Strange Particle Production by Bevatron Neutrons in Propane*

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(Received April 24, 1959)

A liquid propane bubble chamber was exposed to a beam of neutrons with energies up to 6 Bev from the Bevatron. 10 000 pictures of interactions in the hydrocarbon were scanned to detect neutral heavy unstable particles. 349 neutral V-events were found, most of which came from the stainless steel walls of the chamber. 86% of these events could be identified as one or the other or either of the neutral strange particles: Λ^0 or Θ_1^0. The Λ^0/Θ_1^0 ratio is about 0.6.

8200 stars of 2 or more prongs formed by neutrons interacting in the liquid propane were observed in the chamber and 17 of these produced V^0's. An additional 5 V^0's were formed in single-prong events produced by neutrons, and 8 others were produced in events in the propane caused by charged particles.

The energy spectrum of the incident neutrons was estimated from study of π-meson production interactions in the hydrogen. The distribution shows that the neutrons had energies up to 6 Bev with a mean value of about 4 Bev. For the energy range 1 to 6 Bev, the production of strange particles occurs in about 1% of all inelastic interactions of neutrons with hydrogen and carbon.

I. INTRODUCTION

ALTHOUGH neutral strange particles were first produced artificially by neutrons hitting complex nuclei,[1] most studies of these V^0 particles in the collisions of elementary particles have been in π-p interactions. For energies up to 3 Bev, V^0 production by pions striking both free protons and complex nuclei[2,3] appears to be greater than production by nucleons and very few cases of nucleon-nucleon production have been directly observed.[4,5,6] This paper reports results of a production study for neutrons with energies up to 6 Bev interacting both with free protons and with the nucleons within carbon nuclei.

Details of the experimental equipment and the analysis of the V^0 events are discussed in Sec. II; the detection efficiency for V^0 events in this liquid propane bubble chamber is calculated in III. Section IV describes the neutron beam and its interactions in the hydrocarbon and Sec. V discusses the production of neutral strange particles in these interactions.

II. EXPERIMENTAL EQUIPMENT AND ANALYSIS

This investigation of the interactions of neutrons with energies up to 6 Bev was done with pictures from the University of California Radiation Laboratory 13-inch liquid propane bubble chamber[7] in a magnetic field of 12.9 kilogauss. The chamber was operated and the pictures supplied by the Radiation Laboratory group directed by Professor Wilson Powell. The chamber was exposed to a beam of neutral particles traveling forward from a metal (beryllium or copper) target struck by the 6.2-Bev internal proton beam of the Bevatron. The beam traveled about 13 feet in the magnetic field of the Bevatron quadrant so that charged particles were swept out, and the bubble chamber was a distance of about 93 feet from the target, so that most of the unstable neutral particles, except the long-lived Θ_2^0, should have decayed. The beam, assumed to be almost purely neutrons with energies up to 6 Bev, was collimated so that it would enter the bubble chamber through the 1-in. diameter $\frac{1}{8}$-in. thick "thin-window" section of the 2-in. thick stainless steel wall. Some of the beam hit the thick wall producing a background of charged particles throughout the chamber, and some of the neutral particles entering the chamber were secondaries of interactions in the chamber walls.

The 10 000 pictures taken of the bubble chamber exposed to the neutron beam were completely scanned twice, once by a physicist and once by a nonscientist, with all types of interactions being recorded on file cards. The possible V^0's found in the scanning numbered about 700 and were measured on a 3D reprojector. 336 pictures were found that had V^0's decaying within the propane. Thirteen pictures had two V^0's, with some appearing to be "associated production" (the same source for both V^0's). The planes of the V^0's were checked for any "related" events (those with an interaction as apparent source upstream of the V^0 decay); about 50 pictures had V^0's that seemed to be related to "neutral" stars (events with two or more prongs caused by an incoming neutron particle) or the beginning of single prongs. Momenta of charged particles were determined from the curvature of the tracks in the magnetic field. Nevertheless, there were errors in momentum measurements of the V^0 prongs amounting to 10 to 15%, due predominantly to multiple scattering

* Supported in part by the U. S. Atomic Energy Commission.
† Based on work submitted to the faculty of the Graduate School of Yale University in partial fulfillment of the requirements for the degree of Doctor of Philosophy.
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[1] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **90**, 1126 (1953).
[2] Bowen, Cookson, Tagliaferri, and Werbrouck, Bull. Am. Phys. Soc. Ser. II, **2**, 19 (1957).
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[5] S. Lindenbaum and L. C. L. Yuan, Phys. Rev. **105**, 1931 (1957).
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[7] L. Oswald, Rev. Sci. Instr. **28**, 80 (1957).

in the liquid propane. These errors could be tolerated since the search was only for particles fitting the well-known decay schemes:

$$\Lambda^0 \to p+\pi^- + 36.9 \text{ Mev}, \quad \Theta_1^0 \to \pi^+ + \pi^- + 214 \text{ Mev}.$$

The identification of Λ^0 and Θ_1^0 was made by comparing the values of the momenta of the two prongs of the V^0 and the included angle of these prongs as measured on the 3D reprojector directly with curves plotted at the Radiation Laboratory.[8] Not all of the 349 possible V^0 events were analyzed because of the length of time consumed in each microscope measurement, but preference was given to the V^0 events that appeared to be associated and related. Altogether 126 V^0's were analyzed and of these 86% fit either the Λ^0 or the Θ_1^0 decay schemes. The others may have been (a) decays of the Θ_2^0, (b) "pseudo-V" events produced by neutrons hitting loosely bound carbon neutrons to form $n+n \to n+p+\pi^-$ or $n+n \to n+n+\pi^+ + \pi^-$, or (c) events for which momentum errors were very large.

Further analysis revealed 30 V^0's that had sources in the propane, but there were no definite associated-production pairs. To check for associated production events, the lines of flight of the neutral decaying particles were calculated by balancing momentum to determine if the two V^0's in the same picture had a common origin. In 12 of the 13 pictures with two V^0's this was not the case, and in the 13th both lines of flight could possibly have started at the same point in the chamber wall. The number of pictures containing two unassociated V^0's is that expected from random distribution of 336 events through 10 000 pictures. Possible related events were checked by comparing the line of flight calculated from the V^0 prong momenta with the line from the apparent source to the V^0 decay measured on the 3D reprojection screen. The results of this analysis were 30 V^0's that were either Λ^0 or Θ_1^0 that were related to events in the propane: 8 from interactions formed by charged particles, 17 from neutral stars with 2 to 7 prongs, and 5 from single-prong neutral stars. These are summarized in Table I.

III. DETECTION EFFICIENCY

The detection efficiency for V^0's in the chamber is taken to be the product of four factors: scanning, angular distribution, range, and neutral decay.

A

The detection efficiency for the scanners at Yale was found assuming that all V^0's had the same probability of being detected. Of the 349 V^0's, 336 were found by the two scanners, 271 by one and 277 by the other, indicating a combined efficiency of 95%. The other 13 events were found in the preliminary scanning of some of the pictures at Berkeley.

[8] B. Armstrong, University of California Radiation Laboratory Report UCRL-3470, 1957 (unpublished).

TABLE I. Identification of analyzed V^0's listed by source of V^0.

Source of V^0	V^0 decay kinematics fit: Λ^0	θ_1^0	Either	Total
A. Multiprong stars, $\Sigma_i q_i \geq +2$[a]	1	7	1	9
B. Multiprong stars, $\Sigma_i q_i = 0$	1	2	1	4
C. Multiprong stars, $\Sigma_i q_i = +1$	3	0	1	4
D. Single-prong stars ($q=+1$)	1	3	1	5
E. Charged events	3	3	2	8
F. Total	9	15	6	30
G. All analyzed V^0's	32	56	20	108
(*G-F*). Analyzed wall events	23	41	14	78

[a] q_i = electronic charge of a prong (+1 or −1).

B

To obtain an estimate of the number of V^0's missed because the decay plane of the V^0 was steep, the distribution with respect to the angle between the normal to the decay plane and the vertical optic axis was plotted for 200 V^0's apparently formed in the chamber walls. Determination of this angle does not require knowledge of the prong momenta, so that this plot includes unidentified V's and some that do not fit Λ^0 or Θ_1^0 decay kinematics. A uniform distribution over all angles is expected for an isotropic distribution of paths about the beam, as in the case here where the decay distance is small compared to the chamber dimensions. The observed distribution appears uniform over all angles except for a decrease near the vertical decay plane which indicates about 10% of the V^0's were missed.

C

The effect of V^0 particle path length can be seen in the formula for the probability of observing the charged decay mode before the particle escapes from the visible region of the chamber[9]:

$$P = \exp(-l_1 m_i/\tau_i p_i c) - \exp(-l_2 m_i/\tau_i p_i c),$$

l_1 and l_2 are the minimum and maximum distances the neutral particle can travel from its production to recognizable decay, τ_i is its lifetime at rest, m_i its mass, and p_i its momentum, which varies in this experiment from 0.1 to 5.0 Bev/c. For this chamber the extremum distances for particles produced in the upstream wall are $l_1 = 5$ cm and $l_2 = 25$ cm (allowing 5 centimeters for identification) and the formula gives a momentum distribution in agreement with the measurements made on wall-produced V^0's. This distribution was used to weight the probabilities found for particles produced within the chamber. In this latter case l_1 approaches zero, but since the V^0 vertex must be distinguished from the vertex of the source star, l_1 is taken as 0.3 cm. l_2 requires a complicated averaging over all points inside the visible region and over all directions to the bounding planes of this region, using an appropriate distribution with

[9] D. Gayther and C. Butler, Phil. Mag. **46**, 467 (1955).

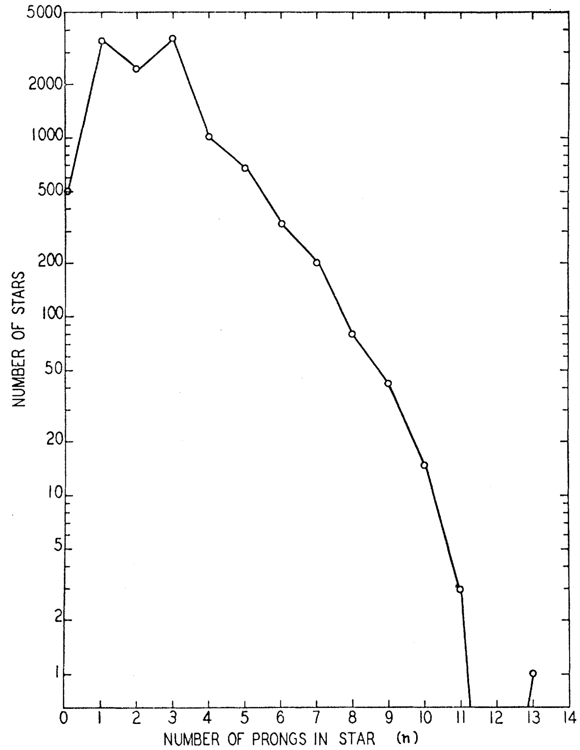

FIG. 1. Star prong distribution, neutron events in carbon and hydrogen.

respect to angle with the incident beam direction. For rough approximation with a cosine-squared distribution,[8] l_2 takes the values 2.5 to 5.0 cm, in agreement with the average of 4.9 cm for the 30 V^0 events produced in the chamber. P does not change appreciably within the above range of l_2 and averages to 60% over a momentum spectrum typical of the wall-produced V^0's.

D

Correcting for neutral decay products, which occur in 4/7 of the cases of Θ_1^0 decay and $\frac{1}{3}$ of the Λ^0 decays,[10] the observed ratio of almost twice as many identified Θ_1^0's as Λ^0's gives the average probability of the charged decay made by a V^0 in this experiment of 50%.

The product of these four factors is 26% for the over-all detection efficiency.

IV. THE NEUTRON BEAM AND ITS INTERACTIONS

In order to get an estimate of the neutron flux and to determine the ratio of carbon to hydrogen events, the stars produced by neutral particles in the 10 000 pictures were counted, using the two sets of scanning cards. Selection of events was such that the star prongs indicated an incident energy for the neutron of at least 0.5 Bev, appreciably above the threshold for pi-meson production. This count gave 8200 such stars with two or more prongs. The distribution with respect to prong number, n, is shown in Fig. 1, including estimates of single and zero prong events. This distribution is a decreasing curve from $n=3$ to $n=11$, but with peaks (note the logarithmic scale of the number of events) at all odd values of n. These peaks are considered to be inelastic hydrogen events (n-p), for which the net charge of outgoing prongs is $+1$. The estimate of single prong ($n=1$) events was made from a sample count which was corrected for elastic n-p events. The total number of events shown in Fig. 1 is 12 000 interactions of neutrons with propane nuclei, producing stars with 0 to 13 prongs, with 9300 of these being carbon events and 2700 hydrogen events.

The ratio of carbon to hydrogen interactions may also be estimated from the neutron interaction lengths in the two materials. For the energy range 0.5 to 6 Bev, average values for the interaction cross sections are 220 and 20 millibarns for carbon and hydrogen, respectively.[11,12] The visible length of the chamber comprises 9 g/cm^2 of carbon and 2 g/cm^2 of hydrogen. Thus for each 41 traversals of the chamber by a neutron there would be 5 stars in the propane, with a ratio of 4 carbon stars to 1 hydrogen star. However, the observed ratio is about 3.4 carbon stars for each hydrogen star, indicating that there is some error in the chosen cross sections and/or the star identification process. Since the phase space calculation discussed below indicates a lower carbon to hydrogen ratio (1.6) the 9300/2700 division appears to be a reasonable one.

The total flux of neutrons with energies above 0.5 Bev is found from the above result: 12 000 stars would be produced by about 1×10^5 neutrons.

The energy spectrum was found for a sample of the stars. The $++-$ events were analyzed to obtain the momentum resultant of the three outgoing prongs. Such events include the n-p interactions (1) $n+p\rightarrow p+p+\pi^-$, (2) $n+p\rightarrow n+p+\pi^++\pi^-$ (3) $n+p\rightarrow p+p+\pi^-+\pi^0$, and the production of three or more π mesons. Interaction (1), which has been found to occur in about $\frac{1}{6}$ of all cases of $++-$ stars,[13] has all outgoing prongs charged and thus the momentum resultant of these three prongs lies in the direction of the incident neutron and represents the incident neutron's momentum. One-sixth of the analyzed $++-$ events had an angle between beam direction and resultant of $\leqslant 4°$ and were considered to be interactions of type (1). The resulting energy spectrum is shown in Fig. 2(a).

Simple phase-space calculations[14] for pion production in nucleon-nucleon interactions were made for pion multiplicities up to 6 to determine the fraction of all

[10] Eisler, Plano, Samios, Schwartz, and Steinberger, Nuovo cimento 5, 1700 (1957).

[11] W. Hess, Revs. Modern Phys. 30, 368 (1958).

[12] Atkinson, Hess, Perez-Mendez, and Wallace, Phys. Rev. Letters 2, 168 (1959).

[13] F. N. Holmquist, thesis, University of California Radiation Laboratory Report UCRL-8559, December, 1958 (unpublished).

[14] G. Fialho, Phys. Rev. 105, 328 (1957).

cases comprised by the single pion production case studied. This fraction was used as a correction to the energy spectrum of Fig. 2(a) and gives the spectrum of Fig. 2(b) for all neutron interactions involving π-meson production (the 1% or so of strange particle production is neglected). The total of 400 $++-$ events indicates that in this experiment there should have been observed a total of 4000 neutron stars in hydrogen, a somewhat larger number than that resulting from the estimates given above. It is possible that some of the 400 $++-$ events actually occurred at the surface of carbon nuclei.

The above phase-space correction for the total neutron spectrum shifts the peak from 3 to 4 Bev in agreement with measurements in a similar Bevatron beam.[13] This reveals that about 5% of the incident neutrons in this experiment were in the energy range 0.5 to 1.0 Bev [shaded in Fig. 2(b)] and were thus incapable of producing strange particles. This reduces

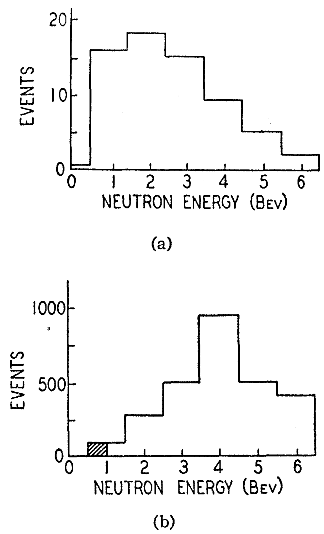

FIG. 2. Neutron energy spectra, neutron-proton events. (a) 66 $p+p+\pi^-$ events. (b) All pion production events to produce 66 $p+p+\pi^-$ events.

the number of possible V^0 sources in the chamber to 11 400 neutron stars.

V. STRANGE PARTICLE PRODUCTION

The Λ^0/Θ_1^0 ratio can be determined from results given in Table I. Of the V^0's that were analyzed. 64% were clearly identified as either Λ^0 or Θ_1^0 with a Λ^0/Θ_1^0 ratio of 0.42; additional less definite cases increase the ratio to 0.63. This ratio of less than unity suggests that there was considerable V^0 production by the $N+N\rightarrow N+N+K+\bar{K}$ reaction, for which the threshold is 2.4 Bev for free $N+N$ and 1.7 Bev for bound $N+N$, compared to $N+N\rightarrow N+Y+K$ with a 1.5- to 1.1-Bev threshold. Although the statistics are poor, the Λ^0/Θ_1^0 ratio appears smaller for the carbon events than for hydrogen. It may be that while Λ^0's are still within the carbon nucleus they interact to form $\bar{\Theta}^0$'s by $\Lambda+N\rightarrow N+N+\bar{K}$. The decrease from H to C agrees with other experiments[15–17] which indicate that, for energies both just above and well above the $K+\bar{K}$ production thresholds, the Λ^0/Θ_1^0 ratio is greater than or equal to unity for hydrogen, decreases somewhat for light complex elements, and then increases as atomic number increases to elements such as lead.

Study of the possible V^0 sources indicates a ratio of carbon to hydrogen stars of about $3\frac{1}{3}$. In the analysis of the neutron interactions, the net charge of +1 was taken as the identification of neutron-on-hydrogen stars. This would make the sources of the V^0's 13 carbon stars (lines *A* and *B*, Table I) and 9 hydrogen stars (lines *C* and *D*). However, since there are 4 (line *B*) of 13 carbon events which are apparently neutron-neutron interactions that do not disturb the remaining nucleons in the carbon nuclei, there must also have been some neutron-proton events at the surface of the carbon nuclei. For this reason the events are estimated to be $16\times(1\pm0.25)$ carbon and $6\times(1\pm0.25)$ hydrogen events, where the errors are those for the statistical fluctuations for such small numbers of random events.

The relative probability for strange particle production is calculated as: (related V^0 events)/[(stars that could produce V^0's)$\times$(detection efficiency)]. For 2600 ±250 hydrogen and 8800 ± 250 carbon stars as determined from the energy spectrum correction, assuming a 20% error in the detection efficiency, the results are (0.9 ± 0.5)% of the hydrogen and (0.7 ± 0.3)% of the carbon interactions produce neutral V^0 particles. When allowance is made for the associated production of two strange particles which may be either neutral or charged, the detection efficiency changes slightly but is within the limits given above. One other possible source of error is zero-prong stars that are sources of V's. The ratio of "wall-produced" V^0's to "propane-produced" V^0's is somewhat higher than is predicted from the equivalent thicknesses of the two materials, so that possibly some of the V^0's had their origin in carbon events where the *n*-*n* interaction produced all neutral products. Such events, although unlikely, might raise the upper limit of the fractional cross section for carbon to about 2%.

VI. SUMMARY

The approximate value for the production of neutral strange particles by neutrons in the energy range 1 to 6 Bev, with peak at 4 Bev, in interactions with both carbon and hydrogen is 1% of all inelastic events. The Λ^0/Θ_1^0 ratio for production by these neutrons in both hydrogen and carbon as well as in the iron of the chamber walls is less than or equal to unity.

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[16] Cooper, Filthuth, Montanet, Newth, Petrucci, Salmeron, and Zichichi, Nuovo cimento **8**, 471 (1958).

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ACKNOWLEDGMENTS

The author would like to express his appreciation to the members of Professor W. Powell's group at UCRL for making these pictures available for study. He wishes also to thank Professor H. L. Kraybill and Professor E. C. Fowler for their constant help and encouragement and the other members of the Yale High-Energy Physics Group for their assistance throughout the analysis of the experiment. He is indebted to the scanners and microscope operators, Mary Sanford, John Hudson, Dick English, and Olga Skovinchow, for their many hours of work.

PHYSICAL REVIEW VOLUME 115, NUMBER 6 SEPTEMBER 15, 1959

Primary Cosmic-Ray Proton and Alpha-Particle Intensities and Their Variation with Time*

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(Received April 22, 1959)

A series of high-altitude balloon flights was carried out in 1957 and 1958 to study the flux of primary cosmic-ray protons and α particles during variations in the total cosmic-ray intensity. The following results are obtained for α particles with energies exceeding 530 Mev/nucleon under 13.5 g/cm^2 of air: (a) During a large Forbush-type decrease the α-particle and proton intensities were closely correlated. This demonstrates that a modulation mechanism is operating on both components. (b) At certain times variations in the α-particle intensity were observed within a few hours which were not accompanied by corresponding changes in the proton flux. This is tentatively ascribed to an anisotropy in the α-particle flux that reaches the earth. (c) While there existed an intensity decrease in the proton flux between 1957 and 1958 which is also observed in the neutron monitor station data, no such variation occurred in the α-particle flux. A division of the α particles into two energy groups (450 Mev/nucleon $\leqslant E_1 \leqslant$ 960 Mev/nucleon and $E_2 \geqslant$ 960 Mev/nucleon) shows (a) that the Forbush decrease is of the same magnitude in both energy groups, (b) that the hourly flux increase observed in some flights is about the same in both energy groups, and (c) that from 1957 to 1958 the flux in the low-energy group increased, while it decreased in the high-energy interval, contrary to the well-known behavior of the proton flux. These independent α-particle flux variations cannot be explained by any of the modulation mechanisms so far proposed. We suggest that occasional solar production of α particles may be responsible for our results.

The absolute flux of α particles with energies exceeding 560 Mev/nucleon at the top of the atmosphere was measured on five different days.

I. INTRODUCTION

VARIATIONS in the total primary cosmic-ray intensity have been observed and studied for a number of years. The main tools for these investigations are permanently installed cosmic-ray monitors that are able to record the intensity over long periods of time. More recently, this work was complemented using aircraft and balloon-borne instruments.

It was possible to show that most variations occur in the primary flux of cosmic-ray particles and are not due to local influences such as geomagnetic or meteorological effects, and it could be demonstrated that the mechanisms that give rise to such variations are solar controlled and must operate within or near the solar system. Extensive work has been carried out to find some model that may account for the observed phenomena, but no unique explanation is as yet available.

Most investigations that were carried out so far on the intensity variations of the primary cosmic radiation are concerned with the total flux of incoming particles. We know, however, that approximately 86% of the primary flux are protons, about 13% consist of alpha particles, while the remaining 1% are still heavier nuclei. The information on intensity variations of the different components of the primary radiation is still very limited. A more detailed knowledge of their flux and of their energy spectrum as a function of time can be used to test the models that were proposed to explain the changes observed in the total cosmic-ray flux. The emphasis of the present experiment is to move a step in this direction through an investigation of some of the time variations of the primary proton and alpha-particle fluxes and a study of the correlation between the two components. If, for example, the total flux of the low-energy primary cosmic radiation is of galactic origin and the intensity modulation takes place in the solar system due to disordered magnetic fields, one would expect very similar changes for each rigidity interval in the proton and α-particle component. Should, on the other hand, solar production of particles with cosmic-ray energies play a more important role than is generally assumed, variations in the ratio of α-particle flux and proton flux are likely to occur. For two reasons, it is advantageous to choose the cosmic-ray alpha particles as the prototype of the heavy primaries.

1. They are, next to the protons, the most abundant component, contributing more than 10% to the primary flux of particles.

* This research is supported by the U. S. Committee for the International Geophysical Year and by the Air Force Office of Scientific Research, Air Research and Development Command, under contract AF 18(600)-666.