" system. This system consisted of a current integrator with a resistor in parallel with the integrator condenser such that the RC time constant was equal to the mean lifetime of the β decay. The condenser voltage is then proportional to the activity. A small correction was also necessary for the five to ten seconds lost turning the beam off and starting the count.

The majority of the decay curves were taken automatically with a ten-channel timer. The output pulses from the usual discriminator were fed through a stepwise potential divider driven by a synchronous motor thus converting time into pulse height. A ten-channel pulse-height analyzer completed the system. For the timing channels used, it was necessary to run through the ten channels several times for a complete decay curve.

At the lower bombarding energies the 650-kv Kellogg electrostatic accelerator provided a monoenergetic proton beam of 50 μa. Above 650 kev it was necessary to use the 2-Mv electrostatic accelerator with a beam in the vicinity of 15 μa.

3. PROTON CAPTURE BY OXYGEN

The F^{17} positrons were detected by a CsI scintillation counter consisting of a 10-mm diameter by 1-mm thick crystal located 1 mm away from the target when this was in the counting position. The discriminator was customarily set to reject electrons of less than a few hundred kev in energy. For this setting the counting efficiency was measured to be about 40%.

It was necessary to correct all the experimental decay curves for the 10-min N^{13} activity produced by proton bombardment of carbon on the target, as well as for background. Counts were taken in 30-sec channels for 30 min after each bombardment, the last 20 min being a measurement of the N^{13} activity for subtraction from the N^{13} plus F^{17} activities recorded in the first ten minutes.

As O^{15} activity ($\tau_{\frac{1}{2}}=120$ sec, $E_{max}=1.70$ Mev) could not be easily distinguished from F^{17}($\tau_{\frac{1}{2}}=66$ sec, $E_{max}=1.75$ Mev), a search was made for N^{14} on the target by measuring the activity yield in the region of the 280-kev resonance[3] in $N^{14}(p,\gamma)O^{15}$. Oxide targets made by heating beryllium in oxygen or tungsten in air showed no sign of N^{14}.

Relative measurements were made with an oxidized disk of beryllium metal as target by comparing the F^{17} yield at 274, 352, and 550 kev with the yield at 616 kev. This showed that the energy dependence of the cross section departed very little from the expression

$$\sigma=SE^{-1}\exp(-2\pi\eta), \tag{1}$$

where S is a constant[4] and $\eta=Z_1Z_0e^2/\hbar v$ with Z_1 and Z_0 the atomic numbers of the nuclei interacting with relative velocity v and center-of-mass energy E. Assuming such an energy dependence, the relative yield measurements could be converted into relative cross-section measurements by integrating the expression

$$Y=\int_0^{E_b}\frac{\sigma}{\epsilon}dE, \tag{2}$$

where Y is the yield, σ the cross section, ϵ the stopping power per oxygen atom, and E_b the bombarding energy. The stopping power depends on the target composition. This was investigated by examining with a magnetic spectrometer the momentum distribution of protons scattered by the target. The distribution of oxygen was found to have a flat maximum at the front surface but a long exponential-like tail extending to a depth corresponding to an energy loss of about 100 kev for 600-kev protons. Assuming the composition BeO at the front surface, it was possible to integrate Eq. (2) numerically using the known stopping powers for beryllium and oxygen.[9]

Owing to the overlapping of the momentum distributions of protons scattered by oxygen and beryllium, the composition was not very accurately determined. This had little effect on the relative measurements but left the absolute cross section with a large probable error.

A target of oxidized tungsten was analyzed by comparison of the yield of protons per momentum interval scattered from the oxide target and from an unoxidized tungsten target. The yield depends on the oxygen concentration through ϵ in Eq. (2). As ϵ for tungsten has not been measured, the values of Bader *et al.*[10] for tantalum were used as the closest approximation. The comparison showed that, to an accuracy of a few percent, the oxide target was uniform to a depth of at least 150 kev for 600-kev protons and had a composition WO_3.

The WO_3 target gave sufficient F^{17} yield at 616 kev for the positron annihilation quanta to be counted, thus making it possible to avoid the awkward problem of measuring the β-counter efficiency. A NaI scintillation

[8] R. E. Pixley (to be published).

[9] Ward Whaling, *Handbuch der Physik* (Springer-Verlag, Berlin, 1958), Vol. 34, p. 13.

[10] Bader, Pixley, Mozer, and Whaling, Phys. Rev. **103**, 32 (1956).

counter was put in place of the β counter with a 0.015-in. sheet of tantalum in front of the 1 in.$\times$1 in. crystal to stop the positrons. Background was minimized by use of a single-channel analyzer set on the 0.51-Mev photopeak. The counting efficiency was measured by the coincidence method. A Na^{22} source on a tungsten backing was mounted in place of the target and an additional γ counter set up to detect the 1.28-Mev γ radiation from $Na^{22}(\beta^+\nu)Ne^{22*}(\gamma)Ne^{22}$. The rate of coincidences between the two counters, corrected for random coincidences and electron capture in the source, divided by the singles rate in the additional counter, gave the counting efficiency.

The yield of annihilation quanta after bombarding the WO_3 target with 616-kev protons is plotted against time in Fig. 1. Background has been subtracted. The vertical and horizontal lines on each point indicate the statistical error and counting time, respectively. Using the counts after the first ten minutes to calculate the N^{13} activity gave the F^{17} yield. The cross section was obtained from the yield by numerically intergrating Eq. (2) using the known energy dependence and the known target composition. This gave $\sigma=0.29\pm0.03$ microbarn and $S=4.2\pm0.4$ kev-barns for $E_p=616$ kev (laboratory bombarding energy).

The values of S are plotted against center-of-mass proton energy in Fig. 2 and are consistent with S being a constant. This is in agreement with the earlier measurement of Warren *et al.*[2] at 1270 kev and has since been confirmed by measurements from 132 to 160 kev by Hester, Pixley, and Lamb.[11] The solid curve indicates the calculated value of S obtained by Christy and Duck.[4]

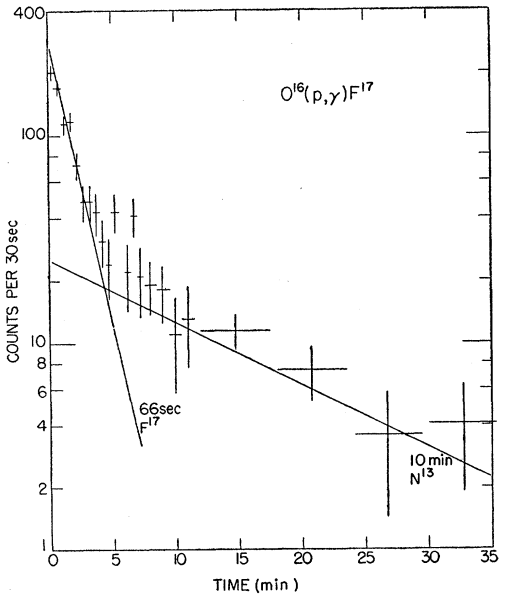

FIG. 1. Decay curve observed for positron annihilation quanta after bombarding a WO_3 target with protons at 616 kev. This is the sum of two runs corrected for background.

[11] Hester, Pixley, and Lamb, University of California Radiation Laboratory Report UCRL-5074, April 1, 1958 (unpublished).

4. PROTON CAPTURE BY NEON

The neon target was prepared by Pixley, Hester, and Lamb[12] by bombarding a water-cooled aluminum sheet with 50-kev neon ions. Assuming all the current was Ne^{20+} the bombardment amounted to about 5×10^{18} Ne atoms/cm^2 which should have been adequate to saturate the surface of the aluminum.[13,14] For the present investigation small pieces were cut from the aluminum sheet. The stability of the targets under proton bombardment was remarkably good; e.g., a target which had been bombarded for 8 min with an energy dissipation approaching 0.5 kw/cm^2 gave the same yield of Na^{21} activity at the 1070-kev resonance for $Ne^{20}(p,\gamma)Na^{21}$ as a target which had been freshly cut from the sheet. A further check was made by heating a target for 18 hours at 300°C. According to the resonance yield of Na^{21}, about half the Ne^{20} had been evaporated by this process.

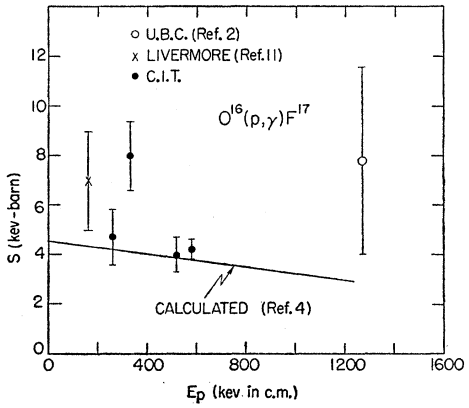

FIG. 2. The cross-section parameter S for $O^{16}(p,\gamma)F^{17}$ plotted against center-of-mass proton energy. Over the range of the experimental measurements, the cross section changes by five orders of magnitude while S remains approximately constant.

A plastic scintillator $\frac{5}{8}$ in.$\times\frac{1}{2}$ in. was used to detect the positrons, the size being chosen to be close to the range of the maximum energy positrons from Na^{21}(2.5 Mev). The plastic was mounted in a close-fitting lead cylinder and the surface exposed to the target covered with a 0.001-in. aluminum foil. An energy calibration was obtained from the Compton distributions for the 2.62-Mev ThC'' and 1.33-Mev Co^{60} γ rays and from the 624-kev Cs^{137} conversion line. The latter gave a peak of 20% width. An efficiency calibration was obtained by measuring the yield of F^{17} activity from a thick WO_3 target. Counts were taken with a discriminator bias of 1.2 Mev to avoid counting back scattered electrons. For this bias the efficiency should be the product of a

[12] Pixley, Hester, and Lamb, University of California Radiation Laboratory Report UCRL-4969, October 16, 1957 (unpublished).
[13] Broström, Huus, and Koch, Nature **160**, 498 (1947).
[14] H. B. Greene, Oak Ridge National Laboratory Report ONRL-2275 (unpublished).

geometric factor and the fraction of the β spectrum accepted.

The Na^{21} counts were taken with a bias of 1.75 Mev which is the end-point energy of the F^{17} decay. However, some F^{17} was still recorded presumably due to the finite resolution and to the interaction of annihilation quanta in the scintillator. No 10-min N^{13} was recorded with the bias at 1.75 Mev. A search for 7-sec Al^{25} and Al^{26} activity ($E_{max}=3$ Mev) was made at the strong resonances at 825 and 933 kev for $Mg^{24}(p,\gamma)Al^{25}$ and $Mg^{25}(p,\gamma)Al^{26}$, respectively. No sudden increase in activity yield was observed at these energies which indicated that the amount of magnesium present was negligible.

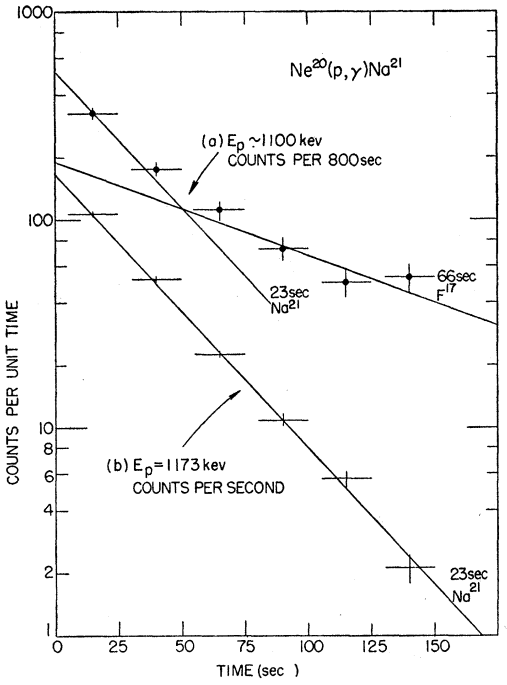

FIG. 3. Decay curves of β activity after proton bombardment of a neon target. (a) Sum of forty runs near 1100 kev. (b) A single run at 1173 kev. Both curves are corrected for background. The timing intervals are indicated by the horizontal bars.

Several attempts were made to observe Na^{21} activity after bombarding neon targets with 630-kev protons. In all cases the decay curves were consistent with 66-sec F^{17} activity and gave no positive indication of Na^{21} activity. From the statistics of the counts recorded during the first 60 sec it was possible to place an upper limit on the yield of the reaction $Ne^{20}(p,\gamma)Na^{21}$ as less than 2.8×10^{-14} Na^{21} per proton at a bombarding energy of 630 kev.

A second measurement was made in the region of 1100 kev. Figure 3 shows the decay curve obtained near 1100 kev and also the decay curve obtained after bombarding at the 1170-kev resonance for $Ne^{20}(p,\gamma)Na^{21}$, previously observed by Broström, Huus, and Koch.[13]

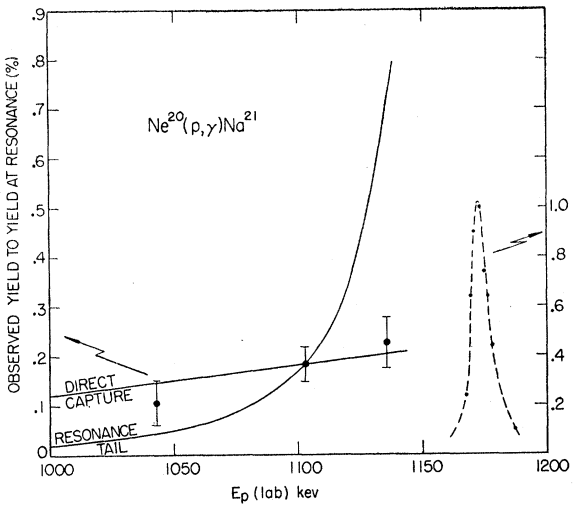

FIG. 4. The ratio of observed yield to the peak yield at resonance for $Ne^{20}(p,\gamma)Na^{21}$. The full curves indicate the expected variation of the yield for direct capture and for the tail of the resonance, both being fitted to the point at 1102 kev.

As the resonance provided a strong source of Na^{21}, it was convenient to measure the nonresonant yield by comparison. For the particular resonance energy involved here, the ratio of nonresonant yield to resonant yield is $0.29\sigma\Delta/\omega\gamma$, where σ is the nonresonant cross section in barns, $\omega\gamma=\omega\Gamma_\gamma\Gamma_p/\Gamma$ for the resonance, and Δ is the target thickness which is assumed to be larger than the resonance width. The apparent width of the resonance was observed to be 10 ± 1 kev (see Fig. 4) and it will be shown later that the intrinsic width is less than 0.7 kev. Broström *et al.* give $\omega\gamma=2$ ev but without any stated error.[15]

The yield was measured at 1042, 1102, and 1136 kev with a view to distinguishing nonresonant yield from any possible yield due to the tail of the 1170-kev resonance. At each energy ten decay curves were taken, the ten runs being preceded and followed by a resonance count. The nonresonant counts were summed and, after background subtraction, analyzed on the assumption that they represented Na^{21} plus F^{17} activities. Figure 4 shows a plot against bombarding energy of the ratio of Na^{21} yield to Na^{21} yield at resonance. The energy dependence of the ratio for yield due to the tail of the resonance alone and due to direct capture alone is also shown. The direct-capture process is quite consistent with the data. It is possible that the resonance does contribute as much as 30% of the yield at 1136 kev, which would imply $\Gamma_p\leq0.7$ kev. Interference between resonant and nonresonant processes is neglected on the assumption that the resonant state decays to a low-

[15] *Note added in proof.*—A gas target measurement by G. C. Thomas and N. W. Tanner (unpublished) has shown that $\omega\gamma=1.3\pm0.2$ ev for the 1170-kev resonance of $Ne^{20}(p,\gamma)Na^{21}$. In consequence the cross section parameter (Table I) is reduced to $S=11\pm3$ kev-barns, including the error from $\omega\gamma$. Extrapolating to thermal energies as above, $S_0=43+12=55$ kev-barns with an uncertainty of perhaps 20 kev-barns.

TABLE I. Calculated and experimental values of the nonresonance cross section parameter of $Ne^{20}(p,\gamma)Na^{21}$. The experimental values are dependent on the value of $\omega\gamma$ measured by Broström *et al.*[13] which may be uncertain by as much as $\pm 50\%$.

	S(kev barns)		
E_p(kev) c.m.	Calc. (reference 4)	Expt.	$\sigma(\mu b)$ Expt.
24	19		
600	6.1	<25	<0.14
1050	4.9	17 ± 3	1.3 ± 0.2

lying state of Na^{21} and that the nonresonant process is direct capture to the 2.43-Mev state of Na^{21}.

Values for σ and S for the nonresonant process were obtained by substituting the data of Fig. 4 into the expression given above for the ratio of nonresonant to resonant yield. The yield at resonance and the target thickness Δ gave a measure of the neon deposit as 2×10^{17} Ne^{20}/cm^2, which was applied to the 630-kev yield measurement to give an upper limit for σ and S at this energy. Results for both energies are given in Table I, along with values of S calculated by Christy and Duck.[4] It must be stressed that the experimental results are also subject to whatever uncertainty exists in the value of $\omega\gamma$ measured by Broström *et al.* This may amount to a 50% probable error.[15]

DISCUSSION

The most striking feature of the two direct capture reactions that have been discussed is the agreement between calculation and experiment indicated in Fig. 2 and Table I. Undoubtedly this is largely due to the extranuclear nature of the process, but we are forced to assume that the relevant states of F^{17} and Na^{21} are very nearly pure single particle states. It is tempting to speculate that there may be some factor which enhances the cross section and is not described in the model used for calculations.

The agreement of theory and experiment lends confidence to the extrapolation of the S value to the thermal energies in stars (several tens of kev for these reactions[5]). For $O^{16}(p,\gamma)F^{17}$ we adopt $S_0=(5\pm1)$ kev-barns which is very much larger than the estimate of $S_0\sim0.1$ kev-barns given by Salpeter.[16] The consequences of the larger cross section have already been discussed by Burbidge *et al.*[7]

For $Ne^{20}(p,\gamma)Na^{21}$ the cross section measured at 1100 kev can be extrapolated via the calculations of Christy and Duck to give a value at thermal energies of $S_0\sim66$ kev barns.[15] The uncertainty in S_0 amounts to about a factor of three. At thermal energies there will also be a contribution to S_0 for $Ne^{20}(p,\gamma)Na^{21}$ through resonant capture by the tail of the 2.43-Mev state of Na^{21}. The resonance contribution was estimated by Marion and Fowler[6] as 12 kev-barns so that $S_0\sim80$ kev-barns. It is reasonably certain that S_0 is not less than 30 kev-barns and is probably larger. However, this is only half the answer required on the neon reactions. The real problem is the relative cross section of $Ne^{20}(p,\gamma)Na^{21}$ which makes Ne^{21} and $Ne^{21}(p,\gamma)Na^{22}$ which destroys it. There is no new evidence on the Ne^{21} reaction since the neon reactions were reviewed by Marion and Fowler.[6] They took $S_0=5.6$ kev-barns for $Ne^{21}(p,\gamma)Na^{22}$, which would imply that Ne^{21} is destroyed less rapidly than it is produced. However, if there is a resonance in $Ne^{21}(p,\gamma)Na^{22}$ near the thermal region, then the position would be completely reversed.

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[16] E. E. Salpeter, Phys. Rev. **97**, 1237 (1955).