implications concerning relationships among the excitation spectra of neighboring nuclides. It has been our purpose to exploit some of these relationships in an attempt to put the model to test. In so doing we have found ourselves in the position of predicting a sizeable number of excited-state spins and, in two cases, the existence of unobserved states. If these predictions should be borne out by experiment then, manifestly, one must regard this as a triumph on the part of the model.

For the most part, consideration has been given to nuclei near mass number 60. This is because we were unable to find a sufficient amount of experimental information for nuclei lying near other closed shells than the ones at 28 and 38 neutrons or protons. It is in some respects unfortunate that this is so, because there is already appreciable evidence that the *j-j* coupling model gives a good account of itself for nuclei of atomic number up to 28.[1] One would be most interested in examining the situation near, for example, neutron or proton number 50.

There are, perhaps, two reasons why one should not be amazed if the elementary considerations discussed here should give a good account of the situation. In the first place one observes that the level spacings of most of the nuclei we have discussed tend to be sizeable; consequently, there would seem to be an excellent chance that assumption (b) of part I is applicable. Secondly, the nature of our analysis was such that we were concerned only with nuclei that had either closed neutron or closed proton shells. Considerations based upon the collective model[21] would seem to indicate that for such nuclei the shell model might be applicable even at relatively high mass numbers.

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Transmutation of Nitrogen by Protons from 100 kev to 135 kev*

WILLIAM A. S. LAMB AND ROSS E. HESTER
University of California Radiation Laboratory, Livermore, California

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A portion of the excitation curve of the thermonuclear reaction $N^{14}(p,\gamma)O^{15}$ has been measured using protons of 100 to 135 kev. The cross section of this reaction ranges from $(8.5\pm3.7)\times10^{-12}$ barn at 100 kev to $(1.4\pm0.3)\times10^{-10}$ barn at 135 kev. The approximate constant S_0 is defined by $S_0=E\sigma\exp(31.281Z_pZ_nA^{\frac{1}{2}}E^{-\frac{1}{2}})$, where E is the energy in the center-of-mass system and is measured in kev, σ is in barns, A is the reduced mass of the interacting nuclei, and Z_p and Z_n are the nuclear number of protons and nitrogen, respectively. Based upon these measurements, $S_0=2.7\pm0.2$ kev-barn.

INTRODUCTION

THE carbon-nitrogen cycle[1] is believed to be one of the principal processes for the conversion of hydrogen to helium in certain classes of stars.[2–4] The reaction studied here, $N^{14}(p,\gamma)O^{15}$, is probably the governing reaction of the cyclic process, since its cross section in the region accessible to experiment is the smallest. Previous measurements have been made of the other reactions in the cycle, namely, $C^{12}(p,\gamma)N^{13}$,[5,6] $C^{13}(p,\gamma)N^{14}$,[7] and their cross sections are larger. Energy generation due to the burning of hydrogen to form helium by this catalytic process will depend strongly on the smallest cross section in the cycle at stellar energies.

DESCRIPTION OF APPARATUS

The high-current ion injector at Livermore[8] was used to provide the beam for these experiments. The beam was analyzed in an electromagnet and then the analyzed beam was collimated so that the energy spread in the beam used in the experiment was less than ±1 kev. The beam diameter at the target was about $\frac{3}{4}$ inch. (See Fig. 1.)

The targets used were water-cooled sheets of titanium

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whose surfaces had been coated with titanium nitride by heating the sheets in NH_3. The target thickness was typically 0.3 to 0.5 mg/cm^2 nitrogen, which constitutes a thick target for these energies. The beam currents used in the experiments were chosen at around 25 ma to optimize between target erosion from beam bombardment and maximum nuclear yield. It was felt that if the temperature rise on the surface of the target could be kept quite low, the loss of the induced activity of O^{15} could be minimized. The targets were mounted on a shaft which enabled the activated target to be reproducibly positioned in front of a scintillation counter where the activity was monitored.

An additional probe, mounted on a sliding seal in front of the TiN target, was used to measure beam power and to adjust the ion accelerator.

The β^+ counter was a 2-in. photomultiplier tube with a $\frac{1}{16}$-in. thick plastic or anthracene scintillator of corresponding diameter which was shielded where possible with 2 in. of lead and had a cover of 0.001 in. of aluminum foil as a light seal. The output of the counter was fed to a 20-channel pulse-height analyzer arranged to count that part of the β^+ spectrum which would optimize the signal-to-background ratio.

The counting arrangement used to determine the yield from the capture gamma radiation consisted of a 4 by 4 in. NaI(Tl) crystal and a 5-in. multiplier phototube whose output was fed to a 20-channel pulse-height analyzer.[6]

EXPERIMENTAL PROCEDURE

A. Counter Calibration

It is necessary to know the absolute efficiency of both the γ counter and the β counter in order to determine the yield of the reaction. In the case of the β counter, three sources were used to determine the efficiency including geometry. The first method involved the determination of the absolute activity of a sample of Na^{24} by means of a calibrated ion chamber that measured the gamma radiation, then taking appropriate aliquots on our TiN targets and measuring the β activity, which was compared with a standard RaD-E beta source. Then to calibrate with a β activity whose end-point energy is similar to O^{15}, a P^{32} sample was prepared and an aliquot was measured on a 4π-beta counter.[9] This was then aliquoted on TiN targets and compared with the other two methods. The estimated error on counter calibration for β counting is $\pm 10\%$ from these procedures.

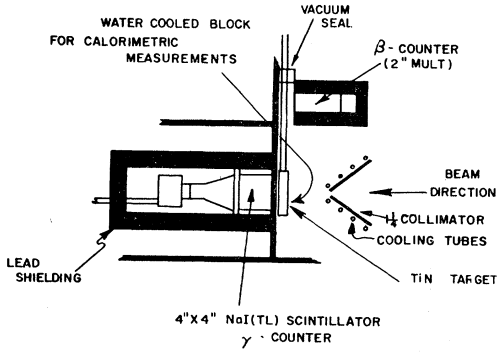

FIG. 1. Diagram of counting arrangement. Parts of the collimating analyzing system are not shown.

The γ counter was calibrated by the following process. Two radioisotopes whose activity is believed known to $\pm 5\%$, namely, Na^{24} and Na^{22}, were used to determine the efficiency of the counting system at two energies, namely, 1.3 Mev and 2.7 Mev. This efficiency then was used to compute the efficiency of the system for the energy interval used in this experiment.[10–12] The average error introduced by this process is estimated at $\pm 20\%$.

B. Accelerating Voltage Measurement

The accelerating voltage was measured by means of a precision voltage divider and a potentiometer. This gives the average voltage since the power supply has an inherent ripple of about 2%. The beam was then centered on the collimating system by adjusting the analyzing magnet which would only pass ± 1 kev from the average value.

C. Beam-Current Measurements

The beam current was measured by means of a thermopile in the cooling circuit of the target probe, which gave an indication of relative power. This reading was then duplicated by means of an immersion electric heater and the power computed from the readings from precision electrical instruments. The power reading combined with the accelerating voltage gave the current. The current was also monitored electrically during the runs; however, because of secondary electron emission, the value was only relative. The error of this measurement is estimated at $\pm 5\%$ of the beam current.

D. Nuclear Measurements

β^+ Counting

Nearly all of the data taken in this experiment were obtained by measuring the positrons resulting from the decay of O^{15}. While every reasonable precaution was taken to insure clean targets of TiN, ever-present carbon nevertheless was the principal contaminant. The experimental procedure consequently was aimed at minimizing the effect of carbon comtamination. It is hoped that the procedure described below enables one

[9] E. Tochlin, U. S. Naval Radiological Defense Laboratory (private communication).
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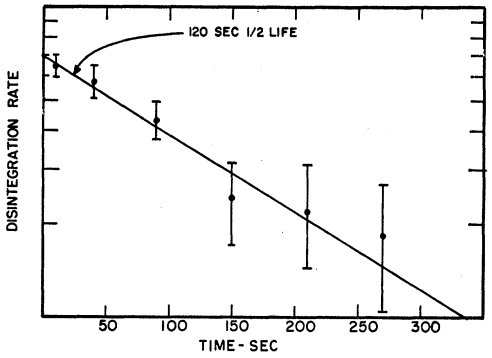

FIG. 2. Decay of activity used to determine yields. The line represents 120-second half-life.

to put some limits on the contribution of contaminants to the measured yield.

The reaction $N^{14}(p,\gamma)O^{15}$ and the subsequent decay of $O^{15}\rightarrow\beta^{+}+\nu+N^{15}$ with a half-life of 120 sec must be distinguished from the reaction $C^{12}(p,\gamma)N^{13}$ followed by $N^{13}\rightarrow\beta^{+}+\nu+C^{13}$ with a half-life of 10.1 minutes. The cross section for $C^{12}(p,\gamma)N^{13}$ is approximately 10 times larger than that for $N^{14}(p,\gamma)O^{15}$; hence, a 10% contamination of carbon on the target would result in the production of about equal numbers of O^{15} and N^{13}.

The targets were bombarded for 3 half-lives of O^{15}, or 360 sec, and the net counts in an interval of 360 sec after bombardment were used to determine the yield of O^{15}.

Counts were recorded for a total of 1800 sec each run and the background was determined from the last 1200 sec. By observing the behavior during the last 1200 sec, one could detect the presence of carbon if the contamination was as large as a few percent, particularly at bombarding energies greater than 125 kev. In this manner the targets were checked for carbon contamination.

The sum of all of the decay data was plotted and is shown in Fig. 2. Although the statistics are poor in the third half-life, it seems reasonable to conclude that the activity used to determine the yields was indeed decaying with a 120-sec half-life.

A second difficulty in this experiment results from the unknown escape of the induced activity of O^{15} from the target during bombardment. Two methods were used to estimate this effect. One was to change the beam current by a factor of about 3 and, with approximately equal counting statistics, attempt to detect a systematic change in yield. This effort failed to show a significant difference with 15% counting statistics.

The second method was to measure the capture gamma radiation from the reaction and note whether the yield based upon this measurement agreed with that taken from positron counting. This measurement was not possible at any but the highest bombarding energies because of the reduced efficiency of the gamma counter.

The compound nucleus O^{15} formed by the capture of protons in N^{14} at bombarding energies of 130 kev is formed at a level intermediate between the 6.82- and 7.61-Mev levels.[13]

The yields were determined on the hypothesis that any photon counted in the energy interval 5.0 to 7.5 Mev represented a radiative capture of a proton in N^{14}.

We feel that this point is more uncertain than the statistics indicate because of possible unknown errors in counter efficiency due to uncertainty in the mode of decay of O^{15} from its excited states.

RESULTS

Figure 3 shows the thick target yield per incident proton on the compound TiN which was obtained from

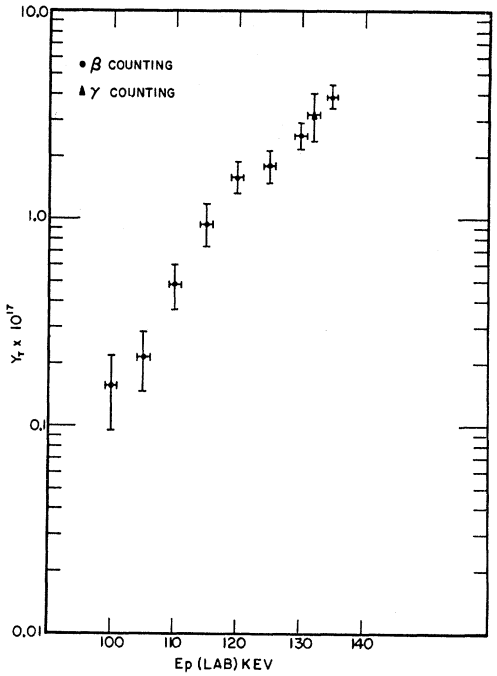

FIG. 3. Thick-target yield/incident proton as a function of proton energy in the laboratory system.

the following expression:

$$Y_t=\frac{N\lambda}{I\times f(\beta)(1-e^{-\lambda t_1})(1-e^{-\lambda t_2})},$$

where Y_t = thick target yield, N = total net counts in time t_2, λ = decay constant for $O^{15}=5.78\times10^{-3}$/sec, I = current in protons/sec, $f(\beta)$ = efficiency of the β-counting system, t_1 = bombardment time in sec, and t_2 = counting time in sec.

Usually $t_1=t_2=360$ sec $=3$ half-lives, except in the case of interruption due to machine spark-down, etc. The single point shown for capture gamma counting

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

was obtained by a similar expression, namely:

$$Y_t(\gamma)=n/[I\times f(\gamma)],$$

where n=net counting rate in counts/sec, I=current in protons/sec, and $f(\gamma)$=gamma counter efficiency.

The errors shown are rms errors due to counting statistics, and estimated systematic errors as discussed previously.

The cross sections shown in Fig. 4 were obtained from the thick target yield, using the following relation:

$$Y_t=\int \frac{\sigma(E)}{\epsilon}dE,$$

where ϵ is the stopping cross section per molecule of TiN and $\sigma(E)$ is the cross section of the reaction. The functional form of the cross section is given by[3,4]:

$$\sigma(E)=(S_0/E)\exp(-31.281Z_pZ_nA^{\frac{1}{2}}E^{-\frac{1}{2}}),$$

where E is measured in the center-of-mass system of the interacting nuclei, A is the reduced mass of the system, and S_0 is an approximate constant. Further manipulation gives the following approximate equation in which the stopping cross section is taken as a constant over the range of energies used here:

$$\sigma(E)\cong\tfrac{1}{2}Z_nY_t(\epsilon/E^{\frac{3}{2}})[1+(E/Z_n)\cdots].$$

If the E is now measured in the laboratory system and in Mev, ϵ will be in Mev-cm^2/TiN (molecule) and is taken at 4.7×10^{-20} Mev-cm^2. The points shown are calculated from the expression. The uncertainty about the stopping cross sections and errors introduced by approximations in the above expression are believed to introduce an additional $\pm10\%$ into the cross section. Differentiating the yield curve gives the same results within the limit of experimental error.

From the cross-section data the cross section factor S_0 can be evaluated for extrapolation to energies of interest in astrophysical processes, namely:

$$S_0=2.7\pm0.2 \text{ kev-barns.}$$

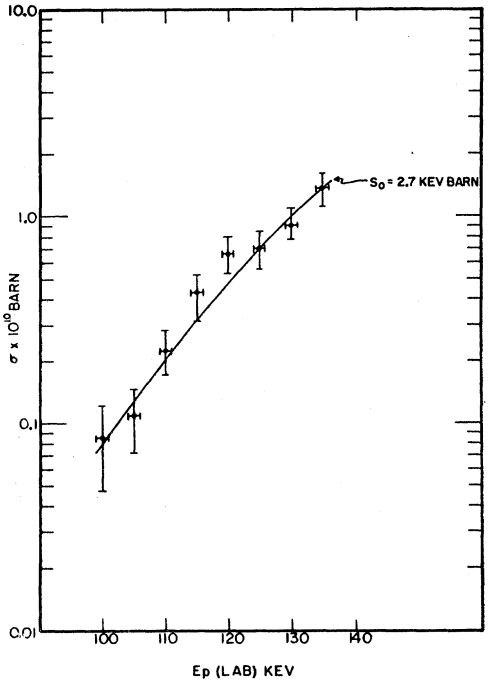

FIG. 4. Cross section as a function of energy in the laboratory system.

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