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Americium 242m and its potential use in space applications

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Abstract. The isotope Am242m is an interesting nuclide as it shows one of the known highest neutron fission cross section. This could be useful in some special applications, like the nuclear reactor for space propulsion proposed by C. Rubbia. A detailed measurement of the energy transfer from the fission fragments to the gas as a function of the path and the gas type is an important item for the evaluation of the engine performances. This was carried out by means of an ionisation chamber. However the Am242m availability, in particular at high isotopic abundance, is still at present a serious drawback. A production model, experimentally tested in thermal nuclear reactors, has been used to evaluate the achievable isotopic abundances. The results are quite below 70% and advise the use of separation techniques for further enrichment. The use of Am242m for other applications like nuclear pumped laser is suggested.

1. Introduction

One of the ambitions of our civilization is the human exploration of the planetary system. This implies inter-planetary journeys over hundreds of millions of kilometres. The performance required to an engine for deep space travel is fundamentally different of the present chemical rockets.

Nuclear power is the most suited energy source for deep space journeys, since the energy produced for unit fuel mass is about 10^7 times larger than the chemical one. Nuclear propulsion combines high specific impulse and thrust reducing launch windows and cruise time.

In the past, several types of nuclear engines for space rockets have been proposed and even tested, such as NERVA [1]. Few years ago C. Rubbia suggested a new kind of engine [2] based on the direct heat of a gas (hydrogen) by means of fission fragments produced in thin fuel layers. Several properties of Am242m, such as the thermal neutron cross section (about 6000 barns), half life (141 years) and number of prompt neutrons per fission (about 3.6), make this nuclide an ideal nuclear fuel for this purpose. Its properties are so interesting that it has also been proposed for other applications, like nuclear battery and nuclear pumped lasers. However a major drawback of Am242m is its availability.

In section 2 of this paper we present the outline of the Rubbia's engine and its development in the frame of the P242 project. An experimental system developed for measuring the energy release of fission fragments in gas, useful for the evaluation of the engine performances, is presented in section

3. In section 4 we deal with the availability and production of Am^{242m}. Finally a spin-off of this space research is presented in section 5.

2. The P242 project

The P242 project (1999-2002) consisted of an Italian collaboration with the purpose to develop an engine for manned deep space travel, in alternative to the present chemical propulsion [3]. Both public and private organizations and industries took part in the project, such as some Italian Universities, the INFN, CRS4, the ANSALDO industries, under the coordination of the Italian Space Agency (ASI).

The basic engine, proposed by C. Rubbia [2], exploits the kinetic energy of fission fragments to directly heat a propellant gas. The fissile material is coated on a support as a layer sufficiently thin to allow the escaping of a significant fraction of fission fragments under limited energy losses. A typical configuration might be one or more internally coated hollow cylinders where the gas is flowing, as shown in figure 1.

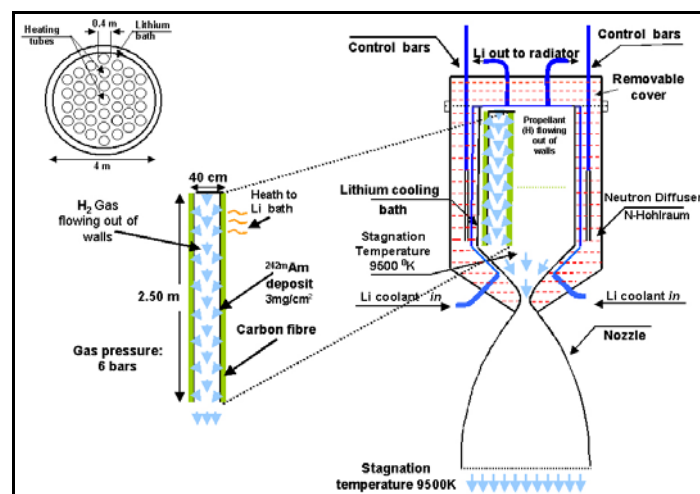


Figure 1. Rubbia's engine outline.

Criticality is a crucial issue in this kind of nuclear reactor. Few possible fuel configurations have been investigated and the corresponding engine performances as a function of the design parameters have been evaluated. In table 1 the results relevant to a single element (tube) are presented. These parameters allow a total thrust of 3200 N and a specific impulse up to 2500 s.

Table 1. Engine single element parameters [4].

Diameter	0.4 m
Length	2.5 m
Fuel layer thickness	3 μm
Power density at layer	2 MW m ⁻²
Nuclear power	6 MW
Hydrogen pressure	6 bar
Tmax, gas	9000 K
Fission fragments heating efficiency	• 20 %
Thrust	87 N

Not all the fission fragments escape from the fuel layer; at least 50% deposit their energy in the layer and its substrate. A detailed analysis [2,5] shows that the efficiency of this type of engine is up to 20%, as reported in table 1. The energy excess is dissipated in the space through radiation panels. Thus, to be effective, the temperature of the radiator must be as high as possible, as the Stefan-Boltzman law dictates. So, the major requirements of the engine are the use of very thin fissile fuel

layers ($\sim 3 \mu\text{m}$) working at high temperature. This prevents from using pure metal americium, having a melting point equal to $T \sim 1270 \text{ K}$ in favour of a compound compatible with hydrogen at high temperature (some americium oxides, americium carbide,...). The fuel layer preparation, the layer support, the diffusion control at high temperature, the deterioration of the layer with burn-up, the americium self sputtering and its radioactivity are some problems that should be settled.

3. Experimental tests

The detailed measurement of the energy transfer from the fission fragments to the gas as a function of the path and the gas type is an important item for the evaluation of the performances of this kind of nuclear device for space propulsion. An investigation has been carried out in Pavia by means of an ionisation chamber which permits the simultaneous measuring of both the specific energy loss of the particle in the gas and the path in the ionisation volume. A schematic view of the device is shown in figure 2 and a partial picture in figure 3.

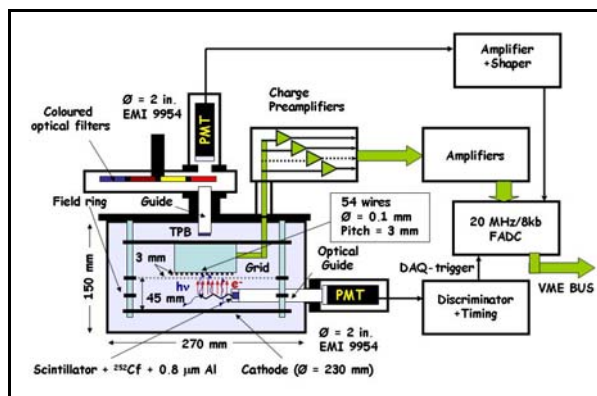


Figure 2. Experimental set-up.



Figure 3. Ionisation chamber.

The ionisation volume is cylindrical with dimensions $h = 45 \text{ mm}$ $\varnothing = 200 \text{ mm}$. It is delimited by the cathode, a circular field-shaping ring and a circular screening grid. The readout chamber is located 15 mm behind the grid and consists of a plane made of 54 stainless-steel parallel sense wires, $100 \mu\text{m}$ diameter, spaced by 1.5 mm. The chamber is contained inside a stainless-steel cylinder by means of a supports fixed to the cylinder lid. The container is instrumented with signal and voltage feed-troughs, a pressure sensor, a pressure safety valve, a gas distributor and a vacuum pumping system. Signals from each sensing wire are amplified by low-noise charge integrator preamplifiers and digitised by means of Flash Analog-to-Digital Converters. The experimental set-up is completed by a fission fragment source and the triggering system. This consists of a photomultiplier (PMT) placed externally and connected horizontally to the chamber container. A cylindrical Perspex light guide allows the optical connection between the PMT windows and the ionisation volume. The light guide design allows the exact positioning at the beginning of the sensitive volume of the chamber of a small plastic scintillator fixed at one ends of the guide. A small quantity of fission material ($\text{Cf}235 < 0.1 \text{ Bq}$), deposited on the scintillator surface by means of self-sputtering and adsorption technique, is used as the fragment source for the experimental measurements. Since in each fission two fragments are generated, one of them moves in the direction towards the ionisation volume and the second interacts in the scintillator, giving rise to a PMT signal. This signal is discriminated and digitized to provide for a logical trigger and T_0 signals.

The chamber has been used to investigate the various possibilities the energy E and the specific energy loss dE/dx are deposited as a function of gas type. The detection method is the same adopted in the time-projection-chambers. The read-out system is structured as a multichannel waveform recorder that stores the charge information collected by the sense wires during the drift of ionisation electrons. As shown in figure 4, once a trigger occurs, hits are independently searched for in every channel as output signal regions of a certain width above the baseline output value. The parameters defining the

hit (height and position) contain the physical information (dE/dx) and are precisely determined. The association between wire/time in the coordinate plane allows a 2D event reconstruction (see box in figure 4).

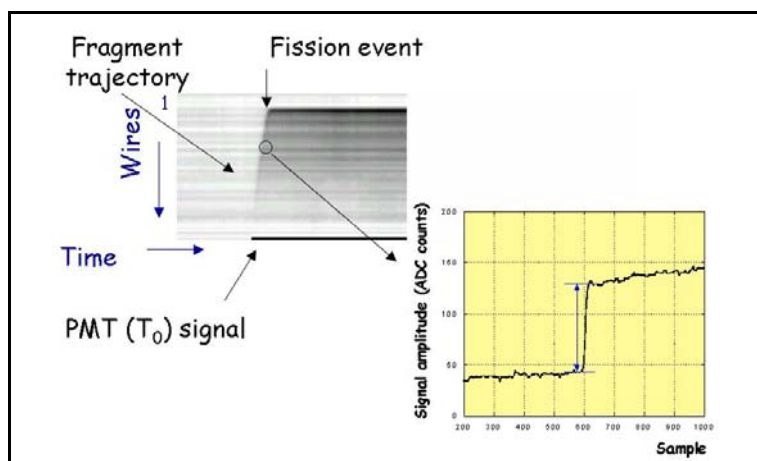


Figure 4. Event reconstruction.

As an example, in figure 5 the deposited energy in hydrogen ($P=1200$ mbar) and the fission fragment residual energy as a function of the path are shown. Here heavy and light refer to the two families of fragments.

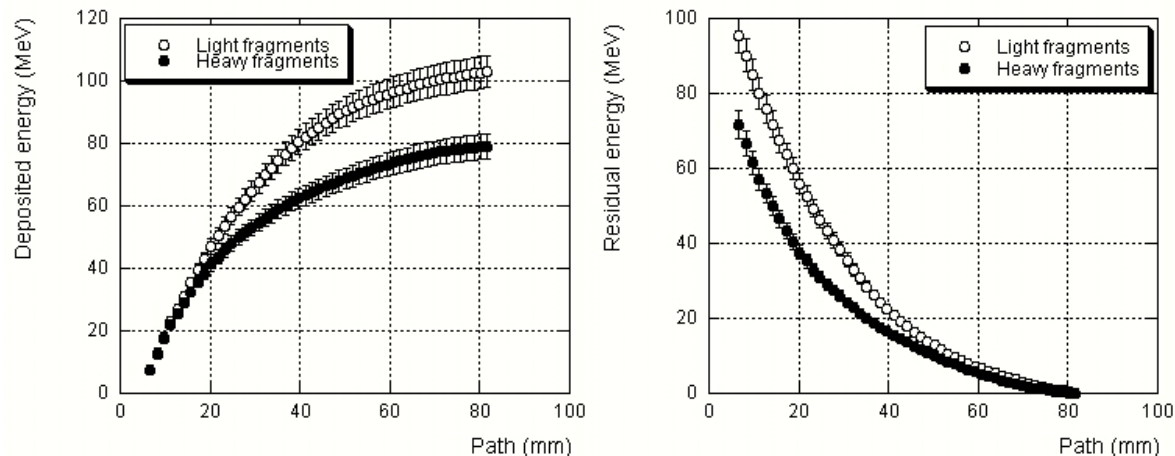


Figure 5. Deposited and residual energy as a function of the fission fragments path in hydrogen.

4. Americium 242m production

As previously mentioned, a major drawback of Am242m is its availability. For instance, in the nuclear wastes from light water reactors the abundance of Am242m is in the low 0.4% of the overall americium as chemical element [6,7]. In the fast flux reactors the abundance could be higher [7], but this type of reactors are very few. When these data are compared to the foreseen applications in nuclear propulsion, which require abundances larger than, say, 70%, the conclusion is that an enrichment process is mandatory. This is a complex and expensive step that could be mitigated starting from a feed having abundance larger than 0.4%, in other words, producing this nuclide in a nuclear reaction.

The Am242m isotope can be produced by neutron capture according to the main reaction $\text{Am}^{241}(\text{n},\gamma)\text{Am}^{242\text{m}}$, and it is destroyed mainly by fission. Figure 6 displays the energy dependence of the reaction cross-sections for the two processes [8].

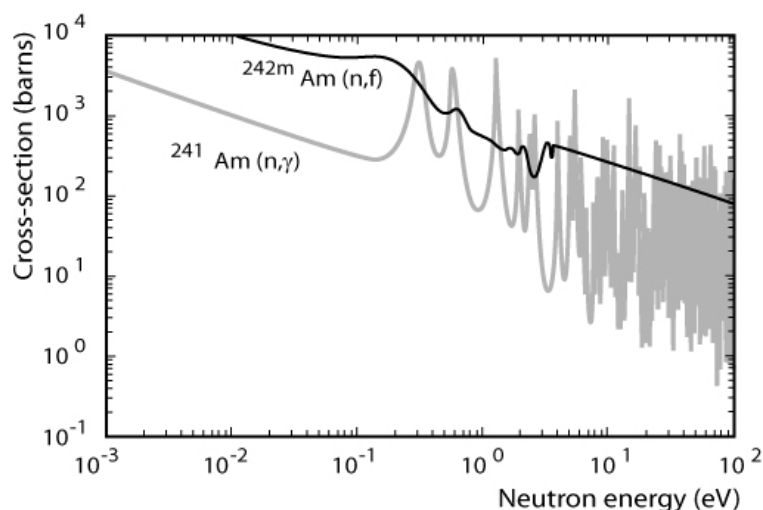


Figure 6. $\text{Am}^{241}(\text{n},\gamma)$ and $\text{Am}^{242\text{m}}(\text{n},\text{f})$ cross-sections at low neutron energies.

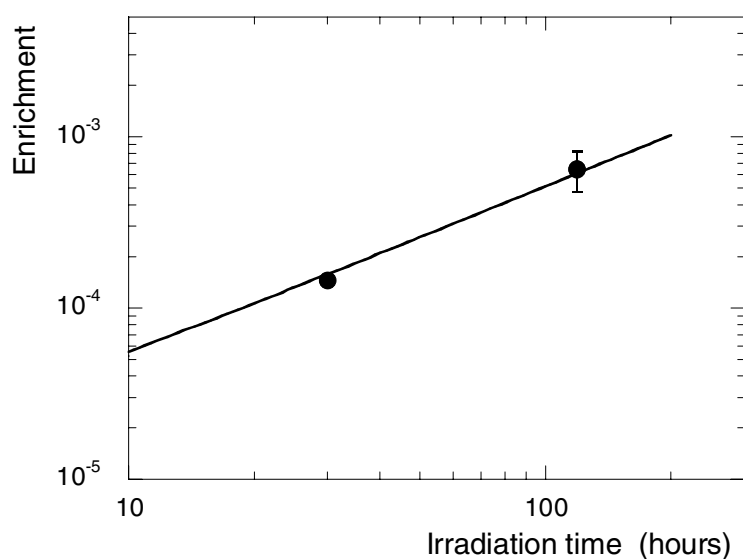


Figure 7. Theoretical (continuous lines) and experimental (dots) atomic ratio versus experimental data obtained at two different irradiation times with bare samples.

It is easily seen that in the region above 0.2 eV, Am^{241} capture cross-section has important resonances useful for $\text{Am}^{242\text{m}}$ production, while the fission cross-section of $\text{Am}^{242\text{m}}$ dominates at thermal energies and greatly decreases in the resonance region. In order to enhance $\text{Am}^{242\text{m}}$ production it is then advisable to suppress as much as possible the thermal neutron flux by means of appropriate filters. For instance, Am^{241} can be surrounded by thermal neutrons absorbers, like Cd or Gd. A model has been built and run in order to follow the kinetics of $^{242\text{m}}\text{Am}$ concentration under

different neutron spectra [9]. Some samples have been recently irradiated and the results obtained are in agreement with predictions. As example, the comparison between theoretical and experimental data for bare samples is presented in figure 7. In any case the achievable isotopic abundances are quite below 70%. Therefore a possible separation technique for further enrichment in Am242m is required.

5. Research spin-off.

The nuclear properties of Am242m are so interesting that the direct exploitation of its fission fragments energy has also been proposed for applications beyond the nuclear propulsion.

In particular in the interaction between fission fragments and a gaseous target, the production of photons is expected, as it occurs in nuclear pumped lasers [10]. In these devices fission fragments are just directly exciting the active medium, as it is in the above discussed nuclear engine. The use of Am242m has the advantage to operate in compact systems.

In order to investigate the production and spectrum of the light produced by fission fragments as a function of the gaseous target, the ionisation chamber operating in Pavia was instrumented with a basic system able to detect the light radiation produced in the drift volume and to select the wavelength of the light pulses in coincidence with ionisation signals. As shown in figure 2, this consists of a second PMT placed externally to the ionisation chamber, in a housing connected vertically to a cylinder containing a rotating dispenser for optical coloured filters. Five filters from SCHOTT-AG were mounted in the dispenser; one slot was let free in order to collect unfiltered the radiation produced in the ionisation volume. The coloured filters characteristics are shown in table 2.

Table 2. Coloured filter characteristic.

Slot position	Glass colour	Wavelength
0	No filter	
1	Yellow	> 400 nm
2	Yellow	> 475 nm
3	Orange	> 530 nm
4	Red	> 630 nm
5	Red	> 715 nm

A cylindrical Perspex light guide allows the optical connection between the system and chamber, looking at the ionisation volume through the transparent wire grid. The spectral sensitivity of the adopted PMT (EMI-9964KB03) ranges from about 350 nm to 750 nm. In order to investigate the presence of photons with wavelength shorter than the PMT sensitivity, the Perspex light guide edge was coated with tetraphenyl-butadiene (TPB) which acts as a wavelength shifter, converting the UV photons to blue light [11]. The PMT signal was shaped, amplified and digitized by the same acquisition chain used for the wire signals. As example, an event presenting a coincidence between ionisation charge and light is shown in figure 8.

The PMT hit height contains the physical information of the light intensity produced for each event. A calibration based on single electron response (SER) allows the quantifications of the detected photoelectrons for each event. Since high-pass wavelength filters are used, data coming from different measurements which use the whole set of filters, are normalized and arranged in order to get a differential count spectrum as a function of the light wavelength. This is finally convoluted with the PMT sensitivity spectrum in order to obtain the relative wavelength spectrum of the light produced during ionisation.

As an example, figure 9 shows the results obtained with three different gaseous targets. Pressures were set in order to optimize the fission fragment path length (about 10 cm). The wavelength spectrum of the pure Ar ranges in the blue region. It is known that this noble gas emits photons at 128 nm which are converted to blue light by the TPB coating. The addition in the gaseous target of a small quantity of methane (5% in volume), which acts as a UV quencher, results in a decrease of the light detected by the PMT, proving the effectiveness of the system.

The third spectrum refers to a gaseous mixture (He 97%, Ne 5%, Ar 2% in volume) that has been used for laser light generation with 585.3 nm photon emission [12].

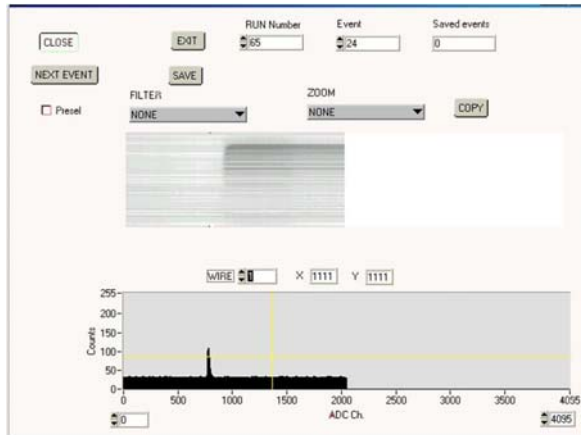


Figure 8. Example of event presenting both ionisation charge and light.

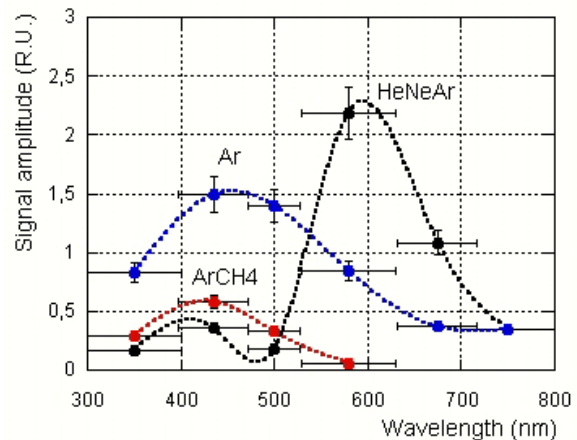


Figure 9. Experimental evaluation of the wavelength of photons produced by fission fragment ionisations in different gaseous target. Interpolating curves are made just as hint.

With the described instrumental set-up it is not possible, of course, to achieve laser action. Instead it is possible to investigate the properties of the optical transitions involved in the lasing as far as the effects, for instance, of gas mixture composition. This lengthy study studies can be made in laboratory without a nuclear reactor while still involving the fundamental physics of the excitation processes; this possibility makes the investigation much easier, cheaper and safer.

6. Conclusions

Am242m allows achieving and maintaining criticality even with thin layer of fissile material and compact system. These features can be exploited in a “fission fragments direct heating” nuclear engine for space propulsion or in other compact device like nuclear pumped laser systems.

A detailed measurement of the energy transfer from fission fragments to a gas as a function of the path and the gas type was carried out by means of an ionisation chamber, together with an investigation on the production and spectrum of the photons generated during the gas excitation.

However, the Am242m availability, in particular at high isotopic abundance, is still at present a serious drawback. A growth model by means of neutron capture in thermal nuclear reactor has been experimentally tested and results are found in agreement.

Acknowledgements

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