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Physical Analysis of Be and C Disintegration Induced by 330-Mev Protons

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The disintegration products of carbon and beryllium emerging from thin targets bombarded by an internal cyclotron beam of 330-Mev protons have been studied. The magnetic field of the cyclotron is employed for momentum analysis and nuclear track plates for detection and range analysis. On plotting radius of curvature *versus* range, various nuclear species are found to fall on identifiable loci. The relative abundances of the products and their momentum spectra are obtained. Hydrogen, helium, lithium, and boron products have been found and their abundances tabulated. Alpha-particles prove to be the most important charged particle product. Beryllium yields significantly more tritium than carbon. Some of the heavy products are found with very high momenta.

INTRODUCTION

SUBSTANTIAL progress has been made in understanding high energy nuclear disintegrations by analyzing the radioactive products remaining in the target after bombardment. Nevertheless, many questions remain unanswered if one is limited to this method for the study of such processes. We have undertaken to develop another method of analysis which provides wholly new information regarding the identifications, populations, momentum distributions, and angular distributions of disintegration products, including those which are not radioactive. Early results[1] obtained on the disintegration products of carbon bombarded by protons were encouraging. The present paper reports a more comprehensive experiment which confirms the previous study and extends it to other momentum intervals and to a comparison element. While a study of these light element reactions appeared to be the most tractable problem at the beginning of the program, we have found that the methods are generally useful, and work is now in progress on a number of other target elements with proton, deuteron, and alpha-particle beams of various energies. Angular distributions of disintegration products, and, in some cases, absolute cross sections are also obtained and will be reported in subsequent publications.

[1] W. H. Barkas and J. K. Bowker, Phys. Rev. 87, 205 (1952).

EXPERIMENTAL ARRANGEMENT

The magnetic field of the 184-inch cyclotron provides a means for analyzing the momentum of nuclear disintegration products emitted from an internal target. Nuclear track emulsion is employed to detect the products and at the same time enables one to measure their ranges. Measurements of the position and direction of a track also suffice for calculation of the radius of curvature of the particle orbit. As supplementary information, the ionization of the track is estimated in a manner to be explained later.

In the present experiment, ribbon targets of Be (8.7 mg/cm^2) and polystyrene (2.9 mg/cm^2) about 2 mm in width were exposed to the circulating beam of protons at a radius of 79 inches. The ribbon extended parallel to the magnetic field, and its smallest dimension was traversed by the protons. The hydrogen in the polystyrene plays no part in the present experiment, and the targets are sufficiently thin that the measured momentum spectrum of no important product is much affected by the target thickness.

The disintegration products, spiraling slightly downward from the forward direction, are collected on plates placed emulsion upward in a plane parallel to the median plane of the cyclotron and $5\frac{1}{2}$ inches below it. The beam is clipped radially by a carbon block on the opposite side of the proton orbit at a radius two inches

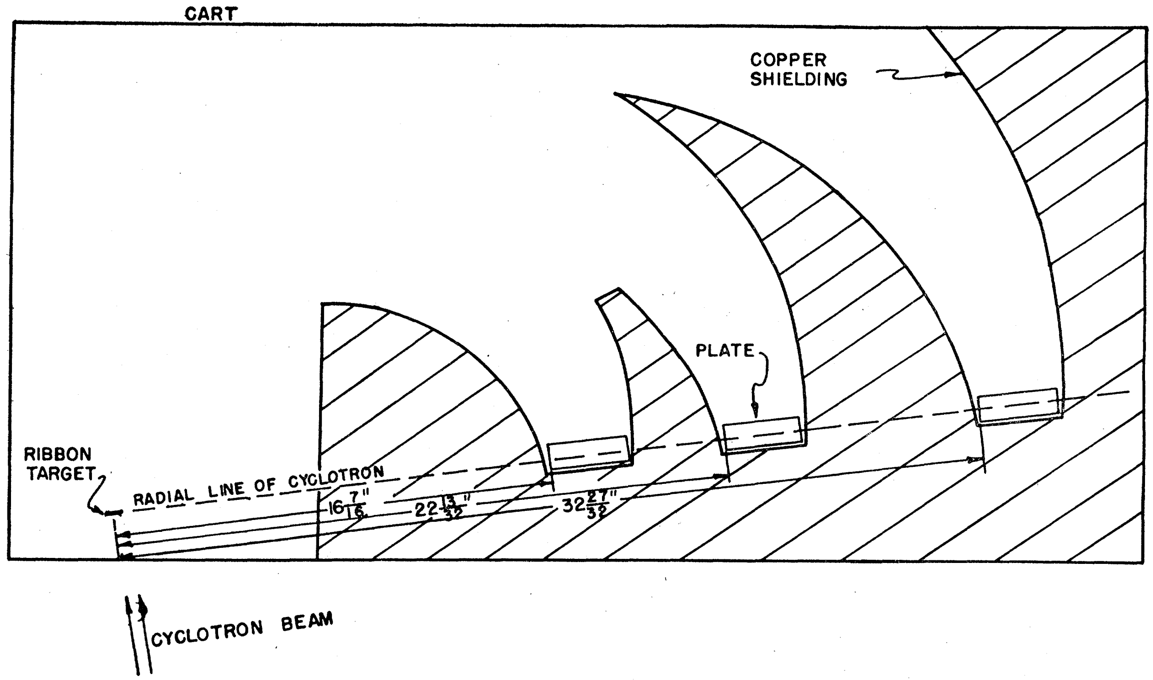

FIG. 1. Plan view of apparatus. The cart loaded with the copper shielding and with the plates in the positions shown enters the cyclotron vacuum tank through an air lock. The cart is low enough to be entirely under the circulating beam; only the ribbon target intercepts the beam. The disintegration products spiral down slightly and enter the plates through the surface of the emulsion. Blocks of wolfram are placed as roofs over the plates to reduce stray light and background particle tracks.

greater than the target radius. Vertical oscillations are also clipped so that the beam is largely confined to the height of $\frac{3}{4}$ inch as determined by radio-autographs of the target. Shielding is placed to protect the plates against stray particles of the main beam and against neutrons from the target. Channels are built in the shielding so as to permit fragments leaving the target with an azimuth angle of $0\pm10°$ to the beam to reach the plates, which are placed on the line extending from the center of the cyclotron to the target. Three 1-in.$\times$3-in. plates are placed at nominal distances of 18 in., 24 in., and $34\frac{1}{2}$ in. from the target so that protons reaching them from the target will have energies of approximately 5, 10, and 20 Mev. Ilford C-2 emulsion of moderate sensitivity is used so as to obtain some ionization discrimination while yet being able to see the higher energy protons in the emulsion. The whole apparatus is mounted on a cart which enters the cyclotron tank through an air-lock, the dimensions of which limits the momentum interval studied. The nuclear fragments enter the emulsion through the surface at a small angle. Figure 1 is a schematic diagram showing the relationship of the target, detecting plates, and shielding.

METHOD OF ANALYSIS

The position, range, and azimuth angle of each track on a measured area of the plate are recorded. In addition the number of gaps, where developed grains are missing, is counted in each track. Only tracks entering the emulsion through the surface with an azimuth angle of $180°\pm10°$ are accepted. The calculated radius of curvature is then insensitive to small errors in the azimuth angle, which could be measured to $\pm1°$. A "radius of curvature" of each orbit is calculated allowing for the pitch of the spiral. The geometrical quantity calculated is equal to $pc/Z'eB$, where p is the total momentum, Z' the number of units of charge carried by the fragment when it is bent in the magnetic field, B is the effective magnetic induction in gauss, and e/c the electronic charge in emu. Using these data, the radius of curvature is plotted against the range, one track determining a point. In such a diagram the points of each nuclear type fall on a characteristic locus. The identification of each locus is made using curves which we have constructed relating radius of curvature and range for the various disintegration products. To do this, we first verified the existing[2] range-energy relations for hydrogen and helium isotopes using readily identified tracks in our plates. From light element targets, we also find numerous "hammer" tracks which are recognized as tracks of Li^8 and B^8. From these, range energy curves for all Li and B isotopes were constructed. The extension of the range arising from electron pick-up by slow ions is evaluated empirically,[3] and good estimates of the range energy relations for other light elements may then be obtained by interpolation and extrapolation. It was observed, as anticipated, that both Li^8 and B^8 splinters

[2] J. J. Wilkins, Atomic Energy Research Establishment Report AERE *G/R* 664 (Harwell, 1951) (unpublished).
[3] W. H. Barkas (to be published).

of low velocity fell on more than one locus, each locus corresponding to the charge carried by the ion when it was bent in the magnetic field. Appropriate[4] correction for the non-uniformity of the magnetic field was made in obtaining the range energy curves. Some loci, notably those of He^3 and H^2, overlap. Identification of such tracks are then made by the gap counts. If G is the number of gaps in a residual range R, and M the ionic atomic weight, then $G/M=f(R/M)$, where $f(R/M)$ is the same function of R/M for all isotopes of an element. Curves of $f(R/M)$, prepared from tracks of other isotopes which had been identified, provided the means for separating completely the He^3 from the H^2.

Background tracks, which arise chiefly from neutron collisions, have not been a serious problem. Selection of tracks which enter the surface of the emulsion in the proper direction serves almost completely to eliminate extraneous tracks, which in any case do not fall on definite loci. This statement must be qualified for some short tracks which we have as yet been unable to analyze. They are supposed to be fragments carrying reduced charges as well as heavy nuclei. In this region the background contamination is unknown.

Reduction of the data from plates at different distances from the target requires some analysis. The conversion of the observed number of tracks of a given species per unit area per unit interval of azimuth angle to the number per unit solid angle per unit radius of curvature interval leaving the target is accomplished in multiplying by the Jacobian of the transformation. The special case of 180° bending here employed is particularly simple and the Jacobian reduces to $2h[1+(\pi r/h)^2]$, where h is the distance of the plate from the median plane, and r is the radius of the orbit projected on the median plane. This transformation has been carried out so that the data from the different plates may be compared. The radius of curvature, as here employed, is $pc/Z'eB$. The momentum corresponding to a given radius of curvature therefore depends on Z'.

RESULTS

The data obtained are presented in Table I. It is normalized so that the same total number of fragments per unit solid angle are considered for carbon as for beryllium. The data from Be and C were plotted on a single diagram in finding the loci. Populations are tabulated only for recognizable loci, and the rest of the tracks are lumped as unclassified nuclei and background. We could not separate Li^6 and Be^7.

[4] W. H. Barkas, Phys. Rev. **78**, 90 (1950).

TABLE I. Normalized number of tracks per unit solid angle per unit radius of curvature interval in percent. The actual numbers of tracks counted are listed below the percentages in each case. Where the number is uncertain because of poor resolution, the number is bracketed. The magnetic field intensity was 14.3 kilogauss.

Radius of curvature interval	Beryllium products 22–24 cm	29.5–31.5 cm	43–45 cm	Carbon products 22–24 cm	29.5–31.5 cm	43–45 cm
H^1	11.6 121	10.0 90	5.9 84	13.1 106	8.8 72	6.7 52
H^2	4.3 45	3.7 34	3.7 52	2.5 20	2.9 24	3.5 27
H^3	4.5 47	4.0 37	3.3 48	1.7 (14)	1.6 13	1.8 15
He^3	4.6 48	4.5 42	1.6 23	3.5 28	3.4 28	2.2 17
He^4	14.0 146	15.4 143	4.1 58	17.1 137	16.9 143	6.2 49
Li^6, Be^7	0.8 (8)	1.2 11	0.2 3	0.9 (7)	0.9 8	0.1 1
Li^7	0.3 (3)	0.3 3	0.3 4	0.8 (6)	0.1 1	0.8 6
Li^8					0.1 1	
B^8						0.1 1
Unclassified products and background	0.7 7	0.7 6	0.6 9	2.1 17	1.2 10	1.1 9

The data reveal the following features: (a) A high percentage of the splinters are alpha-particles, suggesting a high degree of correlation between particles making up alpha-particle groups within these nuclei. The effect seems somewhat more pronounced in C than in Be. (b) From beryllium a significant excess of tritium is found which may be ascribed to an effect of the "extra" neutron in Be^9. (c) The momentum spectra of large nuclear fragments extend out to remarkably high values. Lithium products are found with more than $\frac{3}{5}$ of the momentum carried by the bombarding proton and the B^8 track listed carries the full momentum of the proton. (The identification of the B^8 is certain because it forms a hammer, and its range is as calculated.) (d) No new nuclear species were identified.

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