April 8, 1952 C. C. CARROLL 2,592,115

NEUTRON SOURCE

Filed July 3, 1948

FIG. 1

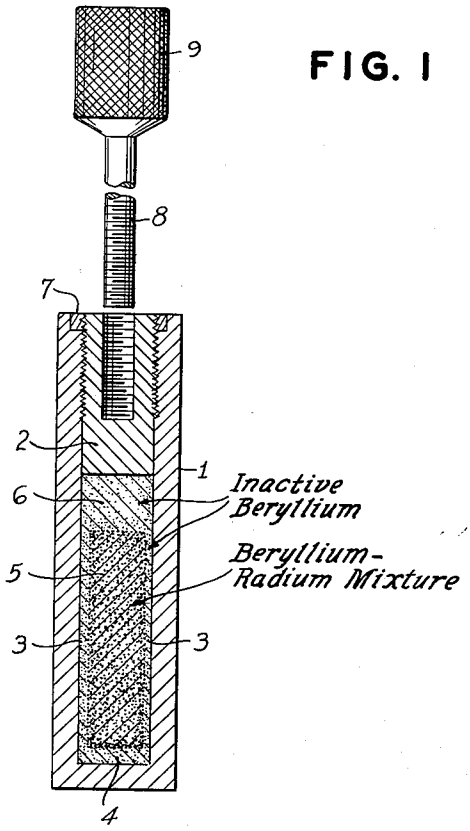


FIG. 3

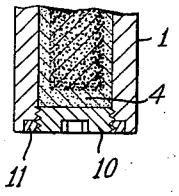
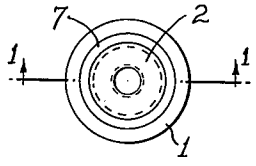


FIG. 2



INVENTOR
Clayton C. Carroll
BY
Pennie, Edmonds, Morton & Barrows.
ATTORNEYS

Patented Apr. 8, 1952

2,592,115

UNITED STATES PATENT OFFICE

2,592,115

NEUTRON SOURCE

Clayton C. Carroll, Madison, N. J., assignor to United States Radium Corporation, New York, N. Y., a corporation of Delaware

Application July 3, 1948, Serial No. 36,925

34 Claims. (Cl. 250—106)

1

This invention relates to the production of neutrons and especially to neutron sources and the method of manufacturing them.

One of the most convenient and economical means of producing neutrons comprises a nuclear reaction of radium with beryllium. This reaction may be expressed by the following nuclear equation:

$$_4Be^9 + _2He^4 \rightarrow _6C^{12} + _0n^1 \quad (1)$$

Neutron emission also results from the bombardment of beryllium by gamma rays which produces alpha particles and neutrons according to the equation:

$$_4Be^9 + \gamma \rightarrow 2_2He^4 + _0n^1 \quad (2)$$

The following nuclear reactions also may occur as a result of delayed radioactivity, but they probably represent only a small increment in the total neutron emission:

$$_4Be^9 + _0n^1 \rightarrow _4Be^{10} \rightarrow _4Be^8 + 2_0n^1 \rightarrow 2_2He^4 \quad (3)$$

$$_4Be^9 + _{-1}e^0 \rightarrow _3Li^8 + _0n^1 \rightarrow _4Be^8 + _{-1}e^0 + _0n^1 \quad (4)$$

$$_4Be^8 \rightarrow _22He^4 \quad (5)$$

Ideally, a homogeneous dispersion of monoatomic radium throughout an infinite number of beryllium atoms will produce a maximum of neutrons. The nearest approach to such a relation would result from an alloy of radium and beryllium metals. However, a true alloy of this nature has never been produced due, in part, to the facts that beryllium has an extremely high melting point and that both beryllium and radium are readily oxidized.

The nearest practical approach to an actual alloy has been achieved by the intimate dispersion of radioactive metal salts in powdered beryllium. This dispersion has heretofore been produced by the evaporation of a solution of a salt, such as an aqueous solution of radium chloride or bromide in the presence of beryllium powder. The resultant mixture was then dried and compressed into a pellet and sealed in a container, usually somewhat larger than the pellet.

Several disadvantages are inherent in such a method, although some of them have not heretofore been appreciated. While it is possible to produce microscopic crystal deposits of the radium salt on the surface of the beryllium particles by the proper choice of solvent and evaporation rate, such deposits as produced by prior methods are not firmly attached to the particle and the crystals are multimolecular in thickness. This results in a mixture having non-uniform

2

neutron emission. Also, the emission efficiency is low because of the absorption function of the radium salt crystals which will intercept and stop part of the alpha radiation before it collides with the beryllium surface. It is impossible to prevent localized deposits of crystals at the time when the mixture approaches the dry state. Additionally, most of the soluble radium salts are hygroscopic, from which it follows that extreme precaution must be used to seal the containers so as to exclude moisture. The presence of water vapor in the closed container with a radio-active substance eventually results in the development of dangerous gas pressures due to decomposition of the water by radium, and also the free oxygen causes oxidation of the beryllium metal. Lastly, the mechanical difficulties of keeping a suspension of metal powder in a radium solution agitated during evaporation renders the operation hazardous to the operator. The foregoing and other factors have heretofore contributed to such non-uniformity of neutron emission that any two sources intended to have like emission would vary over a wide range, and even these would vary over a period of time.

On the other hand, the neutron source of the present invention is extremely stable; and any number of such sources may be made to provide the same emission and to maintain it. The invention includes an improved neutron-emitting dispersion product and method of manufacturing it, as well as an improved capsule or container for the product. In combination, these components provide all the advantages here set forth.

In accordance with the method of the present invention extremely fine beryllium particles are individually coated and combined with a radium salt to form a new radium-beryllium dispersion product, and a quantity of this product is then preferably encased within or surrounded by a layer or jacket of non-radioactive beryllium metal so as to increase the chances that each alpha particle emitted by the radium will collide with a beryllium nucleus to produce a neutron. For this purpose it is preferable that the jacket be in contact with as many as possible of the adjacent radium-coated particles. The product thus encased is placed within a suitable capsule which is then preferably heated to a temperature of about 1500° F. to reduce the radium salt to radium metal, with the result that the dispersion of radium in the beryllium is considerably increased. The capsule is then hermetically sealed and may be readily transported and manipulated as required.

In addition to radium, other radioactive materials may be employed as sources of alpha particles in accordance with the invention, such materials including actinium-X, thorium-X and mesothorium. While the latter is not an alpha emitter, it is a radium isotope and rapidly decays into alpha-emitting products.

The preferred method of manufacturing the radium-beryllium dispersion product together with several modifications in accordance with the invention is described below. The construction of a capsule and the contents thereof arranged in accordance with the invention is illustrated in the drawing wherein:

Fig. 1 shows in cross section, a capsule comprising a neutron source according to the invention, this section being taken along the line 1—1 of Fig. 2;

Fig. 2 is a plan view of the capsule of Fig. 1; and

Fig. 3 shows an alternative modification of the capsule of Fig. 1 in which the bottom is removable.

As above indicated, it has heretofore been proposed to employ as a neutron source a mixture of powdered beryllium and a radioactive salt such as radium chloride or radium bromide. The product of the present invention differs in several important respects from such previous mixtures, including the fact that an insoluble radium salt is directly deposited on the surface of and chemically combined with each beryllium particle. As a result, the physical association of the beryllium and radium salt is more intimate by a considerable degree than in any product heretofore known. Furthermore, the radium salt crystals are more uniform and are smaller than in the previous mixtures so that a given alpha particle is less likely to be wasted by being intercepted by a salt crystal and prevented from collision with a beryllium surface. Since the absorption of alpha particles by the crystal compounds is approximately in proportion to the square root of their molecular weights, the "stopping power" of radium bromide, for example, is nearly 1.2 times that of the carbonate. Also, the dispersion product made by the method of this invention is mechanically stable because the radium salt is firmly attached to the beryllium surface. To this end, the anion should be so chosen that its combination with beryllium likewise forms an insoluble salt. For this reason, the carbonate is preferred because it forms with both radium and beryllium, salts which are substantially insoluble. The particle size of the beryllium and the radioactive material are, in general, to be as small as practicable, for example, the beryllium particles should be of a size which should pass through a 325 mesh screen, viz., should be not substantially larger than 325 mesh. If the particles are thus graded by a 325 mesh screen the average particle size will be somewhat less than 44 microns. The radioactive particles should be no larger than of the order of one-twentieth as large as the beryllium particles, and hence may be of the order of 2 microns, and preferably smaller. By employing radioactive particles of this extremely small order of magnitude, a more uniform and intimate dispersion is attained, and also the chances of interception and absorption of radiations from adjacent radioactive particles are minimized. Precipitation from alcoholic solution results in the formation of finer crystals (viz., less than one micron thick, and

approaching molecular thickness) and decreases the solubility of radium carbonate and hence is preferred in the method of the invention.

An important aspect of the present invention resides in the discovery that a closer approach to an ideal dispersion is achieved when a mixture of radium carbonate and beryllium, as above described, is heated to a temperature at which radium has appreciable vapor pressure, viz., between 1400° F. and 1500° F. In the presence of beryllium metal, the reaction is believed to be as follows:

$$RaCO_3+5Be\rightarrow 3BeO+Be_2C+Ra \qquad (6)$$

From this equation, it will be noted that the carbide of beryllium, but not the carbide of radium, is formed. The fact that elemental radium metal but no radium carbide is formed has been ascertained experimentally. In this manner metallic radium may be deposited on the surfaces of beryllium particles, which results in a highly efficient neutron source comprising beryllium particles a substantial portion of the surface area of which is coated with a film of elemental radium of substantially uniform thickness. If the process is carefully carried out, the beryllium particles will be substantially enveloped with a film of metallic radium. As is pointed out below, it is preferable that such radium-coated or radium-enveloped beryllium particles be interspersed with uncoated, non-radioactive beryllium particles to increase the efficiency of the source.

It has also been found that at a temperature of about 1850° F. and more, radium carbonate decomposes into radium oxide and carbon dioxide. In the presence of beryllium metal, this reaction proceeds to produce beryllium oxide and radium metal. These reactions may be written as follows:

$$RaCO_3\rightarrow RaO+CO_2 \qquad (7)$$

$$RaO+Be\rightarrow BeO+Ra \qquad (8)$$

However, because of the difficulties introduced by the high temperature and other considerations connected with reactions (7) and (8), the reaction indicated in Equation 6 is preferred.

If the heating is carried on under reduced pressure the radium may be deposited on the inside of the container or on other objects placed within it, which may be desirable for some purposes. However, to retain the radium metal within the mixture, it is desirable to heat the mixture at atmospheric pressure or above. Since both beryllium and radium are readily oxidized, the reaction must be carried out in either a neutral or a reducing atmosphere. Radium forms a volatile hydride and beryllium forms a nitride at the temperature of the reaction, so neither a hydrogen nor a nitrogen atmosphere is appropriate in this case. Suitable neutral atmospheres may be provided by the inert gases: helium, argon, neon, etc. Because of the high degree of purity obtainable, argon is here preferred. The stoichiometric quantity of beryllium required in accordance with the Equation 6 is 0.16 mg. of beryllium metal per milligram of radium. If substantially more than this quantity is used for precipitation and then an additional amount of beryllium is ground in with the mixture in accordance with the procedure below described, a minimum of self-absorption of alpha particles results, and the chances of collision between an

outwardly projected particle with a fresh beryllium surface are increased.

The final mixture may then be pressed into a pellet by a suitable die and plunger arrangement, or preferably it may be pressed into a container directly. An advantage in the latter procedure results from the fact that it permits the use of a beryllium-coated foil of a metal, such as silver or platinum, between the walls of the container and the active mass. By this means, the alpha particles which normally would be lost in the walls of the container are made to collide with a beryllium surface thus again to increase the chances of producing neutrons. The advantages just described will result from the use of any of the other alpha-emitting radioactive materials among which are thorium, polonium and plutonium.

The mentioned compression of the powdered constituents results, as is well known in the art of powder metallurgy, in a smaller and more stable product. This may be important in connection with various applications requiring a neutron source of minimum dimensions, and especially in measurements depending on an assumed point source. For this reason a sphere would be preferred, because it has the smallest surface area per unit volume, and should have uniform radiation in all directions, but inasmuch as it is difficult to fill a spherical capsule uniformly, a cylinder has been chosen as the closest practical approach to a sphere. A cylinder of active material having the same height as diameter is therefore the preferred form to approximate a point source.

A desirable procedure in accordance with the invention comprises placing the precipitated mixture in the center of an inactive mass of beryllium powder which in turn is contained in a capsule comprising a cylinder of stainless steel or other non-corrosive metal such as an alloy essentially of nickel and copper with a small proportion of iron, known as "Monel," then subjecting the entire mass to pressure and thereafter heating it to approximately 1500° F. in an inert atmosphere, cooling in the same atmosphere and then sealing the capsule hermetically. By this process the radium as a metal is made to diffuse throughout the beryllium mass to a greater degree, and with more uniformity, than has heretofore been achieved with radium compounds.

The following examples will illustrate the method of the invention more generally discussed above.

To a neutral or an alkaline solution (viz., one having a pH greater than about 6) of 300 mg. of radium element as a soluble salt such as the bromide or chloride dissolved in approximately 15 ml. of water, is added 30 ml. of 95% ethyl alcohol, a weighed quantity consisting of approximately one gram of high purity beryllium powder of approximately 325 mesh, or smaller if obtainable, is carefully added with stirring. The radium is then precipitated by the slow addition with stirring of a solution of 600 mg. of ammonium carbonate in 10 ml. of water. The mixture is stirred intermittently for one-half to one hour and then allowed to stand for twelve or more hours.

An additional 100 mg. of beryllium powder is then weighed on the mat of a tared 30 ml. fine porosity fritted Pyrex glass crucible. A few milliliters of 50% ethyl alcohol are added, and the mixture is swirled until the beryllium is in suspension. The powder is allowed to settle for a few minutes and then the alcohol is drawn through with suction. The active material prepared as outlined in the last preceding paragraph is then filtered through the resultant mat and washed with 50% alcohol until the filtrate shows no chloride ion when tested with silver nitrate. The mixture is heated for approximately one hour at 110° C. to drive off the alcohol.

If the mixture is to be sealed without further heat treatment, sufficient beryllium powder to bring the total used to 2500 mg. is weighed into a boron carbide mortar. The active material is transferred to the mortar and ground for 30 minutes using a boron carbide pestle. The active material thus ground is then ready for transfer to the container or capsule of which a suitable form in accordance with the invention is illustrated in the drawing.

Referring to Fig. 1, the capsule may comprise a container or shell 1 having a central cavity therein. The upper portion of the inside surface of the shell is threaded to receive a plug 2. By way of example, the cavity might be 1 inch long by $\frac{3}{16}$ inch in diameter, and the walls of the shell about $\frac{3}{16}$ inch thick, although any desired dimensions may be used. In accordance with the invention it is preferable that the core of the active material be completely surrounded by beryllium metal. Consequently, before any of the active mixture is inserted into the cavity, a cylinder 3 of a foil of suitable metal, such as platinum or silver, of which a surface has been coated with a layer of beryllium powder, is inserted within the cavity so as to line the same. A layer of beryllium powder 4 is then deposited in the bottom of the cavity within the foil cylinder, and is pressed in place. The radium-beryllium mixture is then transferred to the tared container in three or four portions, each portion being pressed down before the next one is added so as to form a compact mass 5. After the last portion of active material has been pressed down, a quantity, for example approximately 200 mg., of non-radioactive beryllium powder 6 is placed over the top of the active material and the entire mass subjected to considerable pressure. Approximately 25 tons per square inch is a suitable pressure. The sealing plug 2 is then screwed in place and preferably is sealed with a hard solder such as silver solder, which is flowed into a groove in the top of the cylinder formed for that purpose. For convenience in handling the capsule, a rod 8 terminating in a handle 9 may be screwed into a smaller threaded hole, as shown, in the top of plug 2. Although the dimensions of the capsule and of the active material within it may be of any values desired, satisfactory capsules have been made pursuant to the invention in which the cylinders of compressed radium-beryllium mixture have varied in height from about once to twice their diameters. In these instances the diameters of the cylinders varied from $\frac{3}{16}$ inch to $\frac{3}{8}$ inch.

It is well known that radon, which is a gas, results from decay of radium, and that the decay of radium, of radon, and also of some of the decay products of radon, is accompanied by emission of alpha particles. Consequently, it is of importance to retain within the capsule of this invention all of the products resulting from the decay of the radium and so to locate the beryllium within the capsule as to assure the

maximum opportunity for collision of these alpha particles with a beryllium surface.

An alternative construction is illustrated in Fig. 3 which shows a bottom plug 10 sealed with a solder seal 11 similar to the seal 7 at the top of the plug. Although in general it is preferable to form capsules for the present purpose with as few openings as possible, a removable bottom plug is in some instances desirable to facilitate emptying the capsule, as for example, if it be desired to recover the radium in the mixture. In that event by removing the top and bottom plugs the contents of the capsule can be pushed out and the capsule cavity washed if desired. Otherwise the contents can most readily be removed by cutting out the bottom of the capsule.

In the foregoing description referring to Fig. 1, the layer 3 surrounding the mass 5 of radium-beryllium has been stated to comprise a suitable metal foil coated with beryllium metal. An alternative embodiment and one which in many instances is preferable, comprises the substitution of a layer of powdered beryllium metal for the mentioned foil. In this event the capsule may be loaded as follows: First a layer 4 of beryllium metal powder is placed in the bottom of the capsule and pressed down. Next, a rod or plug, having the diameter of the final compacted mass or pellet 5 of the radium-beryllium mixture is centered in the cavity of the capsule and beryllium metal powder is poured in the space between the plug and the inside wall of the capsule 1 to form a sleeve 3 of powdered metal. This powdered metal sleeve is compacted from time to time during the filling process by pressing on the top of it a length of metal tubing which is of size suitable to fit snugly within the space around the central plug. After this sleeve of metal powder has been compacted around the central plug it will remain in place, so the plug is withdrawn and a suitable quantity of the radium-beryllium powder mixture is poured into the cavity within the beryllium sleeve, and tamped periodically during the filling process, as above described. Thereafter the inactive top layer 6 of beryllium is added, compacted under high pressure, and the capsule sealed, as before. The construction resulting from either of the embodiments above described provides a core or pellet of radium-beryllium completely surrounded by a layer or jacket of beryllium metal, which as above explained, increases the neutron emission and thus the efficiency of the capsule as a neutron source.

Various alternative constructions and variations of the embodiments above described, all within the invention, will occur to those skilled in the art. Three such variations comprise the substitution for the layers 4 and 6 of powdered beryllium metal, a disc of solid beryllium metal, or the plugs 2 and 10 may be formed of beryllium, or the inner ends of such plugs may be coated with beryllium. In any event, the object is to form a beryllium jacket enclosing and preferably in contact with the radium-beryllium mixture. The thickness of the beryllium jacket is unimportant so long as it is thick enough to intercept substantially all of the alpha particles.

It has already been explained that greater distribution of the radium in the radium-beryllium mixture is achieved by heating the mixture. If the mixture is to be heated in accordance with the invention it is first transferred to a mortar without addition of further beryllium powder and ground for about 30 minutes. A piece of

annealed platinum foil, of, say, 0.005 inch thickness, is then cut to such dimensions that it may later serve as a cylindrical liner or sleeve 3 (Fig. 1) for the capsule intended to be used. By bending upward two or three millimeters of each edge of this piece of foil a small boat is formed into which a uniform layer of inactive beryllium metal powder is placed so as to cover the bottom and sides of the boat. The active material is then transferred from the mortar to this boat which is placed on a support in a quartz tube of which one end is closed. The air in the quartz tube is displaced by alternately evacuating to, say, 20 mm., and filling it with argon gas at a pressure of approximately one pound in excess of atmospheric pressure, five or more times. The tube is then placed in a combustion furnace the temperature of which has previously been raised to approximately 1500° F. and is heated under pressure for one to two hours. After heating, the tube is removed from the furnace and allowed to cool to room temperature in an argon atmosphere. As before, sufficient beryllium powder to bring the total, including the radium-beryllium mixture cooled as just mentioned, to approximately 2500 mg. is weighed into a boron carbide mortar and the contents of the mortar ground for approximately 30 minutes, preferably in an argon atmosphere. The platinum boat may then be flattened, formed into a cylinder on a suitable mandrel, and inserted into the capsule, active side in, to form the cylinder 3 above mentioned. The ground mixture of active and inactive material is then added, pressed in as before, and the container sealed.

In the event that the capsule structure includes a beryllium sleeve 3 of powdered beryllium metal, and it is to be heated, the procedure above described may be modified as follows: After the entire mass, comprising a radium-beryllium core within a powdered beryllium jacket, has been subjected to a high pressure such as that of 25 tons per square inch above mentioned, the top plug is screwed into place and the capsule is placed in the closed quartz tube as above described. The air is then displaced by pumping argon in and out, as mentioned, after which the capsule containing the mixture is heated at about 1500° F. for approximately 2 hours, and the capsule is sealed with solder as before.

The mentioned operation of grinding the radium-beryllium mixture with additional beryllium powder results in a more uniform mixture and one in which the radium is dispersed in more intimate contact with the beryllium, both being desirable. The grinding does not detach the radium compound from the surface of the beryllium metal particles to any appreciable degree except in the event that the crystal deposit is unusually thick. Thick crystal deposits, if any, are likely to be broken off by the grinding, and this is an advantage, because it decreases the probability that any given alpha particle will be intercepted by an undesirable thickness of salt which might prevent it from striking a beryllium surface. The reason for the unusually strong adhesion between the beryllium particles and the radium carbonate crystals attached to the surface thereof as a result of the present method is not clearly understood, but it is evident that the radium carbonate is chemically attached to the beryllium. The surface of the beryllium particles is chemically active, even in a water slurry, and since this metal forms an insoluble carbonate when carbonate ion is added to solutions of its

salts, an actual system of coordinate valence obtains when radium carbonate is precipitated in the presence of beryllium powder.

What I claim is:

1. A neutron source comprising a mass of minute beryllium metal particles substantially completely coated with radium carbonate crystals in firm adherence to the surface of said particles and of a thickness not exceeding approximately one micron.

2. A neutron source comprising a mass of beryllium metal particles not substantially larger than 325 mesh coated with radium carbonate crystals deposited thereon as an insoluble precipitate.

3. A neutron source comprising a compacted mass of beryllium particles, the surfaces of said particles comprising carbonate ions chemically combined with radium and beryllium.

4. A neutron source comprising a mass of minute beryllium metal particles each of which is substantially coated with radium carbonate crystals in firm adherence to the surface of said particles, intimately mixed with an approximately equal weight of uncoated beryllium metal particles.

5. The method of making a neutron source which comprises compressing in a capsule a mixture of beryllium powder and radium carbonate, heating said compressed mixture in an atmosphere of inert gas at a temperature sufficient to form beryllium oxide and radium, cooling the capsule and its contents in said atmosphere and hermetically sealing said capsule.

6. The method of making a neutron source which comprises compressing in a capsule a mixture of beryllium powder and a radioactive substance, heating said compressed mixture to approximately 1500° F. in an atmosphere of inert gas, cooling the capsule and its contents in said atmosphere, and hermetically sealing the capsule.

7. The method of making a neutron source which comprises compressing in a capsule a mixture of beryllium powder and a mass of beryllium particles each of which is substantially coated with crystals of a radioactive substance, heating said compressed mixture to approximately 1500° F. in an atmosphere of inert gas, cooling the capsule and its contents in said atmosphere, and hermetically sealing the capsule.

8. The method of making a neutron source which comprises chemically precipitating crystals of radium carbonate on the surfaces of minute particles of beryllium, grinding the coated particles together with additional uncoated beryllium particles to form a powder mixture, compressing a quantity of said mixture within a casing of non-radioactive beryllium, and sealing the resulting product within a capsule.

9. The method of making a neutron source which comprises chemically precipitating crystals of radium carbonate on the surfaces of minute particles of beryllium, grinding the coated particles together with additional uncoated beryllium particles to form a powder mixture, compressing a quantity of said mixture within a capsule, and sealing the capsule.

10. The method of making a neutron source which comprises chemically precipitating crystals of radium carbonate on the surface of minute particles of beryllium, grinding the coated particles together with additional uncoated beryllium particles to form a powder mixture, and sealing a quantity of said mixture in a capsule.

11. In the method of making a neutron source, the step which comprises precipitating radium in the form of a carbonate in situ on finely divided particles of metallic beryllium whereby the surfaces of said particles are coated with a tenacious radioactive film.

12. In the method of making a neutron source, the steps which comprise, precipitating radium from a non-acidic alcoholic solution of a soluble salt of radium by the addition of ammonium carbonate while stirring into the solution a quantity of minute particles of beryllium metal, whereby radium in the form of a carbonate is precipitated in situ on the surfaces of said particles and forms a tenacious radioactive coating thereon.

13. The method of making a neutron source which comprises enclosing in a container a mixture of beryllium particles and radium carbonate, and heating said mixture to a temperature between approximately 1400° F. and approximately 1500° F., whereby the radium carbonate is decomposed to metallic radium and the metallic radium is dispersed among and deposited on surfaces of said beryllium particles.

14. The method according to claim 13 characterized in that said mixture is heated in an inert gas atmosphere and is subsequently cooled in the same atmosphere.

15. The method according to claim 13 characterized in that the radium carbonate is admixed with the beryllium by precipitating it on the beryllium particles.

16. The method of making a neutron source which comprises enclosing in a container a mixture of beryllium particles and radium carbonate, and heating said mixture to a temperature between approximately 1400° F. and approximately 1500° F. whereby the radium carbonate is decomposed and particles of beryllium oxide and beryllium carbide are formed and whereby metallic radium is deposited on surfaces of said particles.

17. A neutron source including a mass of a finely divided radioactive substance intimately dispersed among particles of a material which emits neutrons when exposed to the radioactivity of such substance, the particles of said radioactive substance being of a size not substantially larger than two microns, and the particles of said material being not substantially larger than twenty times the size of said radioactive particles, and a jacket completely surrounding said mass, said jacket being formed of a non-radioactive material which emits neutrons when exposed to radioactivity of said substance.

18. A neutron source including a mass of finely divided alpha-emitting radioactive substance intimately dispersed among particles of a material which emits neutrons when exposed to alpha radiation, the particles of said material being not substantially larger than forty microns, and the particles of said radioactive substance being not substantially larger than two microns, whereby minimum interception of alpha radiation occurs in the particles of said radioactive substance.

19. A neutron source including a mass of a finely divided radioactive substance intimately and uniformly dispersed among particles of beryllium, the particles of said radioactive substance being of a size not substantially larger than two microns and the particles of said beryllium being not substantially larger than forty microns, and a jacket completely surrounding said mass, said jacket being formed of a non-radioactive

material which emits neutrons when exposed to the radioactivity of said substance.

20. A neutron source comprising a mass of a finely divided radioactive substance which includes a form of radium intimately dispersed among particles of beryllium, the size of said particles of beryllium being not substantially larger than forty microns, and the size of the particles of said radioactive substance being not substantially larger than two microns whereby minimum absorption of alpha radiation occurs in the particles of said radioactive substance, and a jacket completely surrounding said mass, said jacket being formed of a non-radioactive material which emits neutrons when exposed to the radioactivity of said substance.

21. A neutron source including a mass of finely divided radioactive substance intimately dispersed among particles of beryllium, said substance comprising a salt of a metal selected from the radioactive group which includes radium, actinium-X, thorium-X and mesothorium, the particles of said radioactive substance being of a size not substantially larger than two microns and the particles of said beryllium being not substantially larger than forty microns, and a jacket completely surrounding said mass, said jacket being formed of a non-radioactive material which emits neutrons when exposed to the radioactivity of said substance.

22. A neutron source comprising a mixture of beryllium particles not substantially larger than 325 mesh and a salt of a radioactive metal divided into particles not substantially larger than one-twentieth as large as those of the beryllium, a layer of non-radioactive beryllium enclosing said mixture, and a hermetically sealed capsule enclosing the same.

23. A neutron source according to claim 22 characterized in that said beryllium particles are coated with a salt of a radioactive metal which comprises particles of the maximum dimension of which is less than one micron.

24. A neutron source comprising a mixture of beryllium particles not substantially larger than 325 mesh, and a radioactive substance divided into particles not substantially larger than one-twentieth as large as those of the beryllium, a layer of non-radioactive beryllium enclosing said mixture, and a sealed capsule enclosing the same.

25. A neutron source according to claim 24, characterized in that said beryllium particles are coated with a radioactive substance comprising particles of which the maximum thickness is less than one micron.

26. A neutron source according to claim 24, characterized in that said beryllium particles are coated with crystals of radium carbonate.

27. A neutron source comprising a quantity of minute particles of beryllium, a substantial portion of the surface area of each particle being coated with a film of elemental radium of substantially uniform thickness.

28. An article of manufacture comprising finely divided beryllium substantially enveloped with a film of elemental radium metal.

29. An article of manufacture comprising metallic beryllium substantially enveloped with a film of metallic radium.

30. The method of depositing a radium-containing coating on an object which includes enclosing said object in a vessel with radium carbonate in contact with elemental beryllium and heating the contents of the vessel to a temperature sufficiently high to cause reduction of the radium carbonate to elemental radium and vaporization of radium metal.

31. The method of coating an object with metallic radium which comprises enclosing said object in a vessel with radium carbonate in contact with elemental beryllium and heating the radium-beryllium mixture to a temperature at which radium has an appreciable vapor pressure and of at least 1400° F., maintaining the mixture at said temperature at least until the amount of radium required for coating said article has been liberated from the radium carbonate, and cooling said vessel.

32. The method of coating an object with metallic radium which includes enclosing said object in a vessel with radium carbonate in contact with elemental beryllium and in an inert atmosphere, and heating the contents of the vessel to a temperature sufficiently high to vaporize radium.

33. The method of producing metallic radium which comprises heating radium carbonate in contact with metallic beryllium.

34. As an article of manufacture, an object a substantial portion of the surface area of which is coated with a film of elemental radium metal of substantially uniform thickness.

CLAYTON C. CARROLL.

REFERENCES CITED

The following references are of record in the file of this patent:

UNITED STATES PATENTS

Number	Name	Date
1,061,674	Hoyt	May 13, 1913
1,718,899	Fischer	June 25, 1929
2,326,631	Fischer	Aug. 10, 1943
2,440,999	Anderson	May 4, 1948

FOREIGN PATENTS

Number	Country	Date
114,150	Australia	May 2, 1940