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RELATIVE CROSS SECTIONS OF NUCLEAR REACTIONS INDUCED BY HIGH ENERGY NEUTRONS IN LIGHT ELEMENTS

William J. Knox

September 9, 1948

Berkeley, California

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September 9, 1948

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ABSTRACT

Various light elements from carbon to sulfur were bombarded in the high energy (about 90 Mev) neutron beam of the 184-inch cyclotron and decay curves were taken on the resulting activities. Relative cross sections for certain reactions were obtained by analyzing the decay curves into component activities and comparing the yields with the activity induced in a carbon monitor bombarded in the same beam. Values for 16 reactions are given with a probable error of about ± 10%, as well as upper limits for six other reactions. An apparent regularity among these data is pointed out; cross sections for reactions differing by the ejection of an alpha particle or its components differ by a factor of about three.

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I. Introduction

When a nucleus is bombarded with very high energy neutrons, a large variety of nuclear reactions can occur, resulting in the formation of most if not all the radioactive species below the bombarded nucleus. The cross sections for these reactions are of interest because they may give some idea of the nature of the mechanisms of nuclear reactions at high energies. In the region of light elements the activities of suitable half life for convenient measurement are few enough that relative cross sections for the reactions producing these activities can be obtained from simple analysis of decay curves taken on the bombarded substances. The present work is a survey of relative cross sections obtained in this manner by bombarding elements from carbon to sulfur in the high energy neutron beam of the 184-inch cyclotron.

II. Experimental

The high energy neutron beam was produced by the action of 190 Mev deuterons on a 1/2" beryllium target. This beam emerges through an aluminum window in the wall of the cyclotron tank with a flux at the window of the order of 10^6 to 10^7 neutrons per cm^2 per second as determined by the C^{11} activity induced in a carbon sample, using the $C^{12}(n,2n)C^{11}$ cross section.[1]

[1] E. M. McMillan and H. F. York, Phys. Rev. 73, 262 (1948)

The neutrons in the center of the beam have an energy distribution with a

peak at 90 Mev and width at half maximum of about 27 Mev.[2,3,]

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[2] A.C. Helmholz, E.M.McMillan and D.C.Sewell, Phys. Rev. 72, 1003 (1947)

[3] R.Serber, Phys. Rev. 72, 1008 (1947)

Materials to be bombarded were placed against the window near the center of the neutron beam in the form of foils or samples of powder contained in small bottles and were bombarded for a prescribed length of time with the cyclotron operating at a constant level. The size of the samples was such that the neutron flux was uniform over the area of exposure. In each bombardment a sample of graphite or polystyrene foil was included as a monitor and was bombarded at the same time and in the same position with respect to the beam as the sample under consideration. Attenuation of the beam by the samples themselves or by their containers was negligible because of the high energy of the neutrons and the relatively small amount of absorbing or scattering material involved. At the end of a bombardment a foil or thin uniformly spread sample of the powder was mounted and the decay of the activities produced was followed on a G. M. counter. Each foil or sample was accurately weighed. The samples were spread over an area of from 5 to 14 square centimeters on cardboard or paper backing in order to minimize back-scattering and were counted at geometries of from 3 to 30%. The carbon monitor was of the same shape as the sample and usually was counted at the same geometry. In a few cases when the geometries were different, a correction was determined and applied between a sample and its monitor. Much of the counting data, particularly that on the longer lived activities, was taken on traffic counters which automatically record the register reading at specified intervals.

Standard coincidence and background corrections were applied to all counting rates. The data were then plotted and the decay curves were resolved into their component activities which were identified by their approximate half lives. In most cases the longest lived component was readily identifiable and the half life indicated by the data was used in the resolution. In some cases a small amount of unidentified long lived activity, a few counts per minute above background, was subtracted out before resolution of the major long lived component. After subtraction of the long lived component if the half life of the next component was indicated clearly enough for its identification, the component was resolved from the curve using the accepted value in the literature for its half life. The same procedure was followed for further components if possible. A more detailed description of the individual decay curves is given below.

Each separated component of the decay curve was extrapolated back to the time at the end of the bombardment and a correction was applied for the difference in absorption between the given radiation and the C^{11} radiation in the monitor due to the counter window, air, and half the thickness of the sample. These corrections were of the order of 0 to 12% with the exception of the F^{18} correction in the magnesium samples mentioned below. The relative cross sections were calculated according to the formula:

$$\sigma_1 / \sigma_2 = A_1 T_2 (1 - e^{-\lambda_2 t}) / A_2 T_1 (1 - e^{-\lambda_1 t}),$$

where A is the corrected activity in counts per unit time of a given component extrapolated back to the end of bombardment, λ is the decay constant, t is the length of bombardment, and T is the number of target atoms in the bombarded sample determined from the weight of the sample.

Experimental details regarding source materials used and decay curves obtained from each element bombarded are summarized in the following paragraphs.

Carbon

Samples of pure pulverized graphite or polystyrene foils of empirical composition $(CH)_n$ were used as monitors for all other samples. In both of these materials a single activity was produced which decayed with a half life of 20 to 21 minutes for as long as the decay could be followed. This identified the activity as the well known 20.5 minute C^{11}.

Nitrogen

Be_3N_2 was used as a source of nitrogen because it contains a high percentage of nitrogen and because Be gives rise to no interfering activities of appreciable intensity in the half life range investigated. Decay curves on this material showed the 20.5 minute C^{11} and a small amount of long lived activity which was unidentified. This long lived activity was presumably due to a small amount of unknown impurity in the Be_3N_2. No trace of it was apparent in later bombardments of BeO. After subtraction of the C^{11} activity a 10 minute component appeared which was presumed to be N^{13}. An appreciable amount of 2 minute activity was also produced and was attributed to O^{15} coming from a few percent of oxide impurity which the Be_3N_2 was known to contain. From the amount of this 2 minute component in the decay curve and from the cross section determined for the production of O^{15} from O^{16} the amount of oxide impurity was determined to be about 5% and the correction to the cross sections due to this impurity was calculated and found to be about 3%.

Oxygen

BeO was used as a source of oxygen for the same reasons given for Be_3N_2 above. The decay curves showed well defined 20.5 minute C^{11} and 2.1 minute O^{15} components and an intermediate component of about 10 minutes which was again assigned to N^{13}.

Fluorine

LiF was used as the source material because lithium, like beryllium, gives no interfering activities. The longest lived activity produced decayed with a half life of about 111 minutes and was assigned to F^{18}. In two cases the decay of the F^{18} was followed continuously through five to seven half lives after disappearance of the shorter lived components and the values for the half life were observed to be 110.7 and 111.3 minutes with an estimated probable error of 2 minutes. The shorter lived components had half lives of the order of 1 to 20 minutes as expected for F^{17}, C^{11}, N^{13}, and O^{15} but these could not be quantitively separated from each other.

Sodium

Sodium was bombarded in the form of $Na_2C_2O_4$. No attempt was made to resolve activities of half life 20 minutes or less because they were produced in the carbon and oxygen of the sample as well as the sodium. A considerable amount of 900 minute activity (Na^{24}) was produced and after subtraction F^{18} was easily identifiable. Since it was considered highly unlikely that Na^{24} would be produced from Na^{23} in appreciable quantities by capture of high energy neutrons, a sodium bombardment was made in which lead scatterers were placed around the sample in the neutron beam in order to in-

crease the number of relatively low energy neutrons passing through the sample. This resulted in approximately tripling the apparent cross section for production of Na^{24} while the F^{18} cross section remained constant. Hence it was obvious that the production of Na^{24} was sensitive to neutrons below the 20 Mev detection threshold of the carbon monitor and that it could not be regarded as a high energy reaction.

Magnesium

Thin metal discs of magnesium known to contain about 3% aluminum impurity were bombarded. Na^{24} and F^{18} were clearly resolvable and shorter lived activities were observed but could not be quantitatively separated. The magnesium discs were relatively thick to the soft F^{18} radiation and a high absorption correction of from 30 to 40% was made to the corresponding cross section. Also a correction of a few percent due to the aluminum impurity was calculated using the cross sections determined for the production of Na^{24} and F^{18} in aluminum. The cross reaction for producing Na^{24} is to be considered as an upper limit because of the relatively low threshold for the reaction $Mg^{24}(n,p)Na^{24}$ (about 6 Mev), combined with the possibility that the beam may contain an appreciable number of neutrons below the carbon threshold.

Aluminum

Thin aluminum foils of high purity were used for the aluminum cross sections. Na^{24} and F^{18} were again resolvable and in addition a strong component of about 10 minutes was apparent which was attributed to Mg^{27}. It was assumed unlikely that this 10 minute component was due to any appreciable extent to the 10 minute N^{13} since the production of short lived activities in magnesium was so small. The cross sections given for the reactions producing Mg^{27} and Na^{24} from aluminum are only to be regarded as upper limits since the threshold energies for these reactions are low.

Silicon

Powdered high purity silicon was used as a target. Na^{24} and F^{18} were easily identified and subtracted out leaving a component of about 10 minutes which again was assigned to Mg^{27}. Also a considerable quantity of 2 to 2.5 minute activity appeared which was attributed to Al^{28}. It was assumed unlikely that this activity was due to 2.1 minute O^{15} since O^{15} did not show up appreciably in Al and Mg bombardments. The cross section for the Al^{28} reaction is considered only as an upper limit because of its low threshold and because of the difficulty of resolving it accurately as the fourth component from the decay curve.

Phosphorus

The target material was amorphous red phosphorus. A few counts per minute of long lived unidentified activity presumably due to impurity were subtracted out leaving a well defined 900 minute Na^{24} component. A very strong component of about 170 minutes was observed and was assumed to be Si^{31}. Some deviation from the 170 minute line toward shorter half life occurred near its beginning and probably was due to a small amount of F^{18}. The Si^{31} reaction also has a low threshold and should be considered as an upper limit, since it was observed to be sensitive to scattering material in the beam. Unresolvable short lived components were also present in this decay curve.

Sulfur

High purity flowers of sulfur was used as the target material. The decay curves showed a small amount of activity of approximately 14 day half life attributed to P^{32}, a 900 minute Na^{24} component and a strong 170 minute Si^{31} component. The Si^{31} again showed a deviation toward shorter half life near its beginning probably due to F^{18} but the possible error from this source

was estimated to be less than 10%. The cross section for the reaction producing P^{32} is again an upper limit because of its low threshold and because it was observed to be sensitive to scattering material in the beam.

III. Results and Discussion

Table I gives the values obtained for the cross sections of the various reactions observed, which are specified by giving the target element and the radioactive element produced in a bombardment. Each value is the average of several determinations, and the errors are estimated to be about $\pm$ 10%. All values are given relative to the cross section for the C^{12} (n,2n) C^{11} reaction which has arbitrarily been taken as 1.00. The absolute value for this cross section has been separately determined as 0.022 $\pm$ 0.004 barns[1]. The five values in parentheses should be considered as upper limits because of the low threshold energies for these reactions and because of the known presence of low energy reactions in the beam (see discussion above). The isotopic constitution of magnesium (79% Mg^{24}, 10% Mg^{25}, 11% Mg^{26}) is such that its cross sections are not readily assignable to a single type of reaction. Silicon (92% Si^{28}) and sulfur (95% S^{32}) are close enough to pure isotopes that the true cross sections for these isotopes probably lie within the range of probable errors given for the observed values. No correction has been made to the values given in the table for these isotopic mixtures. The remaining elements bombarded are essentially pure isotopes.

A decrease in cross section is apparent with increasing complexity of the reaction necessary to produce a given product element from various target elements, which is to be expected in general. More significantly, there seems to be a regularity among the relations between reactions which differ

TABLE I

Relative Cross Sections of Reactions Induced by 90 Mev Neutrons

		Product Isotope								
		C^{11}	N^{13}	O^{15}	F^{18}	Na^{24}	Mg^{27}	Al^{28}	Si^{31}	P^{32}
Target Element	C	1.00								
	N	0.40	0.32							
	O	0.31	0.12	0.90						
	F	-	-	-	1.70					
	Na	-	-	-	0.75					
	Mg	-	-	-	0.75	(1.61)*				
	Al	-	-	-	0.21	(1.50)	(0.6)			
	Si	-	-	-	0.17	0.69	0.29	(2)		
	P	-	-	-	-	0.45	-	-	(0.8)	
	S	-	-	-	-	0.21	-	-	0.30	(2)

*(Values in parentheses are upper limits only.)

by the ejection of two neutrons and two protons (or an alpha particle). Consider first the formation of O^{15} and C^{11} from oxygen; the ratio of cross sections is 2.9. The comparison can also be made in cases where the same product is made from different elements, as in the formation of C^{11} from carbon and oxygen, where the ratio is 3.2. Further relations of the latter sort occur in the formation of F^{18} and Na^{24}. For F^{18}, the cross section ratios are: F/Na = 2.3, Na/Al = 3.6, Mg/Si = 4.4, and for Na^{24} they are Mg/Si = 2.3, Si/S = 3.3, Al/P = 3.3. The mean of all these eight ratios is 3.2 (Note that two of the Na^{24} reactions have low thresholds, one of them being an (n,p) reaction. The agreement with the mean ratio may be fortuitous in these cases.) Fig. 1 shows graphically some of the relations described above.

The ratio found here agrees with the value of 3.2 observed in a similar series of cross sections for the production of N^{17} from various elements by deuteron bombardment[4], and roughly with the value of 2.8 found in a comparison of the C^{11} yields from carbon and oxygen under proton bombardment.[5] This regularity is consistent with a simple theory involving

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[4] W. W. Chupp and E. M. McMillan, Bull. Am. Phys. Soc. 23 no. 3, p. 20 (1948)

[5] E. M. McMillan and R. D. Miller, Phys. Rev. 73 80 (1948)

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constant emission probabilities for alpha particles, protons and neutrons, and taking into account various possible paths between a given target and a given nucleus. This and other possible theoretical interpretations involving the distribution of excitation energies in the excited nuclei and other factors are under separate consideration.

The author wishes to express his appreciation to Professor E. M. McMillan for suggesting this problem. The work was performed under the

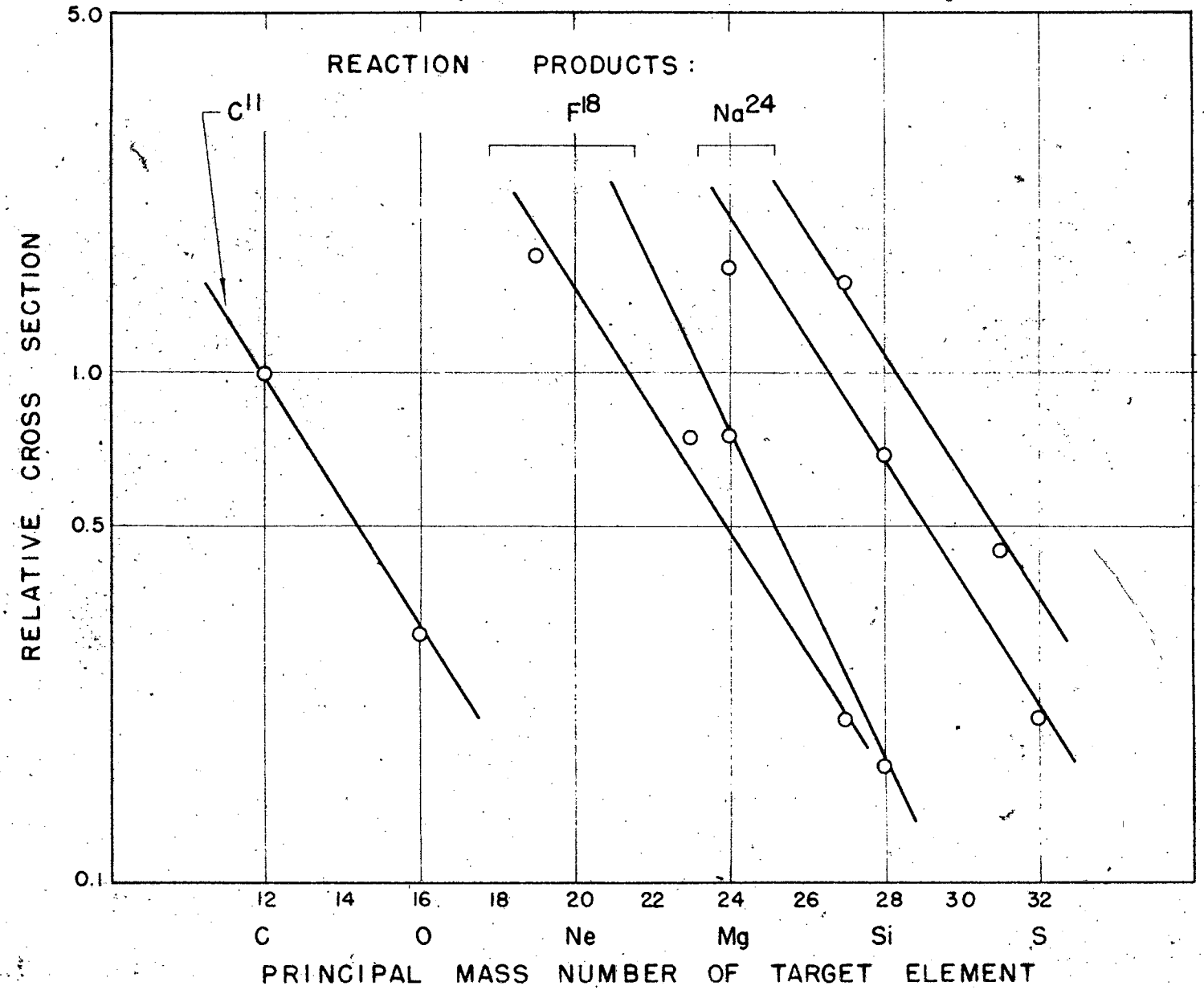

Fig. 1 Relative cross sections for some of the observed reactions, plotted on a logarithmic scale. Lines join cases which differ by the ejection of two protons and two neutrons; they are all drawn with the same slope except for one of the F^{18} lines. See the text for further discussion.

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