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Search for Radioactivity Induced by 800-Kilovolt Electrons

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A filament is mounted on the high voltage end of a Sloan radiofrequency resonance transformer and electrons are accelerated out of the vacuum tank through a thin window at a maximum energy of about 850 kv. About fifty elements have been bombarded with these electrons and examined with a Geiger counter for induced radioactivity. No positive results were obtained. This indicates that the yield is less than 1 activation per 10^{12} electrons of approximately 750 kv, provided that the half-lives have values between some seconds and one or two hours and that the products of disintegration are electrons of over 200 kv energy. The collision cross sections for such reactions have upper limits ranging from 10^{-35} cm^2 for hydrogen to 10^{-33} cm^2 for uranium.

INTRODUCTION

IN the course of development of the Sloan radiofrequency high voltage resonance transformer for the purpose of generating x-rays and for the acceleration of positive ions, it seemed worth while to convert the apparatus into a Lenard tube, so that electrons could be directed outward into the room where they might be conveniently used. High voltage Lenard tubes have been studied in some detail by Coolidge[1] but, as far as we are aware, cathode rays have never been used in an endeavor to assail the nucleus. Theoretically one would expect them to have little or no effect, since the de Broglie wave-length of an electron traveling with approximately the velocity of light is still several powers of ten larger than the nucleus. Furthermore, since the Fermi theory of β-emission postulates the simultaneous emission of a neutrino, one would expect that the reverse process would require the double entry of an electron and a neutrino into the nucleus. If, on the other hand, it were found experimentally possible to make a nucleus become a β-emitter by first driving only an electron into it, the Fermi postulate would seem to require some modification.

APPARATUS

The principles of a radiofrequency high voltage generator have been described by its designer[2] and its performance as an x-ray tube has been published.[3] It is therefore necessary here only to recall that it consists of a powerful short wave oscillator feeding into a single resonant circuit which consists of a single loop primary and a large water-cooled secondary coil both suspended in an evacuated metal tank. The secondary coil acts as a quarter wave-length antenna; its voltage node is at its upper end where it is attached to the grounded tank, and its voltage

* 1851 Exhibition Scholar.

[1] Coolidge, Science **62**, 441 (1925); J. Frank. Inst. **202**, 693, 722 (1926). Gen. Elec. Rev. **35**, 413 (1932).

[2] D. H. Sloan, Phys. Rev. **43**, 213 (1933); **47**, 62 (1935).

[3] Stone, Livingston, Sloan and Chaffee, Radiology **24**, 153 (1935); **24**, 298 (1935).

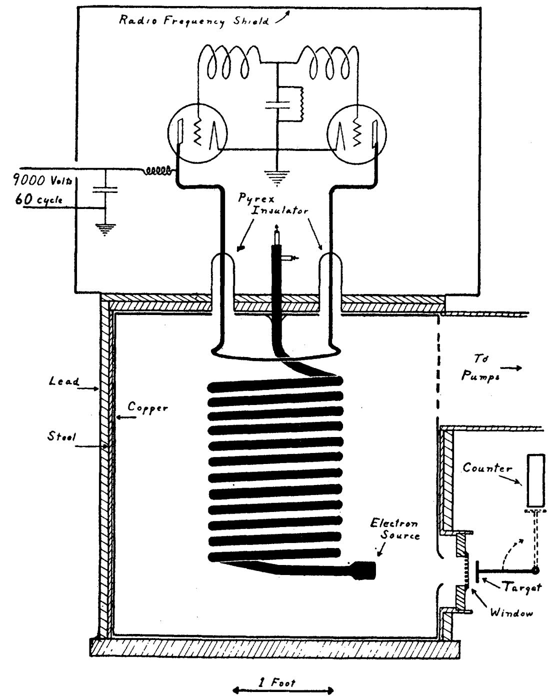

FIG. 1. High voltage radiofrequency resonance transformer, adapted for the acceleration of electrons.

loop is at the lower freely hanging end which executes high frequency oscillations, of about 44 meters wave-length, with an amplitude of some hundreds of kilovolts. When used as an x-ray tube, an anode is mounted on this high voltage end of the coil and a filament is placed at ground potential in the wall of the tank. Surrounding the filament is a grid several thousand volts negative with respect to it, so as to prevent the emission of electrons until the anode has neared the peak of its positive voltage oscillations, thus permitting an approximation to d.c. operation. To convert the apparatus into an electron accelerator of the Lenard type it was necessary to supply a source of electrons at the end of the high voltage coil and to mount a suitable window in the wall of the tank to allow the electrons to escape into the air of the room.

An early attempt at an electron source was simply an eighth-inch tungsten rod sharpened to a point and mounted on the end of the coil; as the voltage rises to a critical value cold emission sets in because of the intense electric field, and the source thus supplies its own bias to prevent emission at low voltage. This device, however, was unstable with regard to quantity and quality of emission, the sharpness of the point being quite critical, and the vacuum had to be lost for every adjustment.

Consequently advantage was taken of the construction of the main coil in order to mount a hot filament at its end. The coil is made of 7/8-inch outside diameter copper tubing within which is a copper tube of 7/16-inch diameter, the latter being covered with a layer of rubber tape to prevent heat transfer from the outgoing to the incoming water; the rubber is protected against erosion by a layer of thin copper tape. The two concentric pipes are therefore insulated from each other and serve admirably as lead wires to conduct current to the filament from a transformer at ground potential. The filament assembly is shown in Fig. 2; a copper glass seal and a tungsten glass seal are used to bring a connection from the inner tube out to the vacuum, the 0.080-inch tungsten rod being connected to the central pipe by a flexible wire for ease in assembly. The glass is protected from high frequency dielectric hysteresis and from cathode

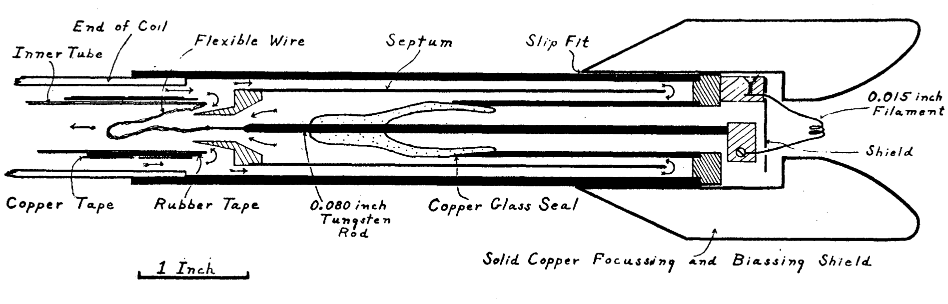

FIG. 2. Details of the filament assembly at the high voltage end of the transformer. The longitudinal hard rubber strips which align the septum have been omitted in the sketch for greater clarity. The direction of the water flow is indicated by arrows.

rays by the surrounding copper tube and by a small shield at the base of the filament. A thin cylindrical metal septum, held in place by longitudinal hard rubber strips (not shown in the figure), directs the water down to the end of the assembly, thus preventing stagnation and consequent boiling. By moving the rounded solid copper tip forward or backward the space charge around the filament can be considerably altered so that emission during the low parts of the voltage waves can be reduced. The filament is 20 cm from the tank wall.

This arrangement, though satisfactory, is not as good nor as flexible as would be an independently biased grid whose potential is controlled by a high voltage wire passing down the inside of the coil, but there are difficulties in obtaining a sufficiently well insulated wire that is small enough not seriously to hinder the flow of water. An alternative possibility would be to build into the filament unit a midget transformer, rectifier tube and filter condenser to supply the potential for a grid, driven through a circuit consisting of the main coil and a low voltage wire inside it.

The window for the electrons consists in a copper foil 0.001 inch thick soldered to a copper plate 2 inches in diameter and 3/16 inch thick and perforated by many 1/8-inch holes spaced 5/32 inch between centers. A water-cooling pipe is silver soldered to the periphery of this disk, which in turn is soldered to a larger brass plate attached with sealing wax to an aperture in the tank wall. The electron beam strikes the window over an area about 1 inch in diameter and currents of 300 microamperes (average, read on a d.c. meter) have been passed through without damage. Windows with larger holes covered with copper, nickel or molybdenum foils melted through in a few seconds, even though additionally cooled with jets of air or water. Scattering of the electrons in the foil and air is sufficient to bend the beam backwards so that a hemispherical glow can be seen, in the darkened room, of about six feet radius. All sealing-wax joints and rubber tubes in the immediate vicinity of the window must be shielded with metal, else a very rapid deterioration sets in due to the bombardment.

Knowledge of the energy of the electrons has been gained by rather rough absorption measurements. A plane collecting plate was mounted on an insulated stand about 2 inches from the window and connected to ground through a microammeter; absorbing foils of aluminum were placed between it and the window. To prevent the registration of electrons scattered around the foils, the collecting electrode was shielded with a diaphragm consisting of a large sheet of 1/4-inch lead with a 1-inch hole cut in it. Correlation between range and energy was made through the data of Varder,[4] the maximum range of 0.048-inch aluminum indicating an energy of 845 kv. To obtain this potential, the average power dissipated as heat in the coil, determined from the temperature rise of the cooling water, was 22.5 kw. The anode power supply (60-cycle a.c. at 9000 volts) totalled 70 kw, including the energy lost in the control resistances. The heating current for the oscillator filaments required 15 kw additional. Absorption curves were taken at a number of potentials applied to the anodes of the oscillator tubes and the heat dissipated in the coil was noted in each case. Comparison between the voltage developed (electron range plus window correction) and the power in the coil shows that these two quantities are quite well related by the equation

$$\text{Kilovolts}_{(\text{coil})} = 183\ (\text{Kilowatts}_{(\text{coil})})^{\frac{1}{2}}.$$

This form of equation was to be expected from elementary considerations, although the experimental value of the constant, of course, depends upon the inductance and capacity of the particular coil and vacuum tank used, as well as on the frequency and wave shape.

Search for Nuclear Disintegration

Because of the large intensity of the incidental x-rays, it was feasible at this time to search only for delayed radioactivity of targets bombarded by the electron beam after the exposure had been made and the high voltage shut off. The points of unprotected Geiger counters (connected to an amplifier and scale of two thyratron recorder) were quickly rendered unstable and useless by scattered electrons, even though no potential was applied to the point during bom-

[4] Varder, Phil. Mag. 29, 726 (1915).

TABLE I. *Elements bombarded and examined for radioactivity.*

Z		Form Used	Z		Form Used
1	H^1	H_3PO_4	34	Se	Metal
1	D^2	D_3PO_4	35	Br	KBr
3	Li	Metal	38	Sr	$SrCl_2$
4	Be	Metal	40	Zr	Metal
5	B	Pyrex, borax	41	Cb	Metal
6	C	solid	42	Mo	Metal
7	N	$Ca(NO_3)_2$	47	Ag	Metal
8	O	Various compounds	48	Cd	Metal
9	F	Ba F_2	50	Sn	Metal
11	Na	NaCl	51	Sb	Metal
12	Mg	Metal	52	Te	Metal
13	Al	Metal	53	I	KI
14	Si	Glass, sand	56	Ba	BaF_2
15	P	H_3PO_4	58	Ce	$Ce(NO_3)_3$
16	S	Solid	60	Nd	Nd $(NO_3)_3$
17	Cl	NaCl, KCl	73	Ta	Metal
19	K	KCl, KI	74	W	Metal
20	Ca	CaO, $Ca(NO_3)_2$	78	Pt	Metal
24	Cr	$K_2Cr_4O_7$	79	Au	Metal
25	Mn	$MnCl_2$	80	Hg	Hg–Cu amalgam
26	Fe	Metal	81	Tl	Metal
27	Co	$CoCl_2$	82	Pb	Metal
28	Ni	Metal	83	Bi	Metal
29	Cu	Metal	90	Th	$Th(NO_3)_4$
30	Zn	Metal	92	U	$U(NO_3)_3$
33	As	As_2O_3			

bardment. Consequently, lead shielded counters were used and a system of levers and control strings arranged such that the operator could move the target into the electron beam and close the opening to the counter or, after the exposure, open the counter and swing the target into position in front of it. This shift could be made within two seconds, from the operator's station in a lead shielded booth across the room. Some of the targets were in the form of metallic disks, others as powder held to a base plate with a thin layer of sealing wax. All of the latter type and many of the former had to be water cooled. The targets were bombarded for three minutes and examined with the counter for five minutes, this procedure being repeated several times for each. The electrons of all velocities totalled about 100 microamperes and the usual peak energy was somewhat over 800 kv.

Table I lists the elements bombarded and examined. In no case was there any evidence of induced radioactivity.

At a very conservative estimate, based on the absorption curves, at least 1 microampere of the bombarding electrons had an energy of 800 kv or over. Counts numbering three times the background would certainly have been recognizable so that, taking into account the solid angle subtended by the counter, a yield of 1 disintegration per second would have been significant, provided that the half-lives were not shorter than about a second nor longer than perhaps an hour, for the bombardments of each element totalled about 10 minutes, and 2 seconds were lost before counting began. If it be assumed that the products of disintegration are electrons of not less than 200 kv energy, they could emerge from the target and reach the counter after starting from a depth as great as that corresponding to 0.043 gram/cm^2, in which thickness the 800 kv bombarding electrons are reduced in energy to 710 kv. We may conclude, therefore, that if electrons of approximately 750 kv produce radioactive nuclei of half-lives measured by a few minutes and emitting β-particles of 200 kv energy or over, the efficiency is not more than 1 disintegration for 10^{12} electrons and that the collision cross sections range in value from not greater than 10^{-35} cm^2 for hydrogen to 10^{-33} cm^2 for uranium.

Pokrowski[5] has stated that x-rays of 90 to 140 kv produce radiations from lead; the activity reported was irregular and although it decreased rapidly in the first few hours following exposure, it apparently accumulated in intensity over many days of intermittent activation. Therefore in the present work not only was lead examined in the routine manner of the other elements, but a piece of lead from the shielding around the vacuum tank was investigated, after it had been exposed to the x-rays produced during several weeks operation. No counts above background were observed even when the lead was placed so close to the counter that particles of 2-mm range would certainly have been detected.

It is a pleasure to acknowledge the friendship and enthusiastic support of Professor E. O. Lawrence. One of us (A.H.S.) is grateful to the Royal Commissioners of the Exhibition of 1851. The experiments have been aided by grants from the Research Corporation and the Chemical Foundation.

[5] Pokrowski, Phys. Rev. **38**, 925 (1931).