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I. INTRODUCTION

Objectives

The original objectives of this investigation were two. It was desired to ascertain how readily and with what degree of certainty it was possible to analyze the disintegrations (i.e., "stars") produced in a Wilson cloud chamber by high energy bombarding particles. It was desired to determine the initial nucleus, the mass and charge of the resulting fragments, their energies, etc. The second objective was a knowledge of oxygen disintegrations, in particular, as a preliminary to the investigation of disintegrations in other gases. This was because oxygen is inherently present in most cloud chamber work by reason of the required presence of water vapor for track production. A knowledge of the characteristics of oxygen disintegrations would permit the effects of the oxygen present to be corrected for in such studies as those of the angular and energy distributions of particles resulting from the disintegrations of other elements.

Analyses

The bombarding particles used were 90 Mev neutrons. It was found that the degree to which any particular star could be analyzed depended upon many factors. These will become evident in the discussions to follow. In general it may be said that
the analyses have been very incomplete. It has been found possible to make a complete analysis of only one oxygen star, i.e., to determine the charge and mass of the particle producing each "prong" or track, the number of neutrons coming off (secondary neutrons), and the energy of the neutron initiating the star. The correctness of even this particular analysis is somewhat in doubt. This is not to say that useful information has not been obtained nor that with better and more careful techniques more successful analyses may not be undertaken.

The particles most readily identifiable are those of the lower atomic and mass numbers, particularly the hydrogen and helium isotopes. The charge of a particle is more easily ascertained than its mass. Except under the most favorable and unlikely circumstances it is impossible to determine much about the directions and energies of secondary neutrons. The term "secondary" is used here to distinguish between the incident, or primary, neutron initiating a star and the secondary neutrons emanating from the star.

Helium Stars

More was actually learned about stars in helium than about those in oxygen. (The reasons for the presence of helium in the gas mixture concern compromises which had to be made among several factors affecting cloud chamber results. These are discussed later.) More was learned about stars in helium because they are fundamentally simpler than oxygen stars. The helium star has only two electronic charges and five mass units, or nucleons --
including that of the incident neutron -- to be accounted for, while the oxygen star has eight and seventeen, respectively.

Thus the helium star can have but two prongs (one for each charge) while an oxygen star might conceivably have as many as eight. (The greatest number of prongs observed in this investigation was five.)

Conclusions

It has been possible to obtain a few general conclusions from this study. These follow.

1. There has been no evidence to disprove and some to substantiate the view that all but a few percent of the kinetic energy of the incident neutron is accounted for by the binding energy of the disintegration plus the sum of the star fragment kinetic energies.

2. In most disintegrations one or more secondary neutrons are present. Nothing can be said about the number of secondary neutrons usually present. There is evidence in a few cases that no or at most one secondary neutron resulted from the disintegration.

3. There is no evidence to disprove and a little to substantiate the assumption that a disintegration fragment may have any combination of charge and mass within the limitations of the charges and mass units present initially and the fact that it must exist long enough (have a long enough half life) to be observed.

4. The study of the helium stars yielded strong evidence that a significant number of the prongs were deuterons \( (\text{H}^2) \) and possibly tritons \( (\text{H}^3) \).

5. There appear to be no special characteristics which would easily distinguish oxygen stars from carbon stars which have been initiated by 90 Mev neutrons.
II. EXPERIMENTAL PROCEDURE

Neutron Beam

The stars studied in this investigation were produced in the neutron beam of the 184-inch Berkeley cyclotron. The neutrons were obtained by bombarding a half-inch beryllium target with deuterons accelerated to 190 Mev. The energy distribution of the neutrons in the forward direction is given by Serber's stripping theory for deuterons\(^1\) and has been checked experimentally.\(^2\) The theoretical distribution is shown in Figure 1. The peak of the beam intensity occurs at an energy of 90 Mev; the width at half peak is about 25 to 30 Mev; and the maximum energy is equal to that of the original deuterons, or 190 Mev.

Cloud Chamber and Stereoscopic Camera

The cloud chamber used was of the rubber diaphragm type (Figure 2). It had a diameter of 16 inches, a depth of 6 inches -- of which about \(3\frac{1}{4}\) inches was illuminated, and was placed horizontally in a vertical magnetic field of 13,300 gauss produced by a peak current of 4000 amperes pulsed through a pair of Helmholtz coils. The field strength was down 4 percent from the central maximum at a radial distance 6 inches from the center of the chamber. The collimated neutron beam entered and left the cloud chamber through two 1-7/8 inch diameter windows of 5 mil aluminum foil which were vertically centered in the chamber walls and
diametrically opposite each other.

Events occurring in the chamber were recorded on Eastman Super XX strip film 1.81 inches wide, using a stereoscopic camera (Fig. 2) having a pair of 127 mm Leica lenses set at f17. The lenses were 4.5 inches apart and about 52 inches directly above the black velvet covering the bottom of the cloud chamber. The plane containing the lens axes was normal to the neutron beam direction. The camera was without a shutter -- the duration of the exposure being governed by the 100 micro-second light flash obtained by the discharge at 1700 volts of one of a pair of 256 micro-farad condenser banks through each of two FT422 General Electric flash tubes. These flash tubes were mounted on opposite sides of the cloud chamber in the space between the Helmholtz coils. The light from each was directed into the chamber by a pair of cylindrical lucite lenses in horizontal beams normal to the neutron beam direction.

The cloud chamber cycle of operation was automatic and occupied a period of two minutes. During this time there were two slow expansions in between each fast expansion. The pulsed current for the magnetic field was supplied by a mine-sweeper generator driven by a 150 H.P. motor. The field was constant at its peak value for about 0.15 seconds. The fast expansion of the chamber occurred during this interval and the cyclotron was pulsed near the end of the chamber sensitive time. The 400-volt clearing field across the chamber was turned off just before the fast expansion. Turbulence in the chamber was minimized by means of a thermostatically regulated circulating-
water cooling system maintained at 19.2° C.

Gas Mixture

The gas used in the chamber contained a mixture of oxygen, helium and saturated water vapor. Alcohol, although useful because it permits a lower expansion ratio, was not used with the water. It was desired to avoid the confusion of having carbon in addition to the oxygen atoms present in the chamber and available for the production of stars. Helium was added as a diluent to lower the stopping power of the mixture while still maintaining a pressure of about half an atmosphere adequate for satisfactory cloud chamber operation. Low stopping power was necessary to minimize the deviations in track curvature arising from multiple scattering, and to extend the length of short range tracks in order that curvatures might be more accurately measured. Hydrogen would have been superior to helium for this purpose were it not for the explosiveness of mixtures of hydrogen and oxygen.

The composition of the gas mixture in terms of the expanded partial pressures at 19.2° C was as follows: oxygen 7.6 cm Hg, helium 26.6 cm Hg, and water vapor at 1.4 cm Hg. The stopping power $K$ of this expanded mixture was calculated to be 0.17 relative to standard air. Comparisons of $\frac{H \rho}{r}$ and range for tracks of several particles identified by other means verified this figure to within about ±10%.

Stereoscopic Projector

The actual measurements of direction, radius of curvature, length, etc. of the star tracks were made with the aid of special stereoscopic projector (Fig. 3). With the exception of a 45-degree
front-surfaced aluminized mirror incorporated for convenience, the lenses and geometry of the camera optical system is duplicated in this projector. Included in the optical path is a 3/4 -inch piece of plate glass intended to compensate for the effects on the optical path of the 3/4-inch plate-glass cloud chamber top.

Western Union arc lamps Type 100 provide brilliant and essentially point sources of light which allow the projection lens irises to be stopped down for adequate depth of focus. The image of each track, in turn, is reproduced life-size on a coated glass sheet (Eastman Recordak Green Translucent Screen Type 75551). This screen is mounted upon a pedestal which permits vertical movement and simultaneous rotation about independent horizontal and vertical axes. The vertical movement corresponds to a similar movement in the cloud chamber; and the rotations correspond to measurements, respectively, of dip angle $\alpha$ and beam angle $\beta$. The pedestal, itself, is attached to the head of a drafting machine (Fig. 3) which allows the screen to be moved horizontally anywhere over the surface of the plate-glass projector top while the beam angle $\beta$ is maintained fixed.

Alignment of Photographs in the Projector

The determination of the spatial relationship of each track with respect to the cloud chamber and neutron beam depends upon first placing each pair of stereoscopic photographs in register such that the spatial relationships of known points in the chamber are correctly reproduced on the projector screen. To this end two fiducial marks in the form of wire crosses (See key to Plate 1) were fastened to the velvet-lined bottom of the cloud chamber. They were placed
exactly 11 inches apart along the general direction of the neutron beam. Two more crosses, on either side of the chamber, were provided for checking purposes.

The manner of using the projector is as follows. Place the translucent screen in a horizontal position and move it vertically until its optical distance to the projector lenses is exactly the original distance (about 52 inches) between the chamber bottom and the camera lenses. Then adjust the focus of each lens separately until the distance between the images of the fiducial marks each projects is just 11 inches. Finally, bring the two sets of fiducial mark images into precise register on the screen. This latter adjustment requires moving one of the pair of photographs with respect to the other and is accomplished by means of vernier controls which allow one photograph to be held fixed while the other is moved in its focal plane. These independent adjustments are two in rectilinear motion at right angles and one in rotation.

**Measurements Made with Projector**

Once a pair of photographs is placed in register by the above procedure the original location of any point in the cloud chamber (e.g., the origin, or center, of a star) which appears in the photographs may be determined by simply raising or lowering the screen and the two separate images of the point coincide. The orientation and dimensions of the track of a charged particle (assuming its path to be planar) may be ascertained by placing the screen in such a position that the two images of the track are in register throughout their visible length.
The beam direction with respect to the projector was defined by two marks diametrically drawn on the glass top of the cloud chamber. (See key to Plate 1.) Their direction defines that of the neutron beam within ±0.5°. This direction is transferred to the projector by placing the reference line BB (Fig. 3) on the translucent screen parallel to these beam marks and then setting the angle \( \beta \) measured by the drafting machine protractor at zero. The line BB is perpendicular to the line AA which coincides with the screen’s horizontal axis of rotation.

The procedure followed in measuring an individual star track is to adjust the position of the screen until the two images of the origin of the star lie on the axis of rotation AA. Rotate the screen in the horizontal plane (beam angle \( \theta \)) and in the vertical plane (dip angle \( \alpha \)) until the two images of the track are in coincidence and the reference line BB is tangent to the track at its origin. The track is now reproduced in space in its original size and location. Its dip and beam angles may be read directly from the protractors. Its radius of curvature \( \rho_s \) in the slant plane is determined by comparing it to template curves. These templates are transparent plastic sheets having a series of arcs of circles scribed upon them. The arcs are of known and progressively increasing radii of curvature. The slant plane is the plane of the track, i.e., the plane occupied by the translucent screen. It is also possible to measure the range of a track which terminates in the illuminated portion of the chamber. In addition some tracks have a perceptible change of curvature over their visible path. For such tracks a measure of this rate-of-change of curvature is possible by determining the initial curvature, the
curvature near the end of the visible range, and the distance between these two points of curvature measurements. (Note: In the future it is hoped to measure rate-of-change of curvature more accurately and in a more direct manner by using templates which have scribed on them curves of known and uniformly varying curvatures. Thus, a track which has a measurable change of curvature will be approximately matched over its visible length, or at least over a considerable portion of its visible length, by selecting a template curve having not only the proper radius at a given point, but also the proper rate-of-change of curvature.

**Stereoscopic Viewer**

As an auxiliary aid in star analyses a stereoscopic viewer was used. It consists of a light box for illuminating the photographs from the back, a holder for the film, and a pair of simple lenses with suitable adjustments for viewing the photographs. This viewer was used in a preliminary study of each pair of pictures for the purpose of determining the number of stars, their approximate locations, number of prongs, general direction of prongs, approximate track densities, etc.
III. POSSIBILITIES AND LIMITATIONS OF STAR IDENTIFICATIONS

By its very nature the cloud chamber offers possibilities for obtaining more information concerning stars than does any other single experimental device. It enables individual events to be studied, and with the aid of the stereoscopic camera and projector it permits a reproduction of each track in its original size, shape and position. The addition of a magnetic field produces a curvature from which some knowledge of the momentum and energy of each particle may be obtained.

Available Data

The data available as a basis for analyzing stars in this investigation may be divided into three categories. These are:

1. general experimental data,
2. individual star data, and
3. auxiliary data on particle characteristics.

The general experimental data include a knowledge of the following:

(a) the direction and energy distribution of the incident neutron beam,

(b) the orientation and intensity of the cloud chamber magnetic field, and

(c) the composition and stopping power of the cloud chamber gas mixture.

The individual star data are those measurements and observations made on each star itself, and include the following information:
(a) the number and relative density of the prongs and
(b) the absolute density, initial direction, initial radius-of-curvature, rate-of-change of radius-of-curvature, and range for each prong. It should be mentioned here that the amount of information obtainable under (b) above varied widely, depending upon the particular circumstances. Perhaps half of it, on the average, was obtainable for any particular prong.

Finally, the auxiliary data on particle characteristics consist of information on the mass and charge of the particles which might reasonably be expected from these nuclear disintegrations; and of curves of energy versus $H_\rho$, $H_\rho$ versus range, and relative ionization versus $H_\rho$ for these particles. $\rho$ here signifies the radius-of-curvature of a particle moving normal to the cloud chamber magnetic field. $H$ is the magnetic field intensity.

The particles which one might expect to observe were assumed to be those appearing on Segre's isotope chart\textsuperscript{3} which had an atomic number less than that of oxygen. It was assumed that any other possible isotopes would be too unstable to exist long enough to be observed. These particles are listed in Table 1. The curves of auxiliary particle characteristics used are reproduced in Figures 4, 5, and 6. Figure 4 relates $H_\rho$ to range in air. The curves for the hydrogen and helium isotopes were obtained from data given by Livingston and Bethe.\textsuperscript{4} The rest were derived from the curve for $H_4$. The derivation was based on the assumptions that the range $R$ of a charged particle is given by $R = (A/z^2)f(v^2)$, and that $H_\rho = \text{const.}$ $(A/z)v$; where $A$ is the mass number, $z$ is the atomic number, $v$ is the velocity of the particle, and $f(v^2)$ is a function of the velocity.
squared, assumed the same for all particles. Thus a point on the curve for a particle of mass number A and atomic number z is obtained from a point of the same velocity on the He\(^4\) curve by the following two equations:

\[ H\rho = (A/z)(2/4)(\rho_{He^4}) \]

and

\[ R = (A/z^2)(4/4)R_{He^4} \]

Figure 5 relates the \( H\rho \) of a proton to its energy. The relativistic correction has been applied at high energies. This graph is used for other particles by applying the non-relativistic equation \( E = (A/z^2)E' \), where \( E \) is the energy of a particle of mass number A and atomic number z at an \( H\rho \) for which the energy of a proton would be given by \( E' \).

Finally, Figure 6 relates the relative ionization of the lighter particles to their radii of curvature in a magnetic field of 13,300 gauss. (This is the field intensity existing in the cloud chamber during this investigation.) The relative ionization of Figure 6 is numerically equal to the specific energy loss in \( 10^3 \) electron volts per cm of path length calculated for a stopping power relative to standard air of 0.12. These curves are based on the theoretical formula

\[ \frac{dE}{dx} = \frac{4\pi ne^4z^2}{m} \frac{2m}{\beta^2 c^2} \left( \ln \frac{2m}{\beta^2 c^2} - \beta^2 \right), \]

which is applicable when

\[ E \ll (\frac{1}{2}m/c^2) \cdot Mc^2, \]
where \(-\frac{dE}{dx}\) is the rate of energy loss (specific ionization) of an ionizing particle of mass \(M\) and charge \(ze\). \(m\) is the electronic mass, \(n\) the number of electrons per unit volume of stopping material, \(c\) the velocity of light, \(\beta\) the ratio of the velocity of the ionizing particle to the velocity of light, and \(I\) the mean excitation energy of the electrons in the stopping material. Das Gupta and Ghosh\(^5\) use a value of \(I\) for air of 82.6 ev and obtain an equation for the specific ionization of a proton in air. This equation, modified by inclusion of the factor \(z^2\) to make it applicable to the specific ionization in air of a particle of atomic number \(z\), is

\[
-\frac{dE}{dx} = 2 \times 10^2 \ \frac{z^2}{\beta^2} \left(9.43 + 2 \ln \frac{\beta}{(1-\beta^2)^{1/2}} - \beta^2\right) \text{ev/cm} \ .
\]

(1)

Using \(\beta\) as a parameter, \(H\rho\) was obtained from the relation

\[
H\rho = \frac{Mz^2}{(1-\beta^2)^{1/2}} = 3.11 \times 10^6 \frac{A}{z} \ \frac{\beta}{(1-\beta^2)^{1/2}} \ \text{gauss-cm}
\]

where \(A\) is again the atomic number of the ionizing particle. If \(H\rho\) is assumed \(1.33 \times 10^4\) gauss then there is obtained for the radius of curvature \(\rho = 23.4 \frac{A}{z} \ \frac{\beta}{(1-\beta^2)^{1/2}} \ \text{cm}.
\)

(2)

The equations (1) and (2) are then parametric in \(\beta\) relating \(-\frac{dE}{dx}\) to \(\rho\).

Identification Procedure - General

The basis upon which star identifications were made is perhaps most readily illustrated by examples. Several are given later in this paper. The steps followed in reasoning out the disintegration reaction producing a star varied, of course, with the data available on that particular star and with the accuracy with which this data was obtainable.
In general, the identification of as many as possible of the individual prongs was first attempted. Failing the complete identification of any prong, an effort was made to ascertain its charge (atomic number) or at least to narrow its probable identity to as few choices as possible. The further identification of the remaining and/or uncertain prongs was then attempted on the basis of the required conservations of charge, mass, momentum and energy for the star taken as a whole. As pointed out at the beginning of this paper, the identifications were usually quite incomplete – only seven helium stars and one oxygen star having been even tentatively identified in their entirety.

Errors of Measurement

For convenience in discussion the overall errors of measurement have been separated into two categories – experimental errors and measurement uncertainties. The term "experimental errors" is used in the usual sense of inadvertent and/or inherent errors, while the term "measurement uncertainties" refers to doubts concerning the best value to be assigned a quantity being measured. For example, the slant radius $\rho_s$ was determined by matching the curve of a particle track to a template curve of known radius. Consecutive template curves have radii differing by about 5%. Thus it was not possible to determine a slant radius closer than to within about $\pm 2\%$. This might be called the minimum possible uncertainty. However, when the visible track is short or indistinct, or is wavy from multiple scattering, it may appear – in the judgment of the observer – to be matched equally well by a number of template curves. The uncertainty in the measured slant radius may then be expressed by stating the range of radii within which its correct value seems to lie –
(e.g., $\rho_s = 38 \pm 4$ cm). The two directly measured quantities suffering the largest uncertainties were slant radius $\rho_s$ and dip angle $\alpha$. The magnitude of these uncertainties, which were usually large in comparison to the experimental errors, are discussed below. The experimental errors arising in the use of the same cloud chamber and projector as used in this study have been investigated by Brueckner, Hartsough, Hayward and Powell in connection with neutron-proton scattering experiments. They checked the accuracy of the projecting apparatus by photographing a drafting triangle at various positions in the chamber and then measuring the angles by reprojection. They found the reprojected angles to be correct within $1/2^\circ$ for small dip angles and to within $1^\circ$ for a dip angle of $60^\circ$. Their data were checked by having the measurements made independently by two different people. They found beam angle $\beta$ measurements were reproducible to within $\pm 1^\circ$.

Errors in curvature due to turbulence were negligible in comparison to measurement uncertainties. Errors in the value of the magnetic field $H$ were about $\pm 3\%$ due to the radial variation in intensity.

Parameters for Individual Prong Identification

There are several pairs of parameters which may serve to establish the identity of an ionizing particle. Those used in this investigation were $H \rho$ and range, $H \rho$ and change-of-$H \rho$, $H \rho$ and specific ionization, and range and specific ionization. The assurance with which these pairs of parameters may be used to identify a particle depends, first, upon the certainty with which the parameters themselves are ascertainable; second, upon the certainty with which the auxiliary particle characteristics (as plotted in Figures 4 and 6) are known; and third, upon the separation between adjacent
auxiliary particle characteristic curves.

Measurement Uncertainties in $H\rho$, Change of $H\rho$, and Range

The uncertainty in $H\rho$ was primarily set by the uncertainty in $\rho$. This uncertainty varied anywhere from 2% or 3% to 50% and more. In general, the longer the visible portion of a track and the smaller its dip angle, the more accurate was the determination of its effective radius of curvature $\rho$. Change-of-$H\rho$ measurements were obtained from the differences of two measurements of $H\rho$. Since these differences were usually of the same order of magnitude as the uncertainties in $H\rho$ themselves, the uncertainties in change-of-$H\rho$ were often ±50 or ±100 percent. The actual measurements of the length of a track as it appeared on the projector screen could be made quite accurately - easily to within a millimeter. Errors in the determination of range in the cloud chamber gas mixture occurred largely because of uncertainties as to the correct dip angle at which to place the screen. These errors were greatest for large dip angles and varied from essentially nothing to more than ±25% of the measured range in extreme cases. Usually when $\rho$ was reasonably well known, the range in the cloud chamber was very well known; and, of course, range could still be measured for very short tracks when $\rho$ could not be determined. However, in using the curves of particle characteristics it is necessary to convert range in the cloud chamber into range in air. This requires a knowledge of the cloud chamber gas mixture stopping power relative to that for air. This is believed to have been known to within less than 10%.

Specific and Relative Ionization

Accurate quantitative measurements of specific ionization were
not available. Such quantitative measurements would have required individual droplet counts on the tracks. A droplet count and an accurate measurement of track curvature are virtually impossible to obtain simultaneously on the tracks of heavily ionizing particles. A track which has been dispersed for a droplet count has a poorly defined trajectory. The observable track characteristic related to specific ionization is what has been called track density or simply density, in this paper. It is really the apparent heaviness of the track and encompasses not only density in its usual photographic sense of opacity but also the width of the track. Unfortunately, the observed density depends not only upon the specific ionization but also upon the chamber illumination, the chamber expansion ratio, the delay between passage of the particle and the taking of the photograph, the dip angle, etc. These factors were variable from one photograph to the next, and even from one track to the next. Thus absolute density could be specified hardly better than to the extent that it was light, medium or heavy. The estimation of relative densities, however, was somewhat better.

Densities of prongs from the same star or of tracks in the same photograph and same region of the cloud chamber could be rather closely compared. However, track density is important only as a measure of track ionization. Since the quantitative dependence of density upon ionization was not known, the most accurate comparisons were those between tracks which appeared to have the same density. For two apparently equal density light tracks, it was felt reasonable to assume that the ionizations differed by 25% or less. This figure was increased to 50% or so for medium density tracks. The relative ionization of
heavier tracks of apparently equal density was considered to be less certain. It is felt there is probably a saturation effect or leveling off of density with increasing ionization at a point where all the moisture in the vicinity of the track has been condensed and no more is available for droplet formation. The comparison of densities certainly permitted differentiating between relative ionizations of two-, ten-, and one hundred-to-one.

Relative Ability to Identify Light and Heavy Particles

Except in the case of some protons, the complete identity of no particles was established with certainty. A number of particles were, however, identified as most probably hydrogen and helium isotopes. That is, both their charge and mass were assigned. In no case could the mass and seldom could the charge of particles having atomic numbers greater than two be even reasonably assigned on the basis of individual track measurements. The reason for this is clear when one considers the separation in the $H_\rho$ versus range curves (Fig. 4) of the particles. Percentagewise the greatest change in mass and charge is obtained among the isotopes of hydrogen and helium. Except at very short ranges (around 0.4 cm and less in air) the curves for the isotopes of elements above helium overlap one another. Furthermore, the curves for the higher elements were obtained on the basis of assumptions which are themselves only partially valid. Thus even when one has a rather accurate determination of $H_\rho$ and range, the identification itself is by no means positive.

The same difficulty in separating the heavier particles occurs when the parameters used are $H_\rho$ and change-of-$H_\rho$. The difficulty
was increased because change-of-\( H \rho \) was usually very unreliably known. It would have been best, of course, to have had curves plotted showing the relationship between these two parameters directly. Such plots will be even more desirable in the event that it is found possible to establish accurately the rate of change of \( H \rho \) by the use of the previously mentioned templates having comparison curves with simultaneously known radii and rates-of-change of radius. However, the \( H \rho \) range relationship was usable because the needed accuracy was not particularly great.

**Identifications by Change of \( H \rho \)**

The procedure in using these curves (Fig. 4) when a change of \( H \rho \) could be measured was this: Assume the identity of the particle. From its observed initial \( H \rho \) determine its range in air \( R_A \). Subtract the observed change in range \( \Delta R_A \) (referred to air) from \( R_A \) to obtain a reduced range and from the chart obtain the corresponding reduced \( H \rho_2 \).

If this chart value and the measured value of \( H \rho_2 \) are in reasonable agreement, then the assumed particle is considered to be a possible identification. If the agreement is much closer than for other particles and if the uncertainty in measurement is not such as to suggest other possibilities, then the identification is considered to be most probable. Such most probable identifications were infrequent and occurred only among the hydrogen and helium isotopes.

**Identification of Light Tracks**

With one exception, specific ionization (or, rather, track density - since that is what was actually observed) in combination with \( H \rho \), or range, was not sufficient alone to identify a track. This was because of the impossibility of estimating from the track density the
specific ionization quantitatively within a factor of 2 and usually within a factor of perhaps 10. Very light tracks were an exception. The lightest tracks were discontinuous or broken (see, for example, Plate 4). The appearance of this characteristic of light tracks is less dependent upon the quality of the illumination than is apparent density. Thus it is a better guide to specific ionization.

These light tracks were always assumed to be singly-charged particles. The reasoning behind this assumption follows. In every photograph there are many light single tracks that pass through the chamber travelling in the general direction of the neutron beam. Certainly the majority of these are high energy protons originating in the walls of the chamber and surrounding air. Among the evidence that they are proton tracks is the similarity of their appearance to that of the high energy proton tracks produced when a block of paraffin is placed in the neutron beam in front of the cloud chamber window. (See Plate 8).

These light single tracks have radii of curvature ranging from perhaps 50 cm to more than 125 cm corresponding, for protons, to specific ionizations of from 20 to less than 8 (in the arbitrary units of Fig. 6) and to energies ranging from 20 Mev to more than 125 Mev. Knowing that the highest energy which a star fragment may have is limited by the maximum energy of the neutron beam, one may ascertain from the $H_\rho$ energy data of Fig. 5 and the specific ionization versus $\rho$ curves of Fig. 6 whether or not there are other particles which might also have comparable ionizations (i.e., of the order of 8 to 20). For example, a 36 Mev triton has a specific ionization of 30
which is the same as that for a 20 Mev proton. A 100 Mev triton has
an ionization of 21. Deuterons naturally have ionizations lying be-
tween those of protons and tritons of the same energy. Thus deuter-
ons and, to a lesser extent, tritons emanating from a star may be en-
ergetic enough to produce light tracks indistinguishable in the absence
of curvature measurements from those of high energy protons. However,
any particle other than these singly-charged isotopes of hydrogen could
not be sufficiently energetic to produce such lightly ionizing tracks.
Even He^3, which is the most lightly ionizing of any of the multiply-
charged particles, is characterized by a specific ionization of 63
when it has the high and extremely unlikely energy of 140 Mev. Thus,
on the basis of observed density alone, one may assume that a light
discontinuous track has to be that of a singly-charged particle.

While a light discontinuous track is excellent evidence that a
particle was singly-charged, additional data are needed to establish
its mass. As an aid in assigning the mass of such singly-charged par-
ticles, adjacent light single tracks may be used as standards for com-
paring densities and curvatures. If two tracks have the same curvature,
the one of greater density has the greater mass and vice versa; the
track of greater curvature (smaller radii of curvature) of two having
the same density has the lesser mass. Experience is the best guide in
determining the degree to which these comparisons may be carried.
Range versus Ionization

The combination of parameters of range and specific ionization
was found to be of negligible value as a means for particle identifica-
tion. Range was never determinable for very light tracks because they
did not stop in the chamber. Tracks of medium density, if they stopped in the chamber, were long enough to permit a fairly good measure of radius-of-curvature and hence identification could usually be attempted on the basis of range and H. The only place where information as to the specific ionization would be of value is where the tracks are so short (less than 5 cm, or so, in the chamber) that the radius of curvature may not be measured with any certainty. These tracks are all quite dense, however, and though it was certainly possible to observe differences in density, there was no way of knowing just how these related quantitatively to specific ionization because of the many factors involved.

(Density, in this instance, refers primarily to track width rather than to opacity, since all these heavy tracks looked quite black.) Once in a while these differences in density may give a hint towards distinguishing between isotopes of hydrogen and nitrogen.

Other Aids to Identification

There are two more characteristics of a track which, presumably, and under favorable circumstances, might help in its identification. They are the phenomena of multiple and single scattering. These were not enumerated earlier because they were of no aid in this investigation. Multiple scattering was observed with many tracks terminating in the chamber and appeared as random wiggles for the last centimeter or so of a track's length (e.g., *1-2, *2-2, *3-1 and *3-3 of Plate 11). There is, no doubt, a correlation between the mass and charge of an ionizing particle and the character of its terminating wiggles. However, no noticeable correlation was found in the course of looking
at the tracks. (It should be pointed out here that no extensive effort was made to find such a correlation, although the possibility was kept in mind throughout the investigation.)

Several cases of single scattering were observed, also (see prongs *2-2 and *3-1 of Plate 5 and *2-3 of Plate 9). In theory, if the mass of the scattering center is known and the scatter angles can be measured, it is possible (assuming an elastic collision) to determine the mass of the scattered particle by application of the principles of conservation of momentum and energy. In particular, if the masses of the scattering and scattered particles are the same, the angle between the paths of the two after scattering will be 90 degrees. In this investigation the mass of the scatterer could have been that of either a helium or an oxygen nucleus - possibly even that of a proton. The path lengths of the scattering and scattered nuclei were so short and/or indistinct in every instance that their directions could not be measured in order to determine the scatter angles.

**Identification of the Star as a Whole**

Sometimes none and usually only one or two of the prongs of a star could be even partially identified individually. Further knowledge of the star was then obtained, if possible, by attempting to balance the charge, mass units, momentum and energy of the star. Of these four quantities, charge is the one most easily accounted for. All particles carrying charges produce tracks and thus visible evidence of their presence though not necessarily of the number of their charges. Since the sum of the charges represented by the prongs equals the number in the original nucleus, a two-prong star can originate from either a helium or an oxygen nucleus, while stars of greater numbers of prongs
can come only from an oxygen nucleus. The sole way of distinguishing a helium star from a two-prong oxygen star is to identify both prongs as isotopes of hydrogen, or to establish that at least one prong carries two or more charges. In the first instance it must be a helium star, and in the second, it must be an oxygen star.

Obtaining a balance of the mass units was more difficult than accounting for the charges. This was primarily because secondary neutrons were usually present but left no track to indicate their presence. For this reason, it was impossible to determine directly how many mass units should be assigned to secondary neutrons. (Sometimes conservation of momentum considerations did indicate definitely that one or more secondary neutrons were present, but not how many.) The second difficulty in obtaining a balance of mass units was in establishing the mass of the visible particles. Generally, the conservation of mass units was only of value in setting an upper limit to the total number of mass units which could be assigned to the visible particles of a star. This upper limit, of course, is the sum of the mass units in the original nucleus and the primary neutron. Finally, of less frequent importance for identification purposes were momentum and energy balances. For a charged particle, momentum = const x $\bar{A} p z$, where $z$ is the number of its charges. A knowledge of its mass is not required to determine its momentum. The kinetic energy of a charged particle, on the other hand, is given in the non-relativistic range by $KE = const \times (\bar{A} p z)^2/A$ where $A$ is its mass number. A knowledge of the particle's mass, in addition to a knowledge of its charge, is, therefore, required to determine its energy.
A momentum balance was chiefly of value in determining the absence or presence of secondary neutrons. Because neutrons leave no track their momentum could not be determined directly. Thus, if the transverse momentum of the visible particles did not balance within their uncertainties it was considered evidence of the presence of one or more secondary neutrons. On the other hand, a successful balance was not considered as proof of the absence of neutrons. This was because secondary neutrons could still have been present, but with a net transverse component of momentum so small as to be masked by the probable errors.

The only stars for which possible momentum balances were achieved were a couple of two-prong helium stars and one five-prong oxygen star. The reasons for this lack of success were many. In the first place, at least a large number, if not nearly all, of the stars contain one or more secondary neutrons, thus obviating the possibility of a balance. In the second place, there was usually insufficient accurate information on all the prongs of a star to enable calculation of the momentum components. Beam angles were usually well-known, but dip angles and $\beta$'s often were not. In fact, for very short tracks, and these were frequently present, curvature could not be measured even approximately because of scattering. In such situations determination of the particle's momentum depended upon a measurement of its range (which was accomplished easily enough) and a knowledge of its charge and mass. These latter were often nearly pure guesses.

An energy balance may be used in connection with a momentum balance as a check on the assumed identification of the star in the absence
of secondary neutrons, or as a means for assigning a lower limit to the
energy which the incident neutron could have had. It is particularly
simple to attempt momentum and energy balances on two-prong stars. For
that reason the remaining discussion will be restricted to two-prong
stars - helium stars, in particular. What follows may be readily gen-
eralized to include multiple prong stars.

Identifying Two-Prong Stars

When both tracks of a two-prong star (e.g., *1 of Plate 1, *3
of Plate 9 and *2 of Plate 11) lie to one side of some plane containing
the incident neutron beam, one knows immediately that their net trans-
verse momentum certainly cannot vanish. Thus, at least one secondary
neutron must be present in order to make a transverse momentum balance
possible. If, further, the \( E \) for each track is known and if the two
particles' identities are known or assumed, one may determine the ki-
etic energy represented by each track and the binding energy of the
reaction. The energy of any secondary neutrons present will not be
determinable directly. The sum of the observed particle energies plus
the binding energies must be equal or less than the energy of the in-
cident neutron energy. One can then say that if the sum of the observed
energies, including the binding energy, is greater than 190 Mev (the
highest possible incident neutron energy), the particle identities are
not as assumed and that if it is less than 190 Mev and greater than 130
or 140 Mev that the particle identities are probably not as assumed.

In the special case where it is possible to achieve a transverse
momentum balance without assuming the presence of one or more secondary
neutrons, it may also be possible to obtain an energy balance. If one
assumes no secondary neutrons the observed particles must be $H^2$ and $H^3$ in the case of a helium disintegration. One can then calculate the energies which the incident neutron must have had. There will be two possible energies depending upon which track is assigned to the $H^2$ and which to the $H^3$ particle. One can also calculate the energy of the incident neutron from its momentum. Its momentum must equal the net forward momentum of the two observed tracks. If this latter value of energy coincides, within the probable errors, with one of the two energies calculated from the observed particle momenta plus the binding energy of the reaction, then one is justified in assuming such an identification to be possibly, though not necessarily, correct.

Finally, when just one secondary neutron is assumed present, it is also possible to ascertain the energy which the incident neutron must have had in order to produce an energy balance. The secondary neutron must have a transverse component of momentum which balances the net transverse momentum of the two observed tracks. Its forward momentum must be such that when added to that of the two observed tracks, the resultant forward momentum is just that which the incident neutron must have had to make its energy equal the sum of the binding, observed particles', and secondary neutron's energies. In case two or three secondary neutrons are assumed, a minimum incident energy may be calculated by considering the secondary neutrons to have all been scattered in the same direction and treating them as a single particle of two or three mass units, as the case may be. The procedure is then exactly as outlined for the single secondary neutron case above. The criterion is again used that if the incident neutron energy is greater
than 130 or 140 Mev, the assumed reaction is improbable and if greater than 190 Mev, impossible.
IV. ANALYSIS OF HELIUM STAR 1 OF PLATE 2

This is a two-prong helium star whose fragments are believed to be either two deuterons and a neutron, or a deuteron and a triton. The data are insufficiently exact to enable either possibility to be chosen to the exclusion of the other.

Preliminary Analysis

A preliminary identification was made through visual observation of the photographs in the stereoscopic viewer. Prong 2 is of very light density and has the characteristic discontinuous appearance which identifies it as singly-charged. Since this star can only be the result of a helium or an oxygen disintegration, the other prong must either be, also, singly-charged or have the seven charges of a nitrogen isotope.

That prong 1 is not a nitrogen isotope is evident immediately upon comparing the predicted ionizations with the observed density. The observed density, although plainly heavier than that of prong 2, is light and certainly does not correspond to a specific ionization D of more than 400. On the other hand, it may be readily determined from the $\mathcal{H}_p - $energy relation (Fig. 5) that an isotope of nitrogen with even an extreme energy of 140 Mev would have an $\mathcal{H}_p$ in the neighborhood of $9 \times 10^5$ gauss-cm corresponding to a specific ionization D (See Fig. 6) of more than 2000; and 140 Mev is an improbably high energy for prong 1, particularly if it should be a nitrogen isotope. Thus 2000 is the very minimum ionization such an isotope could produce. Comparing 2000 with the estimated observed maximum of 400, one concludes that prong 1 cannot be nitrogen and is, therefore, singly-charged.
Hence, the star is the result of a helium nucleus disintegration.

**Detailed Analysis**

The following more detailed analysis is based upon data measured with the stereoscopic projector. It is a good example of the aids to identification provided by energy and momentum balances and relative track densities under favorable circumstances. The data (measured, derived and predicted) are tabulated below, along with their estimated measurement uncertainties. These uncertainties do not give consideration to any errors other than those estimated from the actual measurements on the tracks as they were observed in the projector. Experimental errors such as those caused by multiple scattering, geometry, inexact register of the two negatives in the projector, etc., increase the overall errors by probably several percent.

Table 2 indicates the measured dip and beam angles $\alpha$ and $\beta$, the measured slant radius $\rho_s$, the derived magnetic curvature $H \rho$, and the derived scatter and azimuthal angles $\theta$ and $\phi$. Table 3 gives the transverse and forward momenta in $H \rho$ units, the predicted particle energy $E$, and the predicted specific ionization $D$ according to the assumed identity of each particle. Finally, Table 4 lists all the combinations of hydrogen isotopes and secondary neutrons possible from a helium disintegration. The tabular heading "relative ionization" signifies the ratio of the ionization of prong 1 over that of prong 2 predicted on the basis of their assumed identities and observed $H \rho$'s. The "visible energies" refer to the sum of the energies of the (visible) prongs, also predicted according to their assumed identities and observed $H \rho$'s. The "binding energy" (reaction energy) is that determined for the
assumed process. The "minimum primary energy" is the energy of the
primary (incident) neutron predicted by its minimum forward momentum.
(The meaning of minimum forward momentum will come in a later discus-
sion.)

Three, and perhaps four, of the possible combinations of Table 4 may be rejected immediately by comparing their predicted relative
ionizations with their observed densities. Of course, one treads on
uncertain ground when estimating relative ionization on the basis of
the observed track densities because of the many variables involved.
One must rely largely on experience in arriving at an estimate. It
can certainly be stated with assurance that the relative ionization
lies between 2 and 20 and probably within the narrower limits of 3
and 10. Thus, combinations b, d and g all have predicted ionizations
under 2 which is definitely too small. The value of 18 for combination
e is somewhat high and puts it in the doubtful class.

Possibility of a Momentum Balance

The fact that, within the uncertainties of measurement, the
azimuthal angles $\phi$ (Table 2) for the two prongs are just 180° apart
(i.e., their initial directions are transversely opposed and coplanar)
strongly suggests a possible transverse momentum balance with the ab-
sence of secondary neutrons. In $H\rho z$ units of $10^5$ gauss-cm ($\rho = 1$),
prong 1 has a transverse momentum (Table 3) of $7.3 \pm 0.5$ and prong 2,
of $-7.7 \pm 0.4$. These two figures are in rough agreement, indicating
that all five mass units may be accounted for by the two observed par-
ticles, one being a deuteron $H^2$ and the other a triton $H^3$. However,

since momentum in $H\rho z$ units does not explicitly involve the mass of
a particle, an alternative explanation of this apparent momentum balance is that secondary neutrons are present whose resultant transverse momentum is so small as to be masked by the uncertainties.

**Energy Balance and Minimum Primary Energy**

Recourse may be made to the requirements for simultaneous energy and forward momentum balances to provide a basis for choosing among the several possible particle combinations. The momentum of the primary (incident) neutron must equal the net forward momentum of the two observed particles plus that of any secondary neutrons. A knowledge of this primary neutron's momentum permits its kinetic energy to be determined. This primary neutron energy should be just sufficient to account for the sum of the kinetic energies of the observed particles and secondary neutrons plus the binding energy of the disintegration. (Any other mechanisms by which energy may be absorbed - i.e., emission of gamma rays, excitation of the secondary particles, etc. - are assumed to account for a negligible amount of energy.)

One may proceed in the following fashion. Assume the identity of the observed particles. Obtain their energies in Fig. 5 from their \(E_p\)'s. Sum these and add to the binding energy for the assumed reaction. The total so obtained must equal or be less than the energy which the incident neutron must have had. (It is equal when there are no secondary neutrons.) It is to be compared with the energy calculated for the incident neutron assuming it to have a momentum equal to the observed (particles') net forward momentum. A difference in these two energies has to be accounted for by the presence of secondary neutrons. If the kinetic energies and momenta of these secondary neutrons were determinable,
their energies could be added to the binding and observed particle energies to obtain the (exact) kinetic energy of the incident neutron; and their net forward (or backward) momentum could be added to (or subtracted from) the net forward momentum of the observed particles to obtain the (exact) incident neutron momentum, which in turn would yield the incident neutron's kinetic energy. These two values should, naturally, be in agreement. When only one secondary neutron is present these two values for the primary neutron's energy may be brought into agreement by adjusting the secondary neutron's forward momentum (and, hence, its energy also) to change both values of the primary's energy simultaneously.

On the other hand, when there are two or three secondary neutrons, each, additionally, may have a transverse component of momentum whose vector sum, however, must be negligibly small to maintain the transverse momentum balance already observed for the visible particles. Thus the kinetic energy and forward component of momentum for each of these neutrons are independent quantities. There is then no way of finding the primary neutron's energy. Nonetheless, a lower limit for the primary energy may be obtained. One simply lumps the two or three secondary neutrons together and treats them as though they were one particle having only a forward (or backward) momentum. As in the case of the single secondary neutron this momentum may be adjusted until the two values for the primary energy are in agreement. This final value is then the minimum primary energy; and the net forward momentum of all the particles, including the lumped secondary neutrons, is the minimum net forward momentum.
If this minimum energy approaches, or is greater than, 190 Mev (the maximum energy of the neutron beam) one may conclude the assumed reaction to be improbable or impossible. Using this criterion the combinations a, c, and e of Table 4 may be considered highly improbable since their minimum primary energies are $184 \pm 10$, $171 \pm 10$, and $165 \pm 10$ Mev, respectively.

Combination g can be rejected because of the impossibility of obtaining an energy balance, i.e., this process produces no secondary neutrons and so there is no way by which the net forward momentum may be adjusted to resolve the differences between the primary energies ($76 \pm 2$ Mev and $94 \pm 11$ Mev) obtained in the two different ways.

Of the eight processes possible from a reaction between a neutron and a helium nucleus, all but two have been eliminated as being impossible or highly improbable, either because the predicted ionization did not match the observed track densities and/or because the minimum primary neutron energy required was improbably high. An additional reason for rejecting combination g was the obvious lack of an energy balance. The two remaining processes produce either two deuterons and a secondary neutron (combination f) or a triton and a deuteron (combination h).
V. ANALYSIS OF HELIUM STAR 1 OF PLATE 3

This star is also a two-pronged helium star whose fragments are believed to be either two deuterons and a secondary neutron or a deuteron and a triton. The data are again insufficient to distinguish between the two possibilities.

Preliminary Identification

Prong 1 is very light and discontinuous. It is obviously singly-charged. Prong 2 is therefore either nitrogen or hydrogen. Prong 2 might be described as being of a medium density corresponding to a specific ionization of the order of 1000 or less. Its measured radius of curvature (Table 5) is 27 cm. For $^1H^2$ this radius corresponds to a predicted specific ionization of the order of 10,000 (Fig. 6). This is much too large. Prong 2 is thus also singly-charged; and the original nucleus was helium. That prong 2 is a hydrogen and not a nitrogen isotope is substantiated below, particularly by the change-of-$H_\phi$ data.

Individual Prong Analysis

The observed data on this star are tabulated in Tables 5 and 6. Table 6 includes change-of-$H_\phi$ data for prong 2, along with a comparison of predicted reduced $H_\phi$'s for the isotopes of hydrogen and nitrogen. These data clearly identify the particle as either $H^2$ or $H^3$, with the evidence more in favor of $H^2$. This is about as far as one may go with the identification of the prongs individually.

Detailed Analysis

As in the case of the helium star 1 of Plate 3, a comparison of the estimated observed track densities with the predicted relative
ionizations is useful in rejecting some of the possible combinations of singly-charged particles. The ionizations predicted from the prong \( H \rho \)'s are shown in Table 7, and the predicted relative ionizations for various combinations of the singly-charged particles are tabulated in Table 8. The observed track densities correspond to a relative ionization which is certainly greater than 5. On this basis combinations c, e, and probably h are not possible.

It will be noted in Table 5 that the dip angles \( \alpha \) are negligible. Thus the two prongs lie essentially in the horizontal plane. Further, from their beam angles \( \beta \) it is apparent that their transverse components of momentum are opposed. This suggests the possibility of a momentum balance. Table 7 contains the forward and transverse momenta in units of \( H \rho \)s. Within the measurement uncertainties the transverse momenta cancel. The energies of each prong predicted from the \( H \rho \) and assumed identity of each are also in Table 6. These predicted energies and forward momenta have been used to obtain the energy balances and minimum primary neutron energies of Table 8.

The minimum primary energies for combinations a, b and d are greater than 175 Mev and consequently these combinations are most unlikely explanations of the disintegration. Combinations a, c and e require that prong 2 be a proton. This possibility has already been excluded by the rate-of-change of \( H \rho \) data of Table 6. Finally, combination h has been rejected because of the impossibility of obtaining an energy balance, there being no secondary neutron to account for the discrepancy between the sum of the binding and observed energies, and the energy of the primary neutron determined from the net forward momentum of the observed particles.
Thus, there remain two possible explanations for the star.
These are combinations f and g. Either both prongs are deuterons with one secondary neutron, or prong 1 is a triton and prong 2 is a deuteron with no secondary neutrons present.
VI. BRIEF ANALYSES OF SEVERAL OTHER HELIUM STARS

Star 1 of Plate 1

The fragments of this star are believed to be a proton, a triton and a neutron. The observed data are contained in Table 9. In brief, the analysis proceeded as follows. Since the beam angles $\beta$ for both prongs are negative, there must be one or more secondary neutrons present to balance the transverse momentum. The change-of-$H_\rho$ data suggest strongly that prong 2 is $^3$H. (The observed reduced $H_\rho$ was 3.25 ± 0.5 and the predicted reduced $H_\rho$ for $^3$H was 3.1; while the predicted reduced $H_\rho$'s for $^2$H and $^1$H were 3.9 and 4.1, respectively.) Thus it is automatically required that there be only one secondary neutron, and that prong 1 be $^1$H in order to take care of the necessary five mass units. The observed track densities and predicted ionizations substantiate this choice.

Star 2 of Plate 4.

The fragments of this star are believed to be a triton, a proton and a neutron. The observed data are contained in Table 10.

The azimuthal angles $\phi$ are nearly 180° apart indicating the possibility of a transverse momentum balance, but the $H_\rho$ of prong 2 is so poorly known that this possibility can neither be proved nor disproved. Thus there is no real evidence for or against the presence of secondary neutrons. About the only means of identifying the two prongs are their comparative densities. Prong 2 is extremely light and is most likely $^1$H. Since no upper limit for its $H_\rho$ was ascertainable it may be that the particle was energetic enough to produce such a light track and yet be $^2$H. It is hardly possible that a triton $^3$H could have been sufficiently energetic to give rise to such a
light track.

Prong 1 was identified by comparing its $\beta$ and density with those of the two prongs of adjacent star 3 of the same plate. Prong 1-1 is of slightly greater density than either prong 3-1 or prong 3-2. Its $\beta$ is almost equal to that of prong 3-2 and greater than that of prong 3-1. Since these two prongs cannot be less than protons and are believed to be deuterons -- see analysis of star 3 directly below -- prong 1-1 must be at least a deuteron and probably a triton.

**Star 3 of Plate 4**

The observed data on star 3 of Plate 4 are tabulated in Table 11. The star fragments are probably two deuterons and a neutron.

The difference between the azimuthal angles $\phi$ leaves no doubt that the two visible tracks are non-coplanar and that a transverse momentum balance requires the presence of one or more secondary neutrons. An energy balance also requires the presence of one or more secondary neutrons.

The masses of the two prongs were established by comparing their observed densities and predicted ionizations with those of an adjacent single proton track. This comparison track -- indicated in key to Plate 4 -- was nearly on the same level (in the cloud chamber) as prongs 1 and 2 and was presumably subject to the same illumination. It has an equivalent radius of curvature $\rho$ of 67 cm and is much lighter than prongs 1 and 2. Prong 1 has a $\rho$ of 47 cm and, therefore, has to be $H^2$ or possibly $H^3$ to have produced a heavier track. Prong 2 has a $\rho$ of 61 cm which is not much less than the 67 cm of the comparison proton track. It, too, is most likely $H^2$ to explain the production of a heavier track.
Star 1 of Plate 5

The observed data on star 1 of Plate 5 is in Table 12. The fragments of this star are believed to be a proton, a deuteron and two neutrons.

Both a transverse momentum balance and an energy balance require secondary neutrons. Prong 1 is too heavy in comparison with its observed $H\rho$ to be $H^1$. It must be either $H^2$ or $H^3$ -- probably the former. Prong 2 is quite light. The ionization predicted from its $H\rho$ suggests that it is most probably $H^1$. It definitely is not $H^3$.

Star 2 of Plate 6

The fragments of star 2 of Plate 6 are probably a deuteron, a proton and two neutrons; or a triton, a proton and a neutron. The observed data are in Table 13.

Prong 2 is a very light track. Its $\rho$ is such that the predicted ionization for $H^1$ is 18 and for $H^2$ is 52. An ionization of 52 is certainly too high for the observed density. Thus it must be $H^1$. Prong 1 is of light density but is considerably heavier than prong 2. Its predicted ionization for $H^1$ is 29, for $H^2$ is 85, and for $H^3$ is 160. The observed density is probably too heavy for $H^1$, so it must be $H^2$, or $H^3$. Further, the dip angles are both negative so that a momentum balance requires one or more secondary neutrons.
VII. ANALYSIS OF FIVE-PRONG OXYGEN STAR 1 OF PLATE 7.

This is a five-prong oxygen star whose fragments may be a proton, a triton, three alpha-particles, and a secondary neutron. It is an exceptional star in that there are at least two parameters which may be applied to the direct identification of each prong. Further, the slant plane of each prong is within 16° or less of the horizontal. This means that large dip angles are not present to contribute to large uncertainties in the measurements. (In contrast, the five-prong star of Plate 10 has no prongs ending in the chamber, and all except prong 1 have large dip angles as evidenced by the fading out of their tracks.)

Prong 1 is obviously an isotope of hydrogen because it is of such light density. Both range and curvature may be measured on prong 2, and the remainder (prongs 3, 4 and 5) have a measurable change of curvature over their visible length. Additional clues are obtainable from the relative densities of prongs 1 to 4, and from momentum and energy balances. The measured data and their estimated measurement uncertainties are tabulated in Table 14. From these measurements the derived data of Table 15 are obtained, and, finally, in Tables 16a to 16e, comparisons are made between the derived data and the predicted data for various possible particles.

The main line of reasoning pursued in analyzing this star is as follows. Prong 1 is definitely a singly-charged particle. There is some doubt at this stage of the analysis whether it is a proton or a deuteron. A comparison of its density, which is quite light, with the specific ionization $D$ of 140 predicted from the observed curvature (Table 16a) apparently eliminates $H^2$; such an ionization should produce a heavier track than is observed.
Next, it is observed that prongs 3, 4 and 5 are very nearly of the same density, with possibly #3 being by a small degree the heaviest and #5 a shade the lightest. #3 appears to have a fuzziness which increases its width and apparent density. (The term density, as previously suggested, here combines a measure of both the width and opacity of the track.) Prongs 3 and 4, in addition, have essentially the same radius of curvature $\rho$ and should be identical particles. A charge balance requires that the combined maximum number of charges that prongs 3 and 4 may have is five. (Oxygen has a total of eight positive electronic charges and each of the other prongs must have at least one.) Thus, if #3 and #4 are identical, each may have no more than two charges.

Change-of-curvature data may now be used to narrow the choice still further. By reason of the comparative shortness of its visible length, change-of-curvature was measurable with the least certainty on prong 3. The uncertainty of this data is such that Table 16c and the knowledge that there can be no more than two charges only reduces the choice for prong 3 to either $\text{H}_2^2$, $\text{He}_3^3$, $\text{He}_4^4$ or $\text{H}_3^3$. The uncertainty for prong 4 is considerably less. Reference to Table 16d suggests that prong 4 is most probably $\text{He}_4^4$ or $\text{H}_3^3$. Thus #3 is most probably $\text{He}_4^4$ or $\text{H}_3^3$ also. A further narrowing of the probable identities of prongs 3 and 4 must await identification of the remaining prongs.

From its change-of-$H\rho$ (Table 16e) one might consider prong 5 to be $\text{He}_4^4$. However, the predicted ionization $D$ for $\text{He}_4^4$ is 900, which is 50% greater than the maximum predicted ionization for prongs 3 and 4 if they are likewise assumed to be $\text{He}_4^4$; the observed density
is, if anything, slightly less than that of #3 or #4. The next choice for prong 5, on the basis of its change-of-$H\phi$, is $H^2$ or $He^3$. The predicted ionization of 230 for $H^2$ is reasonable in comparison with that for #3 or #4 when the latter are assumed to be $H^3$'s. Such an assumption is questionable, however, for it requires that prong 2 be an isotope of beryllium ($^4$ charges) in order to satisfy an overall charge balance — prong 1 already having been assigned a single charge. Beryllium is a doubtful assumption for prong 2 because it does not appear dense enough to account for a required specific ionization ten- or twenty-fold greater than that of prong 3, 4 or 5.

On the other hand, if #5 is assumed to be $He^3$, then the specific ionizations are reasonable in comparison with the observed track densities when #3 and #4 are assumed to be $He^4$'s. However, a charge balance now requires that #2 be singly-charged, i.e., either $H^2$ or $H^3$; its predicted ionization D is then too low in comparison with the observed density of #2. Thus #5 can hardly be $He^3$.

Finally, consideration can be given to whether #5 may reasonably be assumed to be $H^3$ if #3 and #4 are assumed $He^4$'s. The specific ionization of 390 for $H^3$ in comparison with 580 and 560 for the $He^4$'s of #3 and #4 is acceptable, but the predicted reduced $H\phi$ for $H^3$ is considerably less than the observed value, — 1.8 instead of $2.6 \times 10^5$ gauss-cm. However, if the estimated uncertainties in slant radii-of-curvature and a 10 percent error in the relative stopping power $K$ of the gas mixture are taken in the appropriate direction, then the predicted and observed values for $H\phi$ are just barely in agreement. That prong 5 is probably $H^3$ is further borne out by the plausible
momentum and energy balances, and the reasonable incident neutron energy that are obtained below with that assumption.

So far it has been decided that #1 is $^1\text{H}$ or $^2\text{H}$, #3 and #4 are $^4\text{He}$, and #5 is $^2\text{H}$. A charge balance now requires that #2 be doubly-charged. By the range-curvature comparisons of Table 16b it may be $^4\text{He}$ or $^6\text{He}$. $^3\text{He}$ is ruled out because its predicted $\Phi$ is too low. $^6\text{He}$ may also be ruled out because, with the previous assumptions already made, it would necessitate more than the allowed 17 mass units available.

This, then, leaves #2 as probably $^4\text{He}$. The predicted ionization for $^4\text{He}$ also seems reasonable in comparison with its own and the other track densities.

Now both the mass and the charge of all but prong 1 has been assigned. #1 is believed to be either a proton or a deuteron. If it is a proton there must be one secondary neutron present to account for all the mass units; if it is a deuteron there can be no secondary neutron. To decide between these two possibilities and to check further on the reasonableness of the assumed identities of the other prongs, a momentum balance and an energy balance may be attempted. This has been done in Table 17. Momentum has been measured in units of $\pi$. The transverse x- and y- components of momentum do not quite balance out. The lack of balance might be explained by large errors in measurement, but may also be ascribed to the presence of a secondary neutron whose momentum, not being measurable, has been unaccounted for in Table 17. The acceptance of this latter possibility is strengthened when it is found that a plausible energy balance is obtained when prong
l is assumed to be a proton rather than a deuteron. This has been done in Table 17. It may be noted that the sum of the energies of the observed particles determined from their $E\rho$'s, masses and charges, plus the binding energy of the reaction (determined from the mass excess of the disintegration fragments with respect to the masses of the incident neutron and initial oxygen nucleus) is 89 Mev, or 4 Mev greater than the 85 Mev determined for the energy of the incident neutron from the net forward momentum of the observed particles. The 4 Mev discrepancy may readily be accounted for by assuming a low energy secondary neutron with forward and transverse momentum components. There is no reason for calculating its (the secondary neutron's) energy, momentum and direction, however, although these quantities are easily determined; the uncertainties in the known quantities needed for the calculations are too large to permit even roughly accurate results. About all that can be said is that the secondary neutron is probably of low energy -- a few Mev at most.

On the other hand, if prong 1 has been assumed a deuteron, the energy of this prong would have been reduced to 13 instead of 26 Mev and the binding energy would have been 32 Mev rather than 34 Mev, thus reducing the sum of the observed particle energies plus binding energy to 74 Mev, or 12 Mev less than that calculated for the incident neutron from the net forward momentum of the visible particles. With the conservation of mass units allowing no secondary neutron to account for any additional forward momentum, the only explanation of this large discrepancy in energies has to be in terms of the experimental errors. The uncertainty extremes are surely great enough so that such an explanation cannot be ruled out. However, it does seem more likely that a secondary neutron was present.
A final suggestion in favor of the presence of a secondary neutron comes from the fact that the 89 Mev figure is closer to the most probable value (90 Mev) for the incident neutron energy than the 74 Mev figure.
VIII. RESULTS

35 of the 65 photographs examined contained the 82 stars studied. These have been tabulated in Table 18 according to initial nucleus and number of prongs.

| 2-prong stars identified as helium | 14 |
| 2-  "  "  "  oxygen               | 14 |
| 2-  "  "  "  unidentified         | 20 |
| Total number of 2-prong stars     | 48 |
| 3-prong stars                     | 20 |
| 4-  "  "                          | 8  |
| 5-  "  "                          | 6  |
| Total                             | 82 |

Table 18. Tabulation of Kinds of Stars Observed

The average number of prongs per oxygen star was 2.8 or 3.1, depending upon whether or not the uncertain two-prong stars are included.

Angular Distribution

Data on these stars sufficient to be statistically significant are meager. The angular distribution of the charged particles of all the stars is given in the histogram of Figure 7. Only three particles have been omitted. Their tracks were so light that it was impossible to obtain even approximate measures of their dip angles and hence to calculate their scatter angles. There was found to be no marked difference in the scattering distribution for the separate categories of stars as tabulated in Table 18; and within the poor limits to which it was possible to identify the individual particles, it is not possible to state whether the angular distribution of light and heavy fragments is different or not.
It will be noted that almost exactly as many particles were scattered through less than 60° as were scattered at angles equal to or greater than 60°. A study of the distribution in $H\theta$ for those particles scattered through less than 60° shows it to be almost identical with the $H\theta$ distribution for those particles scattered through 60° and more.

The angular distribution shown is in the laboratory system. It would be desirable to have it in the center of mass system in order to determine whether or not the scattering is isotropic. If the disintegration were preceded by the formation of a compound nucleus then one would expect the scattering to be isotropic in the center of mass system. If, on the other hand, the scattering occurred primarily as a result of individual collisions between the incident neutron and the nuclear nucleons then one would expect the scattering to be primarily in the forward direction. However, to determine the center of mass the momentum of the incident neutron must be known; and to transform the scatter angle of a particle to the center of mass system its velocity must be known. Its velocity cannot be determined from its $H\theta$ unless its charge and mass are also known. These have not been known with any certainty in most cases, nor has the momentum of the incident neutron been known with any certainty.

$H\theta$ Distribution

It would also be very instructive to have an energy distribution for the visible particles. However, the determination of energy again depends upon an assumption as to the particle's mass and charge in addition to knowledge of its $H\theta$ or range. Instead the distribution in
the observed quantity $H_f$ has been given in the histogram of Figure 6. Again, the distribution has been given for all stars and all charged particles, except as noted; i.e., the $H_f$'s of 34 prongs could not be measured even approximately. These were prongs whose visible lengths were too short and/or whose dip angles were too large. In addition to these 34 prongs there were 32 others which stopped in the chamber whose $H_f$'s could not be determined directly because they were too short and/or crooked from scattering. Their possible $H_f$'s were determined from their range and the best guess as to their charge and mass. The assigned $H_f$'s of 22 of them were less than $2 \times 10^5$; only 2 were greater than $4 \times 10^5$. 20 of them were from two-prong stars. The one particle having an $H_f$ in the range 0 - 1 of Figure 8 actually had both an observed $H_f$ of $0.9 \times 10^5$ and a range in air of 0.9 cm, identifying it as $H^1$. In all honesty, the accuracy of a radius measurement for a track of such short length is highly uncertain and its $H_f$ could well have been two or three times greater than $0.9 \times 10^5$ gauss-cm.

All but 4 of the particles having $H_f$'s of $6 \times 10^5$ or greater and all above $8 \times 10^5$ gauss-cm are believed to have been singly-charged particles. The majority of these above $8 \times 10^5$ gauss-cm came from two-prong stars.

As a measure of the momentum and energy of the visible prongs, the average and root-mean-squared values of $H_f$ have been tabulated in Table 19. In arriving at these figures only data from those stars were used for which $H_f$ (either by direct measurement or from measured range) was available for all prongs of the star. The number of such stars in each category is included in the tabulation.
Differences Between Carbon and Oxygen Stars

There is one further comment that might be made here. During other studies by the Cloud Chamber Group numerous carbon stars have been observed. The oxygen stars observed in this present investigation do not appear essentially different from the carbon stars. That is, their general appearance as observed in the photographs in regard to number of prongs, range, curvature, track density, etc., is indistinguishable from that of carbon stars.
IX. ACKNOWLEDGEMENTS

Acknowledgements are due Dr. Wilson Powell for suggesting the subject of this research, for providing the facilities for carrying it out, for his active interest and encouragement, and for many valuable criticisms. Credit is due Dr. Evans Hayward, Mr. Walter Hart-sough, Mr. James Hulse and Mr. James DeJurens for setting up the cloud chamber and taking the photographs from which the data were obtained. Dr. Hayward also furnished much of the data for describing the apparatus used and made helpful suggestions during the writing of this paper. Miss Marguerite Hayward assisted in many ways and provided the enlargements of the cloud chamber photographs used as illustrations.

This paper is based upon work performed under the auspices of the Atomic Energy Commission.
APPENDIX I

CALCULATIONS FOR DERIVED QUANTITIES

\[ \theta = \cos^{-1} (\cos \alpha \cos \beta) \]
\[ \phi = \tan^{-1} (\tan \alpha \cos \beta) \]
\[ \rho = \rho_0 \cos \alpha \]
\[ R_A = R_G \]
\[ E = \frac{2F}{A} E^1 \quad \text{(In non-relativistic region)} \]

\[ (H\rho^2)_x = (H\rho^2_0) \cos^2 \alpha \sin \beta \]
\[ (H\rho^2)_y = (H\rho^2_0) \left( \frac{1}{2} \sin 2 \alpha \right) \]
\[ (H\rho^2)_z = (H\rho^2_0) \cos^2 \alpha \cos \beta \]
\[ (H\rho^2)_t = (H\rho^2_0) \cos \alpha \sin \theta = (H\rho^2_0) \cos \alpha \sqrt{1 - \cos^2 \alpha \cos^2 \beta} \]

Binding energy = mass defect \times 9.3 \times 10^5 \text{ ev}
APPENDIX II

NOMENCLATURE AND TERMINOLOGY

Beam Direction  -- The direction of the neutron beam in the cloud chamber. The forward direction of the neutrons is taken as positive.

Horizontal plane, or the horizontal  -- Any horizontal plane in the cloud chamber. It is parallel to the beam direction and normal to the direction of the magnetic field.

Vertical plane  -- Any vertical plane in the cloud chamber. It is not necessarily parallel to the beam direction.

Transverse plane  -- Any vertical plane which is normal to the beam direction.

Slant plane  -- The slant plane is always with reference to a particular track or prong. It is the plane containing the initial track direction and the horizontal line perpendicular to the initial track direction. It may be thought of simply as the plane of the track; however, this is not strictly accurate because a charged particle moving in a magnetic field, in general, describes a spiral non-planar path. The slant plane is at the dip angle $\alpha$ to the horizontal.

Initial track direction  -- This is the space direction defined by the tangent to the (curved) track at its point of origin, i.e., at the point of disintegration or collision with the incident neutron. It is taken positive in the forward track direction.
Measured data — Quantities which were measured directly upon the image of the star as projected on the projector screen, e.g., $\alpha$, $\beta$, $R_q$, $\rho$, etc.

Derived data — Quantities which have been calculated from other (usually measured) data, e.g., $\theta$, $\phi$, $R_A$, $H\rho$, $E$, etc.

Predicted data — Quantities obtained from the auxiliary data of Figures 4, 5 and 6 and for which it has been necessary to assume the mass and charge of the particle concerned, e.g., $D$, $E$, predicted $R_A$, $H\rho_2$, etc.

Observed data — Quantities which have been measured or observed directly, or which have been derived directly from measured data. It includes the categories of measured and derived data but not of predicted data.

Visible track or length — That initial portion of the total path length of an ionizing particle which is visible in the photographs and hence, upon which measurements may be made.

Visible or observed particles — An ionizing particle whose path is visible, as opposed to neutrons whose paths are not visible.

Visible energy and momentum — The energy and momentum of visible particles.

Secondary neutron — Any neutron emanating from a star. The term includes the incident neutron after it has left the star when it is not considered to have been absorbed into a compound nucleus.

Primary or incident neutron — The particular neutron from the cyclotron beam which initiated a star.
\( \alpha \) (dip angle) -- The angle between the initial track direction and the horizontal. It is measured in a vertical plane and is considered positive when the track direction in the cloud chamber is downward.

\( \beta \) (beam angle) -- The angle between the beam direction and the horizontal projection of the initial track direction. It is measured in a horizontal plane and is considered positive when the track is counter-clockwise from the beam when looking down upon the chamber. Note: \( \beta \) was also used for the ratio of the velocity of an ionizing particle to the velocity of light in the equation for specific ionization.

\( \Theta \) (scatter angle) -- The polar angle between the initial track direction and the beam direction.

\( \phi \) (azimuthal angle) -- The angle between the horizontal plane and the projection of the initial track direction upon the transverse plane.

\( H \) -- Magnetic field strength in the cloud chamber.

\( \rho_s \) -- Slant radius of curvature. This is the actual radius of curvature of the track as measured in the slant plane. Unless otherwise specified, it is the initial track radius.

\( \rho \) -- Equivalent radius of curvature. The radius of curvature which a particle of slant radius \( \rho_s \) would have if it were moving in the horizontal plane, (i.e., normal to the magnetic field rather than oblique to it) with the same momentum.
\( \rho_{s2} \) and \( \rho_2 \) -- Reduced slant radius and reduced equivalent radius, respectively, referring to second measurement of curvature after change in range \( \Delta R \), along the track.

\( R_0 \) -- Range of a particle in the cloud chamber gas mixture.

\( R_A \) -- Equivalent range of a particle in air at 760 mm Hg and 15\(^\circ\) C.

\( \Delta R \) -- Change in range between track origin and the second measurement of (reduced) radius of curvature \( \rho_{s2} \).

\( K \) -- Ratio of stopping power in cloud chamber gas mixture to stopping power in air at 760 mm Hg and 15\(^\circ\) C.

\( D \) -- Specific ionization of particle on arbitrary scale used in Fig. 6.

\( A \) -- Mass number of particle.

\( z \) -- Atomic number of particle.

\( E \) -- Kinetic energy of particle.

\( E' \) -- Kinetic energy (without relativistic corrections) which a proton would have for the same value of \( H\rho \) as that of the particle under consideration.

\( x, y, z \) -- Subscripts referring to rectangular coordinate components of momentum expressed in \( H\rho \) units.

\( \gamma \) defines the beam direction. \( x \) is the horizontal transverse direction (taken positive to
-- the right when facing in the beam direction) and

\( y \) is the vertical (positive downward) transverse direction.

-- subscript referring to the transverse momentum component expressed in \( H/f \) units. It is the vector sum of the \( x \)- and \( y \)-components and is considered positive when the \( y \)-component is positive (i.e., when there is a downward component of momentum.)


3 E. H. Segre Chart, Addison-Wesley Press Inc.


<table>
<thead>
<tr>
<th>Atomic Number</th>
<th>Isotopes</th>
</tr>
</thead>
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<tr>
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</tr>
<tr>
<td>1</td>
<td>H$^1$, H$^2$, H$^3$</td>
</tr>
<tr>
<td>2</td>
<td>He$^3$, He$^4$, He$^6$</td>
</tr>
<tr>
<td>3</td>
<td>Li$^6$, Li$^7$, Li$^8$</td>
</tr>
<tr>
<td>4</td>
<td>Be$^7$, Be$^9$, Be$^{10}$</td>
</tr>
<tr>
<td>5</td>
<td>B$^{10}$, B$^{11}$, B$^{12}$</td>
</tr>
<tr>
<td>6</td>
<td>C$^{10}$, C$^{11}$, C$^{12}$, C$^{13}$, C$^{14}$</td>
</tr>
<tr>
<td>7</td>
<td>N$^{13}$, N$^{14}$, N$^{15}$, N$^{16}$</td>
</tr>
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Table I. Fragments Assumed Possible from an Oxygen Star
<table>
<thead>
<tr>
<th>Prong No.</th>
<th>$\alpha$ ($^\circ$)</th>
<th>$\beta$ ($^\circ$)</th>
<th>$\rho_s$ (cm)</th>
<th>$H_{\rho}$ ((10^5\text{ gauss-cm}))</th>
<th>$\theta$ ($^\circ$)</th>
<th>$\phi$ ($^\circ$)</th>
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<tr>
<td>1</td>
<td>20±3</td>
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<td>59±3</td>
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<td>94±0.3</td>
<td>20±3</td>
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<td>-9.5±1</td>
<td>-26±0.5</td>
<td>129±6</td>
<td>16.8±0.8</td>
<td>28±0.3</td>
<td>20±3</td>
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Table 2. Observed Data on Star 1 of Plate 2.

<table>
<thead>
<tr>
<th>Prong No.</th>
<th>Assumed Identity</th>
<th>Transverse Momentum ((H_{\rho}s)_t) (\text{MeV})</th>
<th>Forward Momentum ((H_{\rho}s)_f) (\text{MeV})</th>
<th>Predicted Energy ((\text{MeV}))</th>
<th>Predicted Ionization D</th>
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<tr>
<td>1</td>
<td>$H^1$</td>
<td></td>
<td></td>
<td>25.5±0.3</td>
<td>23</td>
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<td></td>
<td>$H^2$</td>
<td>7.3±0.5</td>
<td>-0.5±0.1</td>
<td>12.7±0.2</td>
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<td></td>
<td>$H^3$</td>
<td></td>
<td></td>
<td>8.5±0.1</td>
<td>130</td>
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<td>2</td>
<td>$H^1$</td>
<td></td>
<td></td>
<td>125 ± 10</td>
<td>7.2</td>
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<td></td>
<td>$H^2$</td>
<td>-7.7±0.4</td>
<td>14.9±0.8</td>
<td>67 ± 5</td>
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<td></td>
<td>$H^3$</td>
<td></td>
<td></td>
<td>45 ± 2</td>
<td>38</td>
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Table 3. Momentum Balance and Predicted Data on Star 1 of Plate 2.
<table>
<thead>
<tr>
<th>Key</th>
<th>Assumed Identity</th>
<th>Predicted Relative Ionization (#1 / #2)</th>
<th>Binding Energy (Mev)</th>
<th>Sum of Binding and Visible Energies (Mev)</th>
<th>Min. Primary Energy (Mev)</th>
<th>No. of Secondary Neutrons</th>
<th>Reasons for Rejection</th>
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<tbody>
<tr>
<td>a</td>
<td>H^1 H^1</td>
<td>3.2</td>
<td>28.1</td>
<td>178±10</td>
<td>16±10</td>
<td>3</td>
<td>B</td>
</tr>
<tr>
<td>b</td>
<td>H^1 H^2</td>
<td>1.1</td>
<td>25.9</td>
<td>118±5</td>
<td>119±5</td>
<td>2</td>
<td>A</td>
</tr>
<tr>
<td>c</td>
<td>H^2 H^1</td>
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<td>25.9</td>
<td>164±10</td>
<td>17±10</td>
<td>2</td>
<td>B</td>
</tr>
<tr>
<td>d</td>
<td>H^1 H^3</td>
<td>0.6</td>
<td>19.8</td>
<td>90±2</td>
<td>90±2</td>
<td>1</td>
<td>A</td>
</tr>
<tr>
<td>e</td>
<td>H^3 H^1</td>
<td>18</td>
<td>19.8</td>
<td>153±10</td>
<td>165±10</td>
<td>1</td>
<td>A, B</td>
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<tr>
<td>f</td>
<td>H^2 H^2</td>
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<td>23.8</td>
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<td>g</td>
<td>H^2 H^3</td>
<td>1.8</td>
<td>17.6</td>
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<td>94±11</td>
<td>0</td>
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<td>h</td>
<td>H^3 H^2</td>
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<td>17.6</td>
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<td>94±11</td>
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<td>A, C</td>
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</table>

Table 4. Energy Balance and Minimum Primary Energy for Star 1 of Plate 2.

Reasons for rejection in Tables 4 and 7.

A  Predicted relative ionization too small or too large.
B  Minimum energy of incident neutron too large.
C  Energy balance impossible to achieve.
D  Change-of-Hp data shows prong 2 to be either H^2 or H^3.
\[ H = 1.33 \times 10^4 \text{ gauss} \]

<table>
<thead>
<tr>
<th>Prong No.</th>
<th>( \alpha ) (°)</th>
<th>( \beta ) (°)</th>
<th>( \rho_0 ) (cm)</th>
<th>( H_{05}^{10^5} ) (gauss-cm)</th>
<th>( \theta ) (°)</th>
<th>( \phi ) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5 ±0.5</td>
<td>6 ±0.5</td>
<td>139 ±5</td>
<td>18.5 ±0.7</td>
<td>6 ±0.5</td>
<td>5 ±5</td>
</tr>
<tr>
<td>2</td>
<td>-1 ±1</td>
<td>-150.5 ±0.5</td>
<td>27 ±0.5</td>
<td>3.6 ±0.1</td>
<td>150.5 ±0.5</td>
<td>182 ±2</td>
</tr>
</tbody>
</table>

Table 5. Observed Data on Star 1 of Plate 3.

Initial Observed \( H_0 = 3.6 \pm 0.1 \times 10^5 \text{ gauss-cm} \)

Observed Reduced \( H_2 \) 3.4 ±0.1 \( \times 10^5 \text{ gauss-cm} \)

<table>
<thead>
<tr>
<th>Assumed Particle</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<tr>
<td>Predicted reduced ( H_2 ) after ( \Delta R_A ) of 2.2 cm (10^5 gauss-cm)</td>
<td>3.4 to 3.6</td>
<td>3.1 to 3.4</td>
<td>2.2 to 2.9</td>
<td>1.0</td>
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Table 6. Change-of-\( H_2 \) Comparisons for Prong 2 of Star 1 of Plate 3.
<table>
<thead>
<tr>
<th>Prong No.</th>
<th>Assumed Identity</th>
<th>Transverse momentum $(H_\rho z)_t$</th>
<th>Forward momentum $(H_\rho z)_f$</th>
<th>Predicted energy (Mev)</th>
<th>Predicted Ionization D</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>$^1H$</td>
<td>$1.9 \pm 0.2$</td>
<td>$18.5 \pm 0.7$</td>
<td>$150 \pm 10$</td>
<td>$6.5$</td>
</tr>
<tr>
<td></td>
<td>$^2H$</td>
<td></td>
<td></td>
<td>$80 \pm 5$</td>
<td>$18$</td>
</tr>
<tr>
<td></td>
<td>$^3H$</td>
<td></td>
<td></td>
<td>$54 \pm 3$</td>
<td>$34$</td>
</tr>
<tr>
<td>2</td>
<td>$^1H$</td>
<td>$-1.8 \pm 0.1$</td>
<td>$-3.1 \pm 0.1$</td>
<td>$6.2 \pm 0.2$</td>
<td>$81$</td>
</tr>
<tr>
<td></td>
<td>$^2H$</td>
<td></td>
<td></td>
<td>$3.1 \pm 0.1$</td>
<td>$230$</td>
</tr>
<tr>
<td></td>
<td>$^3H$</td>
<td></td>
<td></td>
<td>$2.1 \pm 0.1$</td>
<td>$390$</td>
</tr>
</tbody>
</table>

Table 7. Momentum Balance and Predicted Data on Star 1 of Plate 3

<table>
<thead>
<tr>
<th>Key</th>
<th>Assumed Identity</th>
<th>Predicted relative ionization (#2 / #1)</th>
<th>Binding energy (Mev)</th>
<th>Sum of Binding and visible energies (Mev)</th>
<th>Min. primary energy (Mev)</th>
<th>No. of secondary neutrons (Mev)</th>
<th>Reasons for Rejections</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>$^1H$</td>
<td>$^1H$</td>
<td>12</td>
<td>$184 \pm 10$</td>
<td>$189 \pm 10$</td>
<td>3</td>
<td>B, B</td>
</tr>
<tr>
<td>b</td>
<td>$^1H$</td>
<td>$^2H$</td>
<td>35</td>
<td>$179 \pm 10$</td>
<td>$186 \pm 10$</td>
<td>2</td>
<td>B</td>
</tr>
<tr>
<td>c</td>
<td>$^2H$</td>
<td>$^1H$</td>
<td>4.5</td>
<td>$112 \pm 5$</td>
<td>$112 \pm 5$</td>
<td>A</td>
<td>A, D</td>
</tr>
<tr>
<td>d</td>
<td>$^1H$</td>
<td>$^3H$</td>
<td>60</td>
<td>$172 \pm 10$</td>
<td>$185 \pm 10$</td>
<td>1</td>
<td>B</td>
</tr>
<tr>
<td>e</td>
<td>$^3H$</td>
<td>$^1H$</td>
<td>2.4</td>
<td>$80 \pm 3$</td>
<td>$82 \pm 3$</td>
<td>A</td>
<td>A, D</td>
</tr>
<tr>
<td>f</td>
<td>$^2H$</td>
<td>$^2H$</td>
<td>13</td>
<td>$107 \pm 5$</td>
<td>$107 \pm 5$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>$^2H$</td>
<td>$^3H$</td>
<td>22</td>
<td>$100 \pm 5$</td>
<td>$106 \pm 10$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>h</td>
<td>$^3H$</td>
<td>$^2H$</td>
<td>6.8</td>
<td>$74 \pm 3$</td>
<td>$106 \pm 10$</td>
<td>A, C</td>
<td></td>
</tr>
</tbody>
</table>

Table 8. Energy Balance and Minimum Primary Energy for Star 1 of Plate 3
<table>
<thead>
<tr>
<th>Prong No.</th>
<th>$\alpha$ (°)</th>
<th>$\beta$ (°)</th>
<th>$\rho_s$ (cm)</th>
<th>$\Delta R_G$ (cm)</th>
<th>$\rho s^2$ $H_0$ (10^5) (gauss-cm)</th>
<th>$\Theta$ (°)</th>
<th>$\phi$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-34.3</td>
<td>-60</td>
<td>76 ± 5</td>
<td>-</td>
<td>-</td>
<td>8.6 ± 0.8</td>
<td>65 -38</td>
</tr>
<tr>
<td>2</td>
<td>4.05</td>
<td>-8</td>
<td>31 ± 0.5</td>
<td>23</td>
<td>24 ± 1</td>
<td>4.2 ± 0.1</td>
<td>9 -28</td>
</tr>
</tbody>
</table>

Table 9. Observed Data on Star 1 of Plate 1.

<table>
<thead>
<tr>
<th>Prong No.</th>
<th>$\alpha$ (°)</th>
<th>$\beta$ (°)</th>
<th>$\rho_s$ (cm)</th>
<th>$\rho s^2$ $H_0$ (10^5) (gauss-cm)</th>
<th>$\Theta$ (°)</th>
<th>$\phi$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-41 ± 1</td>
<td>60.5</td>
<td>108 ± 3</td>
<td>10.8</td>
<td>68</td>
<td>-45</td>
</tr>
<tr>
<td>2</td>
<td>36 ± 3</td>
<td>-37</td>
<td>&gt;100</td>
<td>&gt;11</td>
<td>50</td>
<td>130</td>
</tr>
</tbody>
</table>

Table 10. Observed Data on Star 2 of Plate 4.

<table>
<thead>
<tr>
<th>Prong No.</th>
<th>$\alpha$ (°)</th>
<th>$\beta$ (°)</th>
<th>$\rho_s$ (cm)</th>
<th>$\rho s^2$ $H_0$ (10^5) (gauss-cm)</th>
<th>$\Theta$ (°)</th>
<th>$\phi$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5 ± 0.5</td>
<td>26.5</td>
<td>87 ± 2</td>
<td>11.6 ± 0.3</td>
<td>27</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>-16 ± 0.5</td>
<td>-37</td>
<td>63 ± 1</td>
<td>8.0 ± 0.1</td>
<td>40</td>
<td>205</td>
</tr>
</tbody>
</table>

Table 11. Observed Data on Star 3 of Plate 4.
### Table 12. Observed Data on Star 1 of Plate 5.

<table>
<thead>
<tr>
<th>Prong No.</th>
<th>$\alpha$ (°)</th>
<th>$\beta$ (°)</th>
<th>$\rho_s$ (cm)</th>
<th>$H_{05}/10$ (gauss·cm)</th>
<th>$\theta$ (°)</th>
<th>$\phi$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-6 ±1</td>
<td>37</td>
<td>62.5 ±2.5</td>
<td>8.4</td>
<td>37</td>
<td>-10</td>
</tr>
<tr>
<td>2</td>
<td>-11.5 ±0.5</td>
<td>-10</td>
<td>83 ±2</td>
<td>10.8</td>
<td>15</td>
<td>221</td>
</tr>
</tbody>
</table>

### Table 13. Observed Data on Star 2 of Plate 6

<table>
<thead>
<tr>
<th>Prong No.</th>
<th>$\alpha$ (°)</th>
<th>$\beta$ (°)</th>
<th>$\rho_s$ (cm)</th>
<th>$H_{05}/10$ (gauss·cm)</th>
<th>$\theta$ (°)</th>
<th>$\phi$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-4 ±2</td>
<td>66</td>
<td>52 ±3</td>
<td>6.9 ±0.4</td>
<td>66</td>
<td>-4</td>
</tr>
<tr>
<td>2</td>
<td>-20 ±5</td>
<td>-48</td>
<td>65.5 ±3.5</td>
<td>9.4 ±2</td>
<td>51</td>
<td>206</td>
</tr>
</tbody>
</table>

### Table 14. Measured Data on 5-Prong Star 1 of Plate 7

<table>
<thead>
<tr>
<th>Prong No.</th>
<th>$\delta$ (°)</th>
<th>$\beta$ (°)</th>
<th>$\rho_s$ (cm)</th>
<th>$R_G$ (cm)</th>
<th>$\Delta R_G$ (cm)</th>
<th>$\rho e^2$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-12 ±2</td>
<td>114 ±1</td>
<td>56 ±1</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>2</td>
<td>-13 ±3</td>
<td>130 ±1</td>
<td>14.0 ±0.5</td>
<td>4.0 ±0.1</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>3</td>
<td>11.5 ±2</td>
<td>-60 ±1</td>
<td>37.5 ±0.5</td>
<td>--</td>
<td>11</td>
<td>36 ±1</td>
</tr>
<tr>
<td>4</td>
<td>1 ±1</td>
<td>-10 ±1</td>
<td>38.5 ±0.5</td>
<td>--</td>
<td>21</td>
<td>35 ±1</td>
</tr>
<tr>
<td>5</td>
<td>7.5 ±1</td>
<td>1 ±1</td>
<td>27.5 ±0.5</td>
<td>--</td>
<td>20</td>
<td>19 ±1</td>
</tr>
</tbody>
</table>

$H = 1.35 \times 10^4$ gauss
<table>
<thead>
<tr>
<th>Prong No.</th>
<th>$\Theta$ (°)</th>
<th>$\rho$ (cm)</th>
<th>$H_\rho$ (10^5 gauss-cm)</th>
<th>$R_A$ (cm)</th>
<th>$\Delta R_A$ (cm)</th>
<th>$H_\rho$ (10^5 gauss-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>113</td>
<td>55</td>
<td>7.4</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>2</td>
<td>129</td>
<td>13</td>
<td>1.8</td>
<td>0.68</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>3</td>
<td>61</td>
<td>37</td>
<td>5.0</td>
<td>--</td>
<td>1.9</td>
<td>4.8</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>38</td>
<td>5.2</td>
<td>--</td>
<td>3.6</td>
<td>4.7</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>27</td>
<td>3.7</td>
<td>--</td>
<td>3.4</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Table 15. Derived Data on 5-Prong Star 1 of Plate 7.

<table>
<thead>
<tr>
<th>$\rho = 55$ cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumed particle</td>
</tr>
<tr>
<td>Predicted Ionization $D$</td>
</tr>
</tbody>
</table>

Table 16a. Specific Ionization Comparisons for Prong 1 of Star 1 of Plate 7.

Observed range (in air) $R_A = 0.68$ cm

Observed $H_\rho = 1.8$ gauss-cm.

<table>
<thead>
<tr>
<th>Assumed particle</th>
<th>$He^3$</th>
<th>$H^2$</th>
<th>$He^4$</th>
<th>$He^6$</th>
<th>$Li^6$</th>
<th>$Be^7$</th>
<th>$H^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_\rho$ predicted from $R_A$ (10^5 gauss-cm)</td>
<td>1.4</td>
<td>1.6</td>
<td>1.6</td>
<td>1.9</td>
<td>2.0</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Predicted Ionization $D$ (for $\rho = 13$ cm)</td>
<td>&gt;1000</td>
<td>600</td>
<td>~1500</td>
<td>&gt;2000</td>
<td>&gt;4000</td>
<td>&gt;4000</td>
<td>800</td>
</tr>
</tbody>
</table>

Table 16b. Range-$H$ Comparisons for Prong 2 of Star 1 of Plate 7.
Initial Observed $H_\rho = 5.0 \times 10^5$ gauss-cm

Observed Reduced $H_\rho_2 = 4.8 \times 10^5$ gauss-cm

<table>
<thead>
<tr>
<th>Assumed particle</th>
<th>$H^2$</th>
<th>He$^3$</th>
<th>He$^4$</th>
<th>H$^3$</th>
<th>Li$^6$</th>
<th>Be$^7$</th>
<th>Li$^7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted Reduced $H_\rho_2$ after $\delta R_A$ of 1.9 cm ($10^5$ gauss-cm)</td>
<td>4.9</td>
<td>4.9</td>
<td>4.8</td>
<td>4.7</td>
<td>4.7</td>
<td>4.7</td>
<td>4.6</td>
</tr>
<tr>
<td>Predicted Ionization D (for $\rho = 37$ cm)</td>
<td>140</td>
<td>360</td>
<td>580</td>
<td>260</td>
<td>1000</td>
<td>&gt;1000</td>
<td>&gt;1000</td>
</tr>
</tbody>
</table>

Table 16c. Specific Ionization and Change-of-$H_\rho$
Comparisons for Prong 3 of Star 1 of Plate 7.

Initial Observed $H_\rho = 5.2 \times 10^5$ gauss-cm

Observed Reduced $H_\rho_2 = 4.7 \times 10^5$ gauss-cm

<table>
<thead>
<tr>
<th>Assumed particle</th>
<th>$H^2$</th>
<th>He$^3$</th>
<th>He$^4$</th>
<th>H$^3$</th>
<th>Li$^6$</th>
<th>Be$^7$</th>
<th>Li$^7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted Reduced $H_\rho_2$ after $R_A$ of 3.6 cm ($10^5$ gauss-cm)</td>
<td>5.0</td>
<td>5.0</td>
<td>4.8</td>
<td>4.6</td>
<td>4.6</td>
<td>4.6</td>
<td>4.3</td>
</tr>
<tr>
<td>Predicted Ionization D (for $\rho = 38$ cm)</td>
<td>140</td>
<td>350</td>
<td>560</td>
<td>250</td>
<td>&gt;1000</td>
<td>&gt;1000</td>
<td>&gt;1000</td>
</tr>
</tbody>
</table>

Table 16d. Specific Ionization and Change-of-$H_\rho$
Comparisons for Prong 4 of Star 1 of Plate 7.
Initial Observed $H\rho = 3.7 \times 10^5$ gauss-cm

Observed Reduced $H\rho_2 = 2.6 \times 10^5$ gauss-cm

<table>
<thead>
<tr>
<th>Assumed particle</th>
<th>$H^2$</th>
<th>$He^3$</th>
<th>$He^4$</th>
<th>$H^3$</th>
<th>$Li^6$</th>
<th>$Be^7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted Reduced $H\rho_2$ after $R_A$ of 3.4 cm ($10^5$ gauss-cm)</td>
<td>3.3</td>
<td>3.3</td>
<td>2.7</td>
<td>1.8</td>
<td>0.9</td>
<td>1.1</td>
</tr>
<tr>
<td>Predicted Ionization D (for $\rho = 27$ cm)</td>
<td>230</td>
<td>600</td>
<td>900</td>
<td>390</td>
<td>&gt;1000</td>
<td>&gt;1000</td>
</tr>
</tbody>
</table>

Table 16e. Specific Ionization and Change-of-$H\rho$
Comparisons for Prong 5 of Star 1 of Plate 7.
<table>
<thead>
<tr>
<th>Frong No. Particle</th>
<th>(10^5 \frac{H\rho}{gauss-cm} )</th>
<th>(H\rho z ) ((z \times 10^5))</th>
<th>(H\rho z) (\gamma)</th>
<th>(E') (\text{(MeV)})</th>
<th>(E) (\text{(MeV)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (H^1)</td>
<td>7.4</td>
<td>6.6</td>
<td>1.5</td>
<td>-3.0</td>
<td>26.</td>
</tr>
<tr>
<td>2 (He^4)</td>
<td>1.8</td>
<td>2.8</td>
<td>0.8</td>
<td>-2.3</td>
<td>1.6</td>
</tr>
<tr>
<td>3 (He^4)</td>
<td>5.0</td>
<td>-8.4</td>
<td>-2.0</td>
<td>4.9</td>
<td>12</td>
</tr>
<tr>
<td>4 (He^4)</td>
<td>5.2</td>
<td>-1.8</td>
<td>-0.1</td>
<td>10.3</td>
<td>13</td>
</tr>
<tr>
<td>5 (H^3)</td>
<td>3.7</td>
<td>0.0</td>
<td>-0.5</td>
<td>3.7</td>
<td>6.6</td>
</tr>
<tr>
<td>Net Momentum Components</td>
<td></td>
<td>-0.8</td>
<td>-0.3</td>
<td>13.6</td>
<td></td>
</tr>
<tr>
<td>Total kinetic energy of observed particles (\text{(MeV)})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>55</td>
</tr>
<tr>
<td>Binding energy of reaction (\text{(MeV)})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>34</td>
</tr>
<tr>
<td>Sum of observed and binding energies (\text{(MeV)})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>89</td>
</tr>
<tr>
<td>Minimum energy of incident neutron determined from net forward momentum of visible particles (\text{(MeV)})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>85</td>
</tr>
</tbody>
</table>

Table 17. Momentum and Energy Balances for Star 1 of Plate 7.
<table>
<thead>
<tr>
<th>Type of Star</th>
<th>2-Prong</th>
<th>3-Prong</th>
<th>4-Prong</th>
<th>5-Prong</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All</td>
<td>Probably</td>
<td>Probably</td>
<td>Unknown</td>
</tr>
<tr>
<td>Number of Stars</td>
<td>32</td>
<td>7</td>
<td>13</td>
<td>12</td>
</tr>
<tr>
<td>Average $H\rho$ (10^5 gauss -cm)</td>
<td>4.7</td>
<td>9.1</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>rms $H\rho$ (10^5 gauss -cm)</td>
<td>6.0</td>
<td>9.7</td>
<td>4.1</td>
<td>4.8</td>
</tr>
<tr>
<td>Proton energy corresponding to rms $H\rho$ E'</td>
<td>17</td>
<td>45</td>
<td>8</td>
<td>11</td>
</tr>
</tbody>
</table>

Table 19. Mean and RMS Values of $H\rho$. 
Figure 1. - Theoretical Energy Distribution of Neutron Beam
I5-INCH HELMHOLTZ-COIL CLOUD CHAMBER

FIGURE 2
Figure 5—Proton Energy vs. $H_p$
Figure 6. Specific ionizations vs. $\rho$
Figure 7. - Angular Distribution of All Particles from All Stars
Figure 8. - Hp Distribution of All Particles from All Stars

Note: Total number of particles = 218.
Of these 34 had Hp's that could not be measured.
20 of the 34 probably had Hp's > 6 \times 10^5 \text{ gauss-cm}.
14 of the 34 probably had Hp's < 6 \times 10^5 \text{ gauss-cm.}
Key to Plate 3
Key to Plate 6
Key to Plate 7
Beam Direction

Key to Plate II