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Search for Nuclear Isotopes for Use in a Nuclear Battery

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Performance of a radioisotopic thermoelectric generator for a human-portable energy source is discussed. The design of thermoelectric generators is not considered. Instead desirable characteristics of the radioisotope are used to search for reasonable candidates with a half-life measured in weeks and generating radiation that could easily be shielded. Because radioisotopes with short half-lives would have limited shelf-lives, a search was undertaken to discover if isomers with different decay paths existed with characteristics that would lead to a useful energy generator design. The results indicate several interesting cases for energy storage in radioactive isotopes. Two of the most interesting cases uncovered were ^{121}Te and ^{254}Es. However, intermediate levels that could be used to connect the various nuclear energy levels are not currently known. Measurements of transition rates that can be stimulated between the desired levels are also needed to determine the practicality of this concept. Such research is now possible using the intense gamma beam that can be produced using free-electron laser light backscattered from relativistic electrons.

Introduction

THERE is a continual rise in the consumption of batteries in the United States. In the commercial world, batteries are found in portable computers, construction tools, and entertainment devices. U.S. military personnel currently consume several million heavy, nonrechargeable, environmentally deleterious batteries every year to power their communications equipment. Because of the cost of these batteries and the special requirement for hazardous waste disposal, the total cost of providing a remote, portable energy source is consuming an ever increasing share of the budget. In the future we expect to see a continual rise in new portable systems such as circular saws and more powerful drill motors for the construction industry and helmet-mounted displays, aids for vision and hearing, and environmental sensors for the military. With these, we will see a growing need for energy generation to power these devices. The limiting component to accomplish this goal is a human-portable energy source to power the technology.

In addition to human-portable energy sources, we see a growing interest in developing robotic sensors. In the military, they are envisioned to perform missions as diverse as covert imaging in constrained areas, biological–chemical agent detection, and urban battlefield communications enhancement. In the commercial sector, electrical-powered vehicles are sought to halt the rise in greenhouse gasses. These larger systems demand lightweight, efficient, high-density power sources not dissimilar to the human-portable sources.

Currently, to meet these demands, batteries and fuel cells, microturbines, thermophotovoltaics, and improved thermoelectrics with efficiencies nearer to the Carnot efficiency are being investigated. The hope is that one of these technologies will result in an efficient way to generate electricity at power levels below 5 kW. One power generation system that has received relatively little attention is the radioisotopic thermoelectric generator (RTG).[1] This technology has provided power for remote beacons; underwater sensors for the Navy and NASA; and Navy and Air Force space missions such as Galileo, Ulysses and Cassini.[2,3] These power systems are based on an encapsulated radioisotope assembly to produce heat and a thermoelectric converter to produce electricity. These systems have been manufactured by the Department of Energy (DOE) for over 35 years.[1,4,5]

Power generators using ^{238}Pu and ^{90}Sr have been fielded for space applications, navigational buoys, weather stations, and ocean bottom applications. All of the fielded designs have emphasized long operating times and unlikely human contact. For these reasons, the current operating systems are unsuitable for any human-portable energy source.

There are a large number of engineering issues associated with the design of an RTG such as helium gas production from alpha decay, thermal design that is dominated by heat dissipation, thermoelectric generator design, and fuel containment vessels. The dominant concern is nuclear safety, which has prevented consideration of an RTG for human-portable power systems.

Some of the radiation safety issues could be removed for applications in robotics, transportation, and human-portable systems if a suitable radioisotope could be found with the following characteristics:

1) The radioisotope would have a half-life measured in weeks, removing any requirement for hazardous waste disposal.

2) The radioisotope would produce radiation that could easily be shielded. Alpha emitters can easily be shielded. Betas with energies below 1 MeV could be shielded with 0.4 mm of aluminum. The gamma-ray shielding required is a function of the photon energy. For gamma energies below 1 MeV, the linear absorption coefficient of lead is ≈0.8/cm and for aluminum it is ≈0.2/cm. Thus, 9 mm of lead and 35 mm of aluminum would reduce the intensity of 1-MeV gammas by 50%.

An example of an isotope with suitable characteristics is ^{210}Po. It has a half-life of 138.37 days, its decay products (alpha particles) are easily shielded, and the daughter nucleus produced by decay (^{206}Pb) is stable. We estimate its energy-generating capability by calculating the energy generated by nuclear decay.

The decay rate of a radioisotope is given by

$$\frac{\mathrm{d}N}{\mathrm{d}t} = -\frac{0.693}{\tau_{\frac{1}{2}}} N_t = -\lambda N_t$$

where $\lambda = 0.693/\tau_{1/2}$ and where $\tau_{1/2}$ is the time it takes for one-half of the nuclei to decay to the daughter nucleus. N_t, the number of nuclei available for decay at a time t, is given by

$$N_t = N_0 e^{-\lambda t}$$

To obtain the power generated, we simply multiply the rate by the energy of a single emission, here the energy of the alpha particle. The power generated as a function of days for 1 g of ^{210}Po is shown in Fig. 1.

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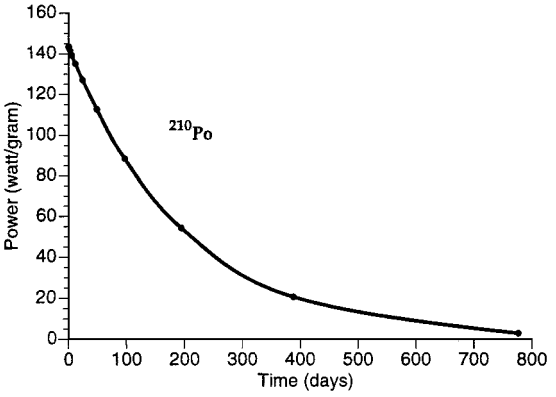


Fig. 1 Power per gram generated by ^{210}Po as a function of time.

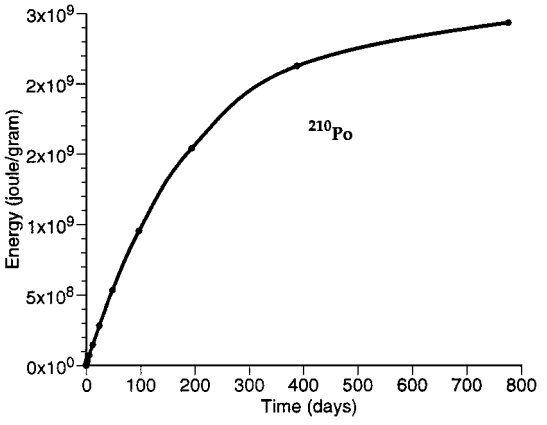


Fig. 2 Energy per gram generated by ^{210}Po as a function of time.

The total energy produced by the isotope ^{210}Po is obtained by integrating the decay rate

$$E_{\text{total}}(T) = E_\alpha \int_0^T \frac{\mathrm{d}N}{\mathrm{d}t}\,\mathrm{d}t = E_\alpha N_0[1 - e^{-\lambda T}]$$

The result of the integration is shown in Fig. 2.

Over 100 W of thermal power for 100 days would be generated by 1 g of ^{210}Po. The metal has a melting point of 254°C so that it could be used in its pure form in a thermal generator. It is available currently at a cost of about $3600 curie from Oak Ridge National Laboratory.[6]

The design of thermoelectric generators is not considered in this paper. However, commercially available thermoelectric generators such as the Bismuth Telluride based unit (Model HZ-20) made by HiZ Technologies, Inc. (information available at URL: http://www.cts.com/crash/hiz/websiteO4.htm) allow an estimate of the performance using any of the isotopes considered here. For example, Model HZ-20 will generate 19 W of electricity with a heat flux of 9.5 W/cm^2 at 230°C. The device weighs 114 g and has a rated efficiency of 4.5%. If we multiply the energy produced by the nuclear decays discussed in this paper by 0.045, we will get an approximate measure of the performance of a speculative nuclear battery.

Concept

The problems with the ^{210}Po thermal generator are 1) the need for prompt production of the isotope if a reasonable operating lifetime is to be realized; 2) the inability to turn the device off, hence heat generation would occur both in the field and in storage; and 3) all radioisotopes with short half-lives would have limited shelf lives, producing a logistic difficulty.

Nuclei can exist in energy states with different decay rates and different emission processes. A search was undertaken to discover if isomers with different decay paths existed with characteristics that would lead to a useful energy generator design. If any isomers were found, a further investigation would be made to learn if their energy levels could be coupled via easily generated electromagnetic radiation such as x-rays or gamma rays. The procedure used to perform the search is described next.

The concept of a nuclear battery driving the study is based on a conventional RTG design differing only in the use of an isotope with two isomeric states. One state (state 1) with a lifetime on the order of a year would provide shelf life for the battery. The second state (state 2) would have a lifetime measured in days or months and would be the decay process used to generate power.

We have restricted our attention to isomers separated by energies less than 1 MeV decaying via relatively low-energy alpha particles or beta rays, which can be easily contained. Stopping these charged particles in a shield will convert the radiation energy into thermal energy. The limitation on energy separation of 1 MeV was based on what we considered to be an upper limit on a practical design of a lifetime conversion device. If the short-lived state (state 2) lies within 1 MeV of the long-lived state (state 1), and if a transition to this state can be induced using, for example, a portable high-voltage power supply (forming x-rays, low-energy electrons, or gamma-ray beams), then the energy of the long-lived state can be extracted via the short-lived state, giving an increase in power proportional to the ratio of the lifetimes. We performed a further reduction in viable candidates by eliminating isotopes that decayed primarily via internal conversion of gamma rays because conversion of this radiation to heat energy seems difficult to engineer. This is the concept of a nuclear battery.

Isotope Search

We conducted our search of all isotopes contained within the standard library resources[7–20] and private communications (Ref. 21 and private communication from D. D. McNabb). The search was made for isotopes that contained two states: 1) state 1 with an energy level that has a lifetime $\tau_{1/2} > 6$ months, to provide shelf-life for the battery and 2) state 2 with an energy level having a lifetime of 1 year $> \tau_{1/2} > 12$ h, to extract energy for power generation at a useful rate.

The isotopic candidates were further screened with another set of parameters for state 2 that had half-lives of $\tau_{1/2}$ greater than 1 day, 12 h, 1 h, or 1 s, respectively. In all cases, the absolute value of the energy difference between state 1 and state 2 was restricted to be <1 MeV.

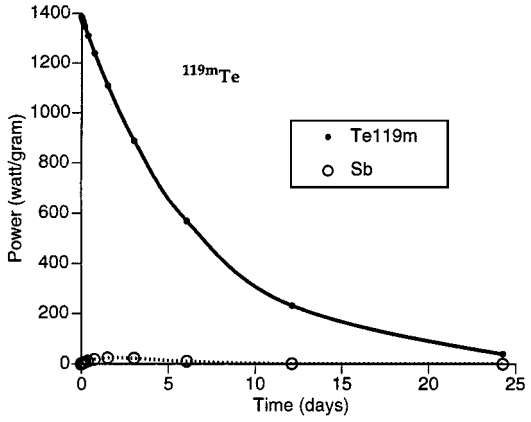
We used the RKIN computer code [a relativistic kinematics code containing the mass table of Audi-Wapstra (see Ref. 22)] to find the values of the separation energies for S_α, S_p, S_n, S_d, $S_{3_{He}}$ and S_{3_H}. These results enabled us to determine the excitation energy required to allow for decay in these various modes on the basis of energy conservation alone. Cases which required greater than 1 MeV of excitation energy before these particle decay modes could occur were removed from consideration. This reduced the isotopes of interest to the following eight: ^{119}Te, ^{121}Te, ^{133}Ba, ^{178}Hf, ^{179}Hf, ^{194}Ir, ^{198}Au, and ^{254}Es.

By looking at all of the values, we were able to select all isotopes with energy levels greater than any of the S values. For example, if ^{254}Es had an $S_p = -4.595$ MeV but had an energy level at, for example, $E_{\text{level}} = 5$ MeV, then it would be able to proton decay on the basis of energy conservation alone. Quantum mechanical selection rules and the nuclear wave functions would be the final arbitrator and would determine the probability of decay. This technique was not successful because none of the isotopes had energy levels that were higher than the separation energy S values.

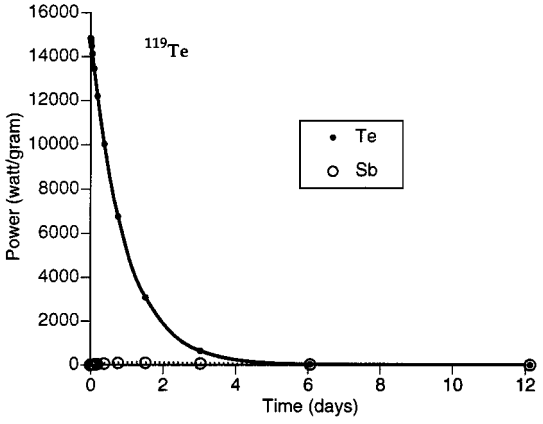
It was necessary to evaluate each energy level and decay mode. As already mentioned, isotopes that decayed via internal conversion of gamma rays were eliminated due to the complexity of extracting heat from the process. The restriction led to the elimination of five isotopes:

1) Isotope ^{119}Te was rejected because of the very short half-lives. It had storage times less than 20 days and energy production less than 2 days[18] (see Figs. 3 and 4).

2) Isotope ^{133}Ba has two isomers. One with a $\tau_{1/2} = 10.5$ years and one with a $\tau_{1/2} = 38.9$ h. The short-lived state decays via internal conversion. For that reason we ignored its use.[18]

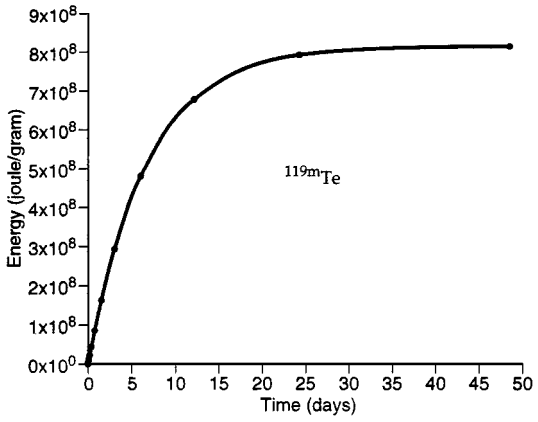


Metastable state with $\tau_{1/2} = 4.7$ days

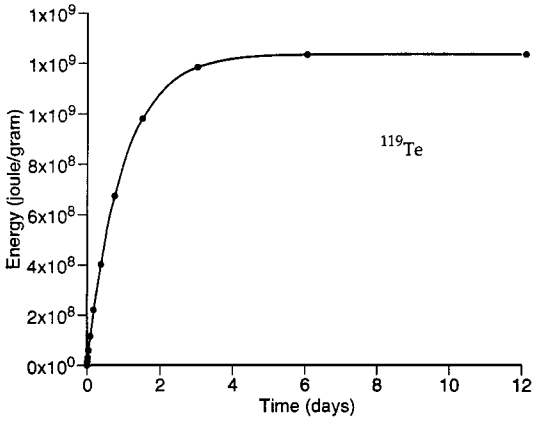


Ground state with $\tau_{1/2} = 16$ h, as a function of time

Fig. 3 Power per gram generated by ^{119}Te, where solid curves are for ^{119}Te and dashed curves are for the daughter nucleus antimony (sb).



Metastable state with $\tau_{1/2} = 4.7$ days



Ground state with $\tau_{1/2} = 16$ h, as a function of time

Fig. 4 Energy per gram production in ^{119}Te.

3) Isotope ^{178}Hf has three isomers. One is stable, a second has a $\tau_{1/2} = 4$ s, and the third has a $\tau_{1/2} = 31$ years. The decay paths for the latter two are via internal conversion and, thus, are not of interest.[18]

4) Isotope ^{179}Hf is similar to ^{178}Hf, and the decay path via internal conversion eliminated it from the list.[18]

5) Isotope ^{198}Au has two isomers with a $\tau_{1/2} = 2.7$ days and $\tau_{1/2} = 2.3$ days. The shorter lifetime is associated with internal conversion. This fact and the very similar lifetimes make it an unlikely candidate.[18]

This elimination process left us three isotopes that we thought would make good isotopic battery candidates: ^{121}Te, ^{194}Ir, and ^{254}Es. A discussion of each follows.

In the case of ^{121}Te, the metastable $\frac{11}{2}^+$ state at 293.98 keV with a half-life of 154 days, would be the energy storage state. If this were excited to the $\frac{7}{2}^+$ level at 443.12 keV (via M2), this level would rapidly decay (85.3 ns) via E2 to the $\frac{3}{2}^+$ state at 212.19 keV, which would then (M1) decay finally to the $\frac{1}{2}^+$ ground state. E2 is an electric quadropole transition, M1 is a magnetic dipole transition, and M2 is a magnetic quadropole transition. The decay process is shown in Fig. 5.

The ground state of ^{121}Te has a half-life of 16.78 days and would be the energy extraction state. In the storage state, the power production of 5 W (Fig. 6a) is low because the major decay route is through internal conversion (in this study we have ignored internal conversion processes because of the engineering complexity they introduce). On conversion from the $\frac{11}{2}^+$ state to the $\frac{1}{2}^+$ state, we can extract a power level of 400 W (Fig. 6b). Operating times as long as 40 days and storage times of 400 days would be possible.[18] Energy per gram production is shown in Fig. 7.

For ^{194}Ir, the power production for the two states is shown in Fig. 8. The short-lived state (19.15 h) produces energy for around 2 days (Fig. 9b). The long-lived state (171 days) yields storage times approaching 400 days (Fig. 9a).[18] The ground state of ^{194}Ir is 1^-

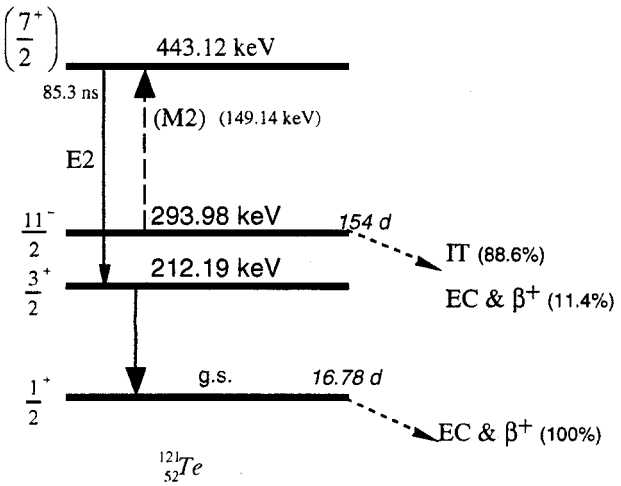


Fig. 5 ^{121}Te energy levels (keV) and possible transition (dashed line [M2]) to go from the metastable state (at 293.98 keV) to the ground state; orbital electron capture (EC) and isomeric transition (IT) indicated. Level identification in parenthesis $(\frac{7}{2})^+$ indicates the assignment is in question.

with a half-life of 19.15 h. The long-lived isomeric state at 190 keV has a half-life of 171 days and beta decays. It has spin 10 or 11. The spectroscopic information to move from the isomeric state to the ground state is unknown.

The ^{254}Es isotope shows promise for the development of a practical nuclear battery. As can be seen in Fig. 10, the 7^+ ground state of ^{254}Es has a half-life of 275.7 days, which will provide a reasonable shelf life for a battery. The decay of this state is almost entirely via alpha-particle emission. This is attractive because alpha

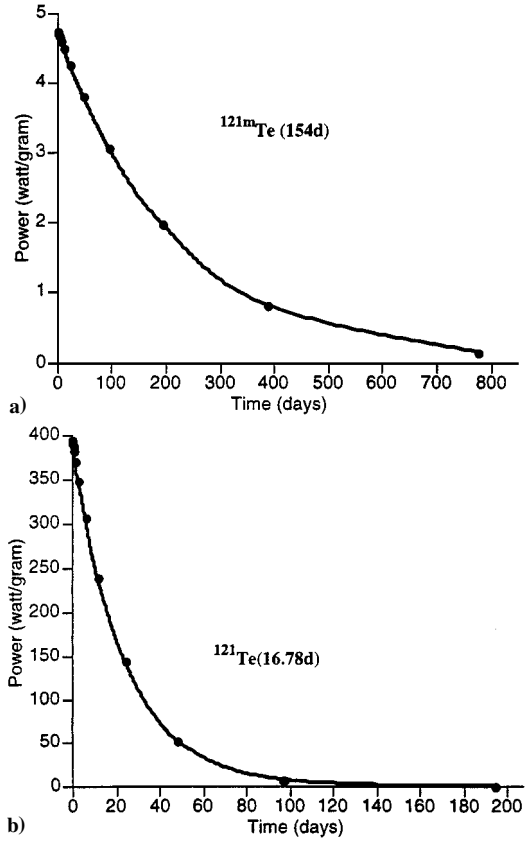


Fig. 6 ^{121}Te power per gram generation as a function of time a) for the metastable state (293.98 keV) having $\tau_{1/2}$ = 154 days and b) for the ground state having $\tau_{1/2}$ = 16.78 days.

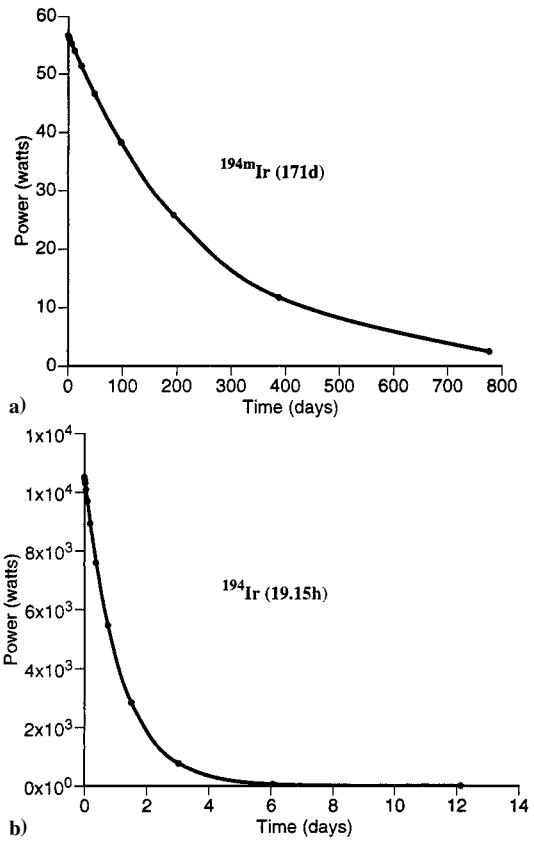


Fig. 8 Power per gram production in ^{194}Ir as a function of time a) for the metastable state having $\tau_{1/2}$ = 171 days and b) for the ground state having $\tau_{1/2}$ = 19.15 h.

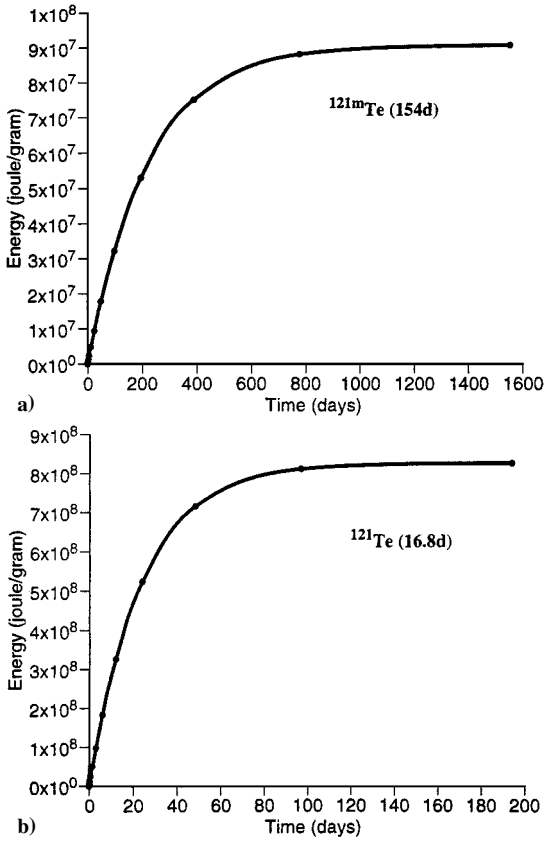


Fig. 7 ^{121}Te energy per gram production as a function of time a) for the metastable state (293.98 keV) having $\tau_{1/2}$ = 154 days and b) for the ground state having $\tau_{1/2}$ = 16.78 days.

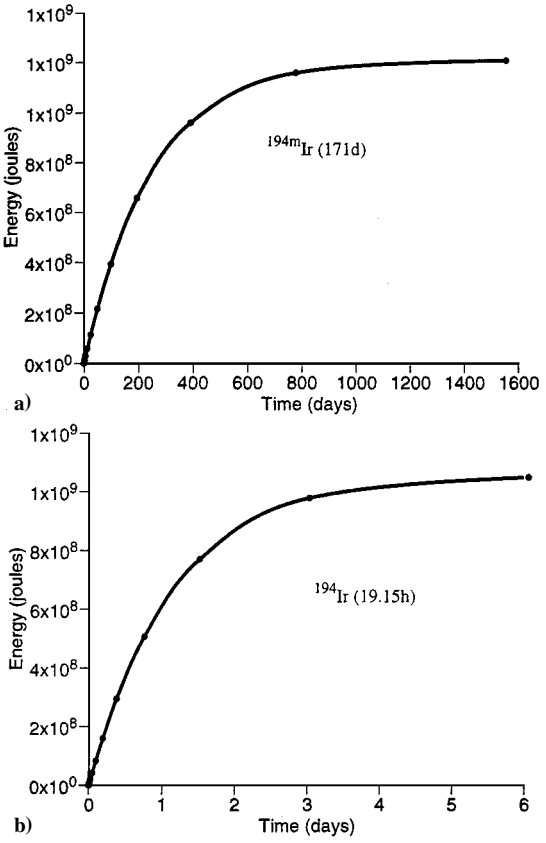


Fig. 9 Energy per gram production in ^{194}Ir as a function of time a) for the metastable state having $\tau_{1/2}$ = 171 days and b) for the ground state having $\tau_{1/2}$ = 19.15 h.

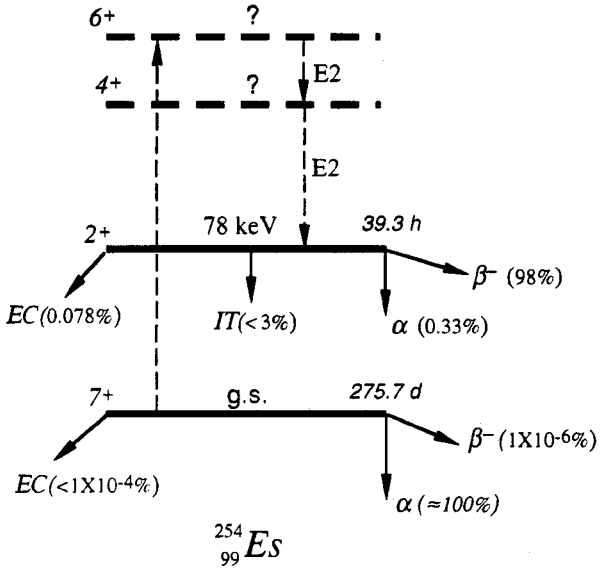


Fig. 10 Decay processes for the ground state 7^+ and the isomeric state (2^+ at 78 keV) in ^{254}Es where dashed lines indicate a hypothetical scenario for an induced transition from the ground state to the isomeric state.

particles can be easily contained and will not present a radiation hazard. Most of the alpha particles that are emitted have an energy of 6.428 MeV. Some soft gamma rays are also produced, but their energies are below 86 keV, and can therefore be easily contained. The residual daughter nucleus, ^{250}Bk, β^- decays, emitting electrons with energies below 1.78 MeV. Again these are easily contained, as will be discussed. This leads to ^{250}Cf, which has a 13-year half-life, which we considered stable for this study.[18]

^{254}Es as a Nuclear Battery Candidate

What makes ^{254}Es an exciting candidate is the existence of a metastable state just 78 keV above the ground state with a half-life of 39.3 h. If the energy stored in the ground state could be transferred to this state, one could have a battery that would produce adequate power for 4 days or more. This metastable state has a spin parity of 2^+ and decays mainly via β^- decay to ^{254}Fm, with the emission of electrons whose energy is primarily 0.477 MeV. With a half-life of 3.24 h, ^{254}Fm decays into ^{250}Cf via the emission of 7.3-MeV alpha particles. Again, because ^{250}Cf has a half-life of 13 years, we consider it stable and stop our energy calculations here (see Figs. 11 and 12).

As a first estimate of the power gain that could be achieved with this system, we can use the ratio of the half-lives of the ground state and the metastable state. Because the metastable state has a half-life about 170 times shorter than the ground state, we should expect a factor of 170 increase in the power deliverable from the two states.

In what follows, we will present estimates of the power that could, in principle, be stored in 1 g of ^{254}Es in its ground state and the power that would be available if the nucleus could be forced into the metastable state at 78 keV. This will be followed by a discussion of the availability and estimated cost of obtaining sufficient amounts of ^{254}Es to allow for production of a battery.

Energy Release from the 7^+ Ground State of ^{254}Es

In the 7^+ ground state, 1 g of ^{254}Es will primarily produce alpha particles with the following energies: 93% with energy of 6.532 MeV, 2.6% with energy 6.461 MeV, and 1.8% with energy 6.521 MeV. These particles can easily be stopped in a relatively thin layer (0.02 mm) of lead. If all of the alpha-particle energy is converted into heat, the amount of power produced when the battery is created would be about 71 W. Because the half-life of the ground state of ^{254}Es is ≈276 days, the power output will be about 45 W slightly over 6 months later. A plot of the power output as a function of time is shown in Fig. 11.

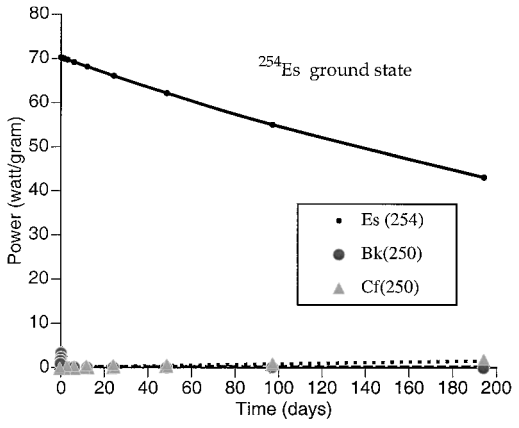


Fig. 11 Power per gram production from the ground state of ^{254}Es as a function of time; power production from two of the daughter nuclei (^{250}Bk and ^{250}Cf) found to be almost negligible in comparison to that of the ground state of ^{254}Es.

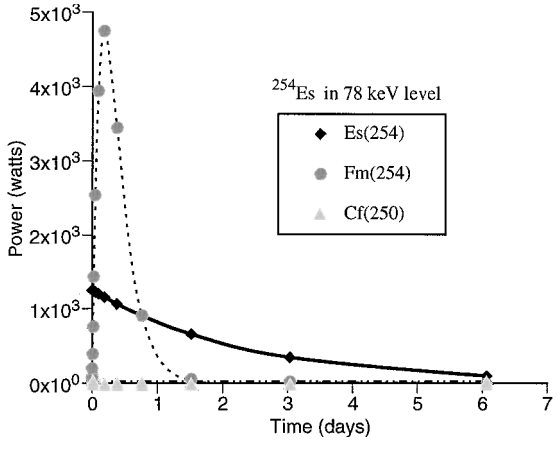


Fig. 12 Power production from the 78-keV metastable state of ^{254}Es as a function of time and power production from two daughter nuclei, (^{254}Fm and ^{250}Cf).

Of course the decay of this state of ^{254}Es produces the daughter nuclei ^{250}Bk and ^{250}Cf. Note that 83% of the ^{250}Bk electrons have an energy of 0.75 MeV, 6.2% have an energy of 0.71 MeV, 4.8% have an energy of 1.74 MeV, and 4.8% have an energy of 1.78 MeV. The electrons from ^{250}Bk are also easily stopped in a thin (0.34 cm) layer of aluminum, for example. The half-life of ^{250}Bk is 3.2 h, resulting in a negligible contribution to the power output from ^{250}Bk after the first day. Finally, the alpha emitting nucleus ^{250}Cf is formed with a half-life of 13 years. As shown in Fig. 11, even after several hundred days, the contribution of these alpha particles to the power output is quite small.

Energy Release from the 2^+ State at 78 Kiloelectron Volts

If the 1-g sample of ^{254}Es could be excited into the 2^+ metastable state at 78 keV, the short lifetime (39.3 h) of this state would make it possible to have a huge increase in the power output of the sample. The 78-keV state decays primarily via β^- decay, with the electrons being emitted with energies of 0.474 (55%), 0.434 (16%), and 1.168 (18%) MeV, respectively. The effective energy of these electrons can be taken to be 0.67 MeV. The electrons can be stopped in a thin (0.08 cm) layer of aluminum. Because the decay constant for this state is 170 times greater than that of the ground state, if all of the nuclei were put into this state, the power output at $t = 0$ would increase from 71 W to 1.1 kW. A plot of the power output for this gram sample as a function of time is shown in Fig. 12, along with the power produced by the daughter nuclei. Clearly, a viable energy source would be available for 3 or more days after the original trigger. Naturally, one could discharge a fraction of the stored energy in a given trigger, saving the rest for future uses.

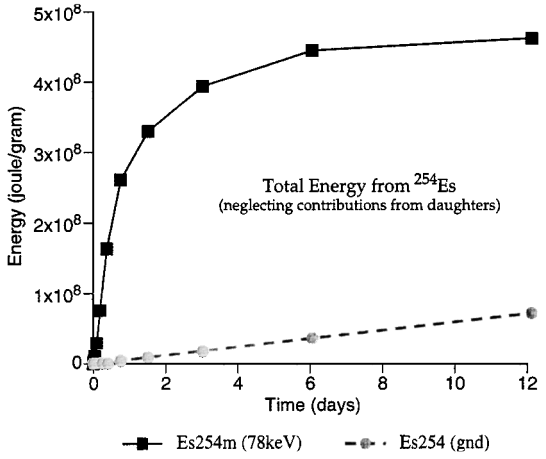


Fig. 13 Total energy produced from the decay of the 78-keV metastable 2^+ state in ^{254}Es via β^- decay as a function of time (——) and energy produced in the ground state of ^{254}Es via alpha decay (– – –).

If ^{254}Es is to be used as a nuclear battery, it is necessary to stimulate the transition from the ground state to the metastable state. Unfortunately, there is at present no known path that leads from the ground (2^+) state of ^{254}Es to the 78-keV (7^+) state.

Excitation of the 78-Kiloelectron-Volt Level

Although the 78-keV energy gap is small, a direct excitation via, for example, gamma rays of this energy, is highly unlikely. The $7^+ \rightarrow 2^+$ transition would correspond to very inhibited M5 gamma rays. No such decay from the $2^+ \rightarrow 7^+$ has been observed.

On the other hand, excitation through a series of cascade transitions seems more reasonable. If, for example, a rotational band existed so that low-lying 4^+ and 6^+ states were present, then one could imagine excitation as shown in Fig. 10.

Other similar scenarios are conceivable. The trick is to find the required levels. If their energies are low enough so that gamma rays can be produced using sources or a small high-voltage supply producing bremsstrahlung, then the battery could, in principle, be discharged in a reasonable package. If an excitation scheme could be found, then the energy production during use of the battery would be as shown in Fig. 13.

Further research on the level spectrum of ^{254}Es is required to ascertain whether such a scheme is realizable. This research is now possible using the intense gamma-ray beam that can be produced using Free Electron Laser light backscattered from a relativistic electron beam.[23] At this point, no known levels fulfill the requirements needed to produce a practical solution. As already stated, ^{254}Es shows appealing promise as a nuclear battery material, but a detailed knowledge of its excited state spectrum is unavailable.

Production and Cost of ^{254}Es

A production scheme for ^{254}Es has been proposed.[24–26] Isotope ^{254}Es can be produced in a high-flux reactor by accumulating ^{252}Cf (Ref. 24) by irradiating ^{252}Cf targets with neutrons producing ^{253}Cf, which decays to ^{253}Es, which is then irradiated with neutrons to produce ^{254}Es (cadmium is used as a filter of thermal neutrons so that ^{254}Es does not burn up through fission via thermal neutrons):

$$^{252}\mathrm{Cf}(n,\gamma)^{253}\mathrm{Cf} \xrightarrow{\beta^-} {}^{253}\mathrm{Es}(n,\gamma)^{254}\mathrm{Es}$$

or by the reaction[26] of

$$^{248}\mathrm{Cm} + {}^{48}\mathrm{Ca\ projectiles} \rightarrow {}^{252-254}\mathrm{Es} + {}^{252-254}\mathrm{Fm}$$

One possible production scheme of ^{254}Es devised by Hoffman is as follows[26]:

The first step is preparation: 1) irradiation of ≈1 g of ^{252}Cf in a high-flux reactor for ≈20 days followed by ≈20 days of cooling to allow the 18-day isomer of $^{253}\mathrm{Cf} \xrightarrow{\beta^-} {}^{253}$Es, 2) irradiation in the maximum thermal flux for ≈5 days followed by a short decay period, and 3) irradiation in a cadmium-filtered flux for 24–28 days; numerous shutdowns are needed at this stage to replace the cadmium filters and spent fuel assemblages.

The second step is purification: 1) isolation and purification of the Einsteinium fraction in the target, 2) decay for ≈6 months to allow the 20-day isomer of ^{253}Es to decay to the 276-day isomer of ^{254}Es before accelerator irradiation, and 3) enhanced production could be realized by wrapping the ^{252}Cf with cadmium.

The third step is production: 1) estimated time to produce as much as 4 μg (Ref. 24) of ^{254}Es from ^{252}Cf ≈ 15 months (Ref. 26) and 2) from 1 mg of ^{252}Cf, production of ^{254}Es in microgram amounts has ranged from 0.06 μg (Ref. 25) to ≈4 μg (Ref. 24).

The estimated time to produce ^{254}Es from ^{252}Cf is ≈15 months (Ref. 26). Production of several milligrams of ^{254}Es has been achieved at the High Flux Isotope Reactor Facility (HFIR) at Oak Ridge National Laboratory[27] (information also available at the University of California, Berkeley, website URL: http://www.cofc.edu/nuclear/edu.html) and ^{254}Es has been made at the SM-2 high flux reactor in Russia.[24,25] A program called the Large Einsteinium Activation Program was proposed in 1984 by Lawrence Berkeley, Lawrence Livermore, Los Alamos, and Oak Ridge National Laboratories to enable the production of heavy and superheavy element isotopes at the HFIR at Oak Ridge.[26] The designed turn-around time for ^{254}Es production was about 9 months. Rapid production requires soft neutron spectra.

The cost estimate to produce ^{254}Es is not known at this time. Microgram amounts of ^{252}Cf, which is used to produce ^{254}Es, are available from Oak Ridge National Laboratory for $60.00/$\mu$g (Ref. 6). Cost estimates for the use of a high-flux reactor, like the HFIR at Oak Ridge National Laboratory, as well as chemical analyses and purification of ^{254}Es during its production is not known.

Summary of Results and Conclusions

The results of this study indicate several interesting cases for energy storage in radioactive isotopes. Two of the most interesting cases are ^{121}Te and ^{254}Es. Through excited transitions between energy levels, a power of 400 W can be obtained from ^{121}Te. For the isotope ^{254}Es, the ground state 7^+ has a half-life of 275 days and the 2^+ state some 78 keV above the ground state has a half-life of only 39 h. If an allowed pathway exists between the two levels that could be transitioned at a reasonable rate, then the 71 W available in 1 g of the ground state becomes almost 5 kW of power for about a 1 day period and reduces to ≈1 kW for about 1.5 days. However, intermediate levels, which could affect the transition, remain to be discovered. Further research on ^{254}Es is needed. Measurements of transition rates that can be stimulated between the desired levels are also needed to determine the practicality of this concept. This research may now be possible using the gamma-ray beam that can be produced using inverse Compton scattering.

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