Radiative Capture of Protons in Oxygen at 140 to 170 kev*

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The thick-target yield of the reaction $O^{16}(p,\gamma)F^{17}$ has been measured by bombarding Al_2O_3 targets with protons from 140 to 170 kev using currents from 3 ma to 10 ma and counting the induced positron activity of the F^{17}. The thick-target yield ranges from $(1.9\pm1)\times10^{-17}$ beta/incident proton at 140 kev to $(1.47\pm0.15)\times10^{-16}$ beta/incident proton at 170 kev. The corresponding cross sections are $(4.6\pm2.4)\times10^{-11}$ barn at 140 kev and $(2.34\pm0.3)\times10^{-10}$ barn at 170 kev. The activity was identified by observing the half-life. The cross-section factor S_0 was found to be 6.8 ± 1.4 kev-barns between 140 kev and 170 kev bombarding energy.

INTRODUCTION

THE reaction $O^{16}(p,\gamma)F^{17}\rightarrow O^{17}+\beta^++\nu$ followed by $O^{17}(p,\alpha)N^{14}$ has been discussed by Burbidge *et al.*[1] as a part of the CNO cycle which is a generalization of the CN cycle. This series of reactions is believed to take place in the hydrogen-burning shells of red giant stars. In the absence of resonances, the reaction rate at stellar energies is controlled by the barrier-penetration dependence of the cross section. The approximate expression for the cross section valid in the energy range of this measurement is

$$\sigma(E)=\frac{S_0}{E_c}\exp(-31.28Z_pZ_nA^{\frac{1}{2}}/E_c^{\frac{1}{2}}), \qquad (1)$$

where $\sigma(E)$ is in barns (10^{-24} cm^2), E_c is center-of-mass energy in kev, Z_p and Z_n are the nuclear numbers of the interacting nuclei, A is the reduced mass of the system, and S_0 is an approximate constant given in kev-barns.

The purpose of the measurement discussed here is to establish the value of the quantity S_0 for the reaction $O^{16}(p,\gamma)F^{17}$ to enable extrapolation of the value of the cross section to energies of interest in astrophysical processes.

EXPERIMENTAL PROCEDURE

The counter and target assembly used in this experiment are shown in Fig. 1. A magnetically analyzed beam of protons from a high-current ion injector[2] impinged on a target which could be moved in front of a β counter to measure the induced activity after bombardment. The entire target assembly was insulated from ground and biased from -5 to -30 kv to obtain the additional energy required to make this measurement. The beam currents used in this experiment ranged from 3 to 10 ma over a $1\frac{1}{2}$-inch diameter beam spot. With beam currents as high as 15 ma, slight target erosion was noticed on visual inspection of the target.

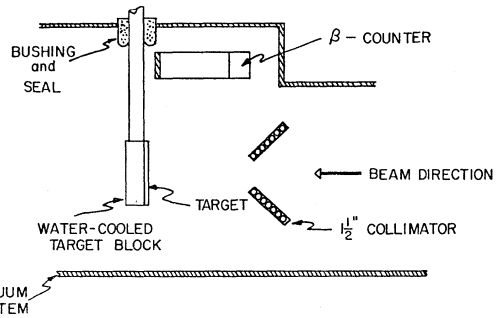

FIG. 1. Diagram of target and counting equipment.

The thick Al_2O_3 targets were prepared by electrochemically anodizing[3] aluminum sheets. They were mounted in a water-cooled probe which could be placed $\frac{1}{4}$ inch in front of a $1\frac{1}{2}$-inch diameter anthracene crystal. The $\frac{1}{8}$-inch-thick anthracene crystal was covered with 1-mil aluminum foil. A 6292 photomultiplier tube was used.

The beam current was deduced by measuring the beam power with a calorimetric apparatus and the bombarding energy by means of a voltage divider. The voltage divider was calibrated on the $B^{11}(p,\gamma)C^{12}$ resonance at 163 kev.

The efficiency of the counting system was determined by using a P^{32} source $1\frac{1}{2}$ inches in diameter mounted on aluminum backing; P^{32} was used because it has the same end-point energy as the F^{17} activity. The spectrum end point of a RaDE source was periodically checked to see that the gain of the counting system did not change.

RESULTS

The F^{17} activity was identified by observing its half-life. The counting rate for any individual run was too low to indicate anything more than a short-lived activity, but the addition of several runs made the counting statistics sufficient to establish a reasonable identification. Figure 2 shows a decay plot of the induced short-lived activity utilizing the runs taken at 165 kev and 170 kev bombarding energy; this was used to identify the activity as F^{17}.

The target was bombarded for 198 seconds, three half-lives of F^{17}, and counted for 1800 seconds. The cosmic-ray background was well established and was subtracted

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

[2] W. A. S. Lamb and E. J. Lofgren, Rev. Sci. Instr. **27**, 907 (1956).

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from the counting data. The data taken during the last 1500 seconds of the counting period were examined to determine the initial counting rate of N^{13}, the product of the principal contaminant, ubiquitous C^{12}. The appropriate number of N^{13} counts was then subtracted from the data taken during the first 198 seconds to obtain the yield of F^{17}. Due to the low F^{17} counting rate and the high background caused by N^{13} and cosmic rays, the statistical uncertainties are large. The range of statistical uncertainty is 15% to 43% at 170 and 140 kev, respectively. The thick-target yield Y_t is given by

$$Y_t=\frac{nq}{\text{eff}I\tau(1-e^{-t_1/\tau})(1-e^{-t_2/\tau})}, \tag{2}$$

where n is the total number of counts of F^{17} in the

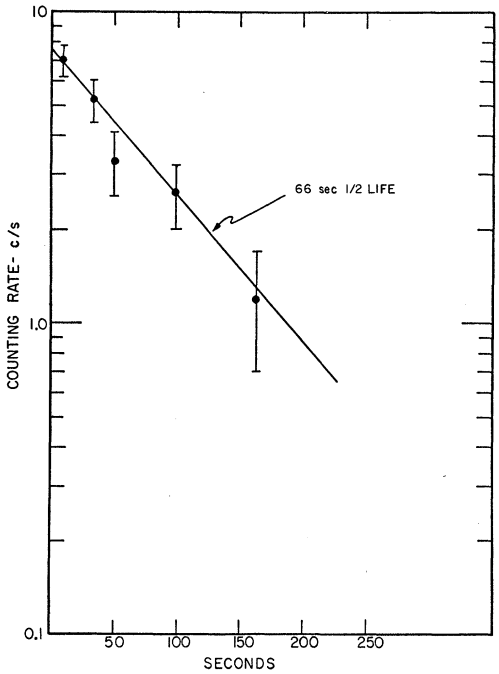

FIG. 2. Decay of the short-lived activity used to identify F^{17}.

interval used, 3 half-lives (198 sec); q is the charge per proton in coulombs; τ is the mean life of the F^{17} activity in seconds; I is the bombarding current in amperes; eff is the efficiency of the counter; and t_1 and t_2 are the bombardment time and the counting time, respectively, in seconds.

The thick-target yields are shown in Fig. 3. The errors indicated are statistical errors. The estimates of the systematic errors are voltage measurement ± 2 kev, beam current $\pm 6\%$, and the counter efficiency $\pm 7\%$.

The cross section with statistical uncertainties is shown in Fig. 4 and is obtained by integrating the expression

$$Y_t=\int_0^E \frac{\sigma(E)}{\epsilon}dE, \tag{3}$$

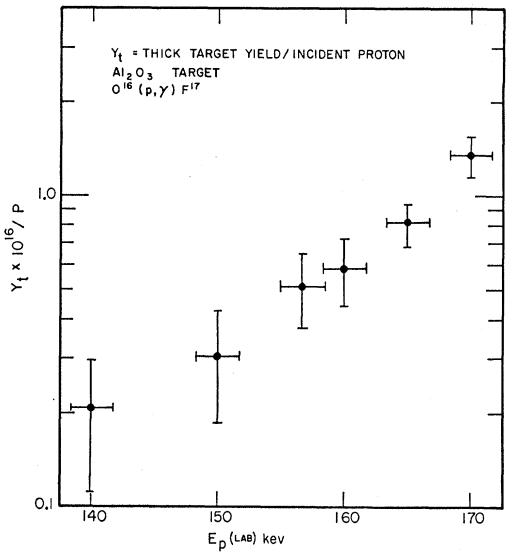

FIG. 3. The thick-target yield is shown here as a function of the proton energy in the laboratory system in kev.

where $\sigma(E)$ is given by Eq. (1), and ϵ is the stopping cross section per oxygen atom in Al_2O_3 which is assumed constant over the energy range studied here. Substituting Eq. (1) into Eq. (3) and performing the integration gives

$$\sigma\cong\frac{Z_n\epsilon Y_t}{2E^{\frac{1}{2}}}\left(1+\frac{E^{\frac{1}{2}}}{Z_n}\cdots\right), \tag{4}$$

where E is in the laboratory system and now measured in Mev, Z_n is the nuclear number of oxygen, and

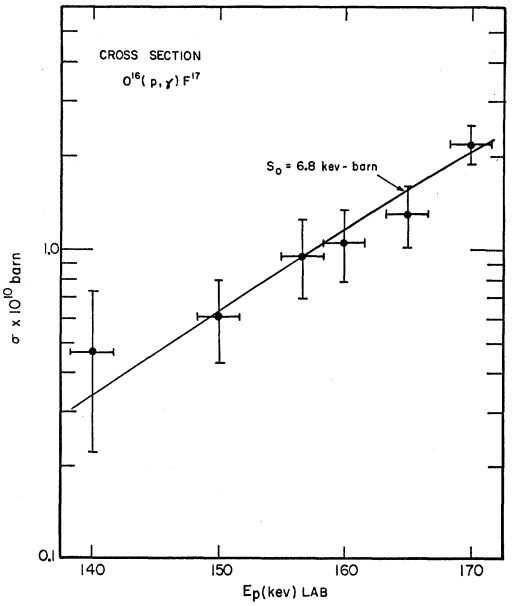

FIG. 4. The cross section in barns is shown as a function of the proton energy in kev in the laboratory. The curve drawn through the experimental points is that represented by $S_0=6.8$ kev-barns.

TABLE I. Value of the cross section σ in barns and S_0 in kev-barns at energies shown.

E_p kev (c.m.)	$O^{16}(p,\gamma)F^{17}$ σ barns	S_0 kev-barns	
132–160	See Fig. 4	6.8 ±1.4	UCRL, Livermore
259	(4.9 ±2.7) $\times10^{-9}$	4.5 ±2.7	C.I.T.
332	(3.8 ±1.0) $\times10^{-8}$	7.6 ±2.0	C.I.T.
580	(2.6 ±0.5) $\times10^{-7}$	3.6 ±0.8	C.I.T.
	(3.14±0.34)$\times10^{-7}$	4.34±0.47	C.I.T.
753	(11.1 ±1.5) $\times10^{-7}$	5.83±0.79	U.B.C.

$\epsilon=28\times10^{-21}$ Mev-cm^2.[4] It is believed that the approximations in expression (4) and uncertainties in the stopping cross section introduce an additional 10% to the error given on the yield.

A systematic error that is difficult to determine is the loss of induced activity due to target erosion during bombardment by the beam. A feeling for the magnitude of this effect on the measured yield was obtained by varying the beam current by a factor of 3 at the same energy. With similar counting statistics no systematic difference was observed. The effect of this error would cause the cross section to be larger than given here.

Table I shows a comparison of the value of S_0 from the measurements at the California Institute of Technology[5] and the University of British Columbia.[6] We believe our value $S_0=6.8\pm1.4$ kev-barns is in substantial agreement with the values shown here taken at higher bombarding energies.

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[4] Ward Whaling, Kellogg Radiation Laboratory, California Institute of Technology (unpublished).

[5] N. Tanner, California Institute of Technology (private communication).

[6] G. W. Griffiths, University of British Columbia, Vancouver (private communication).

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Measurements of Light Masses with the Mass Synchrometer*

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A complete account is presented of all results obtained with the mass synchrometer before November, 1957. Included, besides measurements made before March, 1957, tentative values of most of which have been published with little discussion by the author and/or by others, is an extensive later set of measurements on 40 parent ion doublets. From least squares analyses of 39 of these doublet values and of 11 selected earlier values and from three other earlier values are derived what are believed to be the best values obtainable from all synchrometer data of the mass excesses of the 14 nuclides from which all ions studied are composed. These are H^1, D^2, He^4, B^{10}, B^{11}, C^{12}, N^{14}, O^{18}, Ne^{20}, Ne^{22}, S^{32}, Cl^{35}, Cl^{37}, and A^{40}. Best values of all measured doublets are also tabulated. Statistical analyses indicate that, for external consistency of results, the internal errors given should be multiplied by either 2.35 or 3.6 (the larger fraction applying primarily in cases where ions are formed by molecular dissociation). They also indicate that, except in cases where ions are formed with appreciable kinetic energies, the external error of the mean of twenty measurements of a doublet separation made with present techniques is about one part in 4×10^7 of the mass number. The agreement of the best values with the latest comparable values obtained at the University of Minnesota is excellent for the important mass excess C−12 and satisfactory in nearly all other cases. Agreement with comparable values obtained from measurements of nuclear reaction energies is fairly good except for C_3-HCl^{35} and $Cl^{35}-35$, the synchrometer values of which appear to be in error.

INTRODUCTION

AFTER conversion of the mass synchrometer in late 1951 from a pulsed beam[1] to an rf[2] device, its modification in 1952 to essentially its present form and development of the peak matching techniques which have so greatly enhanced the precision of doublet measurements, the first reasonably reliable doublet measurements were made in early 1953. These, together with a brief description of the instrument and the measuring equipment and procedure then used, were published in a letter and two abstracts.[3] Since that time a large number of measurements have been made. Results of nearly all but the most recent set of these have also been published by the author and/or by others in reports cited below. However, to date, published

* Work performed under the auspices of the U. S. Atomic Energy Commission.

† Now on leave at Project Matterhorn, Princeton, New Jersey.

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[2] L. G. Smith, *Mass Spectroscopy in Physics Research*, National Bureau of Standards Circular No. 522 (U. S. Government Printing Office, Washington, D. C., 1953), p. 117; Phys. Rev. **85**, 167 (1952).

[3] L. G. Smith and C. C. Damm, Phys. Rev. **90**, 324 (1953); **91**, 481 (1953).