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THE MECHANISM, CHARACTERISTICS AND POTENTIAL OF THE BETA-EXCITED X-RAY SOURCE

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PREFACE:

The beta-excited X-ray utilizes the very familiar phenomena of bombardment of some target material in order to effect the production of useful photons of electromagnetic energy. The vacuum X-ray tube accomplishes this with the conventional cathode-ray which strikes the anode at high energies. The beta-excited device, however, is unique in that it has no need for the Coolidge vacuum tube and complex associated circuitry, but simply utilizes the beta particles emanating from certain radioactive isotopes during their transition. In the case of either the conventional mechanism or the beta-excited principle; 'white radiation' or *bremsstrahlung* as well as the *characteristic radiation* of the target material results from the target-electron interaction. These two components of the electromagnetic radiation may be utilized together, or the bremsstrahlung discriminated against as in X-ray diffraction, and the characteristic radiation specifically applied to analysis, absorptimetry, or radiography. The conventional X-ray system in its present fine stage of perfection has the advantages of high intensity, short exposure times and commercial adaptation to most problems in radiography, therapeutic and diagnostic radiology and analysis. However, the conventional X-ray generator suffers from the disadvantages of bulkiness, non-portability, need for intricacy of circuitry and electrical power source, and complex mechanical design. Such features are a distinct handicap in use in the field or for emergency application in remote areas where power is not available.

The beta-excited source, on the other hand, does present a new and intriguing potential for the special usages detailed above. The advent of the easily available pile produced syuthetic radionuclide has made possible valuable variations in its design. The source is small, stable and has zero power requirements. It is simple in construction and operation. It is easily portable and its reliability and stability makes its use in the field or in remote areas quite feasible. Such a source principle was investigated in this laboratory to evaluate its usefulness as a low energy, planar X-ray radiator for gross apposition radiography. The physical mechanism and development of such a planar source, as well as the small compound source-target is described herein.

The beta-excited source is, for the present, still a research tool and an intriguing study in physical design. It does, however, offer for the future some potential for a distinct type of X-ray source which eventually may find some direct application in radiography, radiology, analysis and testing.

This report consists of two prime sections. The first covers a review of the physical mechanisms extant in the source, the radionuclides applicable to the device, and their availability from the reactor, as well as some basic design features of the

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source. The second portion details the characteristics of the specific beta-excited source developed and used experimentally in this laboratory. This will review some of the experimental results obtained with these sources by radiography and by gamma-ray recording scintillation spectrometer traces. This latter section concerns the experimental work done with a planar source design (termed the *apposition source*), plus some characteristics of the compound beta-excited source.

PART I

THE BETA EXCITATION MECHANISM:

The basic processes which are essential to all *direct* or *indirect* photon production, associated with the radioactive transition of the isotope, are: X-radiation through ionization, bremsstrahlung, internal conversion, photoelectric absorption, gamma emission, and pair production (see Table I). Initially, with the discovery of the naturally occurring radionuclides and later with the advent of the ubiquitous synthetic radioactive isotope, it was proposed that the simple gamma processes would compete with the cathode-ray tube methods of X-ray production, in the low and medium energy ranges. Evaluation of the energy characteristics of the gamma emitters (both natural and synthetic) showed their electromagnetic radiation to be generally too high for ordinary radiography, analysis and absorption studies. Not more than three nuclides show even theoretical application of their photon emission for the lower energies below 100 Kev. The beta-excited source, however, exhibits some potential in the lower energy regions by utilization and control of the two processes of bremsstrahlung and ionization.

TABLE I

PHOTON PRODUCTION PROCESSES*
ASSOCIATED WITH THE RADIONUCLIDE

1.	X-radiation by Ionization.
2.	Bremsstrahlung.
3.	Internal Conversion.
4.	Photoelectric Absorption.
5.	Gamma Emission.
6.	Pair Production.

*This listing includes secondary as well as primary photon production processes.

The radioactive isotope of thulium (Tm^{170}) has been studied in consequence of its 84 Kev photon and is a good example of direct photon emission. It provides one one of the few examples of moderately successful low energy photon application. Unfortunately Tm^{170} is not an example of simple low energy photon emission. Figure #1 is the decay scheme as given by Hollander, Perlman and Seaborg[1]. Branched-chain decay occurs with the production of two distinct beta spectra, (shown as diagonal arrows). The more energetic beta is .968 Mev and the weaker is .884 Mev. The

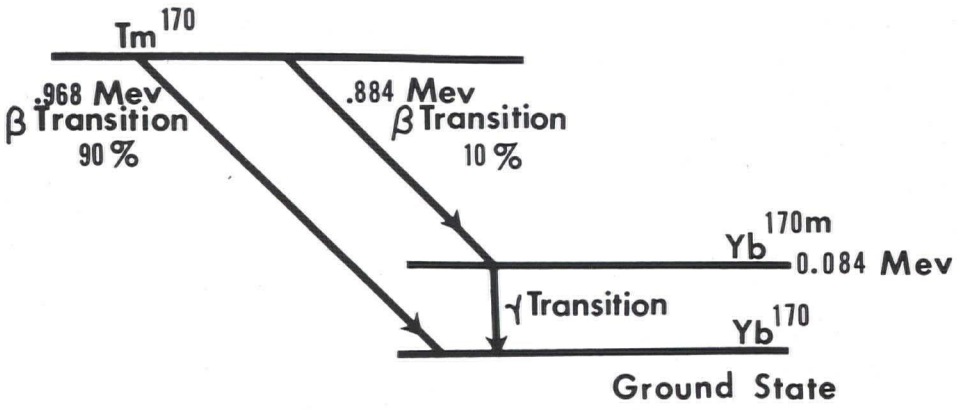

Figure 1

The simple thulium-170 transition is shown. The branched chain decay is through either the .968 Mev beta emission. This decay scheme is by Hollander, Perlman and Seaborg[4]. The .084 Mev gamma from the metastable Yb^{170m} is useful in study of production mechanisms and self absorption in the beta-excited source.

latter is followed by the 84 Kev photon from the excited Yb^{170m} daughter product. Study of the decay of this radionuclide has clarified some of the characteristics of the beta-excited mechanism which exists along with the simple photon emission from the metastable ytterbrium-170. Graham[2] has fixed 25% of the branched-chain decay as proceeding through the Yb^{170m} condition. The ground state is reached through emission of the 84 Kev photon or by internal conversion. According to Graham, this is a complex consisting of:

One; 0.084 Mev gamma radiation occurring with about 3% frequency.

Two; Yb K X-rays, 5% frequency.

Three; YB L and M X-rays, present in about 17% of the Tm^{170} transitions. Thus, emission, from the Tm^{170} falls into three categories.

(a) The two beta spectra.

(b) The 0.084 Mev gamma.

(c) The K, L and M shell YB^{170} X-rays.

This investigation of this radiation complex has provided an experimental basis for the study of varied aspects of the beta-excited source. The influence of changing source thickness, for Tm^{170} has been investigated by Liden and Starfeldt.[3] It was found that with increasing source thickness;

(1) The 84 Kev photon intensity rose to an asymptotic value which was imposed by the self-absorption of the source material which served as an internal shield.

(2) The relative percentage of Yb K X-rays decreased and the percentage of Tm K X-rays increased.

(3) The intensity of bremsstrahlung increased rapidly with increasing source thickness.

For source surface concentrations of 10^3 mg/cm^2, the intensity of bremsstrahlung was equal to that of the thulium K X-rays plus the ytterbium K X-rays.

The average 'white radiation' energy was around 100 Kev. This is a good example of the undesirable, high bremsstrahlung production rates which frequently 'smother' the desirable characteristic X-rays produced in the beta-excited X-ray source.

The primary components of the beta-excited photon source are essentially the same as those of the conventional X-ray device; much more simple in design detail. The requirements are; *first,* beta particles of the proper energy; *second,* an array of target atoms arranged in the beta flux for impingement by the particulate radiation.

Figure No. 2 describes schematically the two main mechanisms as well as one of several secondary phenomena. The radioactive isotope S, at the left, is the source of the beta particles (straight arrows) which impinge on the target volume T. Ejection of electrons through this collision process from the innermost electron shells results in *characteristic X-radiation* from the target atoms CX in the schematic). The second process of interest, consisting of the accelleration of the beta particle charge as it passes near the target atom nuclei, results in the continuous *white radiation,* or bremsstrahlung photon. This is designed as B. An important secondary effect is shown at the bottom of Figure No. 2. The beta particle charge is accellerated in the target T, which process results in the bremsstrahlung photon which is shown. This in turn interacts with the K shell of a target nuclei with the ejection of a planetary electron with the resulting production of a characteristic X-ray (CX) when this vacancy is filled. This fluorescence target radiation may be an important component of the total photons produced. In addition, these three phenomena may be supplemented by other combinations of photon production in the K, L and M target shells, as well as more complex effects through the fluorescence mechanism.

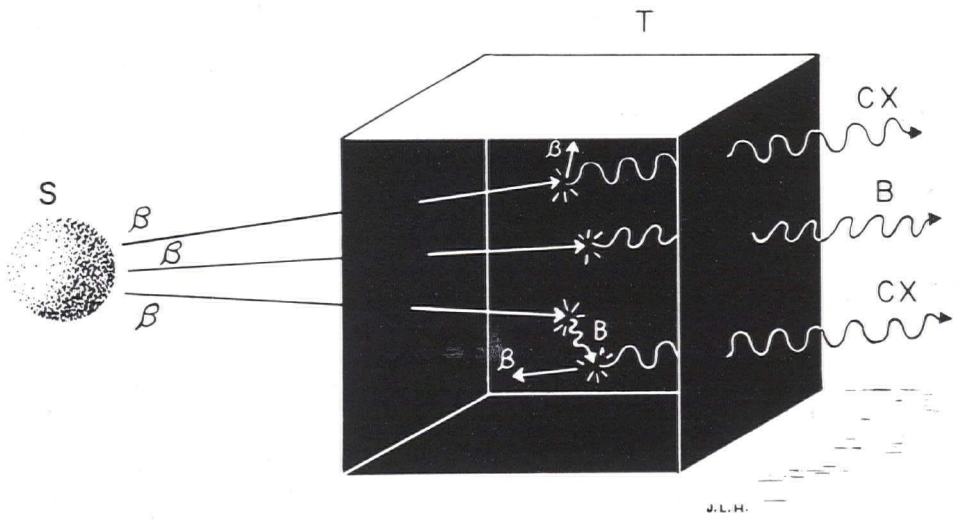

Figure 2

Some modes of production of X-radiation, by the beta-excited source are illustrated. *Characteristic X-ray* production is shown as CX. *Bremsstrahlung* production is shown as B, and the fluorescence photon process (CX at bottom) by the three-step mechanism on which bremsstrahlung B produced in T by the beta particle creates the characteristic radiation CX by interaction with the inner shell electrons of the target element.

The two physical mechanisms of *bremsstrahlung production* and *X-Ray production* may be separated into five separate modes (Table No. II). These are; *internal bremstrahlung, external bremsstrahlung, electron capture bremsstrahlung, internal X-rays* and *external X-rays*. These five processes, of varying importance in the individual case, make up the entire photon production picture in the beta-excited source. These processes are reviewed briefly in the following paragraphs.

TABLE II

PHOTON PRODUCTION SYSTEMS

BREMSSTRAHLUNG
1. Internal Bremsstrahlung.
2. External Bremsstrahlung.
3. Electron-Capture Bremsstrahlung.
CHARACTERISTIC X-RAYS
4. Internal X-rays.
5. External X-rays.

Internal bremsstrahlung photons are produced at the parent nuclei concurrent with the change of nuclear charge which occurs upon the emission of the beta particle from the radioisotope. Internal bremsstrahlung has been shown to be independent of the Z number of the element by Stahel and Gullissen[4] and Wu[5]. Additionally, it makes up only a small fraction of the total bremsstrahlung. Bolgiano[6] has demonstrated that this electromagnetic radiation consisted of only $2.32 \cdot 10^{-3}$ mass units per beta disintegration for P^{32}, $1.9 \cdot 10^{-3}$ for Y^{91}, and $.84 \cdot 10^{-3}$ for radium-E; this being in agreement with theory. This photon flux is relatively unimportant in the beta-excited source.

External bremsstrahlung is that electromagnetic radiation produced concurrent with the deflection and accelleration of a beta particle as it passes through a nuclear field other than that of the parent atom. For thin targets, the energy of the external bremsstrahlung is proportional to Z^2 (atomic number of the target nuclei). The probability of emission of an external bremsstrahlung photon of a specific energy is proportional to the square of the target's Z number. The probability of external bremsstrahlung production decreases with the reciprocal of the photon energy[7]. External bremsstrahlung is the more important component of the total bremsstrahlung flux. In general, when a low energy source is desired (particularly true for the most energetic beta emitters), or when the characteristic radiation is the specific radiation required, then the external bremsstrahlung is that photon which must be minimized through design considerations.

Electron-capture bremsstrahlung is the counterpart of internal bremsstrahlung. This radiation is formed upon the nuclear capture of an atomic electron. Such photon production, again resulting from the change in the nuclear charge, is relatively small in magnitude. The frequency of this phenomena has been set at about 3.10^{-5} quanta per radioactive disintegration for Fe^{55}. Bradt[8] fixed this photon energy at about 70 Kev for this transition.

It might be of some significance to consider the relative fractions discussed above for the energetic P^{32} pure beta emission. Each P^{32} disintegration has assiciated with it; internal bremsstrahlung energy of 2.10^{-3} $m_o c^2$ units per transition and $8.2 \cdot 10^{-3}$ units of external bremsstrahlung, for aluminum target material, and about $56 \cdot 10^{-3}$ units of external bremsstrahlung for lead targets. This latter value illustrates the effect of increasing Z values on the energy dissipated in external bremsstrahlung per beta disintegration.

Internal X-rays are made up of those charactistic photons produced through ionization by the betas within the extended radioactive source itself. Such photon production is least important in the thin, carrier-free source and conversely is most apparent in the thick source. Carrier-free, source material will not show the effect as readily as the nuclide which is greatly diluted with its stable istopic component. In the latter case, the probability of ionization within the source is greatly enhanced by the presence of a large number of source atoms which, in this case, function as target nuclei (as in Figure #II). Beta emitters with a long half-life, such as Sr^{90} and Y^{90}, have been proposed as sources of characteristic internal X-radiation by this mode[9,10].

External X-rays are those characteristic photons emitted by external target atoms which are distinct from the beta emitting nuclei. These target atoms emit their characteristic X-ray photons in consequence of the ionization suffered from the beta particle impingement. External targets of A1, Sn, Ag, Cu and Pb, as well as some others, have been studied for the beta-excited effect[7, 11, 12]. Since we are concerned with work with the low energy, beta-excited source, the prime consideration is in the production of *external X-radiation* and of *external bremsstrahlung*. For the case of the low energy source, or for analysis or testing, the external X-radiation may be of first consideration. The external bremsstrahlung is important, for low energy work, in the sense that it introduces an unwanted high energy spectrum, which must be eliminated. Internal X-rays and internal bremsstrahlung are ordinarily not a desirable component of the X-ray flux. They may be important design considerations only in the sense that they are to be minimized, or eliminated. Internal bremsstrahlung, it has been pointed out earlier, is a rather unimportant component. Internal X-rays, on the other hand may make up a very significant portion of the total photon flux. Fortunately, they may be reduced by the use of proper design principles in the beta emitter itself.

RATIO OF CHARACTERISTIC TO 'WHITE' RADIATION:

The expression;

$$\frac{\left(\frac{dE}{dX}\right)_{(rad.)}}{\left(\frac{dE}{dX}\right)_{(ion.)}} = \frac{E\,Z}{800}$$

gives the electron energy loss per unit beta path length for bremsstrahlung (rad.), in ratio with the ionization (ion). E is the energy of the beta particle, in Mev, with which the electron enters the target. Z is the atomic number of the target material. This

is for monoenergetic electrons and does not strictly apply to the actual case where the betas exhibit a spectral characteristic. The expression shows that the ratio of bremsstrahlung to characteristic X-ray energy will be increased when the beta-ray energy, or the target Z, is increased. Usually, in the low energy source or for analysis applications, source design considerations are directed at the reduction of this ratio. The key to fabrication of the partical low energy, beta-excited X-ray source lies in the beta energies utilized, or more accurately, the spectral character of this particulate radiation, and in the ionization to bremsstrahlung ratios, which is obtained through the proper choice of source and target material.

Reiffel[13] has pointed up the paucity of data on efficiencies. Lebeouf and Stark[11] have shown the efficiencies in Table III. For characteristic tin X-rays, they obtained efficiency values of about 1% for S^{90} — Y^{90} source betas, and about .3% for the less energetic Pm^{147} betas. 6% and .3%, respectively, were found for tin targets for *external bremsstrahlung,* for the same radiation. The change of efficiency with change in beta energy is significant. Efficiency values as high as 10% have been given by Reiffel[13] for lead targets. These efficiencies are in terms of photons produced per unit beta particle which is incident upon the target material. Sr^{90} — Y^{90} and radium-E have efficiencies of 10^{-3} to 10^{-4} for internal X-ray production (Reynard[10]). The 'white spectra' from the tin target will mask the external X-ray production with the energetic Sr^{90} — Y^{90} source.

TABLE III
BETA-EXCITED SOURCE EFFICIENCY
IN PHOTONS/INCIDENT BETA*

Energy	K X-ray**	Source	Bremsstrahlung
Sr^{90} — Y^{90}	2.2 MEV	$1x10^{-2}$	$5x10^{-2}$
Pm^{147}	.22	$3x10^{-3}$	$3x10^{-3}$

**L and M X-rays may also be present.
*Leboeuf and Stark[11], (for Sn target).

APPLICABLE RADIOISOTOPES:

It is obvious from the review of the action of the thulium source that the radionuclide must be a pure beta emitter. The A. E. C. catalog, of pile irradiations, lists almost 100 routinely available nuclides. It is a serious hinderance to the designer of the beta excited source that only a minor fraction of these are pure beta emitters. The balance being made up almost entirely of combined beta-gamma emitters. The gamma radiation from these radioactive isotopes usually is of such an energy and intensity to mask the function of the beta-source. Table IV lists the characteristics of some of these isotopes which emit gamma rays. The photon energy ranges from .7 to 3.8 Mev. Where the nuclide is also a beta emitter, this high photon energy obviates the use of the nuclide in a beta-excited source, particularly for applications below 100 Kev.

Slightly less than 20% of the isotopes routinely produced in the Oak Ridge pile are useful pure beta emitters (for application to the beta source). Table V lists fourteen of these. The maximum spectral energies range from 18 Kev to 2.2 Mev. Sr^{90}, Y^{90}, P^{32}, Pm^{147}, Ca^{45} and W^{185} have been studied for their potential in the beta-

TABLE IV
GAMMA EMITTING, PILE PRODUCED RADIOSOTOPES*

Radionuclide	Half-Life**	Gamma Energy*** (Mev)
Sodium-24	15.06 h	2.754 #
Gallium-72	14.3 h	2.51 #
Lanthanum-104	40 h	2.50 #
Iridium-194	19 h	2.1 #
Antimony-124	60 d	2.04 #
Arsenic-76	26.8 h	1.7 #
Praseodymium-142	19.2 h	1.59 #
Silver-110m	270 d	1.516 #
Potassium-42	12.44 h	1.51 #
Europium-152, -154	12 y; 16 y	1.40 #
Cobalt-60	5.27 y	1.33 #
Bromine-82	35.87 h	1.312 #
Iron-59	45.1 d	1.289 #
Tantalum-182	115 d	1.223 #
Scandium-46	85 d	1.12 #
Zinc-65	250 d	1.12 #
Rubidium-86	19.5 d	1.08 #
Rhodium-106 (Ru^{106})	30 s	1.045 #
Cesium-134	2.3 y	0.794 #
Tungsten-187	24.1 h	0.78 #
Zirconium-95	65 d	0.754 #
Niobium-95	35 d	0.745 #
Barium-137m (Cs^{137})	2.6 m	0.662

*U.S.A.E.C. Catalog of Radioisotopes.
**h, hour; d, day; y, year; m, minute; s, second.
***The energy given in each case is the maximum gamma energy which occurs in 5% or more of the radioactive transitions.
#Also a beta emitter.

excited X-ray source[7,14]. Not all pure beta emitters are useful in the beta-excitation mechanism. Design and fabrication limitations may be imposed by; one, *the available form* (chemical and physical), in which the isotope may be irradiated; two, the *half-life*, which, when short, limits the isotope's usefulness to experiment only; three, *the specific activity*, which will fix the output intensity and indirectly influence design efficiency and the minimum source volume available (this latter is a critical factor since it fixes the minimum exposure times in analysis or radiography); four, *the maximum particulate energy*, which will influence the photon production efficiency and the

$$\frac{dE/dX\ (rad.)}{dE/dX\ (ion.)}\ \text{ratio.}$$

Several of the isotopes in Table V are ruled out for use in the *low energy source* due to the high maximum energy of the beta spectra. Some of the materials are available as carrier-free elements. Use in this form will provide the greatest concentra-

TABLE V

PILE-PRODUCED PURE BETA EMITTERS*

T½**	Radioisotope	Maximum Energy (Mev)
2.54 D	Yttrium —90	2.18
13.7 D	Praseodymium —143	0.932
14.3 D	Phosphorus —32	1.701
53 D	Strontium —89	1.463
73.2 D	Tungsten —185	0.428
87.1 D	Sulfur —35	O.167
163 D	Calcium —45	0.254
2.6 Y	Promethium —147	0.223
12.4 Y	Hydrogen —3	0.01795
25 Y	Strontium —90	0.61
85 Y	Nickel —63	0.067
5568 Y	Carbon —14	0.155
2.12×10^5 Y	Technetium —99	0.29
3.08×10^5 Y	Chlorine —36	0.714

*U.S.A.E.C. Catalog of Radioisotopes.
**D, day; H, hour; Y, year.

tion of betas per unit source volume and will fix self absorption at a minimum value for a given activity. Approximation to a point source may be a critical design factor in the beta-excited source fabrication. This may be especially important for certain usages in radiography. A true point source obviously cannot be realized physically but an attempt to approach this end may be necessary to design the particulate source (beta) into the smallest possible volume, without sacrificing the source intensity. The smallest volume ultimately obtainable is controlled by the highest specific activity of the beta emitter which is chosen. This, in turn, will be controlled by pile characteristics, half-life, age and the chemical and physical forms available. Table VI gives the spherical volume into which one curie of beta emitter, with an arbitrary density of five, may be packed; assuming that carrier-free material is available. The radius of the beta source would be only 170 microns for the tungsten sphere. It should be

TABLE VI

SPHERICAL VOLUME OCCUPIED BY ONE CURIE OF CARRIER FREE MATERIAL*

Isotope	Volume	Radius in Centimeters
W^{185}	2.1×10^{-5}	1.71×10^{-2}
T^{170}	3.1×10^{-5}	1.95×10^{-2}
Co^{45}	1.0×10^{-6}	$.62 \times 10^{-2}$
Pm^{147}	1.9×10^{-4}	3.57×10^{-2}
Tl^{204}	3.1×10^{-4}	4.20×10^{-2}
Sr^{90}	1×10^{-3}	6.2×10^{-2}
Sr^{90} - Y^{90}	5×10^{-4}	4.93×10^{-2}

*Assuming an arbitrary density of 5. Some of these isotopes are not routinely available in carrier-free form. They are shown only as examples.

pointed out that W^{185} is not routinely available in the carrier-free form, and is used here only for an example. However, this isotope, if available as carrier-free material would have associated with it; 9.660 curies per gram. For Ca^{45} the specific activity would be about 20,000 curies per gram. We must review, at this point, the fact that we are speaking only of the beta emitting nuclide and its associated physical dimension. The dimensions of the *assembled beta-excited photon source* are fixed by the beta range in the target, plus other considerations. These dimensions, with the proper source design, therefore, can be made quite small. Source dimensions approximating those in the Coolidge X-ray tube are feasible. P^{32}, Pr^{143}, Sr^{89}, S^{35}, Ca^{45}, Pm^{147}, H^3, Sr^{90}, Y^{90}, C^{14} and Tc^{99}, (all pure beta emitters) may be obtained in the carrier-free form or in a special *very high specific activity form.*

PHYSICIAN DESIGN:

The components of the beta-excited source fall into two main units. The first is the *isotopic source of betas.* The second is the *target material.* These two may be fabricated and arranged in juxtaposition in many physical, chemical and geometrical forms and combinations. However, in the following paragraphs, the more simple classical designs of target geometry will be reviewed. Targets fall into the three general categories listed blow:

(A) *Transmission* target type.

(B) *Reflection* target type.

(C) *Fluorescence* target type.

The *transmission* or 'casing' target is one in which the coherent, combined beta paths, up to the point of origin of the X-ray photon, plus the resultant photon path, traverses the target volume from side to side. The *reflection* target functions in a manner analogous to the target in the conventional X-ray tube. In the reflection type, the trajectory of the incident beta plus the path of the resulting photon occupy the volume on only one side of the target plane. The *fluroescence* target is one in which the characteristic target X-rays are induced by beta-excited photons from a second target (this latter target usually being intimately designed with the beta source). It is obvious that a single target may experience one, or all, or combinations of these functions. Generally however, the target design and orientation will provide for *one primary function.* The three types of target design are shown in Figure #3. Figure #3a schematically illustrates the transmission target which is shown as the volume TT. This is placed in proximity to the radioactive source S. The beta particles which are designated as the straight arrows impinge upon TT and the X-ray photons (B and CX), which are produced, traverse TT and exit from its other surface. The *backing target* BT is often used in this geometry to improve the efficiency. The 'sandwich' which is illustrated is made up of only one transmission target. BT is a reflection target which is useful in this binary target design. This laminated source design is quite applicable to the fabrication of a planar source design and will be treated later in detail. The transmission target TT must be at least as thick as the maximum range of the source betas so that none of the particulate radiation may escape by passing entirely through TT. Added target thickness however will serve only to harden (through self-absorption) the X-ray spectrum emerging from the right side of TT. This is undesirable. Figure #3b illustrates a technique which makes possible the use

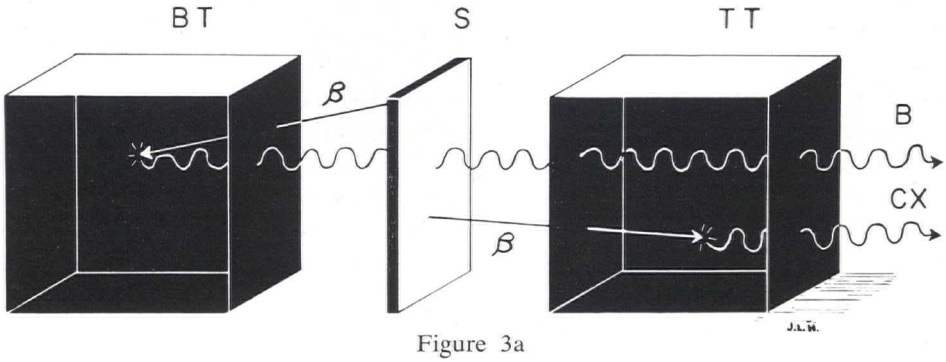

Figure 3a

TT is a transmission type target for the beta-excited source. Beta radiation from S (straight arrows) are absorbed in TT. The resultant ionization process produces the characteristic X-rays CX. Bremsstrahlung may result from the beta interaction with the backing target BT. This target utilizes the reflection mode (see text). The sandwich design with BT, S and TT is used to increase source efficiency.

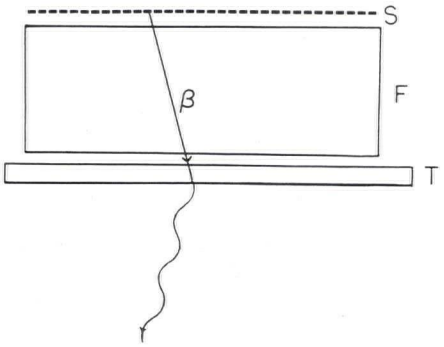

Figure 3b

A low Z number absorber F is interposed between the source S and the target T. Proper choice of thickness of F will reduce the energy of the betas impinging upon T and will allow use of a thinner target. The bremsstrahlung to ionization ratio may be reduced by this technique.

of transmission targets which are thinner than the maximum range for that material. The source S at the top has a layer of low Z material (F) such as lucite placed below it. On the bottom of this is the transmission target T. In this case, beta radiation from S expends some of the energy in F before reaching T. The beta's total energy on reaching the top surface of T is now much reduced from that extant when it left the surface of S. This means that the $\frac{E\ Z}{800}$ ratio (equation #I) is now reduced (in favor of the ionization process). The use of a thinner transmission target T may be desirable but this technique can have some pitfalls. Improper choice of absorber thickness F disproportionately extracts only the low energies from the radionuclide's beta spectrum and may leave the more energetic side only slightly affected. This is possible because we are dealing with a spectral character. This will then mean a greater bremsstrahlung to X-ray ratio. Thus, the beta spectrum shape and the maximum beta energies must be taken into account when using this system. The absorber method radically reduces efficiency of the source mechanism by extracting betas from the total flux which ordinarily would impinge upon the target, and for this reason is ordinarily not used.

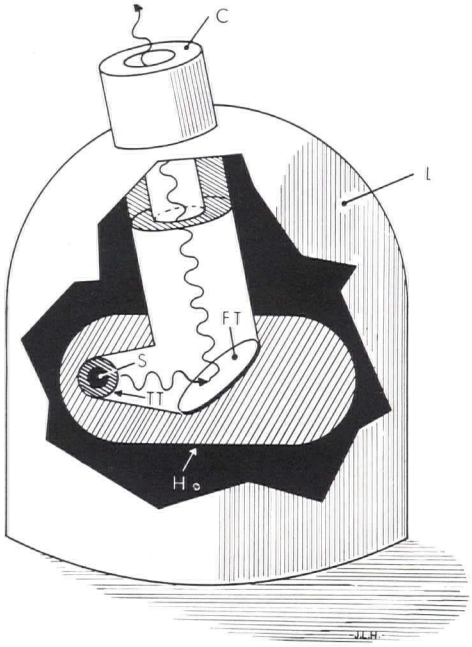

Figure 4a

This is an example of a fluorescence target design. The fluorescence target FT is mounted in proximity to a casing target TT which surrounds the intense beta emitter S, which here is in the shape of a sphere. The inherent inefficiency requires that good geometry and a small, intense beta source be used. This in turn will require heavy shielding at H, L and C.

Figure #4a is a schematic illustration of a beta-excited fluorescence target type. This is a cross section through the source and its associated radiation shielding. The beta emitter is in the form of a tiny sphere of carrier-free material, and is designated by S in the sketch. The casing or transmission target TT is fabricated as a shell completely surrounding the sphere S and of maximum range thickness. The fluorescence target FT is exposed to the bremsstrahlung and X-rays which are produced in TT (wavy line). S and TT can be imbedded in a collimator or gun which is directed at FT. Those photons which impinge upon FT may produce an appreciable amount of characteristic or fluorescence radiation, providing that the variables of self absorption and resonance are properly oriented. The characteristic resulting photons may be passed throught a system of collimators, C. The Source S in such a design must be very intense. Therefore, it may be wise to house this in some dense shielding, H, such as hevimet. This will serve to stop that random radiation which is not directed at FT. The collimator (C) may also be made of hevimet. The whole may be housed in a lead shield of spherical or semi-spherical design. The source efficiency of such a system is very low; probably being of the order of 10^{-3} fluorescence photons per beta disintegration. This is for the case of best geometry. In the practical case the efficiency would be 10^{-1} to 10^{-2} below this. The advantage of this system is that it can produce essentially monochromatic X-radiation. It has certain potential in analysis and particularly for calibration work.

Figure #4b shows a hypothetical reflection target design in cross-section. The intense sphere of beta emitter, S, is embedded near the center of the lead shielding sphere L. The particulate beta radiation, straight arrows, strike the reflection target RT. Some of the beta particles are reflected or scattered from the surface into the volume of the aperture, but these are absorbed by a thin window of low Z material, such as lucite, which is shown here as F. Other beta particles which impinge upon RT interact with the target material and bremsstrahlung and X-rays are produced. This electromagnetic energy may be propagated in all directions. That which passes through the aperture volume may be utilized for radiology or radiography. The filter F will present little obstacle to the photon (curved arrow). The reflection target type is less efficient by a factor of ten than the transmission type but it is highly useful where the photon absorption in the target material is high, or where very low energy betas must be used with a very thick target. Target mixtures, such as lead-barium, have been proposed for a greater spread in photon energies. Targets which are fabricated at an atomic or molecular level with the source will be discussed in the following section.

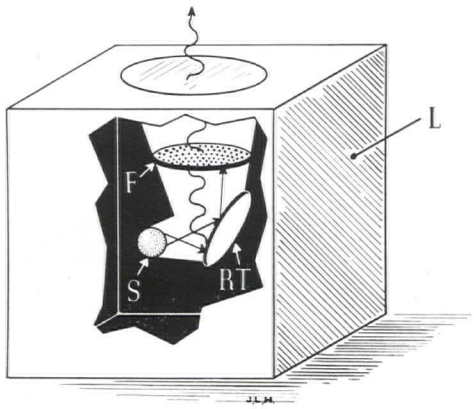

Figure 4b

The reflection target RT is embedded in a lead shield L near the intense beta source S, in this schematized cross section of the reflection target system. The low Z filter F absorbs the betas which are scattered from RT. Photons (curved arrow) pass the filter and are collected outside the shield. This is a less efficient technic than the transmission target. This model of a beta-excited source type has its almost exact counterpart in the conventional X-ray tube.

Although the target type is of some importance, the relative orientation of both target and the beta source is also of considerable importance. Table VII lists these possible orientations as; separate, intimate, mixture, compound and elemental. The photon production efficiency, which is of prime importance, is especially dependent

TABLE VII

RELATIVE SOURCE-TARGET GEOMETRY

1. Separate Source-targets.
2. Intimate Source-targets.
3. Mixture Source-targets.
4. Compound Source-targets.
5. Elemental Source-targets.

upon the relative juxtaposition of beta source and target. Figure #5a gives an example of source and target volume arranged in separate geometry, (A). Obviously, this

is the least efficient positioning because of the beta losses imposed by the inverse square law. The greater the separation, the lower the efficiency. However, such separation is often necessary because of a need for collimators between S and T. B in Figure #5a is the same source, S, and target T in intimate *geometary*. This is obviously a much more efficient geometrical design than A.

In C the 'sandwich' of backing target, BT, source S, and transmission target T is shown. This is a reasonably efficient design and is discussed in the following text. An obvious extension of the sandwich design is the shell or casing target in intimate contact with a small sphere of the beta emitter. This latter source-target geometry is highly efficient when the beta source sphere has negligible self absorption.

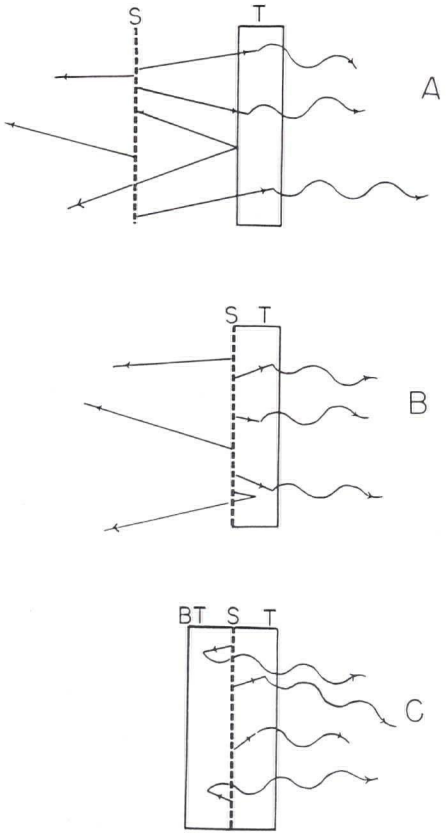

Figure 5a

A, B and C represent respectively examples of *separate, intimate* and *'laminar'* or *'sandwich'* source-target geometries (top to bottom).

It is apparent, from the point of view of geometry, that greater efficiency can be expected from the geometries in which the source is more intimately packed with the target material. This may be extended to the logical conclusion that positioning on the macro, micro and atomic scale should produce progressively better photon production efficiencies. Figure #5B presents in idealized form the source target geometry representing a source-target *mixture* design, M, on the left, and the *compound* design, C, on the right. In each case, the beta emitting radionuclide is represented by the small x's and the target atoms as the solid dots. When the beta-source material

and the target are mechanically mixed, the rather irregular, but close, disposition of the two components in M will be achieved. In actual practice this irregular orientation will not be on the atomic level as shown; but rather, each component will exist in small clumps or crystallites with irregular spacings between these groups. The source and target, in M, may be mechanically mixed as a complex powder, slurry, amalgam or liquid suspension. One might precipitate two separate compounds simultaneously and pack the damp mixture together and then allow to dry. In general, this method of mixtures should reduce losses due to beta source absorption and to the inverse square law, and will result in an improved photon production efficiency. Another method, which is illustrated under C, provides for a more intimate and regular positioning of the target and source. This is accomplished by introducing the source atom

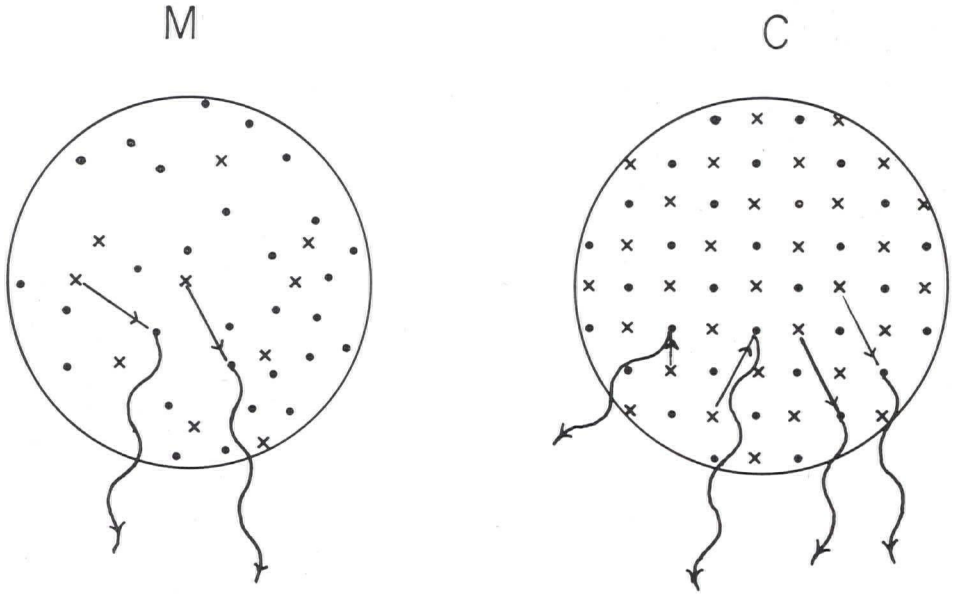

Figure 5b

M represents the *mixture method* of positioning target material near the beta source. This might be as a powder, slurry, suspension, colloid, etc. The small x's represent the isotopic beta emitters. The dots are the aggregates of target atoms. Note that the beta sources would be expected to be irregularly spaced.

C represents the *compound source-target geometry*, with the radioactive atoms (x) and the target atoms (dots) arranged in a crystal lattice. This very close positioning of the beta source and target atom can greatly improve the likelihood of an interaction between beta and target atoms.

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and the target atom or atoms into the same chemical compound. This compound may be in the form of small or gross crystallites, but it is preferable that the whole mass be grown as a single crystal. In such a model, it is possible to surround each radionuclide with several target atoms, as shown in Figure #5B. Very uniform and intimate positioning is possible by this method. The probability of interaction between the beta particle and the target atom is enhanced since the separations are only of the order of atomic dimensions. The compound and mixture source-target arrangements have the advantage of containing the source within small dimensions and of packing the two

components in a very intimate array. It might be pointed out that solutions of beta-source and target material will also establish the uniform and close mixing seen in C. It is difficult to categorize this target type for M or C, since it may have a different function at its periphery. However, it may be classed as an adaptation of the transmission target. It is obvious that the betas which originate near the surface of such a source may escape into the space outside the source, thus causing a beta exposure problem and a health hazard. Figure #5C shows such a source packed into a spherical void in the center of a spherical filter of low Z. The betas expend their energy in this filter, whereas the electromagnetic radiation passes with negligible absorption.

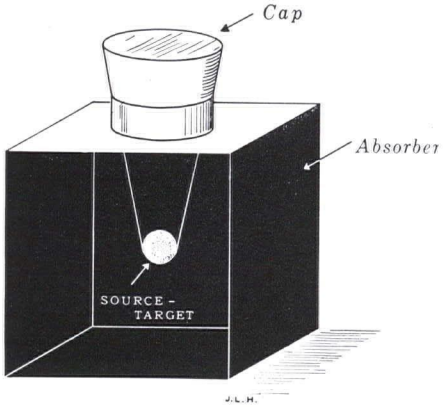

Figure 5c

The small spherical *mixture* or *compound* source-target arrangement (cross-hatch) may be sealed into a spherical, or cubical, lucite shield, as shown, so that betas escaping from the periphery of the source are stopped by the surrounding low-Z filter material.

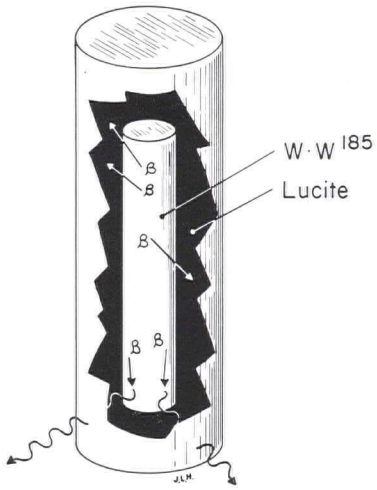

Figure 6

This is the elemental source-target geometry in which irradiated W185 are incorporated into the W wire crystal structure. Betas from the W185 utilize the surrounding tungsten atoms as a target array. Lucite absorbs the peripheral betas.

Possibly the most intriguing source type is the *elemental source-target* design. Figure #6 is an idealized sketch of this. This source type has this beta source element and the target element all in a single physical form, and this in a closely packed crystal structure. This unique advantages of this technique are obvious. Some of the disadvantages are not as clear but will be dealt with in the following. The center rectangle, in Figure #6, represents a small diameter pure tungsten rod which has been irradiated in the neutron flux of the Oak Ridge Pile. Its specific activity is about 100 millicuries per gram of W. The W^{185} beta radiation from this pure emitter will use the surrounding tungsten atoms, within the metal crystal, as target material. Internal and external bremsstrahlung will result, as well as the characteristic X-radiation of tungsten. The low Z filter which encases the metal will absorb the peripheral escaping betas. An obvious advantage is the possibility of prefabrication of complex designs in the metal before irradiation. The source-type is not without its problems. The source may have an extremely high absorption coefficient for its charactistic X-rays. It may be limited to relatively small sources, or thin sections of metal, since it may exhibit

considerable self absorption for the characteristic or the entire photon spectrum. This would be especially true of a dense metal tungsten source.

The activated beta-excited source is another physical form which affords some unique potential. This involves pile neutron activation of the entire beta-excited source and as a consequence requires some special characteristics. This system will be termed hereinafter, the *'compound source-target activation process'*. Ordinarily the creation of the beta emitter takes place either by a neutron irradiation process in the pile or through the phenomena of fission. I^{131} and Sr^{90} are products of the latter process. W^{185} is a product of the neutron irradiation system. Ordinarily the beta emitter (either non-processed or prefabricated) is created separately from the target material by pile irradiation. *Separate beta source activation* refers to the insertion, alone, of this beta source material, into the pile for activation. The radio-active nuclide, thus produced, is then used 'as is' or processed for insertion into the beta-excited source. This more conventional method allows fabrication to take place *only before* the irradiation. Post-irradiation fabrication of the very intense beta sources is not practical due to the severe health-physics hazards. *Compound source-target activation* refers to the simultaneous exposure to the pile's neutron flux or both the target and the beta source material. This is done with the entire source in its final assembled form. This special design is quite practical where the target material is relatively short lived. A good example would be for the case of iodine incorporated as target material. I^{128}, with its short half life, makes it practical to incorporate calcium as a stable calcium ion into a calcium iodide crystal and to place this for neutron activation into the pile. The neutron flux will produce, of course, a tag in which the iodide compound will have incorporated Ca^{45} and I^{128} in its structure. The very short-lived I^{128} will decay to negligible proportions leaving the stable iodine, plus the longer lived Ca^{45}. The Ca^{45} will serve as a pure beta source and the I^{127} the target material. The advantage here is that the extremely hot source needs no special post-irradiation fabrication or fitting to the target following irradiation. This greatly minimizes the problem of personnel exposure and the necessity for difficult remote control operations and facilities. The relative neutron cross sections for the two elements in the compound are important. Obviously, if the short lived material has a cross section 10^6 times greater than that of the pure beta emitter; then the source may be useless for a very great length of time following irradiation. Coleman[7] has suggested the use of multiple radioactive sources to obtain the proper beta spectrum.

Requisites for irradiation and shielding must be considered prior to insertion of a source component into the pile. Some of these criteria are listed in the following:

1. Physical size.
2. Purity.
3. Source stability.
4. Radiocontaminants present (due to trace impurities or daughter products).

PART 2

The following section covers the experimentation with specific beta-excited X-ray sources. The isotopes which will be discussed were often purposely chosen because of their short half lives. This simplified the disposal and waste hazards.

Additionally, the quantities used were of relatively low total activity. Total amounts used in the individual sources were of the order of one millicurie. The low activities used were practical since these sources were designed for strictly experimental purposes. The exposure times which were used could be, as a consequence, quite long. The lower activities, utilized here, enabled the workers to carry out routine manipulations without complex procedures imposed by health physics hazards. Additionally, exposure time was not a critical factor as it would be in radiology, radiography or surface therapy.

Activity levels for the practical beta excited source would probably begin in the 10^2 mc range, or above, and would extend well into the multicurie level. Rather massive and complex shielding may be necessary in such very high-activity practical sources. This has been a major disadvantage to the high level beta sources[13]. Important criteria to consider in shielding design are as listed; the minimum shielding allowable (from a tolerance dose standpoint; bremsstrahlung production in the shielding material; characteristic external radiation from the high Z shield; fluorescence from the shield; and advisability of the use of low Z primary and a high Z secondary shield lamination.

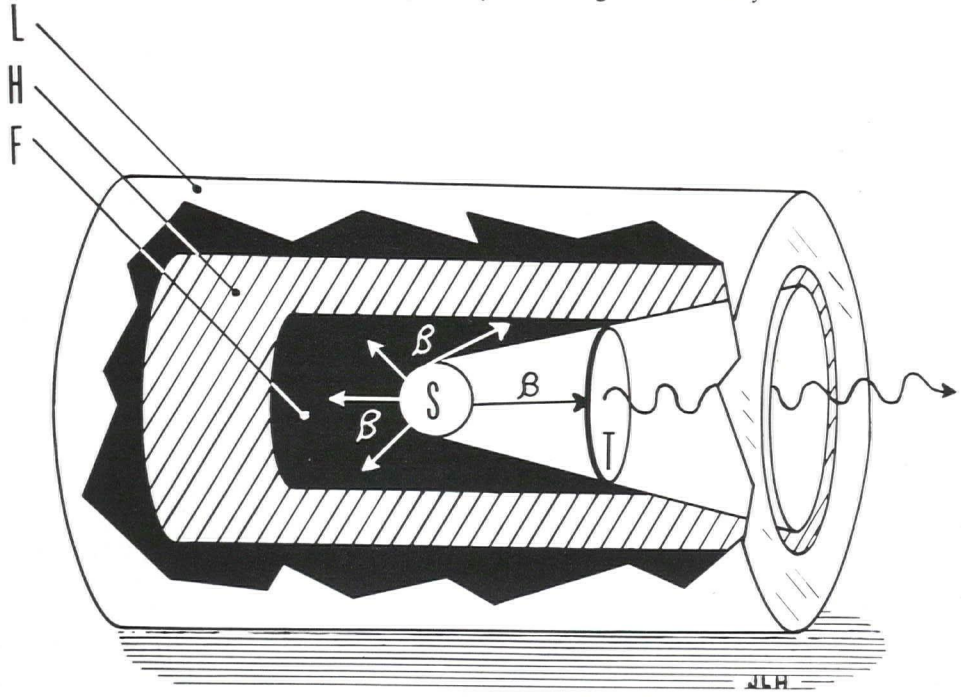

Figure 7

This schematic illustration of the use of a primary and secondary shield for the beta source. The low Z shield F absorbs the betas directed at the lead shield. This reduces the probability of production of undesirable bremsstrahlung photons in the shield.

Figure 7 illustrates the use of low Z filter F (lucite) near the source S to absorb those betas not directed at the target and composed of a material which will not produce bremsstrahlung or energetic external X-rays. The use of the low Z absorber near the beta emitter may actually make the shield less bulky by eliminating the

greater portion of the beta induced, high energy, photon production within the shield which immediately surrounds the source. The function of the rest of the shield will be confined only to absorption of back-scattered electromagnetic radiation from the target and from that photon production which takes place in the source itself.

THE APPOSITION SOURCE:

The initial research into this source type at this laboratory developed through an investigation of a low energy X-ray source of planar design with a required dimension of about 2 centimeters diameter. This was to have some applications in gross apposition microradiography and autoradiography. Very thin uniform layers of Cr^{51} produced by vacuum evaporation had been studied for this purpose when construction of the planar beta-excited source was initiated, Figure #8. This is an application of the sandwich design which was described earlier, in which the source is in laminar form between the two layers of target material. The beta ray source, S, of P^{32} (carrier-free; as the phosphate), Sr^{90}—Y^{90} or Pm^{147} may be plated either on the transmission target TT or on the backing target BT. H is a brass assembly sleeve. L is the source's cylindrical brass body. This design constitutes an attempt to provide a uniform, planar source of X-rays from the copper targets. Targets thickness is chosen for maximum range for the maximum energy beta of the particular istope utilized. Figure #9 is a view of the disassembled source. The device is roughly one inch in diameter and one inch tall. The source intensities were of the order of one millicurie of pure beta emitter. No extra shielding was used for the experimental work done with this source. Deposition of the pure beta emitter from a solution in the form of a phosphate as a uniform layer presented a problem difficult of solution. The uniform deposit was secured by a technique involving deposition on a thin layer of paper and subsequent cutting of the deposit area to fit the source. This technique results in very uniform distribution of the dried down material.*

The diminutive size of the source is graphically represented in Figure #9. In order to increase the intensity over that used in the experimental studies, it would be necessary to incorporate some shielding about the cylinder shown in Figure #9. Even so, the entire source (shield plus source and target) could be kept in a sphere less than 4" in radius. This is still a great deal less than the required space for the conventional X-ray circuitry. The planar source was to be used for gross apposition studies, as in Figure #10. The laminated source is placed in apposition with a very small subject P, which in turn is positioned on the autoradiographic emulsion E. Resolution of the system was of some importance and some investigations were carried out with this general configuration. For best resolution, the ideal impingement angle with the emulsion for the X-ray photons, formed in the target material BT and TT, is at 90° to the emulsion surface. This target design provided photons which strike the emulsion surfaces at all angles. Important factors here will be the thickness of the emulsion, the subject's length and the gross dimension of the source. The resolution will be better when the emulsion is thin and the subject is large relative to the emulsion thickness. The separation between source and emulsion surfaces will also be of some importance. Resolution studies were carried out by the device in Figure #9 and in the geometry as shown in Figure #10. Generally the subject thickness was of the same

*Paper in preparation.

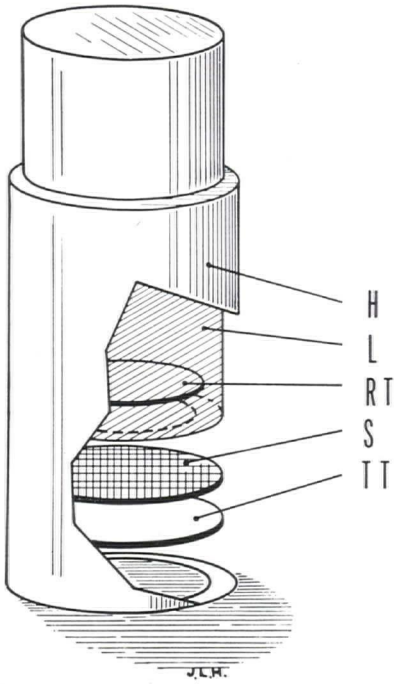

Figure 8

The planar, apposition, beta-excited X-ray source is schematized in cross-section. This was designed for gross apposition microradiography. Constructed on a laminar target design, TT and RT are the transmission and reflection targets respectively. S is the beta source (Figure 7).

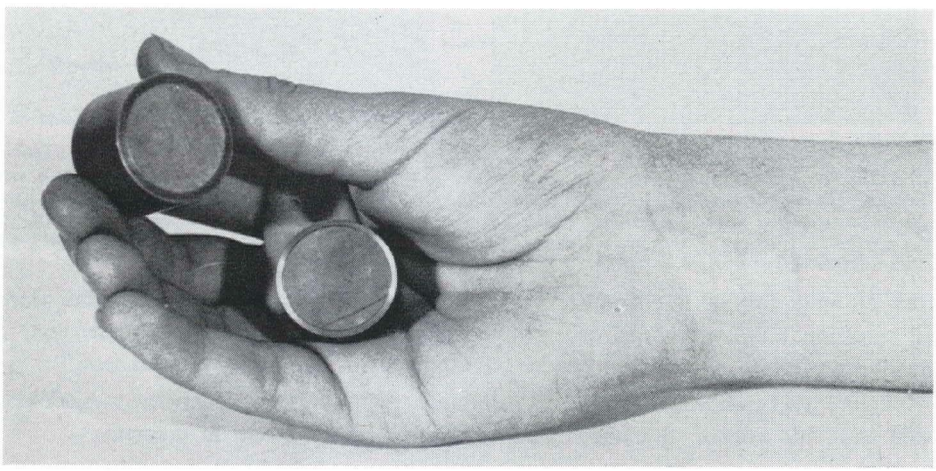

Figure 9

The small size of the disassembled, planar beta-excited photon source is shown here.

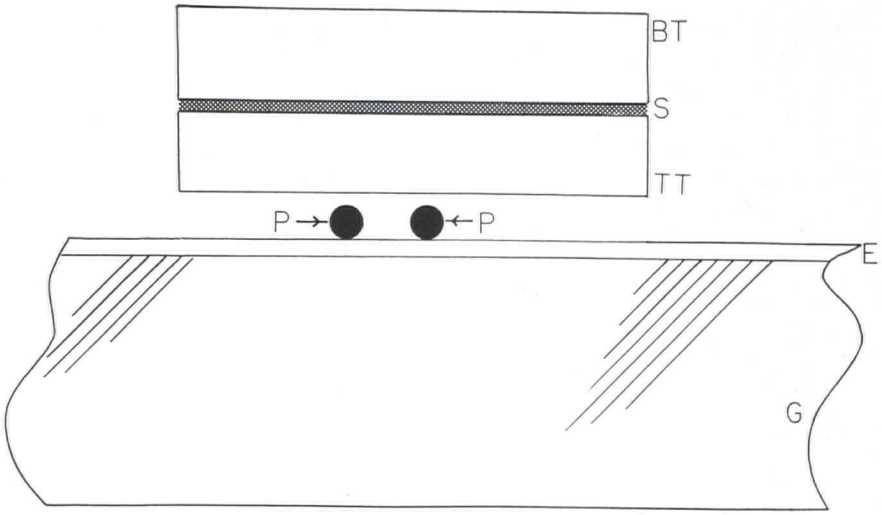

Figure 10

Gross apposition set up for planar beta-excited X-ray source. BT and TT are backing and trans. mission targets respectively. S is the radioactive source. P represents the macrostructure under investigation. E is the photographic emulsion and G the backing.

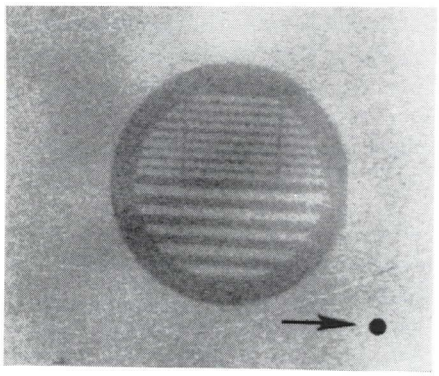

Figure 11a

This is an apposition exposure with the beta-excited source outlined in Figure 7. The subject is a copper screen one mil thick. The copper disk is about 3 mm in diameter. (See the silhouette lower right, arrow,)

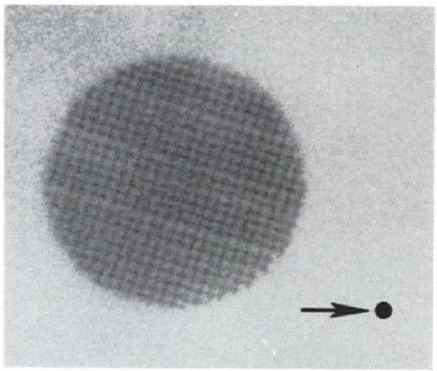

Figure 11b

A 200 mesh nickel screen was used here with the copper sandwich source in Figure 7. Structures which are resolved are grossly of the order of 50 microns in size. (The disk's size is shown at the arrow).

order of magnitude as the emulsion thickness and the separation between the source and emulsion was also of this order of magnitude. However, the gross dimensions of the subject, (length and breadth) were large relative to the emulsion thickness.

Figure #11a shows the resolution obtained in a study in which the subject consisted of a thin copper disk about .005" thick and about 2 mm in diameter.

This resolution study with this patterned copper foil shows a resolution which is of the order of 75 microns. The resolution of the very thin segments of this grid illustrate the presence of some low energy radiation from this beta-excited source. Figure #11b is another apposition exposure made with a 200 mesh nickel screen which

was ⅛" in diameter. A beta source, consisting of about one millicurie of P^{32}, in solution as the phosphate, was dried down on a special, thin, paper lamination, sandwiched between the two targets BT and TT in Figure #8. The apposition exposure was for 1.5 hours on Kodak medium lantern slide emulsion and development was in Dektol for 3 minutes. Resolution shown by this exposure is of the order of 50 microns. Extension of these resolution studies below this level was difficult, due to the problem of finite grain size in the m.l.s. emulsion. The variations in background density are due to unequal beta emitter surface concentration. Most deposition concentrations were less than 1 mg per sq cm. The contrast available here demonstrates that some low energy radiation is available from the spectrum of this source despite the high maximum energy of the betas. As is the case with most apposition work, the quality of the images depend largely upon the excellence of contact between the emulsion, subject and the source of radiation. Where the contact is quite perfect resolution of the order of 25 microns seems possible even for very thin specimens.

The apposition source which is described here was designed entirely for experimental purposes and was charged with a low-level beta source. Such a source could be increased in activity many fold. Where exposure times are unimportant, or where the source can be fixed to the subject for rather lengthy periods, therapy dosages may be administered to the surface layers from such a source. This has no immediate application for human usage but may have some usefulness in animal experimentation. An interesting facet of this apposition design is that it may be constructed to fit

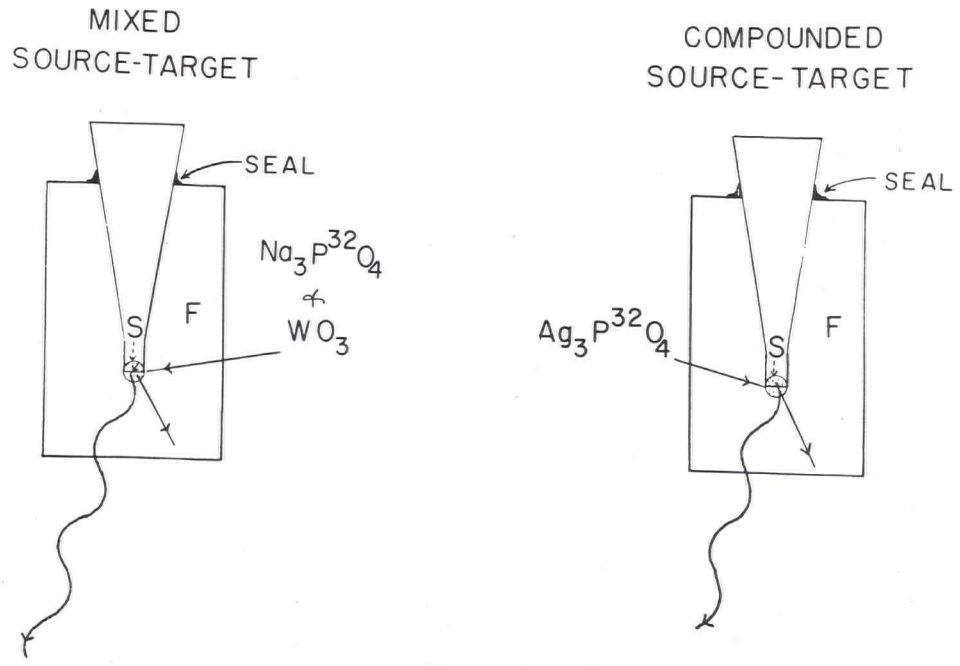

Figure 12

The beta-excited source types are illustrated in schematic form. The mixture of $Na_3P^{32}O_4$ and WO_3 as powders on the left illustrate a 'miture source'. P^{32} serves as the beta source, tungsten as the target. The 'compound source' on the right is made up with the target silver and radioactive P^{32} incorporated into the same molecule. The diameter of these packed sources may be two to three millimeters. This will give good resolution when subjects and sources are separated by about 20 cm.

any type of complex surface. Thus, it might be fabricated to fit a certain portion of the skull of an animal for surface therapy studies.

In addition to the apposition source above, some exposures were carried out with both the *mixed* and the *compounded* source-target geometries, which were described earlier. Figure #12 is a schematic of the devices which were used for this. The mixture type shown on the left in Figure #9 may consist of any two distinct materials (they may be elemental, or chemical compounds) usually in a powder form. One material incorporates the isotopic beta emitter and the other contains the target material. These materials may be mixed in a variety of techniques as described earlier. However, the intimacy of mixing cannot exceed by much the macro-scale. A technique, evolved here, consists of the precipitation of the two materials and packing of the still damp compounds into the lucite body. This obviates certain problems of health-physics associated with the dried powders. P^{32}, in the phosphate, serving as the beta source, and tungsten introduced into the mixture as the oxide are examples of the mixed source-target in Figure #9.

The compound which contains both the beta source and the target atom is a more efficient means of beta-excitation and is shown on the right in Figure #9. Silver phosphate contains both source and target atoms and when grown as a single crystal gives uniform geometry at separations of the atomic dimension. For the example given, each P^{32} atom will be accompanied in the crystal lattice by three target atoms of silver. This latter design was utilized, but facilities were not available at this laboratory for growing of radioactive single crystals. The compound (Ag_3PO_4) was packed in the receptacle in the lucite housing. The volume in which this source is packed may be made quite small. By mounting the source at a distance from the object and the X-ray emulsion, this small size maybe utilized to produce good resolution of relatively small objects. The dimension of this source type approximates the focal spot size of some X-ray tubes used for radiology. For the 3 mm source, resolution of 100-200 microns was anticipated.

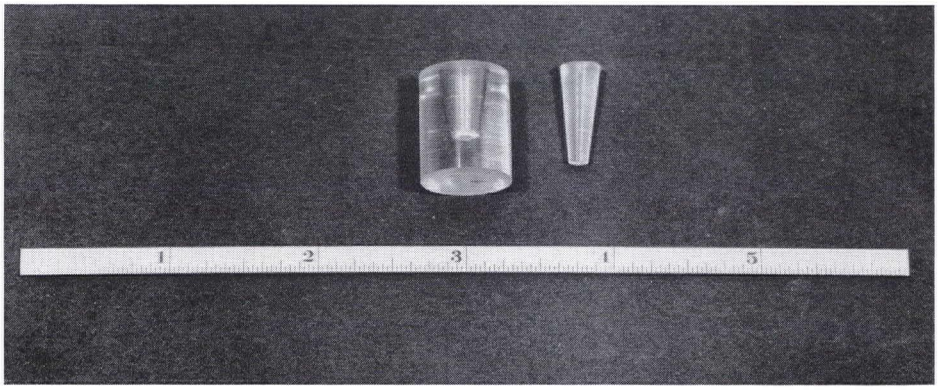

Figure 13

The disassembled lucite housing for the compound beta source. The void for the compound is cylindrical in shape.

The disassembled lucite body is shown in Figure #13. The cavity in this case is cylindrical in shape and about 3 mm in diameter and 3 mm high. This source type

suffers from a lack of intensity, but if this disadvantage can be obviated, this compact resolution source could be a competitor with conventional X-ray devices for use in the field. The lucite housing is about one inch tall by 1" in diameter.

The quality of X-ray production by this source was evaluated grossly here by radiography of miniature electronic tubes. Brownell[14] has used phantoms consisting of paraffin embedded with materials of various density to evalute the radiological quality of such sources. Figure #14 is a reproduction of a radiographic exposure of a miniature electronic tube. The beta-excited source was of the compounded type. It consisted of a 3 mm diameter silver phosphate source. The beta activity was 2.4 millicuries. This was mounted in a lucite housing similar to the one in Figure #13. The phosphate was packed into the void and sealed in with a clear lucite solvent (ether). This results in a relatively clean lucite source from a health-physics viewpoint. The subject was positioned on a special casette*. The source was rigidly suspended above the casette at a distance of 20 cm. The source was 50 to 75 milligrams. The exposure was for about 100 hours on special Kodak X-ray *Royal Blue emulsion* which carried the designation *SO-1197. Dupont Lightening Intensifiers* were used. The fine structure of the tube is moderately well delineated. Some of the leads which are

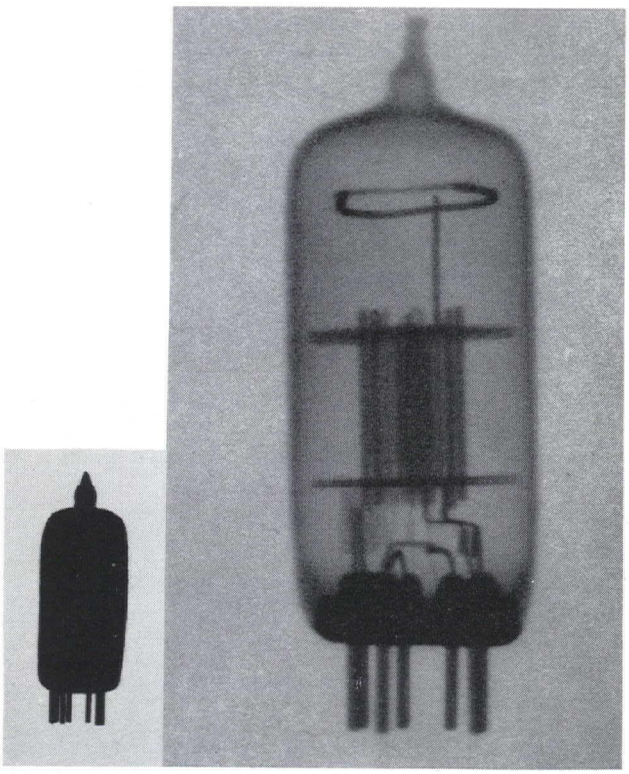

Figure 14a

Exposure of a miniature electronic tube by a 3 mm spherical silver phosphate source oriented at 20 cm from the subject. Some wires 5 mils in diameter are well resolved. Relative size of subject is shown in silhouette at left..

*To be reported.

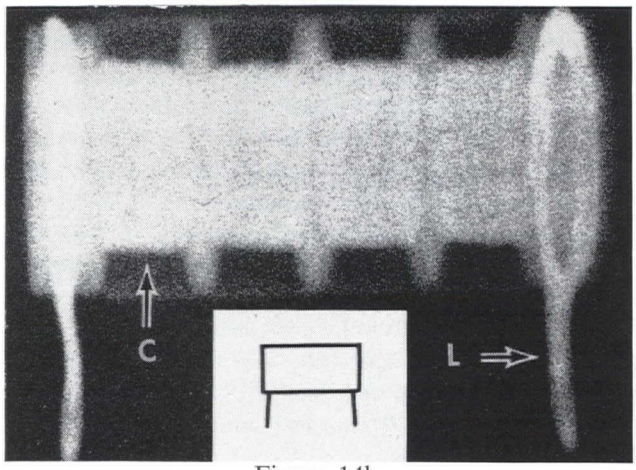

Figure 14b

Radiograph of a precision resistor made with the 3 mm silver phosphate compound source embedded in a lucite holder as shown in Figure 13. Subject's outline is shown.

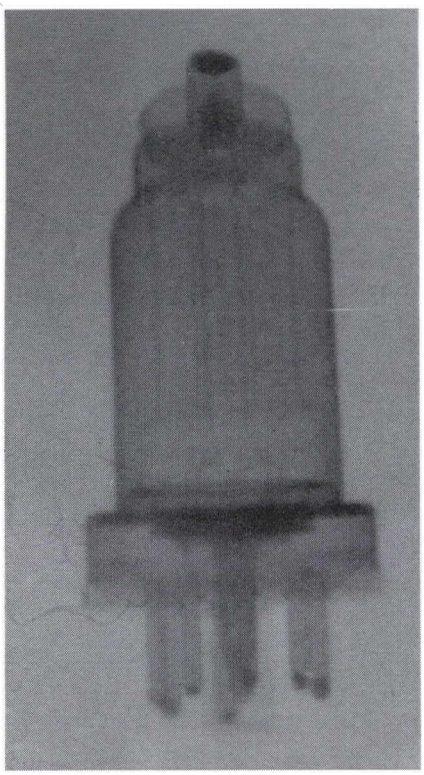

Figure 14c

Radiography of an all-metal tube with the compounded source-target.

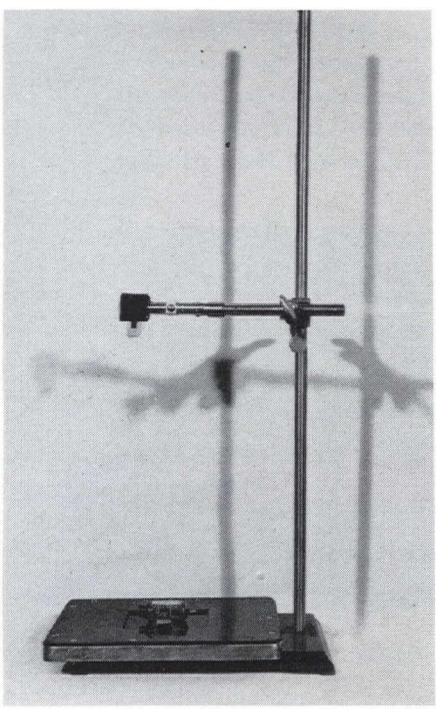

Figure 14d

An exposure in progress. This is the silver phosphate compound source.

visible are of 5 mil tungsten which indicates moderately good resolution (about 120 microns in diameter) for this unrefined laboratory set-up. The gradations in contrast and the continuous tone of the glass shield indicate that some X-radiation, of the low energy character desired, must have been produced. Some characteristics of this spectrum will be described in the following. Figure 14b is a similar exposure of a precision ceramic resistor which was made with a compounded silver phosphate source similar to the one described above. The metal end strips L are clearly visible. The inner core of resistance wire winding is delineated (arrow) as well as the segmented ceramic insulator disks. The paper cover is shown by the light line at the top and bottom. This is a positive copy of the radiogram. Some contrast may be observed between the various components of the subject. Because of its gross nature the inherent resolution is not well defined with this subject.

The exposures which are shown above were done with a low-level beta source and as a consequence the exposure times are relatively long. These times could be conveniently reduced by a factor of 10^2 by concentration of more P^{32} into the crystal lattice. This might reduce the exposure times to about twenty minutes. It might be possible to reduce this time still further (Brownell[14]).

A tendency towards 'flatness' or lack of proper contrast in these exposures may be attributed to the higher energy bremsstrahlung component of the total X-ray spectrum. This effect may be reduced by using a lower energy beta particle to reduce the $\frac{E\,Z}{800}$ ratio. Brownell[14] proposes that the homogenous source target is the best avenue for development of a radiography source with the desired contrast for resolution and differentiation of tissue and bone.

SUMMARY

The key to the usefulness of the X-ray photons from the beta-excited source lies in two characteristics; a, the intensity obtainable or rather the production efficiency; b, the spectral character of the total electromagnetic radiation obtained. Figure #15 is a copy of the spectral recording made from the compounded source described above. This tracing was done an a NaI recording, gamma ray, scintillation spectrometer*. The energy of the particulate radiation was high (in this case P^{32}). The target was of a relatively high Z number and thus the higher energies might be anticipated in the bremsstrahlung. These may be seen in the trace. No characteristic photons are evident in this spectra, which extends to about 400 Mev, but this may be masked by the inherent lack of resolution of the spectrometer. Further refinements are needed for both the planar copper target source and the compounded source to reduce the high energy component. Promethium-147 with tin targets has been proposed by Leboeuf and Stark, as a source favoring the lower energy, characteristic radiation of tin.

Table VIII gives some of the factors affecting the beta-excited source's efficiency and its photon spectra. The intensity of the X-radiation produced by the beta-excited source, or more accurately; the overall efficiency of the device, may be substantially improved by what we may term geometric factors. This includes better positioning be-

*Courtesy of the Phoenix Project, University of Michigan, Ann Arbor, Mich.

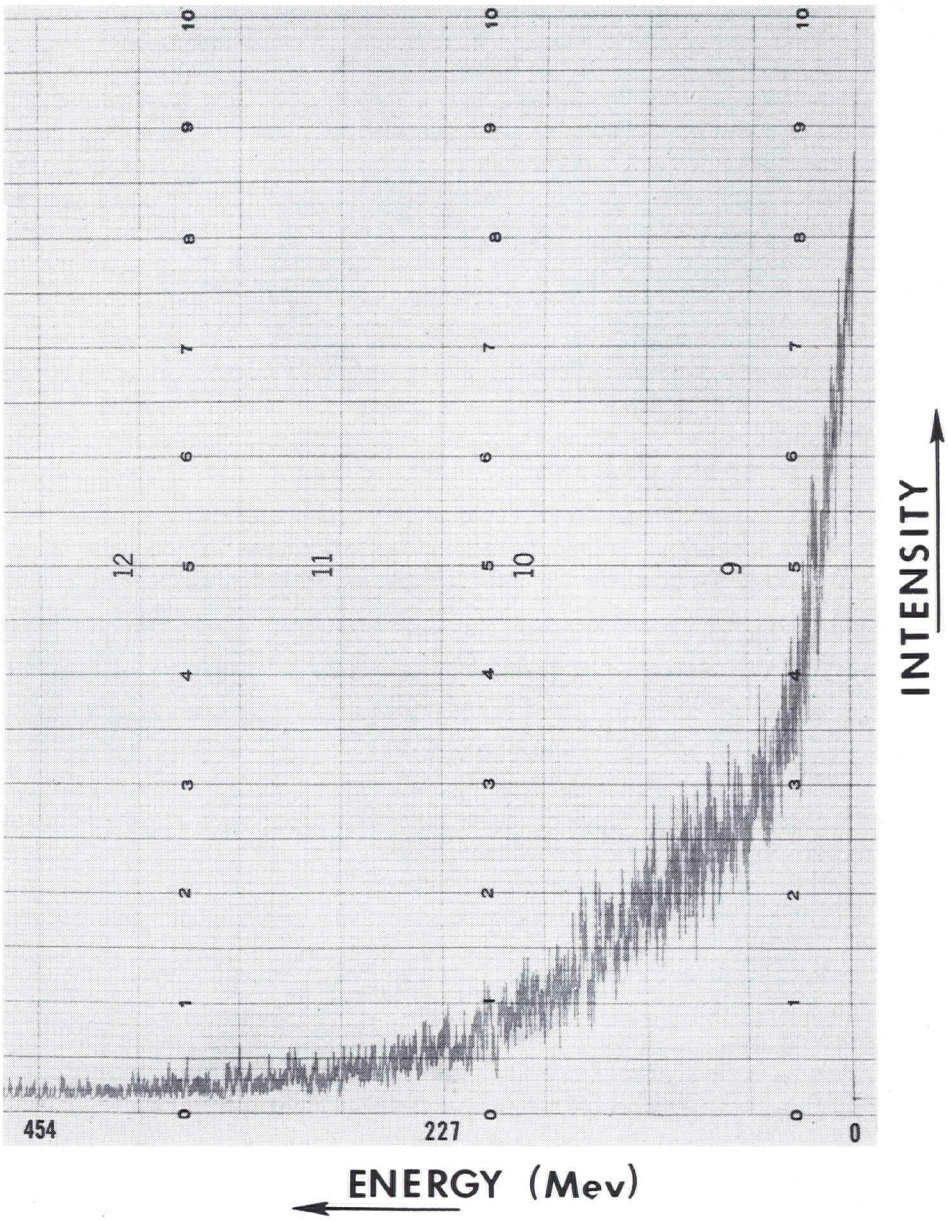

Figure 15

A scintillation spectrometer trace of the photon spectrum from the copper casing source shown in Figure 5. Energies range out to about 450 Kev. Energy is plotted right to left on the condensate; relative counts on the abscissa. This is a direct copy of the spectrometer trace which was run from right to left.

TABLE VIII

SOURCE IMPROVEMENTS

(1)	Spectral adjustments.
	a. Target Z.
	b. Beta-ray energy.
	c. Self absorption
(2)	Efficiency adjustments.
	a. Geometry (spatial).
	b. Target type.
	c. Source energy.
	d. Source configuration.
	e. Absorption and scatter characteristics.

tween the components of the source. The energy of the beta radiation and the target type are also concerned. In the case where bremsstrahlung, and particularly high energy bremsstrahlung, is to be minimized and characteristic X-ray production enhanced, the target Z should be kept as low as possible and the beta energy reduced by absorption techniques, shown earlier, or by careful selection of the proper natural beta energy. The problems of self-absorption and resonance absorption must be obviated by proper choice of the target material.

Some workers [14,13,7] have described beta excited sources applicable to diagnostic radiology. Other potential applications include; radiography, thickness gauging and analysis, density measurements, absorption chemical analysis, fluorescence analysis using the white spectra of the simple source. The source portability, small size, stability and zero power consumption indicate that the first real application of this source may be for radiography and radiology in the field or in other locations where power is not conveniently available. The low overall efficiencies which are currently available (10%[13] for the transmission target type and 1% for the reflection design) obviate this mechanism as a serious commercial competitor to the conventional X-ray device where electrical power is available, at least for the present time. The diagnostic X-ray tube operating at one millampere beam current may out-produce the one curie beta source by a factor of 10^4. The most recent report[14] on Pm^{147} compounded sources indicates that a factor of $2 \cdot 10^3$ exists between the diagnostic X-ray device and the promethium source type developed. Sacrificing some of the conventional performance expected of the radiological exposure, an improvement factor of about $6 \cdot 10^1$ is still essential. The portability, compact size and zero power consumption may eventually make this unit attractive for both analysis and radiology. An example in non-destructive analysis might be the study of the characteristics of suspension cable surfaces, where exposure time is not critical, on some inaccessible portion of a bridge. In such a location the small isotope-powered fluorescence target unit could be attached and left for many hours for exposure. An example in radiology could be emergency applications in disaster areas where power has been disrupted. In such a case some of ultimate in quality might be sacrificed. Here the beta-excited X-ray source could inform the physician of the gross condition of broken bones and immediate emergency care could be adjusted by this information.

The beta-excited X-ray source may also have some potential as a standardization unit for target characteristic radiation. It may be applied in teaching the principles of photon production and it has a distinct use in the experimental laboratory where a stable, inexpensive source of low intensity X-radiation is desired for varied research uses.

REFERENCES

1. Hollander, J. M., Perlman, I., Seaborg, G. T.: Table of isotopes, Rev. Mod. Physics 25:613, 1953.

2. Graham, R. L., Wolfson, J. L., and Bell, R. E.: The disintegration of Tm^{170}, Canad. J. Physics 30:459, 1952.

3. Liden, K., and Starfelt, N.: Gamma-rays, x-rays and bremsstrahlung from Tm^{170} sources, Archiv. Fysik 7:109, 1953.

4. Stahel, E., and Guillissen, J.: The inner breaking gamma radiation of radium E, J. phys. radium 1:12, 1940.

5. Wu, C. S.: Continuous x-rays excited by the beta-particles of P^{32}, Physical Rev. 59:481, 1941.

6. Bolgiano, P., Madansky, L., and Rasetti, F.: Continuous gamma-ray spectrum accompanying beta-decay, Physical Rev. 89:679, 1953.

7. Coleman, E. W., Brownell, L. E., Purohit, S. N.: Studies on x-rays and bremsstrahlen from source-target mixtures; preliminary report and literature survey, University of Michigan, Engineering Research Institute, Report No. 2471-1-P, 1956.

8. Bradt, H.: K capture of Fe^{55}, Helvet. phys. acta 19:22, 1946.

9. Liden, K., and Starfelt, N.: Characteristic x-rays from thick beta-ray sources, Archiv. Fysik 7:193, 1954.

10. Renard, G.: Internal bremsstrahlung spectrum of P^{32} in the low-energy region, J. phys. radium 14:361, 1953.

11. Leboeuf, M. B., and Stark, B. T.: Excitation of characteristic x-rays by beta particles, G. E. Report HW-31961, May 27, 1954.

12. Edward, J. E., and Pool, M. L.: Characteristic x-rays excited by beta particles, Physical Rev. 69:549, 1946.

13. Reiffel, L.: Beta-ray-excited low-energy x-ray sources, Nucleonics 13:22, March 1955.

14. Brownell, L. E., Coleman, E. W., Fox, C. J., and Nehemias, J. V.: Studies on x-rays and bremsstrahlen from source-target mixtures; reports covering period, November 1956—November 1957, University of Michigan, Engineering Research Institute, Report No. 2471-2-F, 1957.

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