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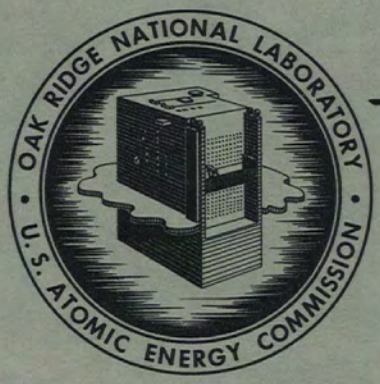
Physics and Mathematics

NUCLEAR REACTION CROSS SECTIONS FROM THE NITROGEN BOMBARDMENT OF SULFUR

D. E. Fisher



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ELECTRONUCLEAR RESEARCH DIVISION

NUCLEAR REACTION CROSS SECTIONS FROM THE NITROGEN BOMBARDMENT OF SULFUR

D. E. Fisher

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Submitted as a Dissertation to the Graduate Council in partial fulfillment of the Requirements for the degree of Doctor of Philosophy

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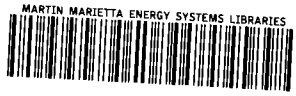

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CHAPTER I

INTRODUCTION

One of the earliest models of nuclear reactions is that of the compound nucleus, first put forth by Niels Bohr(1) in 1936. According to this model the incident particle strikes the target and fuses with it to form a compound nucleus; the kinetic energy of the projectile is shared among all the consituents. The main assumption of the model is that the nuclear reaction can be divided into two states-the formation of a compound nucleus and its subsequent decay-and that these two stages are independent of each other.

During the following years Weisskopf and co-workers formulated a statistical theory describing the decay of the compound nucleus(2). As had been suggested by Frenkel(3), the nucleus was thought of as a number of nucleons in thermodynamic equilibrium, losing its excitation energy by the evaporation of particles. A "nuclear temperature" was defined which governs the energy distribution of the emitted particles. The theory attempts to describe the nuclear level density, the energy spectra of particles emitted in a nuclear reaction, and thus predict reaction cross sections. Experiments testing the theory may deal, then, with any of these phenomena.

Previous Work

Early qualitative investigations of the theory of nuclear reactions were described by Bethe (4) and by Konopinski and Bethe (5) without any detailed determination of the quantities involved.

Experimental evidence concerning the statistical decay of a compound nucleus is difficult to collect because of the possibility of direct interaction between the bombarding projectile and the target nucleus. At high bombarding energies this direct interaction may overshadow the compound nucleus mechanism. Yet at low incident energies the statistical theory may be invalidated inasmuch as it requires that the compound nucleus be excited highly enough so that a great many energy levels are involved.

Peaslee, in his survey (6) on intermediate energy nuclear reactions, reports the following: Barschall (7) measured total cross sections for the neutron bombardment of many elements ranging in mass number from 50 to 230, for incident energies in the range 0.1-3.0 Mev. The theory predicted a monotonic decrease in cross section with increasing energy. Barschall did not observe this. Miller et al. (8) bombarded 23 elements from iron to bismuth with neutrons of 0.05-3.2 Mev and measured total cross sections. Their results agreed with those of Barschall. Walt et al. (9) continued the above experiments on nine more elements in the same mass region and got the same results. Okazaki et al. (10) extended the experimental work to include the bombardment of neodymium, samarium, erbium,

ytterbium and hafnium with neutrons of 0.06-3.0 Mev. Their results agree with the others. Weisskopf and co-workers (11) modified the theory to account for the above results on the basis of a single particle interaction. The new theory accounted for the gradual change in cross section with atomic weight.

Paul and Clarke (12) bombarded 57 elements with 14.5-Mev neutrons. They found that for mass numbers greater than 100, experimental cross sections for (n, p) and (n, α) reactions were as much as 10^4 times greater than predicted by theory. The (n, 2n) cross sections, however, agreed with theoretical values. They concluded that a direct interaction mechanism was operating in the (n, p) and (n, α) reactions. Brolley et al. (13) measured (n, 2n) reactions from the bombardment of Cu^{63} and Mo^{92} with neutrons at energies from threshold to 27 Mev. They found good correlation with theory up to 16-18 Mev, where the experimental cross sections dipped rapidly. They concluded that at this energy tertiary reactions became important.

Gugelot (14) reports that Hirzel and Wäffler (15) measured $\sigma(\gamma, p)/\sigma(\gamma, n)$ ratios and found that the (γ, p) reaction is 10^3 times larger than the theory would predict. An explanation of this by Schiff (16) was that the residual nuclei did not have all states excited due to the peculiarities of γ-ray absorption. Levinger and Bethe (17) explained (γ, p) reactions by the direct interaction of the photon with one of the protons of a nuclear alpha particle. Nabholz et al. (18), from (γ, α) reactions on $Br^{79, 81}$ and utilizing experimental (γ, n)

results, gave good theoretical correlation for $(\gamma, \alpha)/(\gamma, n)$ cross sections. Toms and Stephens (19) measured photoprotons from cobalt, initiated by bremsstrahlung x-rays, and found good correlation with theory if it was assumed that 10% of the protons came from a direct interaction mechanism.

Bradt and Tendham (20) bombarded silver and rhodium with alpha particles at 15-20 Mev and measured (α, n) and $(\alpha, 2n)$ cross sections. They made the assumption that the sum of these two cross sections would give the total cross section for alpha particles on the targets considered, and compared this value to that predicted by theory. The theoretical value agreed with their measured value. Kelly and Segre (21) bombarded bismuth with 38-Mev alpha particles and 19-Mev deuterons. The deuteron excitation functions were explained by Peaslee (22) on the basis of a non-compound nucleus stripping reaction. Cross sections for $(\alpha, 2n)$ and $(\alpha, 3n)$ reactions were measured and compared to statistical theoretical predictions. Agreement was found. Bleuler et al. (23) bombarded Ag^{109} with 19.5-Mev alpha particles and measured (α, n) and $(\alpha, 2n)$ excitation functions. In their calculations they neglected possible proton emission. Their calculated cross sections agree with their measurements.

According to the statistical theory, a ratio of particle emissions (such as the ratio of protons emitted as compared to neutrons emitted) from a given compound nucleus should be independent of the mode of formation of that nucleus. Peaslee (6) reports that

these relative probabilities may change by an order of magnitude depending on the nature of the incident particle. Experiments quoted by Peaslee with γ-induced reactions (15) at 17 Mev and neutron-induced reactions (12, 24) at 14 Mev showed that the fraction of proton emission compared to neutron emission from a compound nucleus was 100 times larger than predicted by the statistical theory. It is possible that a knock-on process here has obscured the statistical results. The fraction seems to increase with increasing Z while statistical theory predicts that proton emission will fall off as Z increases past 40.

On the other hand, Cohen et al. (25) compared the (p, 2p) reaction on a Mg^{25} target with the (N^{14}, 2p) reaction on a C^{12} target. Both reactions involve the Al^{26} compound nucleus. After corrections for barrier penetrations were applied, the cross sections were "quite comparable". However, the (N^{14}, α) and (N^{14}, 2α) cross sections were about two and four times larger, respectively, than those for the (p, α) and (p, 2α) reactions. This was possibly related to the original alpha particle structure of the C^{12} target.

Ghoshal (26) bombarded Ni^{60} with 40-Mev alpha particles and Cu^{63} with 32-Mev protons, in each case forming the compound nucleus Zn^{64}. According to the theory, the probability of this compound nucleus forming specific reaction products is the same in each case, providing corrections are taken into account which recognize that different excitation energies are involved in each case.

Ghoshal obtained experimental results giving better than fair agreement with theory, and until 1950 this experiment was among the most conclusive in favor of the compound nucleus. However, his experimental cross sections for the (α, 2n) reaction are about 4 times less than for the (α, pn). This result is not at all what one would expect from the theory. It might be explained (7) on the basis that the residual nucleus from the (α, pn) process is Cu^{62}, an odd-odd nuclide, whereas Zn^{62}, the (α, 2n) product, is even-even. Odd-odd nuclei are known to have level densities larger than those of even-even nuclei by a factor of approximately 12, and the level densities enter into the statistical theory quite heavily. This point is not considered in the calculations by Ghoshal.

Skyrme and Williams (27) bombarded tungsten and carbon with 157-Mev protons. They measured the differential cross sections for neutron emission at various energies and found that the shape of the curve agreed "fairly well" with theoretical predictions. They assumed some direct interaction was present.

Feld (28) interpreted the data of Barschall et al. (29) on energy distributions from the inelastic scattering of neutrons at energies from 1.5 to 3.0 Mev. The data from tungsten targets correlated with statistical theory; that from lead and iron targets did not fit the theory. He presented a theory which accounted for the lead and iron data on the basis that only a few energy levels were involved. Graves and Rosen (30) measured the energy distribution

of neutrons inelastically scattered from carbon, aluminum, iron, copper, zinc, silver, cadmium, tin, gold, lead, and bismuth. The neutrons emitted in the energy range 0.5 to 4.0 Mev had a Maxwellian distribution, as expected from the statistical theory, but the energetic dependence of the level density did not vary with the mass of the residual nucleus as the theory predicts it should. Graves and Rosen concluded that the excitation energy of the compound nucleus was not shared by all the particles. Gugelot (14) measured the energy spectra of neutrons emitted from reactions initiated by 16-Mev protons on beryllium, aluminum, iron, rhodium, gold, and tellurium. His values for nuclear temperature agreed with those of Graves and Rosen. Cohen (31) found that the angular distribution of neutrons from alpha-induced reactions could be approximately reproduced by statistical theory, but it was evident to him that some other process was also effective.

Levinthal et al. (32) measured the energy distributions of protons inelastically scattered from carbon and aluminum. The incident energy was 31 Mev. The distribution was correlated with theory and fit the predictions "fairly well" at excitation energies above 15 Mev. Below this energy, the observed values deviated from predictions. Eisberg and Igo (33) bombarded lead, gold, tantalum, and tin with 31-Mev protons and measured the inelastic scattering energy distributions, angular distributions, and total cross sections. They took measurements at 30, 45, 60, 90, and 135 degrees. The

energy distributions were not Maxwellian; statistical theory predicts they should be. The differential cross sections were peaked forward; statistical theory gives an isotopic distribution. The total cross sections were larger than predicted. They concluded that the incident proton may hit the rim of the target and be scattered from there without forming a compound nucleus.

Eisberg et al. (34) measured the energy spectra of emitted protons from the alpha bombardment of gold, silver, and copper, at 40 Mev. Their results agreed with the predictions of statistical theory for proton energies above about 4 Mev. Below this energy, they concluded, some other process interfered. Gugelot (35) bombarded aluminum, iron, nickel, copper, silver, tin, platinum, and gold with 18-Mev protons and measured the energy distribution of the inelastically-scattered particles. The distribution agreed with statistical theory at high excitation energies. He also found an anisotropic particle distribution which lead him to believe that a direct interaction was present. In an attempt to eliminate this interference he measured the energy distribution at 150 deg and calculated the level densities. Using these values he calculated values of $\sigma(n, p)$ and $\sigma(n, 2n)$ for rhodium and platinum and compared these values with the experimental results of Paul and Clarke (12). He obtained good agreement. His observed $\sigma(p, n)$ reaction for silver targets, however, differed by an order of magnitude from his calculated value.

Millar (36) bombarded silver and bromine with 70-Mev bremsstrahlung and measured the energy spectra of emitted alpha particles. The statistical theory correctly predicted the shape of the curve and the position of the peak.

Experiments testing the statistical decay of the compound nucleus by the usual methods of nuclear physics are, then, hampered by the interference of various direct interaction mechanisms. These mechanisms are expected to become ever more important as the incident energy is increased, but even at low bombarding energies they may obscure the compound nucleus process. Bombardments with 14-Mev neutrons by McManus et al. (37) measuring the energy distribution of emitted protons, show that a surface proton may receive nearly all the incident energy and leave the nucleus immediately. This type of reaction was considered by the authors to be most important at 10 to 30 Mev. Below 10 Mev, such a reaction may take place throughout the entire nucleus, competing with formation of a compound nucleus (38). A further discussion of surface reactions is given by Austern et al. (39).

Many of the afore-mentioned experiments (those dealing with the emission of high energy particles) are discussed by Cohen (40). He concludes either that some non-compound nucleus process is operative, or that some unknown selection rules are important. Eisberg (41) cites evidence in support of the contention that a direct interaction, preferably with surface nucleons, is the explanation.

Heavier bombarding projectiles which travel at the same velocity as light particles produce compound nuclei with greater excitation energy. In addition, this energy is shared among many incident nucleons; therefore, the probability of energy exchange with the target nucleons is much greater than in the foregoing experiments. The utilization of a heavy ion as the bombarding projectile has the further advantage that the nuclear binding energy of the incident ion will enter into the excitation energy of the compound nucleus. In the case of nitrogen on sulfur this may account for nearly half the total excitation energy. Heavy ion bombardments, then, are a logical method of obtaining experimental results at higher excitation energies.

Chackett et al. have utilized a nitrogen accelerator which produces a continuous energy distribution up to 125 Mev, the beam intensity falling off rapidly above 50 Mev. They put forth a "buckshot" theory to account for their results with aluminum targets (42). This theory assumes, in general, that only part of the nitrogen projectile fuses with the target. Souch, (43) analyzing the Cl^{38}/Cl^{34} ratio formed in the aluminum bombardments, concluded that the buckshot theory is more valid than is the compound nucleus hypothesis. Greenlees and Souch (44) bombarded chlorine and reported that their data from this experiment could be made to fit either theory. They suggested that more information is necessary and may be obtained from monoenergetic heavy ions.

Nitrogen ions are acclerated to 28 Mev in the Oak Ridge

National Laboratory 63-inch cyclotron, with a full width at half maximum 600 Kev in the deflected beam. A nitrogen ion at this energy has a velocity equal to that of a 2-Mev proton. The low incident velocity should make direct interactions unlikely; the nitrogen should completely fuse with the target to form a compound nucleus in which the excitation energy will be shared equally among all the nucleons. If this is so then, according to the assumptions proposed by Bohr (1), the decay of this nucleus will not depend on the manner in which it was formed. These ions would seem to be ideal for testing the theory.

Zucker and co-workers have for the past several years been conducting such experiments on a series of targets. A systematic survey of nuclear reactions induced by nitrogen ions has been undertaken (45). Various correlations with theory have been computed. In this experiment a more complete comparison is attempted.

Present Experiment

Natural sulfur was bombarded with nitrogen ions at incident energies ranging from 20 to 28 Mev. At this latter energy the V^{46} compound nucleus is excited to 33.3 Mev.

The reactions listed in Table 1 were computed to be possible results of evaporation from a compound nucleus. The half-lives in this table refer in each case to the first nuclide listed. The Q-values were computed from the table of masses by Wapstra (46). Q-values

TABLE 1

POSSIBLE REACTIONS FROM THE V^{46} COMPOUND NUCLEUS

Product Nuclei	Half life	Q
Ti^{45} + p	3.09 hours	+8.66
Sc^{44} + 2p	3.9 hours	+1.8
Sc^{44m} + 2p	2.44 days	+1.55
Ca^{43} + 3p	stable	-6.582
K^{42} + 4p	12.5 hours	-17.41
V^{45} + n	1 second	+10.34
Ti^{44} + pn	20 years	
Ti^{43} + p2n	0.6 seconds	
Sc^{43} + 2pn	3.9 hours	-9.58
Ca^{42} + 3pn	stable	-14.52
Sc^{42} + α	0.66 seconds	+8.0
K^{38m} + 2α	7.7 minutes	+0.808
K^{38} + 2α	1 second	+0.808
Cl^{34} + 3α	32.4 minutes	-6.03
Sc^{41} + nα	0.8 seconds	-4.45
Ca^{41} + pα	10^5 years	+2.3
Ca^{40} + pnα	stable	-6.07
Ka^{40} + 2pα	stable	-6.61
A^{37} + p2α	35 days	-4.28

for nuclides not listed in these tables were computed from the semi-empirical data of Cameron (47).

Not all the listed reactions were observed. In some cases the residual nucleus is stable, or its half-life is either too long or too short for convenient study. In other cases the reaction was energetically forbidden. The following reactions were observed:

$$S^{32}(N^{14}, p)\,Ti^{45} \quad (1)$$

$$S^{32}(N^{14}, 2p)\,Sc^{44} \quad (2)$$

$$S^{32}(N^{14}, 2pn)\,Sc^{43} \quad (3)$$

$$S^{32}(N^{14}, 2\alpha)\,K^{38}. \quad (4)$$

In addition the reaction:

$$S^{32}(N^{14}, N^{13})\,S^{33} \quad (5)$$

was observed. It does not appear to go through the V^{46} compound nucleus, is identified as a transfer reaction and is treated separately.

In the case of each reaction to be studied, the radioactive product nuclei were chemically separated and their yields measured by absolute beta counting. Smooth curves drawn through the yield vs energy curves were differentiated to obtain excitation functions. The cross sections at 27 Mev for reactions (1), (2), and (4) were then compared with predictions based on statistical decay theory of the compound nucleus. In the theoretical calculations, the procedure as set forth by Blatt and Weisskopf (48) was extended by including both odd-even effects (49) and shell structure effects (50) on the nuclear level densities, and by including in the theory the possibility of compound nucleus deexitation by gamma emission. In addition, the effect of nuclear spins of

the emitted particles was taken into account.

There are certain assumptions which are included in the original theory, such as specific values for nuclear radii and a certain prescribed dependence of level densities on energies. In this experiment the nuclear radius was not varied but calculations were made for two values of the energy dependence of the level densities.

CHAPTER II

EXPERIMENT

Bombardment Techniques

Targets were made by pressing ZnS at a pressure of five tons/in.^{2} into brass molds 3/4 in. in diameter. ZnS was chosen as the target material primarily because of the ease with which it could be handled chemically, as compared to sulfur powder. Nuclear reactions on the zinc were prohibited by the Coulomb barrier of 31.4 Mev, calculated from the relation

$$B = Z_1 Z_2 \ e^2/(A_1^{1/3} + A_2^{1/3})\ r_o, \qquad (6)$$

where B is the Coulomb barrier; Z_1 and A_1 refer to the nuclear charge and mass, respectively, of the nitrogen ions; Z_2 and A_2 refer to the target nucleus; and r_o is equal to 1.5×10^{-13} cm. The most energy available in the center-of-mass system was 23 Mev. The targets were approximately 0.1 in. thick, that is, infinitely thicker than the range of energetic nitrogen ions. The ZnS was obtained from the General Chemical Division of Allied Chemical and Dye Corporation and was reagent grade. The sulfur was natural sulfur, containing 94.06% of S^{32}. The ZnS was thoroughly

dried in an oven before pressing, and the targets were stored in a desiccator. The targets as used presented a hard uniform surface which did not change under bombardment and which was found to be stable at bombardment temperatures.

The target for each run was placed in the external beam of the 63-inch cyclotron and bombarded for periods ranging from ten minutes for product potassium to three hours for scandium.

The energy of the incident beam was measured by observing the energy of recoil protons. The experimental apparatus is shown in Fig. 1, taken from Reynolds et al. (51). The recoil protons pass through a 9.5 mg/cm^2 nickel foil and then through a collimator which permits passage of only those protons having an angle less than five deg to the incident beam. The protons then pass through 42.76 mg/cm^2 aluminum and 1.3 cm of air into an Ilford C-2 nuclear emulsion. The range of the protons in the emulsion was measured. From the known range-energy relations for protons in the emulsion (52); in air, aluminum, and nickel (53); for nitrogen ions in nickel (51); and from the energy relations of nitrogen and recoil protons, the incident nitrogen energy was calculated. The energy of nitrogen is related to that of recoil protons at zero degrees, from conservation of energy and momentum relationships, by

$$E_N = 3.99\, E_p. \tag{7}$$

The incident energy was found to vary from 27.2 to 28 Mev from day

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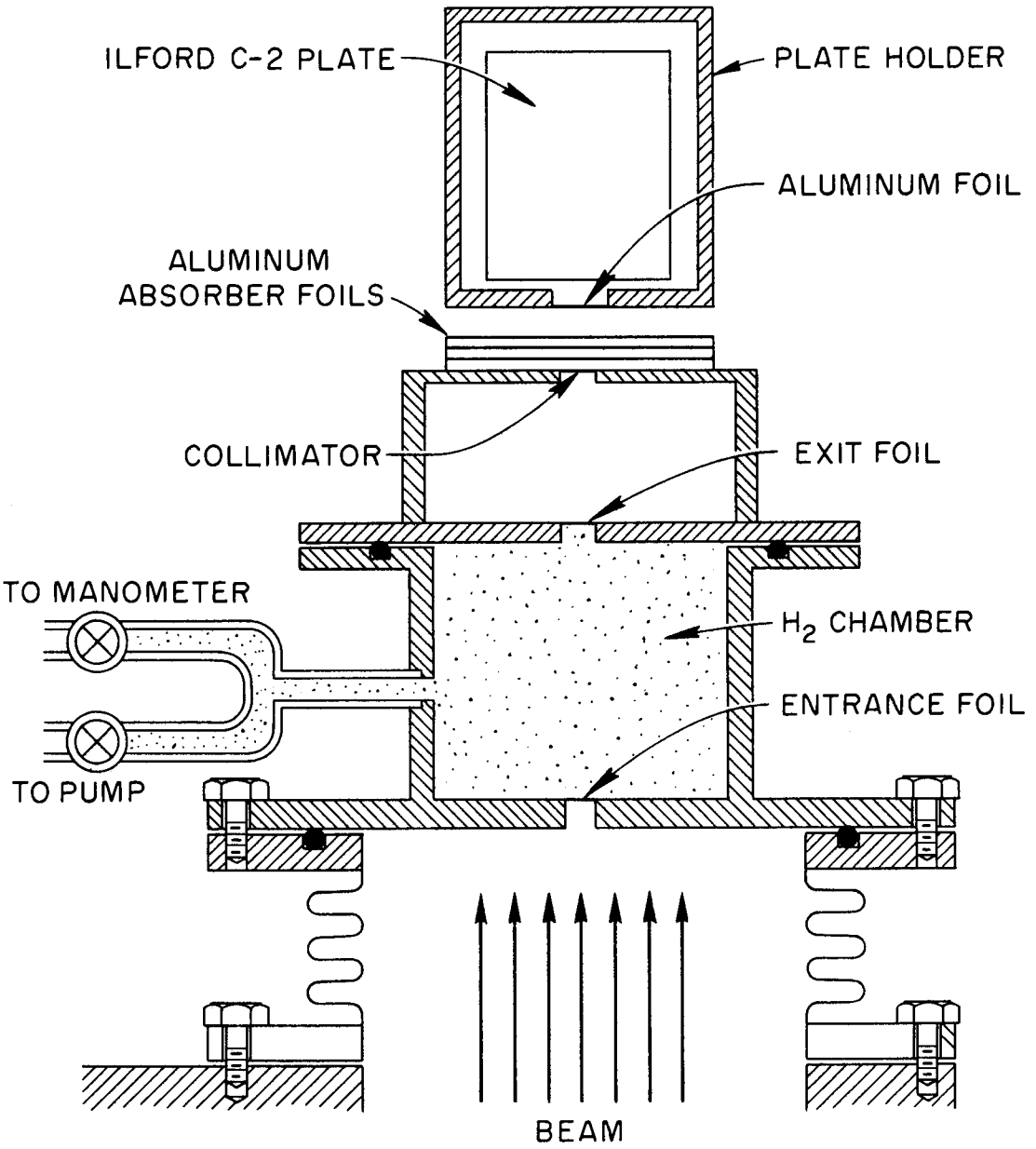

Fig. 1. Energy Determination Apparatus.

to day, with about a 0.6 Mev full width at half maximum.

The energy of the incident beam was degraded by placing nickel foils, in steps of approximately 0.5 mg/cm^2, between the beam and the target. From the range-energy relations of nitrogen in nickel (51) the energy of the beam hitting each target was calculated. The beam current was integrated with a vibrating reed electrometer; it was usually about 0.3 microamperes.

Chemical Techniques

According to Eqs. 1-5 the following elements were to be isolated chemically: potassium, titanium, scandium, and nitrogen. In addition, it was deemed necessary to add vanadium holdback carrier in all cases. A slight amount of vanadium might have been formed by the reactions:

$$S^{34}(N^{14},\gamma)\,V^{48} \qquad (8)$$

$$S^{34}(N^{14},n)\,V^{47} \qquad (9)$$

Zinc was present from the ZnS target.

It was determined that both scandium and titanium could be removed from the same target. The technique, as follows, was modified from that given by Stevenson and Folger (54):

Titanium and Scandium: The half life of Ti^{45} is 3.09 hours. The metastable state of Sc^{44} has a 2.44 day half life; the half life of the ground state is 3.9 hours. The half life of Sc^{43} is 3.9 hours.

The target was dissolved in concentrated HCl and heated to drive off all H_2S. Titanium and scandium carriers equivalent to about 10 mg of each element were added along with holdback carriers. Scandium was precipitated with saturated oxalic acid. The remaining solution was scavenged five times with oxalic acid, then TiO_2 was precipitated with $KBrO_4$. This was washed several times with hot water, then redissolved in concentrated HCl. TiO_2 was precipitated again with concentrated ammonia. The precipitate was washed with hot water, ignited at 800° C in a muffle furnace for thirty minutes (55), cooled, and weighed after transfer to a counting cup. Time: 2 hours. Yield: 40-60%. The scandium precipitate was washed with hot water and then with oxalic acid. It was dissolved in concentrated nitric acid. The scandium was then precipitated as the oxide with concentrated ammonia. It was washed with hot water, ignited in platinum in a muffle furnace at 700° C forty minutes (55), cooled, and weighed after transfer to a counting cup. Time: 2 hours. Yield: 30-80%.

The technique for potassium was taken from the Oak Ridge National Laboratory Master Analytic Manual, No. 1-216451, and is as follows:

Potassium: The half life of K^{38} is 7.7 minutes. The target was dissolved in a test tube containing concentrated HCl and about 5 mg potassium carrier. Holdback carriers were added. Twenty ml of pH 2.8 buffer were added, 10 ml of 0.6% sodium tetraphenyl boron

reagent were added and the potassium precipitated as potassium tetraphenyl boron, $K(C_6H_5)_4B$. The precipitate was washed once, dried, transferred and counted. It was weighed after counting. Time: 15 minutes. Yield: 45-80%.

The nitrogen technique was modified from that used for potassium and is as follows:

Nitrogen: The half life of N^{13} is 10.1 minutes. The target was dissolved in concentrated HCl and carriers were added. 6N NaOH was added and the solution was boiled. NH_3 escaped and was distilled into a cooled solution containing pH 2.8 buffer and 0.6% sodium tetraphenyl boron. The nitrogen precipitated as $NH_4(C_6H_5)_4B$. It was washed once, dried, transferred, and counted. It was weighed after counting. Time: 20 minutes. Yield: 30-60%.

Carriers were prepared as follows:

Titanium: Approximately 20 g of $TiCl_4$ was dissolved in enough water to give about 500 ml of solution. The solution was then assayed. $Ti(OH)_4$ was precipitated from 5 ml of the solution by the addition of concentrated ammonia. The precipitate was filtered and washed with water containing a few drops of ammonia. It was ignited in a platinum crucible in a muffle furnace at above 700° C for 30 minutes (55), then cooled in a desiccator and weighed. Results gave 10.42 mg of titanium per ml of solution, with an error of ± 1.5% for a standard deviation from a series of measurements.

Scandium: 1.6947 g of Sc_2O_3 was dissolved slowly in hot con-

centrated HCl to a volume of about 100 ml. The solution was assayed as follows: 2 ml of the solution was diluted with 0.5 ml of water and $Sc(OH)_3$ was precipitated with 2.5 ml concentrated ammonia. The precipitate was centrifuged and the supernatant decanted. The precipitated was washed with water containing a few drops of ammonia and ignited in a platinum crucible in a muffle furnace for thirty minutes at 600-700° C (55). Results gave 10.54 mg of scandium per ml of solution, with an error of ± 3.72% for a standard deviation from a series of measurements.

Potassium: 9.5383 g of KCl was dissolved in water and taken to 500 ml volume in a volumetric flask. This gave 10.005 mg potassium per ml and was felt to be more accurate than an assay would be.

Nitrogen: 1.202 g of NH_4Cl was dissolved in water and taken to 500 ml of solution in a volumetric flask. This gave 0.6297 mg nitrogen per ml of solution and was thought to be more accurate than an assay would be.

Vanadium: 17.848 g of V_2O_5 was dissolved with difficulty in concentrated HCl and the volume brought to 500 ml. Two ml of this solution was diluted with one ml water and 4 drops 30% H_2O_2. It was evaporated in an oven at 110° C for thirty minutes (55). It was a blue liquid which solidified immediately upon removal from the oven. It was cooled and weighed, and gave 19.495 mg vanadium per ml of carrier solution if the residue was V_2O_5. Some V_2O_5 powder was obtained from the stock room and heated to above 650° C for thirty

minutes. Upon removal from the muffle furnace it was identical with the above. Since the carrier was to be used solely for holdback purposes, it was not thought worthwhile to spend more time on the problem of assaying it.

Counting Techniques

In general the counting technique was the same for all residual nuclei studied. After each bombardment the target was removed from the cyclotron, chemically processed, and then counted.

Calibration

Each nuclide was counted in a stainless steel cup, supported by cardboard plates, beneath end-window Geiger counters enclosed in lead shields. Geometry was maintained as constant as possible for all samples, and constant with that of a Ra-DEF standard which was used to calibrate each counter. The standard was obtained from the National Bureau of Standards and was certified to have had an activity of 201.8 disintegrations per second on March 1, 1950.

The calibrations were performed by counting the standard with various amounts of aluminum absorber between it and the counter and extrapolating the rate on semi-log paper to zero absorber. Such a plot is shown in Fig. 2. The Ra-DEF source has radiation consisting of negatons with a 22.2-year half life from Pb^{210}, alpha particles of half life equal to 2.6×10^6 years from Bi^{210}, and 138-day alpha particles from Po^{210}. The absorbers cut out the alpha activity

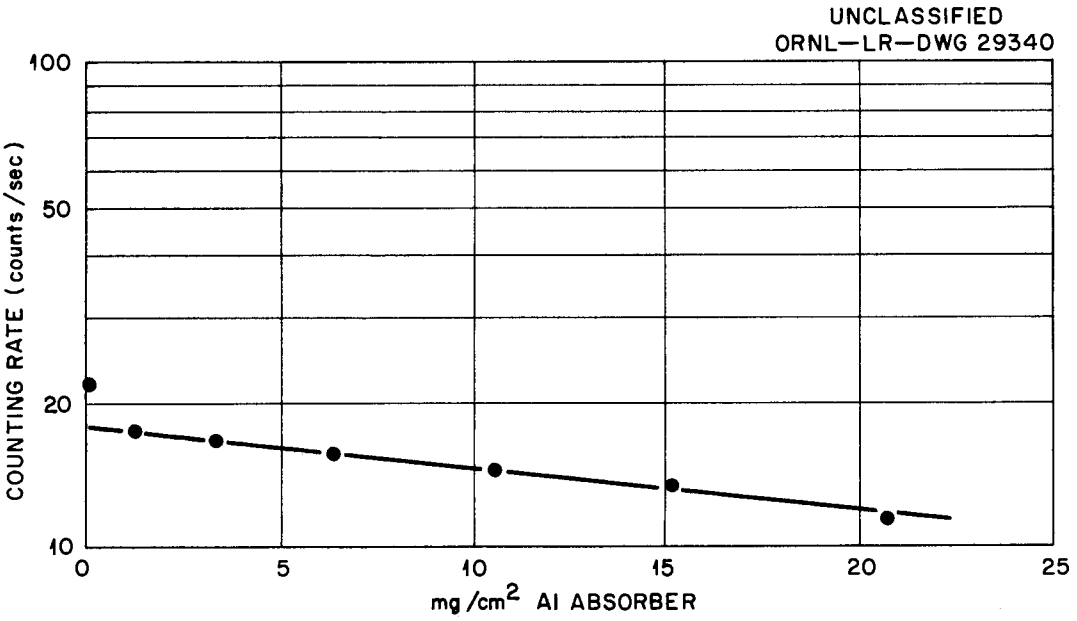

Fig. 2. Ra-DEF Calibration.

while their effect on the negatons emitted was small. The absorbers used ranged from 1.63 to 20.8 mg/cm^2 of aluminum. A back-scatter correction factor of 1.54 was applied to the calibration. No corrections were applied for air scattering, scattering by the sides of the lead shield, or window absorption. Window thicknesses varied about 2.0 mg/cm^2 of mica. A back-scatter correction factor of 1.6 was applied to all nuclides counted in accordance with experiments performed in this laboratory by M. L. Halbert. Burtt (56) has shown that the saturation back-scatter correction is independent of the maximum beta energy if that energy is above 0.5 Mev. Preliminary experiments done in this laboratory by J. J. Pinajian showed that self-absorption of beta particles at these energies, and for the amount of material being counted, could be neglected. Corrections were made for K-capture branching ratios and for isotopic abundance of S^{32} in the target material. The background rate in each counter was about 0.4 counts per second and was measured to a statistical accuracy of one per cent.

Experimental values

Half lives were assigned to the nuclides as shown in Table 2. These half-life values are the best available in the opinion of the author.

TABLE 2

ASSIGNED HALF LIVES

Nuclide	Half life	Reference	
Ti^{45}	3.09 hours	H. E. Kubitschek	(57)
Sc^{44m}	2.44 days	Hibdon, Pool, and Kurbatov	(58)
Sc^{44}	3.9 hours	Hibdon, Pool, and Kurbatov	(58)
Sc^{43}	3.9 hours	Hibdon, Pool, and Kurbatov	(58)
K^{38}	7.7 minutes	Green and Richardson	(59)
N^{13}	10.1 minutes	Siegbahn and Slatis	(60)

In each case a straight line corresponding to the best half life was drawn through the experimentally determined points. This line was fitted to the points visually, and was later extrapolated to determine the activity of each nuclide at the end of bombardment. Each nuclide was counted down to background level to ascertain whether any long-lived nuclide was present. A typical decay curve for Ti^{45} is shown in Fig. 3. Points shown are counting rates minus background, with standard deviations as indicated on typical points.

A decay curve characteristic of Sc^{44} is shown in Fig. 4. Two activities are present: a 2.44-day activity due to the metastable state of Sc^{44}, and a 3.9-hour activity due to both Sc^{44} and Sc^{43}. A straight line with half life equal to 2.44 days was drawn through the lower points as shown and extrapolated back to end of bombardment. The activity due to this state was then subtracted from the total to determine the 3.9-hour counting rate.

To determine the relative yield of the Sc^{44} and Sc^{43} isotopes of 3.9-hour half life, several scandium samples were gamma counted on a scintillation spectroscope with a sodium iodide crystal. Sc^{44} has a 1.47-Mev positon and a 1.16-Mev gamma ray. Sc^{43} has a 1.19-Mev positon and only low energy gamma rays. A graph showing the gamma counting rate as a function of gamma energy was expected, then, to show a peak due to annihilation photons from both isotopes, plus a peak at 1.16 Mev due to both states of the Sc^{44} isotope. Such a graph is shown in Fig. 5, showing the activity at two times. The peak

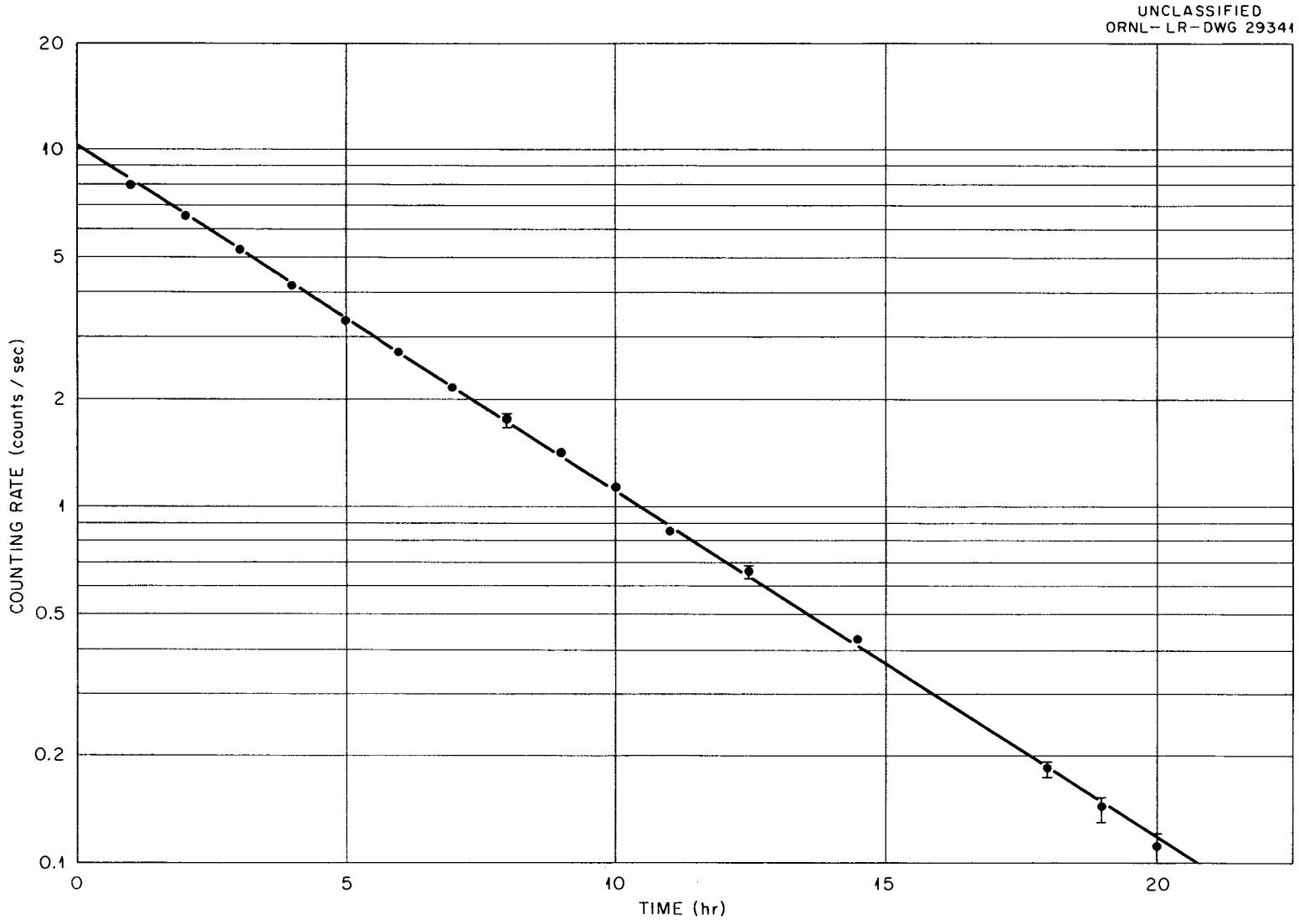

Fig. 3. Typical Ti^{45} Decay Curve.

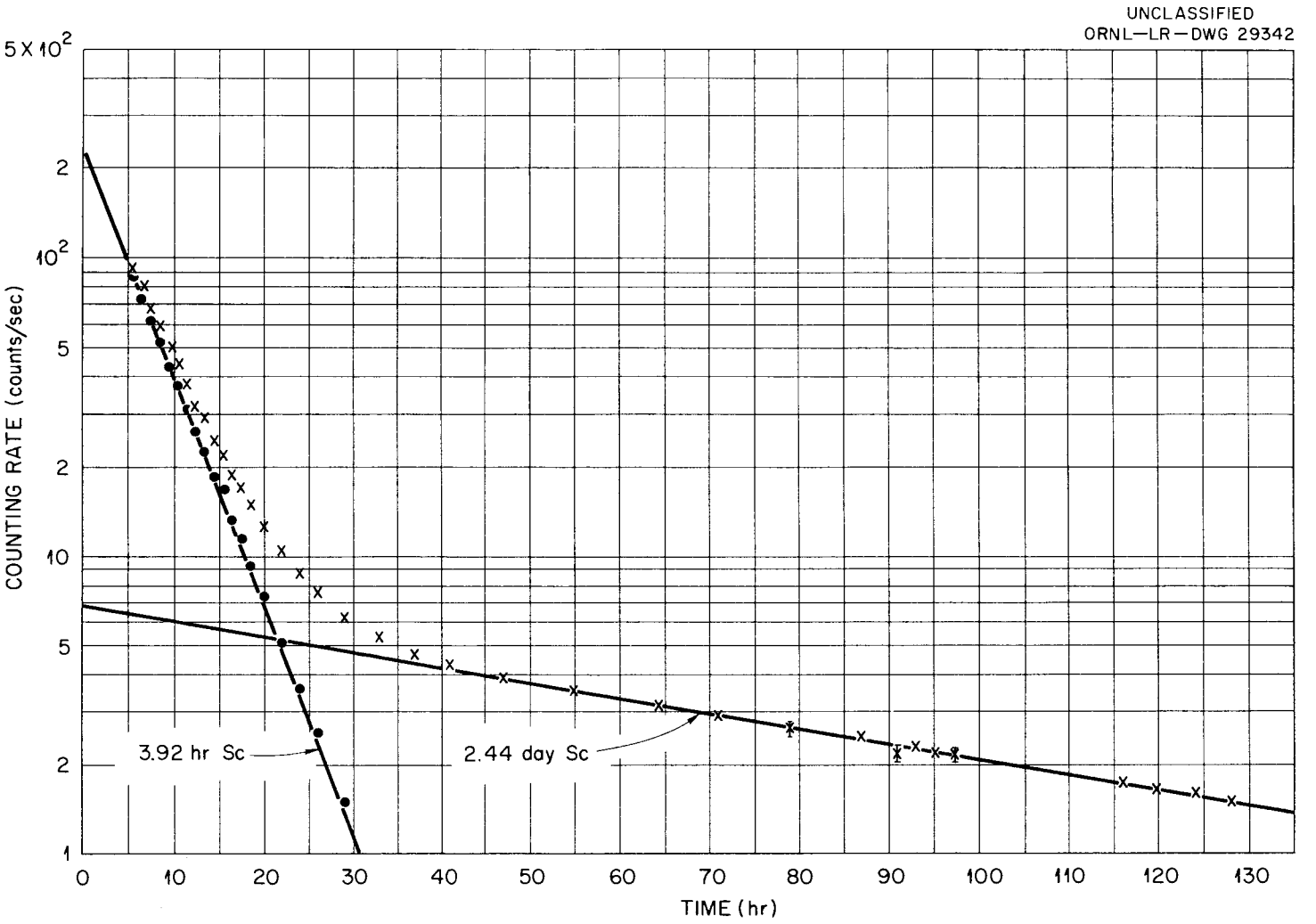

Fig. 4. Typical Sc^{44} Decay Curve. Crosses indicate total counting rate. Dots indicate rate after subtraction of 2.44-day activity.

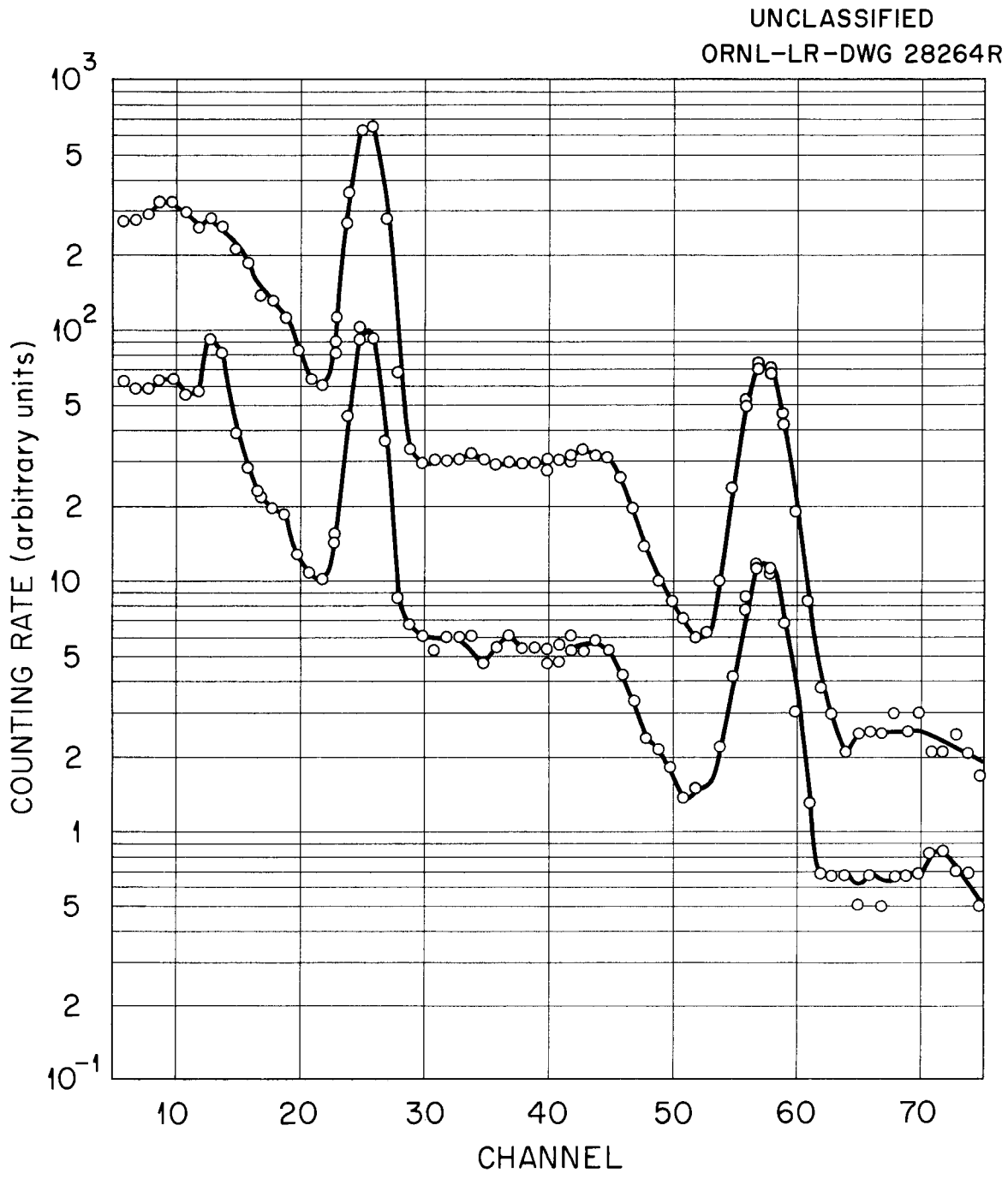

Fig. 5. Scandium Gamma Spectrum.

at channel 57 is due to the 1.16-Mev gamma.

The observed gamma counting rate at a particular time t' indicated the activity due to Sc^{44m} and Sc^{44}_{o} at that time, where Sc^{44m} is the metastable state and Sc^{44}_{o} is the ground state. From the decay curve plotted on the basis of geiger counting, as in Fig. 4, the activity due to Sc^{44m} and that due to $(Sc^{44}_{o} + Sc^{43})$ was known at time t'. Then subtracting the activity due to Sc^{44m} from the gamma activity gave that due solely to Sc^{44}_{o}. This was compared to the activity due to both Sc^{44} and Sc^{43} measured by the geiger counting to determine the relative activities of each isotope.

The efficiency of the scintillation apparatus was determined with a Rb^{86} source obtained from the Radioisotopes Division of the Oak Ridge National Laboratory. The Rb^{86} has a 1.77-Mev negaton and a 1.08-Mev gamma ray. It was precipitated from HCl solution by sodium tetraphenyl boron, with KCl carrier, and was beta counted to determine its disintegration rate. The ratio of gamma to beta disintegrations was taken from Nuclear Level Schemes (61). A graph of the Rb^{86} standard is shown in Fig. 6.

Decay curves for K^{38} and N^{13} are shown in Figs. 7 and 8. The potassium showed a small amount of long-lived activity which was assigned to the ground state of Sc^{44}. This activity was therefore subtracted from the observed rate as is indicated on the graph. The curve thus obtained fitted the K^{38} decay rate.

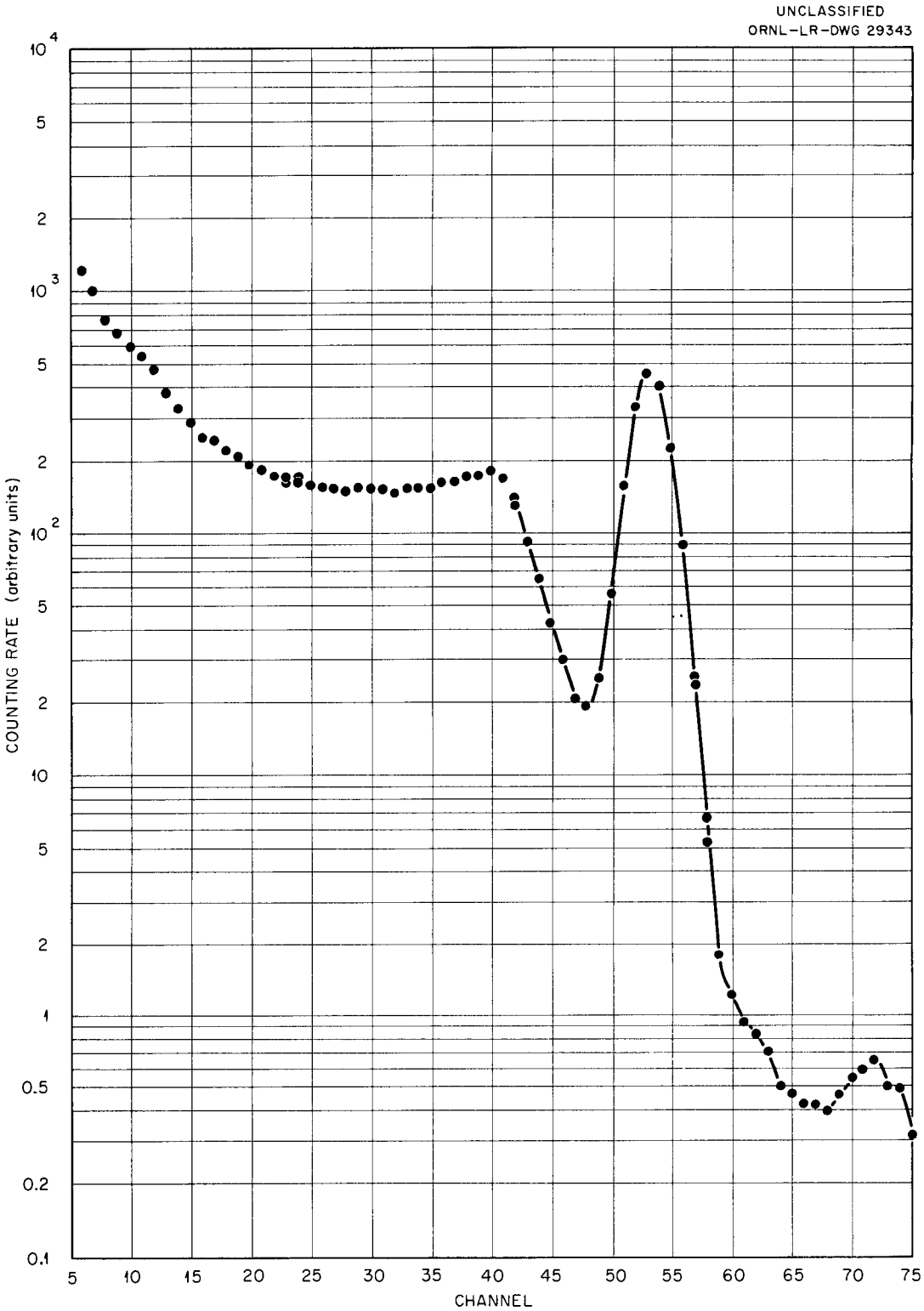

Fig. 6. Rb^{86} Gamma Spectrum.

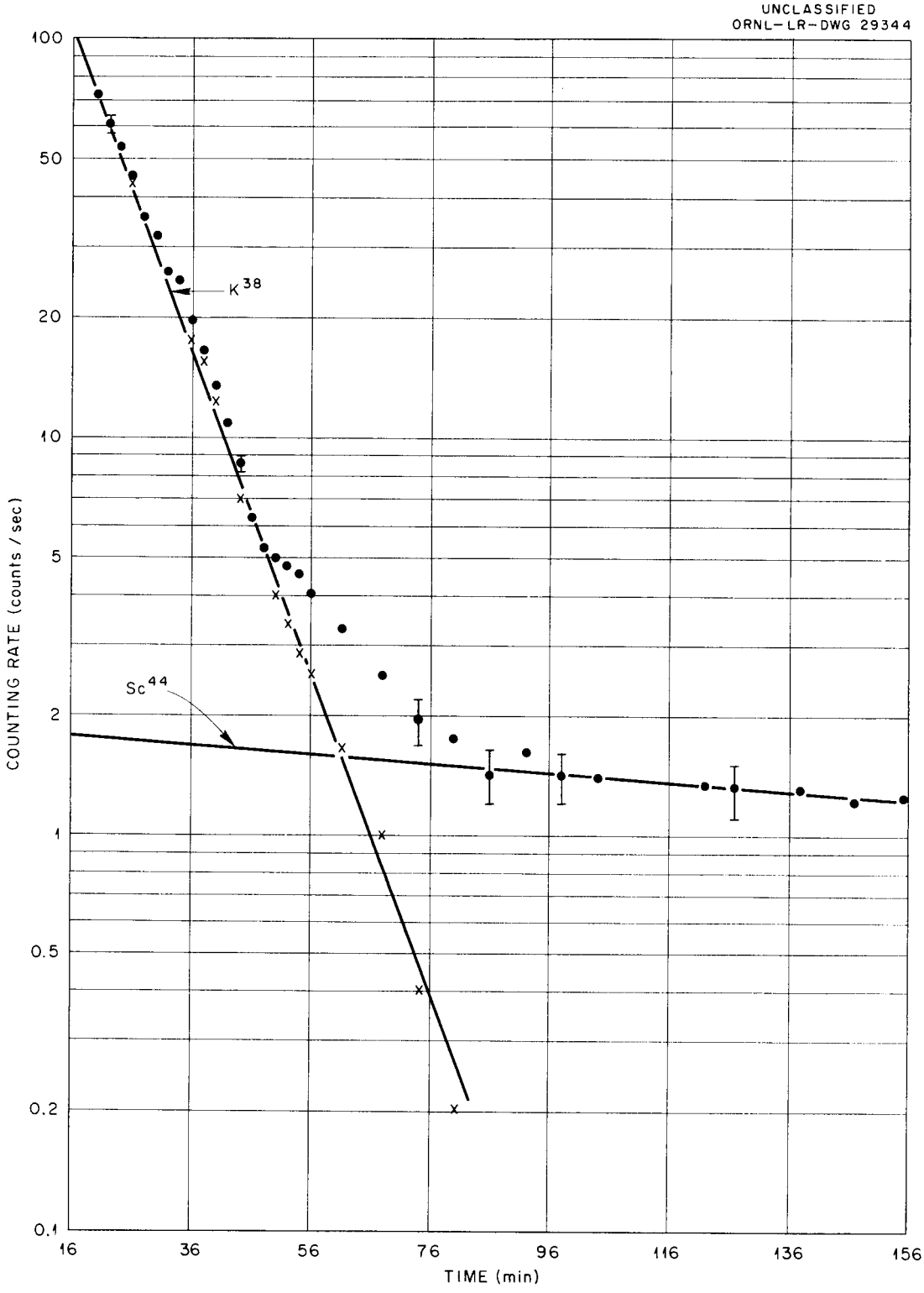

Fig. 7. Typical K^{38} Decay Curve. Dots indicate total counting rate. Crosses indicate rate after subtraction of Sc^{44} activity.

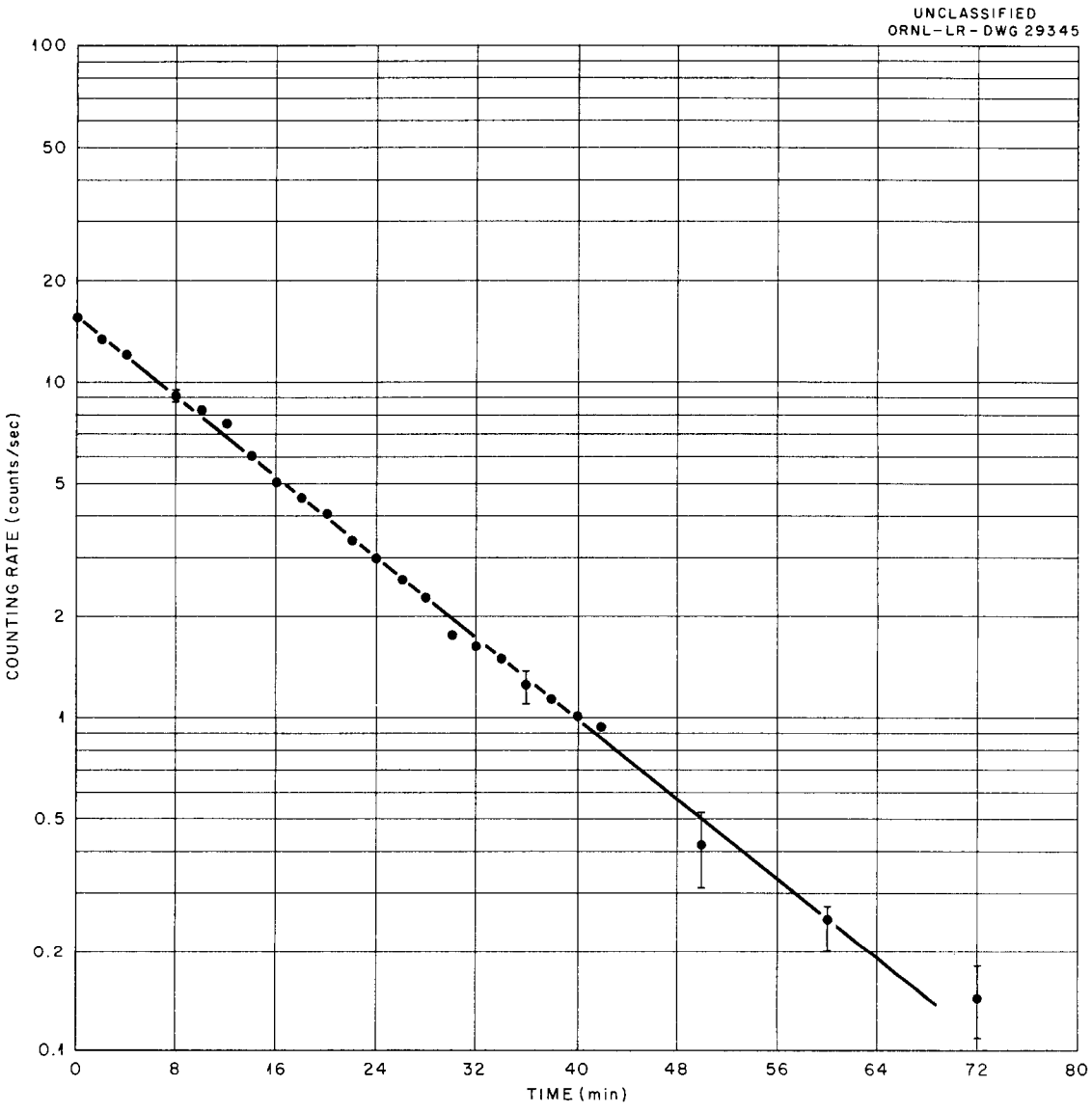

Fig. 8. Typical N^{13} Decay Curve.

CHAPTER III

CALCULATIONS AND RESULTS

Each nuclide was beta counted for a length of time equal to about ten half lives. As each nuclide was counted, the disintegrations were automatically recorded on a tape. The counting rate for each nuclide, corrected for background, was plotted on semi-log paper. Straight lines with slopes determined by the assigned half lives were drawn through the experimental points, as shown in Figs. 3, 4, 7, and 8. These lines were extrapolated to the end of bombardment.

The yield of nuclear reactions formed per incident particle was then calculated for each run by the equation

$$Y = \frac{(dN/dt)}{E_c \cdot E_p \cdot R \cdot B_k \cdot K \cdot I(1-4^{-\lambda t})}, \qquad (10)$$

where (dN/dt) = counts per second at end of bombardment,

E_c = chemical efficiency,

E_p = counter efficiency,

R = N^{+3} beam current expressed as the number of nitrogen ions hitting the target per second,

B_k = backscatter correction = 1.6,

K = K-capture branching ratio,

I = isotopic target abundance of S^{32} = 0.94,

λ = decay constant,

t = length of bombardment.

The chemical efficiency was determined by weighing each separated sample and assuming that complete chemical exchange took place between reaction products and carrier. At the counting rates involved, a maximum of 80 counts per second, no correction was needed for resolving time of the counters. The K-capture branching ratio for Ti^{45} and Sc^{44} was taken from Nuclear Level Schemes (61), for K^{38} from Endt and Kluyver (62), and for N^{13} from Ajzenberg and Lauritsen (63).

Nuclear reaction yields were determined at several energies for each nuclide. In each case, the incident energy was degraded until activity could no longer be measured. The yields were plotted against energy as shown in Figs. 9 and 10. Relative yields of Sc^{44}_{o} and Sc^{43} were determined as described in the previous section. Sc^{44}_{o} accounted for 84% of the total 3.9-hour activity. The yield as shown for Sc^{44} is the sum of the yields due to the ground state and to the metastable state.

The thick target yield measured at any incident energy E is expressed as

$$Y = n \int_{o}^{E} \sigma(E)\, dE. \qquad (11)$$

Therefore to determine the excitation functions smooth curves drawn through the experimentally determined yield vs energy points were differentiated. The equation for the cross sections was derived as follows:

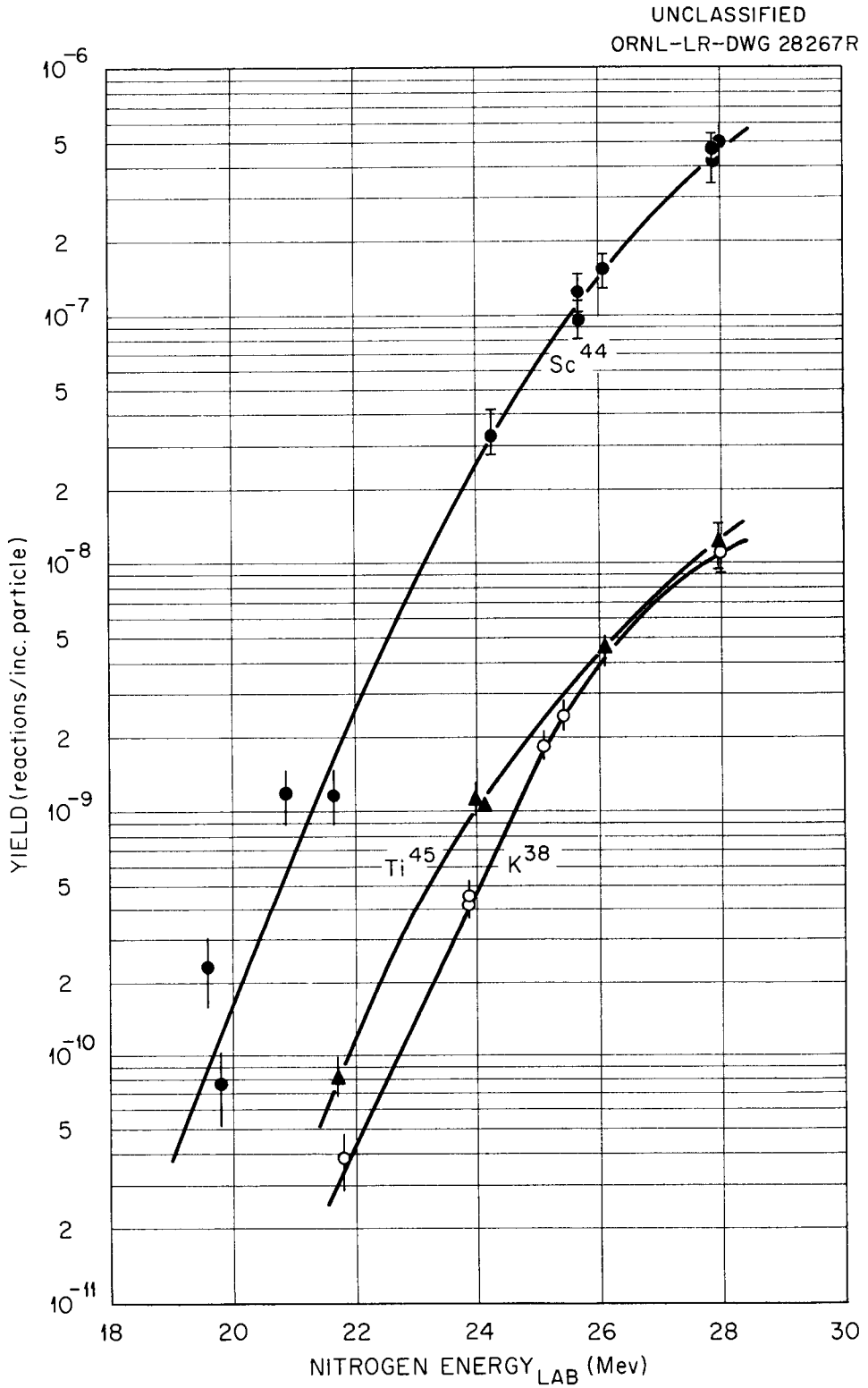

Fig. 9. Yields vs Nitrogen Energy.

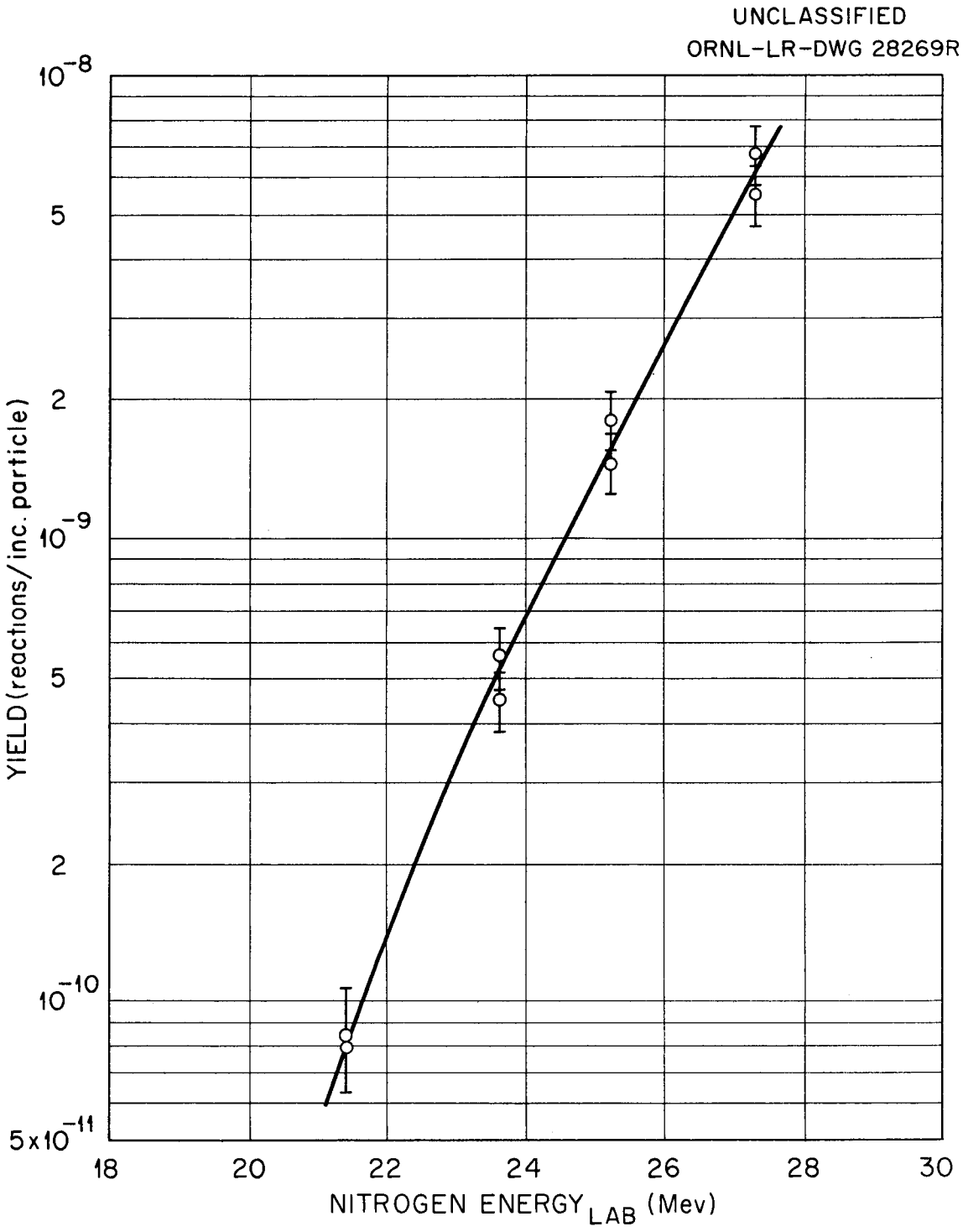

Fig. 10. Yield vs Nitrogen Energy for (N^{14}, N^{13}) Reaction.

$$Y = n\sigma, \tag{12}$$

over a small interval dE, where

σ = cross section in cm^2, and

n = number of target atoms per cm^2.

Then

$$\frac{dY}{dE} = \sigma \frac{dn}{dE}, \tag{13}$$

if σ is considered to be constant over the small energy interval dE, as is nearly the case.

To determine dn/dE the following argument was used: Range-energy relationships are usually given in terms of dE/dx. Then

$$\frac{dn}{dE} = \frac{dx}{dE} \frac{N \cdot I \cdot D}{A_{ZnS}\, 10^3}, \tag{14}$$

where

D = density of ZnS in mg/cm^2,

x = range of nitrogen in ZnS in cm,

$N = 6.023\ 10^{23}$ = number of sulfur atoms per mole of ZnS,

I = isotopic abundance of S^{32},

A_{ZnS} = molecular weight of ZnS.

The stopping power S_j^i was defined as equal to dE/dx for particles i incident on material j. The quantity needed for Eq. 14 is S^N_{ZnS}. This was determined, according to the discussion by Allison and Warshaw (64), from

$$\frac{1}{S^N_{ZnS}} = \frac{A_{Zn}}{A_{ZnS}\, S^N_{Zn}} + \frac{A_S}{A_{ZnS}\, S^N_S} . \qquad (15)$$

S^N_{Zn} was taken as equal to S^N_{Ni}, which was taken from the data of Reynolds, Scott, and Zucker (51); S^N_S was taken from the relative stopping powers of sulfur and nickel for protons of the same velocity. S^P_{Ni} was taken from the data of Allison and Warshaw (64); S^P_S was interpolated from the same data.

A plot of the stopping power of ZnS for nitrogen ions vs nitrogen energy is shown in Fig. 11. This method of calculating the range of nitrogen ions in target meterials has been previously checked by Reynolds and Zucker (45) for aluminum. Then

$$\sigma = \frac{dY}{dE}\,\frac{dE}{dx}\,\frac{A_{ZnS}\, 10^3}{N \cdot I \cdot D} . \qquad (16)$$

These cross sections are plotted against incident nitrogen ion energy in the laboratory system in Figs. 12 and 13 and are listed at various incident energies in Table 3.

The errors in the absolute yields are on the order of 20%, due mainly to the inherent difficulties of Geiger tube calibrations. Satistical errors associated with low counting rates became important at the lowest incident energies. This fact is shown on the yield curves in Figs. 9 and 10. No errors were plotted on the cross section curves as these were obtained by differentiating the smooth curves drawn to fit the experimental yield points.

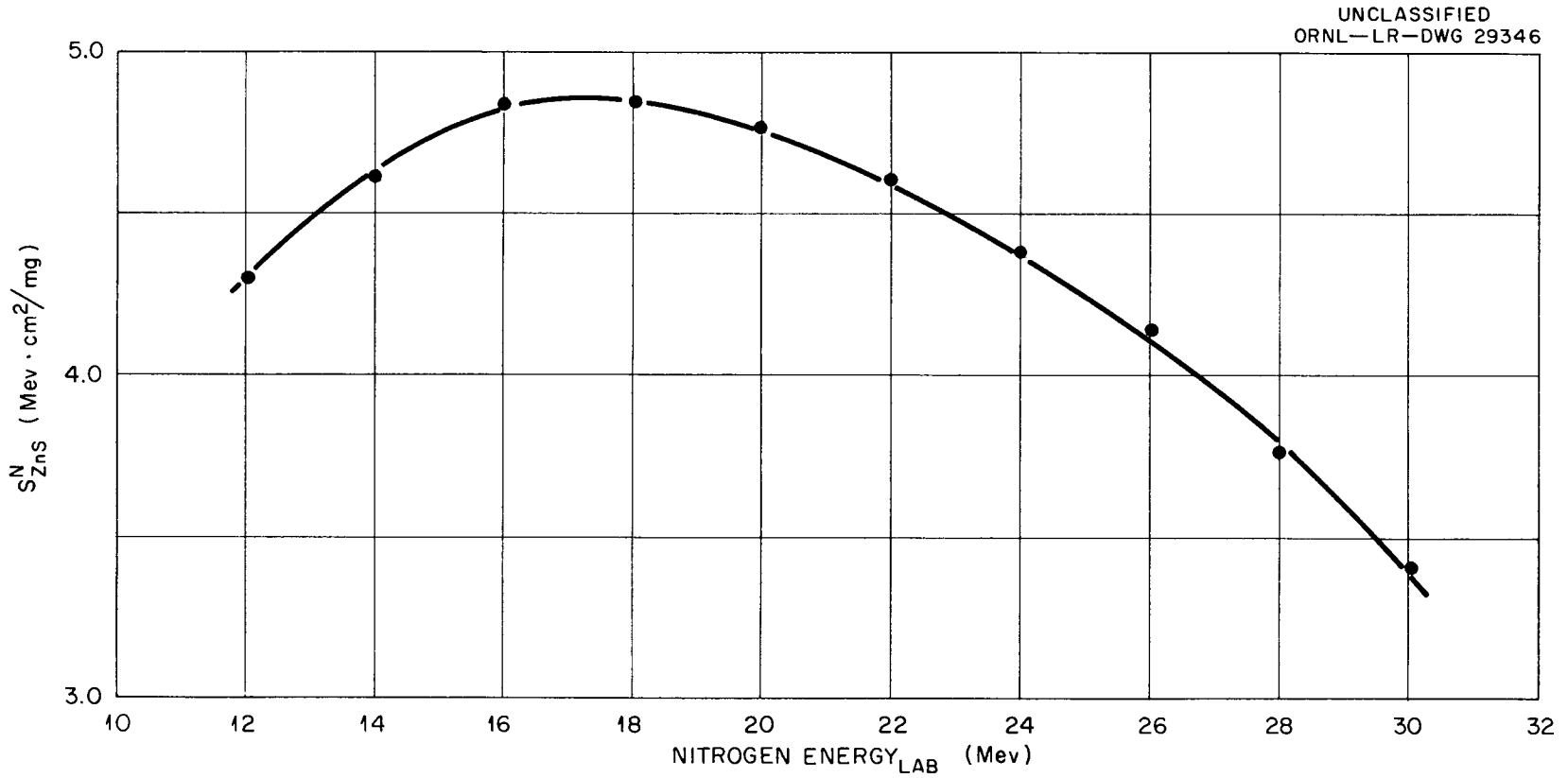

Fig. 11. Stopping Power of ZnS for Nitrogen Ions vs Nitrogen Energy.

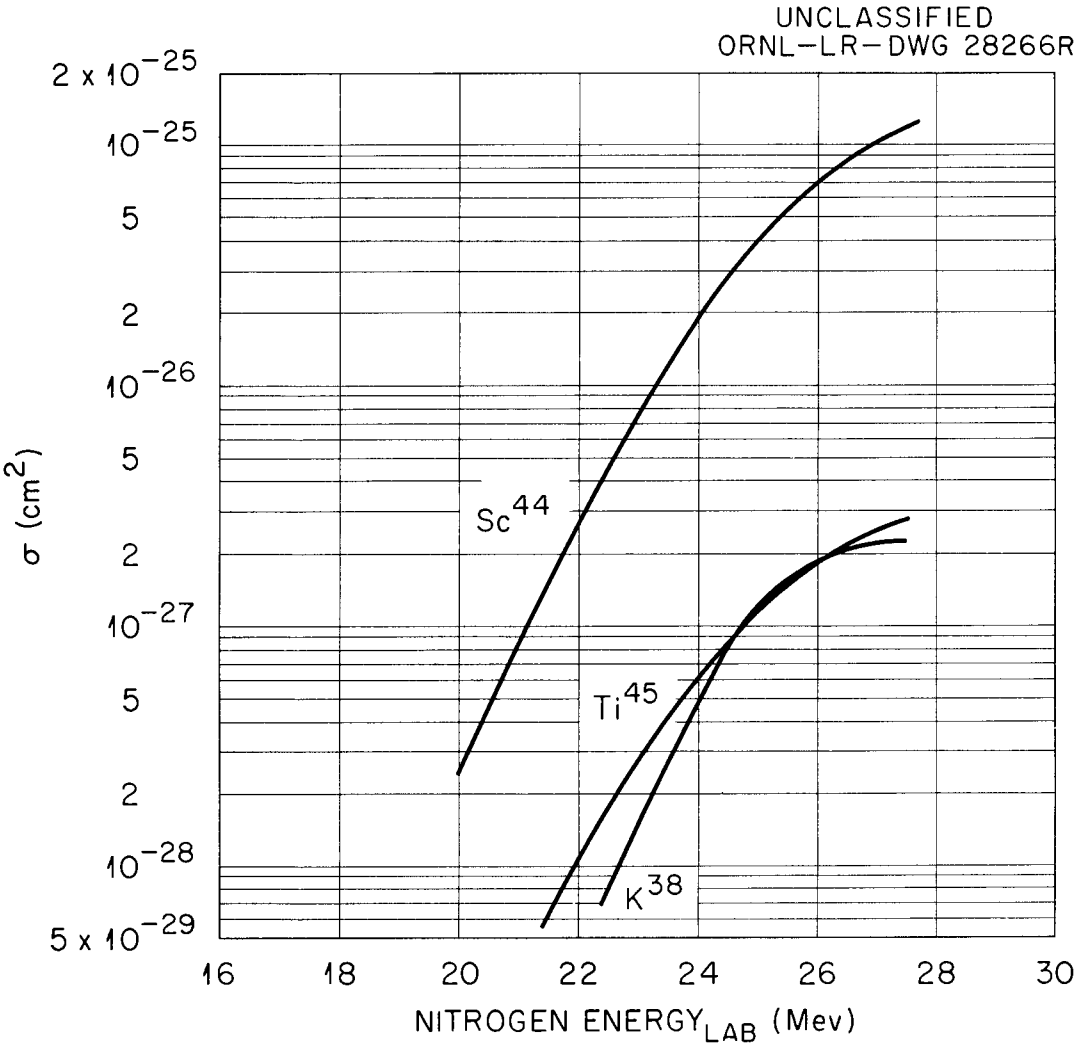

Fig. 12. Cross Sections vs Nitrogen Energy.

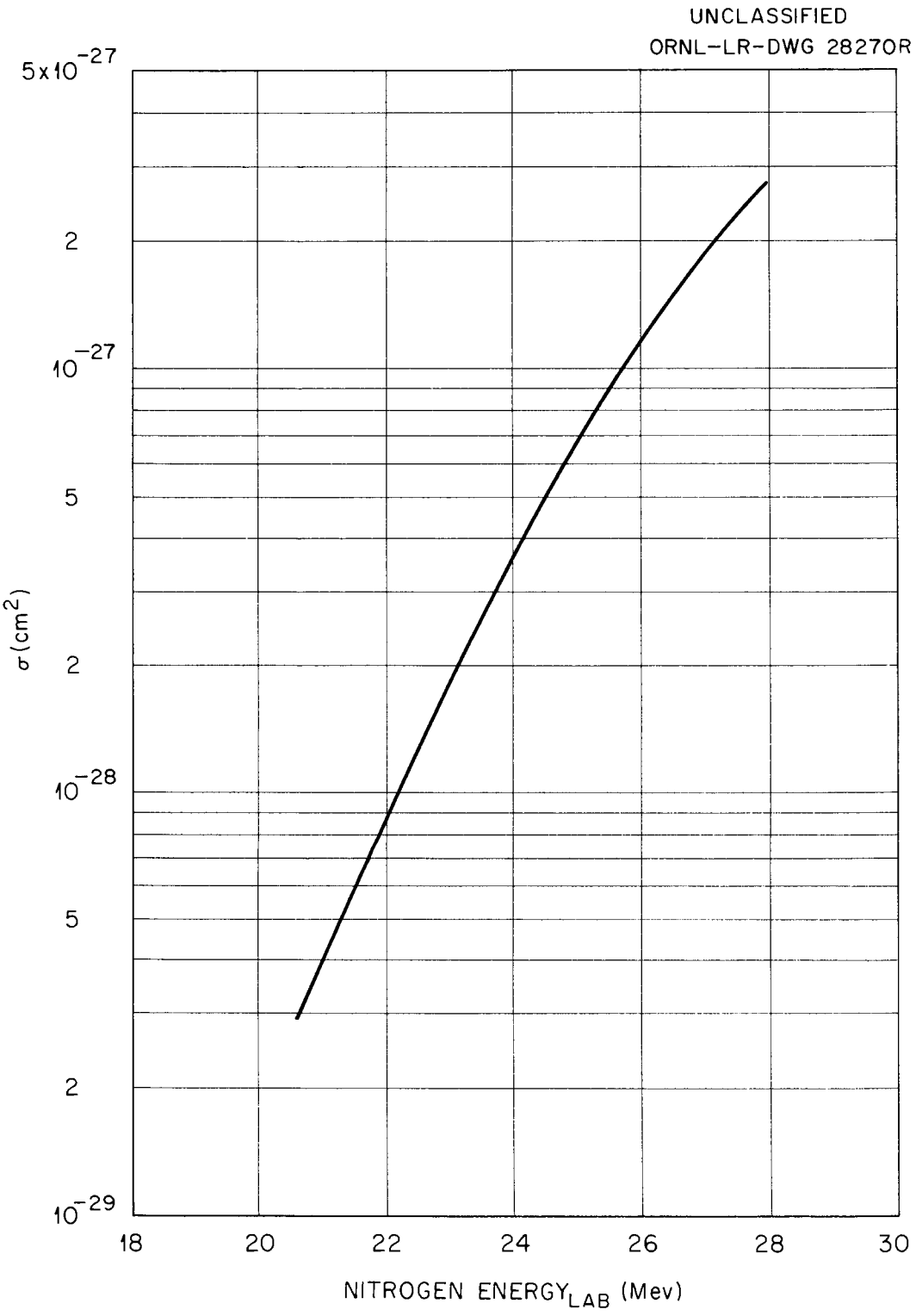

Fig. 13. Cross Section vs Nitrogen Energy for (N^{14}, N^{13}) Reaction.

TABLE 3

MEASURED CROSS SECTIONS

Nuclide	Cross Section in millibarns				
	20 Mev	22 Mev	24 Mev	26 Mev	27 Mev
Ti^{45}		0.108	0.59	1.84	2.49
Sc^{44}	0.245	2.64	18.5	68.5	101
K^{38}			0.46	1.83	2.22
N^{13}		0.09	0.375	1.19	1.89

CHAPTER IV

DISCUSSION

Niels Bohr, in the formative paper (1) on compound nucleus decay, postulated that it is possible to divide a nuclear reaction into two distinct steps:

1. The formation of a compound nucleus, and
2. The disintegration of this nucleus.

The following assumption has been made: that these two steps can be considered independently, that is, the disintegration of the compound nucleus will not depend on the manner in which it was formed, (neglecting the spins and orbital angular momenta involved).

Bohr bases his assumption on a nuclear model consisting of a group of nucleons with short-range forces but with strong interactions over these short ranges. The process can be visualized as follows: the bombarding projectile hits the target nucleus and fuses into it. Its energy is quickly shared among all the nucleons present, in what is now a compound nucleus. The formation that has just been described depends on such factors as the nature of target and projectile, the projectile energy, et cetera. The compound nucleus will, however, disintegrate in a manner independent of its formation.

Then the cross section of a nuclear reaction can be written as

$$\sigma(ab) = \sigma_c(a)\ P(b), \tag{17}$$

where the reaction we are considering is initiated by projectile a incident on the target and is concluded by the evaporation (or fission, or splitting, et cetera) or particle b from the compound nucleus. The factor $\sigma_c(a)$ is the "capture" cross section for the formation of the compound nucleus by the ineraction of projectile a and target. P(b) is the probability that the compound nucleus, once formed, will decay by emitting particle b. In this paper, a is the nitrogen ion and b may be an alpha particle, neutron, proton, or photon. For purposes of this discussion deuteron and tritium emission has been neglected.

The quantity $\sigma_c(a)$ for nitrogen ions incident on sulfur is not well known; existing tables do not cover the wide range of parameters needed due to the large masses involved. Correlation with experiment is thus must meaningful when ratios of total cross sections are computed:

$$\frac{\sigma(ab)}{\sigma(ac)} = \frac{\sigma_c(a)\ P(b)}{\sigma_c(a)\ P(c)} = \frac{P(b)}{P(c)}\ , \tag{18}$$

It is ;then the probability of a particular particle being emitted that is of most theoretical concern to this experiment. An expression for P(b) can be derived by making use of the "reciprocity theorem":

$$\frac{\sigma(ab)}{\lambda_a^2} = \frac{\sigma(ba)}{\lambda_b^2}\ , \tag{19}$$

where λ_a is the wavelength corresponding to the energy of incident

particle a, as

$$\lambda_a = (2M_a E'_a)^{-1/2}, \tag{20}$$

where M_a is the reduced mass of a and E'_a is the incident energy in the center-of-mass system. Then expressing P(b) as

$$P(b) = G(b)/G, \tag{21}$$

where G may be considered as a level width [that is, G/t is a decay rate; G(b)/t being the rate of decay by emission of particle b, and $G = \sum_c G(c)$] and referring to Eqs. 17 and 19 we find

$$P(b) = \frac{\sigma_c(b)\, k_b^2}{\sum_i k_i^2 \sigma_c(i)}, \tag{22}$$

where $k_i = 1/\lambda_i$ and the sum is extended over all possible particle emissions.

Each particle b that is emitted from the compound nucleus will come off with a certain energy given by

$$\epsilon_b = E'_a + Q, \tag{23}$$

where E'_a is the center-of-mass energy carried in by particle a, and Q is the energy released in the (a,b) reaction. Recoil energy of the residual nucleus is neglected. ϵ_b can be given by

$$\epsilon_b = \epsilon_{bm} - E_b^*, \tag{24}$$

where ϵ_{bm} is the maximum kinetic energy that particle b can carry off, and E_b^* is the energy left in the residual nucleus as excitation energy. If E_b^* is large enough further particle emission can occur.

The shape of the energy distribution for particles b emitted with an energy ϵ_b between ϵ_b and $\epsilon_b + d\epsilon_b$ is given by

$$P(\epsilon)\,d\epsilon = \sum P(b), \tag{25}$$

where the sum includes all final states of particle b within the interval $d\epsilon$. The number of terms in this sum is given by the number of levels of the residual nucleus with an energy E_b^* which lies between E_b^* and $E_b^* - d\epsilon$. This number of terms is designated by $w(E_b^*)\,d\epsilon$, and $w(E_b^*)$ is called the level density. The relative energy distribution of the outgoing particle b can be calculated from Eqs. 22 and 25 as

$$N(\epsilon_b)d\epsilon = \text{const}\,\epsilon_b \sigma_c(b,\epsilon)\, w(E_b^*)\,(2s+1)d\epsilon_b, \tag{26}$$

where $\sigma_c(b)$ is now the inverse cross section for the emission of b from the compound nucleus; that is, it is the cross section for the formation of the compound nucleus by particle b, with energy ϵ_b, incident on the residual nucleus. The quantity s is the nuclear spin, with values of 1/2 for proton and neutron, 0 for alpha particles. $\sigma_c(b)$ for protons, neutrons, and alpha-particles can be interpolated from the graph and tables given by Blatt and Weisskopf. The existing data for charged particles do not cover energies of emission greater than twice the Coulomb barrier. At these energies, an asymptotic

equation is used:

$$\sigma_c(b) = \pi(R + \lambda\!\!\!^{-})^2 \left[1 - \frac{R.B}{(R + \lambda\!\!\!^{-})\epsilon_b} \right],$$

where

$R = r_o A^{1/3} + D$

$r_o = 1.5 \times 10^{-13}$ cm

$D = 1.2 \times 10^{-13}$ cm, for alpha particles and

$= 0$ for protons

ϵ_b = energy of particle b in the center of mass system

B = Coulomb barrier.

To calculate the probability of particle emission, the "F-factor" is introduced as

$$F_b = \sum_i k_i^2 \sigma_c(i), \tag{27}$$

where the sum is extended over all energies at which particle b can be emitted. The sum is expressed as an integral as

$$F_b(\epsilon_{bm}) = \frac{2M_b}{\hbar^2} \int_o^{\epsilon_{bm}} (2s+1)\epsilon_b \sigma_c(b,\epsilon) w(E_b^*) d\epsilon_b, \tag{28}$$

and the probability can be expressed as

$$P(b) = F_b / \sum_i F_i, \tag{29}$$

where the sum is extended over all particles emitted. In this paper i includes protons, neutrons, alpha particles, and photons. To calculate the probability of gamma emission an F-function was determined

for photons from Eq. 27 and analogous to Eq. 28 as

$$F_\gamma(\epsilon_{\gamma m}) = (\hbar c)^{-2}\int_0^{\epsilon_{\gamma m}} \epsilon_\gamma^2 \sigma_c(\gamma,\epsilon) w(\mathbf{E}_\gamma^*) d\epsilon_\gamma. \quad (30)$$

When proper unit conversion factors are utilized, this F-function is additive with those defined in Eq. 28. The factor $\sigma_c(\epsilon, \gamma)$ in Eq. 30 is the capture cross section for photons on the residual nuclei. This was calculated from the approximate equations for magnetic dipole and electric quadrupole radiation given in Blatt and Weisskopf. The giant resonance due to electric dipole radiation was not included in the final calculations, although preliminary consideration showed it would not change the final results by more than a few percent. The remaining factor in Eqs. 28 and 30 is the level density, an expression for which can be approximately derived by considering the logarithm

$$S(E) = \log w(E), \quad (31)$$

and defining

$$\frac{dS}{dE} = \frac{1}{T(E)}. \quad (32)$$

T will then have energy dimensions and is considered to be a "nuclear temperature" by analogy with thermodynamics. S is analogous to the entropy of the residual nucleus, S being the logarithm of the level density, and Eq. 32 then corresponds to the thermodynamic relation between temperature and entropy. Omission of the Boltzmann constant from the original definition of S leaves T with energetic dimensions.

Then dE/dT must equal zero at T = 0, extending the analogy to include the third law of thermodynamics. If we assume that E(T) can be expanded in a power series around T = 0, it must therefore begin with a quadratic term. The further assumption is made that all higher powers of T can be neglected in the expansion. Then

$$E = aT^2 \text{ and}$$
$$S = \int dE/T = 2(aE)^{1/2} + \text{const and}$$
$$w(E) = C \exp 2(aE)^{1/2}. \qquad (33)$$

Absolute values of C do not enter into the calculations since ratios are involved. The value of a, however, is extremely important. The values given in Blatt and Weisskopf have not been supported by experiment. Porges (65) bombarded silver and copper with 40-Mev alphas and calculated a value of a equal to about 2 Mev^{-1} and independent of A, where A is the mass number of the residual nucleus. Comparisons between theory and (α, 2n) cross sections determined by Temmer (66) and Kelly and Segre (21) give the same result. Slow neutron resonance measurements (67) of level spacings give larger values of a, values which are strongly functions of A. Energy emission spectra (30, 33, 35) from inelastic scattering of protons and neutrons give high values of a which are less dependent on A. Excitation function experiments (13, 23) give low values for a. A discussion of possible errors and causes for the variety of results are found in Porges (65).

Eisberg et al. (34) bombarded several elements with 40-Mev alphas and observed evaporated protons. They got a value of $\underline{a}$ which is low and not a function of A. Igo and Wegner (68) summarize the above papers. They arrive at two main estimates of $\underline{a}$: one giving $\underline{a}$ as relatively constant and equal to approximately 2, the other giving $\underline{a}$ as function of A (as would be expected from a Fermi gas model) not in disagreement with Lang and Le Couteur's (69) dependence on A/10.5.

A previous analysis of cross sections from nitrogen on sodium (45) shows that values of $a = A/10.5$ provide fair agreement between experiment and theory. Further nitrogen-induced experiments by Zucker (70) and by Goodman and Need (71) give results in agreement with $a = A/10.5$. On the basis of the above papers, two values of $\underline{a}$ seem to emerge; namely $a = 2$, and $a = A/10.5$ which was chosen for the calculations described in this experiment and which was felt to be the more valid of the two. The calculations were then duplicated using $a = 2$.

The constant C in Eq. 33 is related to both even-odd and shell structure characteristics of the residual nucleus. Even-odd effects were taken into account by utilizing the averaged empirical relationship of Brown and Muirhead (49):

$$\frac{W_{oo}}{12} \sim \frac{W_{oe}}{5} \sim \frac{W_{ee}}{1} . \qquad (34)$$

For example, C for an odd-odd residual nucleus was taken to be 12/5 that for an odd-even nucleus. Shell structure effects were calculated from the work of Newton (50) who arrives at the following equation

$$D_o = A^{5/3}(\bar{j}_n + 1)^{1/2}(\bar{j}_z + 1)^{1/2}(E_b^* + 3t)^2 \exp\left[8.75 - 0.4982(\bar{j}_n + \bar{j}_z + 1)^{1/2} A^{1/3} E_b^{*\,1/2}\right], \quad (35)$$

where $wD_o = 1$, $\bar{j}_n$ and $\bar{j}_z$ are averaged angular momentum quantum numbers, E_b^* is the excitation energy of the nucleus, and $t = (6\pi^{-2} G^{-1} E_b^*)^{1/2}$ where G is a shell-dependent factor given in Fig. 4 of the paper by Newton. The reciprocals of ratios of D_o-values for a set of nuclei were taken to be the ratios of the constant C. All the quantities in Eqs. 28 and 30 could now be numerically estimated.

Fig. 14 is a diagrammatic respresentation of the evaporation process. Calculations were made in a step-wise procedure as follows: A 27-Mev nitrogen ion incident on S^{32} yields a compound nucleus of V^{46} with $E^* = 32.6$ Mev, E^* being the excitation energy given by

$$E^* = E'_N + Q, \quad (35)$$

where E'_N is the center-of-mass nitrogen energy and Q is calculated from the masses of nuclides involved.

Considering first reactions (1) and (2), (the p and 2p out reactions), the probability that V^{46} at this excitation energy would emit a proton, neutron, or alpha particle was calculated from Eqs. 28 and 29.

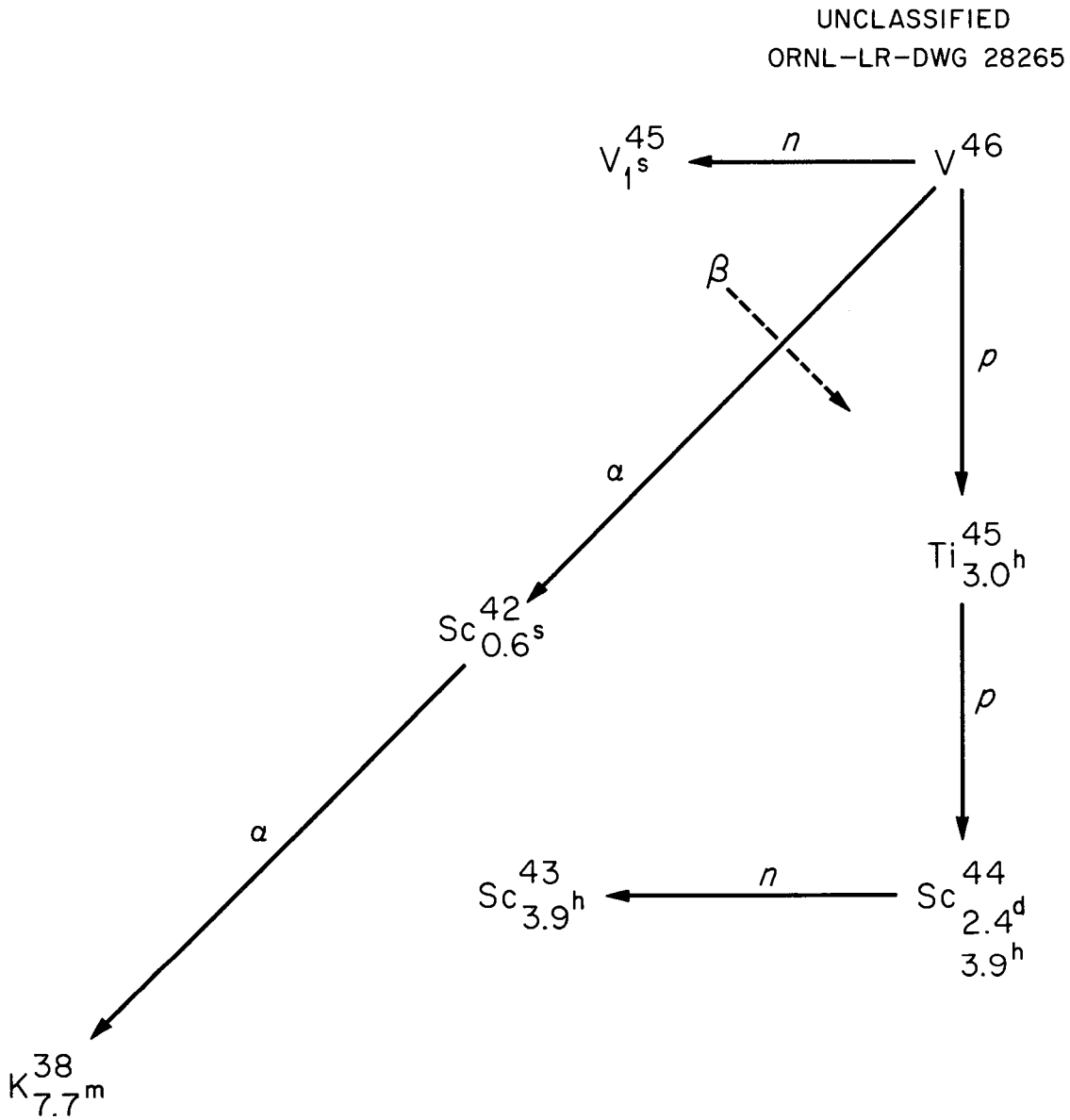

Fig. 14. Diagram Showing Position of Nuclides.

The quantity under the integral was evaluated at different energies ϵ_b and then graphically integrated. It was found that 65.3% of the V^{46} nuclei formed would decay by proton emission. The energy spectra of emitted protons were calculated from Eq. 26, and thus the density of occupied states in Ti^{45} was found. Results of the calculation are illustrated in Fig. 15. A further contribution to the Ti^{45} yield would be expected to come from the (N^{14}, n) reaction leading to V^{45} which emits positrons, forming Ti^{45}, with a half life on the order of one second. Calculations similar to the above show that only 21% of the V^{46} decays by neutron emission. The preponderance of initial proton emission is due to the Q-values involved. Further calculations show that contributions to the total Ti^{45} yield from this reaction should amount to 1-3% and have therefore been ignored in the remainder of this discussion. This low value is due to the Q-values involved in further particle emissions from the V^{45} nucleus which make such reactions extremely likely, and the yield of V^{45} only about 2% of the Ti^{45} yield.

The available states of Ti^{45} were arbitrarily broken into level widths 4-Mev wide, and the fraction of emitted protons that left Ti^{45} in each band was calculated. That portion of occupied states lying below the energetic barrier for further particle emission will remain as Ti^{45}. These states are shown in the shaded portion of Fig. 15. All higher occupied states will again emit particles or gamma rays.

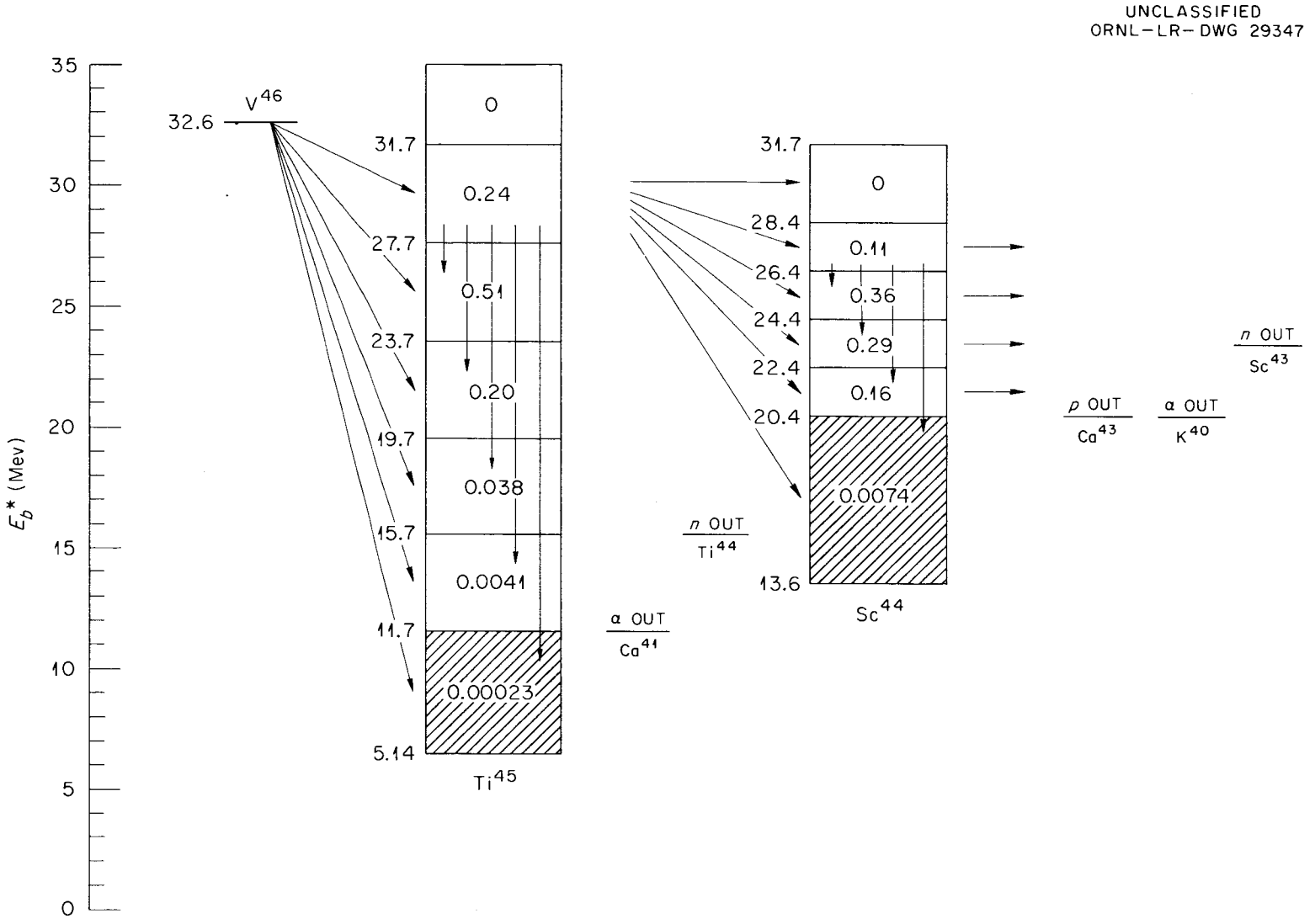

Fig. 15. Diagram Showing Schematics of Evaporation Calculations.

Each level band was treated as a separate compound nucleus. The top most level band was considered first: the probability that it would evaporate a proton, neutron, alpha particle, or photon was calculated. Photon emission would leave again a Ti^{45} residual nucleus, but in a lower energy state, one corresponding to the energy of the emitted photon. Thus, an additive correction was made to each lower lying level band. The next lowest band was then treated in the same fashion, and so on. It was found that gamma emission increased the portion of Ti^{45} remaining below the energetic barrier from 2.3×10^{-4} to 6.8×10^{-3}; that is, of each Ti^{45} nucleus formed from V^{46}, 0.68% remained as Ti^{45} while 99.32% emitted another particle and formed another nuclide.

Some 65.9% of the Ti^{45} emitted a proton to form Sc^{44}. This nuclide was treated in an analogous manner, the level bands being made 2-Mev wide in this case. The final portion remaining as Sc^{44}, after particle and gamma emissions were considered, was found to be 0.363; that is, of the Sc^{44} nuclei formed from the proton emission of Ti^{45}, 36.3% remained as Sc^{44}.

In an analogous manner, $\underline{\alpha}$ and $\underline{2\alpha}$ emission from the V^{46} nucleus was considered: 13.4% of the V^{46} emitted an alpha to form Sc^{42}, and 1.99% of this emitted another alpha to form K^{38}; 31.7% of this remained as K^{38}.

Comparison of Results

Cross sections for each nuclide relative to the capture cross section of nitrogen on sulfur were calculated by multiplying the fraction of the original V^{46} which decayed into the nuclide times the fraction so formed that remained as the nuclide. Ratios of cross sections were calculated as in Eq. 18 and compared to experimental results.

Calculations were made for two values a, and for two circumstances: gamma emission was included in one set, and excluded in the other. Results are shown in Table 4.

It is seen that when gamma emission is included in the calculations, according to Eq. 30, then a value of a = A/10.5 gives good correlation with experiment for the $\sigma_{Sc^{44}}/\sigma_{Ti^{45}}$ ratio. Experimental yields of K^{38} are much greater than those predicted by the theory. Actually, since the ground state of K^{38} has a one second half life and was thus not counted, its total cross section is still higher. The value a = 2 does not give agreement with experiment.

If gamma emission is not considered, then a = A/10.5 does not seem to be valid, while a = 2 gives results in agreement with the measured values for $\sigma_{Sc^{44}}/\sigma_{Ti^{45}}$.

A careful examination of the processes involved leads to the conclusion that gamma emission should be considered in the calculations. The above results show that a lack of this consideration may

TABLE 4

COMPARISON OF RESULTS

Nuclides	Experimental	Theoretical			
		Gamma Emission		No Gamma Emission	
		$a = \frac{A}{10.5}$	$a = 2$	$a = \frac{A}{10.5}$	$a = 2$
$\frac{\sigma_{Ti^{45}}}{\sigma_{Sc^{44}}}$	.024	.025	.16	.0047	.032
$\frac{\sigma_{Sc^{44}}}{\sigma_{K^{38}}}$	45	185	18	105	14

lead to low values of a, as found in previous papers (13, 21, 23, 65, 66). In all these papers gamma emission was not considered.

The neutron transfer reaction (5) gives results in agreement with those of similar reactions previously studied in this laboratory (72). G. Breit (73) has indicated that if the cross section of such a reaction is plotted against an E^* defined by

$$E^* = E' - B + 1/2\, Q, \tag{36}$$

where E' is the incident center-of-mass energy and B is the barrier energy, then a plot will be obtained which is independent of target nucleus and will vary from one target to another depending only on angular momentum changes in the transferred nucleon. Such a plot for several target elements is shown in Fig. 16. Cross sections for all elements other than S^{32} are taken from the paper by Zucker et al (72). The targets do tend to group themselves in distinct bands, with the exception of Na^{27}, in general accordance with the theory.

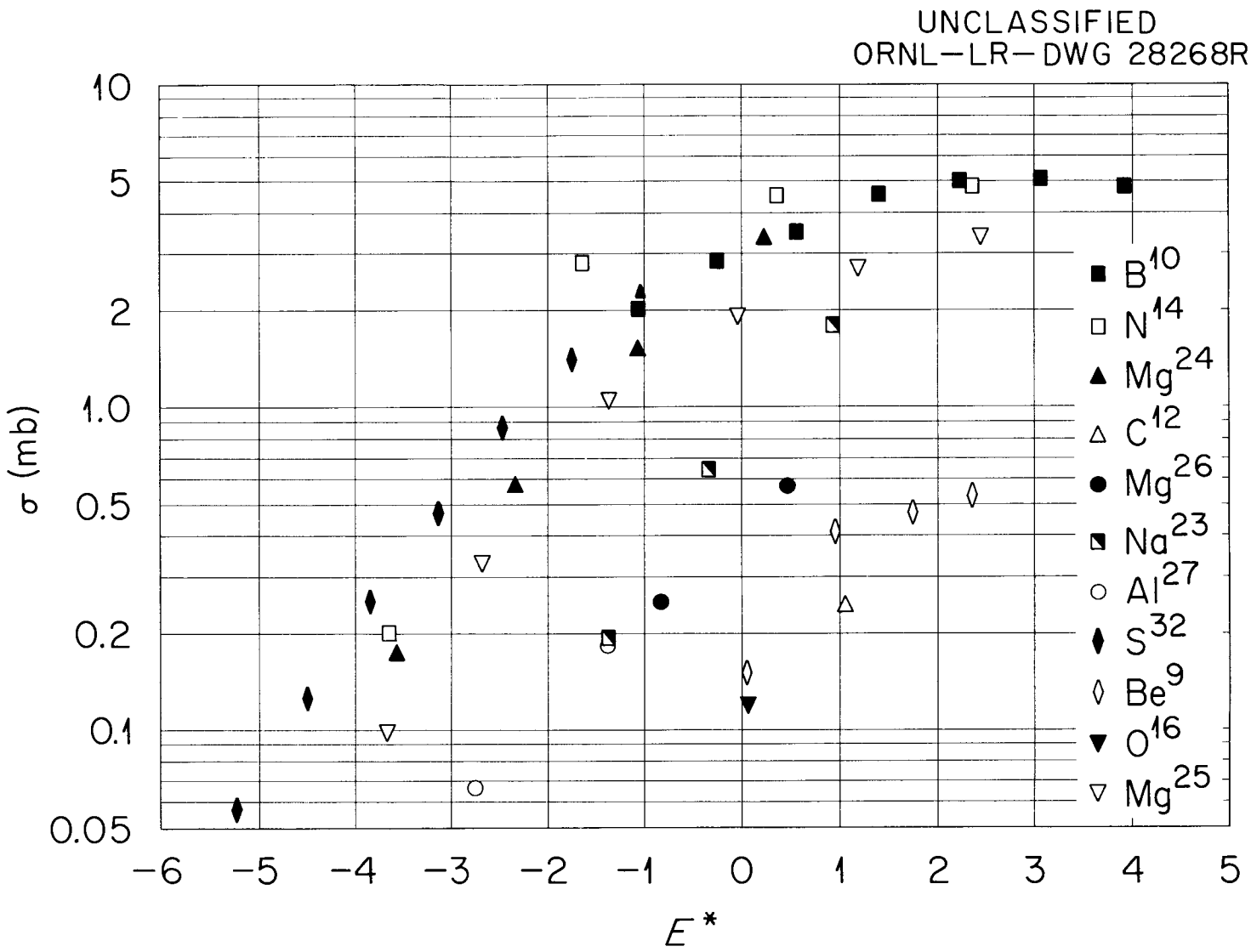

Fig. 16. Cross Sections for Neutron Transfer Reactions vs $E^* = E_{cm} - B + 1/2Q$.

CHAPTER VII

CONCLUSIONS

Four nuclear reactions initiated by the nitrogen bombardment of natural sulfur were experimentally observed, excitation functions were measured, and the cross sections of three of these at a bombarding energy of 27 Mev were compared with predictions based on the statistical theory of compound nucleus decay. One of the reactions was a nucleon transfer mechanism and its cross section was compared to similar reactions; the comparison gave qualitative agreement.

The predictions of the statistical theory were calculated for two values of the parameter a. The value a = A/10.5 gave good agreement with theory for the(N^{14}, p) and (N^{14}, 2p) reactions in view of the approximations necessary. The predicted value of the (N^{14}, 2α) reaction was at least four times less than the experimental value. It had been noted in a previous paper (25) that alpha-out reactions from the nitrogen bombardment of C^{12} are higher than predicted. A possible explanation may be related to the "alpha particle structure" of C^{12} in that the compound nucleus retains a "memory" of the original target. Sulfur-32 may also exhibit this property, and this may account for the variation from theory. However there is no real evidence for such an explanation, and the variation may be simply a failure of the theory. The ratios of cross sections calculated with a = 2 did not agree with the experimental values when gamma emission was considered.

When the emission of gamma-rays was not included in the calculations, $a = 2$ gave better correlation than did $a = A/10.5$.

The work done here indicates that a compound nucleus process is operative in the nitrogen bombardment of sulfur, in the energy region considered. The statistical theory of compound nucleus decay gives predictions in agreement with observed results, with the exception of the alpha-out process. It is assumed that another mechanism, such as an incomplete compound system formation, may be involved in this reaction.

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