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and related nuclear data**

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PHYSICAL ASPECTS OF NEUTRON PRODUCTION AND RELATED NUCLEAR DATA

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Abstract: Accelerator Driven Systems are innovative options in the field of nuclear fission energy, based on the use of neutrons produced in a spallation target to feed a sub-critical reactor. The nuclear physics reactions involved in these systems are described and it is shown that specific new nuclear data are needed, especially for the optimisation of the target-blanket assembly. Recent experimental programs raised by the recent interest in accelerator-driven systems are presented.

1. INTRODUCTION

During the last years, Accelerator Driven Systems (ADS) has appeared as a promising innovative option, within the field of nuclear fission energy, that could be helpful to transmute long-lived nuclear waste or produce energy with reduced radiotoxicity. In an ADS (see the paper by M.Salvatores in this conference for more details), a high-intensity proton beam (10 to 250 *mA*) bombarding a spallation target made of a heavy material (most often Pb or Pb-Bi) is coupled to a sub-critical reactor core. High fluxes of neutrons are produced by spallation reactions in the target. These neutrons, after being more or less moderated, are used to drive the sub-critical blanket where energy is produced and long-lived nuclear waste - plutonium, minor actinides or fission products - can be burned. Part of the generated energy is recovered to supply the accelerator. Various schemes of ADS, based on different technical choices and incineration strategies, have been proposed all around the world [1, 2, 3] to reduce the long term radiotoxicity of nuclear waste. In the concept from Rubbia [4], accelerator-driven systems are viewed as Energy Amplifiers which, provided that the thorium-uranium is used instead of the uranium-plutonium cycle, could produce electricity while generating less long-lived isotopes.

The interest in ADS has recently given rise to new requirements for nuclear physics data in various fields, ranging from spallation, which takes place in the target, to capture or fission reactions, that occur inside the sub-critical blanket. A major effort to acquire new high quality experimental data and build evaluated data files or validated nuclear physics models, in order to design ADS, is presently being done in several laboratories.

2. NUCLEAR REACTIONS INVOLVED IN ACCELERATOR DRIVEN SYSTEMS

Interactions, taking place in ADS, call for nuclear physics from GeV to eV. Fig.1 shows the various nuclear reactions that can be encountered in the target-blanket assembly. In the spallation target, an incoming (around 1 GeV energy) proton undergoes a spallation reaction with one target nucleus. The interaction is quite complex and generally viewed as a two-step process: the incident light particle

Figure 1: Nuclear reactions occurring in an ADS.

first interacts with the individual nucleons inside the target heavy nucleus through successive nucleon-nucleon hard collisions in the so-called Intra-Nuclear Cascade (INC) stage. During this stage, the cascade develops inside the nucleus leading to the emission of nucleons and possibly pions through the excitation of a Δ resonance, sharing the incident proton kinetic energy on many nucleons. This results in the heating of remaining nucleus. The second stage is then the de-excitation of the hot nucleus either by evaporation of low energy light particles, mainly neutrons, leading to a heavy residue, or by fission. The light fast particles escaping the nucleus can undergo cascade with other nuclei of the thick target, inducing a multiplication of the number of emitted neutrons. This process is often called inter-nuclear cascade and is described by a high energy transport code in which the elementary cross-sections are obtained through physics models describing the INC and evaporation-fission stages. The residual nuclei left after evaporation or fission are generally radioactive and decay by α , β or γ emission.

Most of the charged particles generated by the spallation process are slowed down and stopped inside the target or its container because of Coulomb interaction, while the low energy neutrons interact in the target, in the structure materials and in the sub-critical blanket through reactions such as (n, xn) , (n, γ) or $(n, fission)$. These nuclear reactions are well known in reactor physics, however, in an ADS they involve nuclei usually not present or not important in classical reactors like target elements, isotopes to be transmuted, etc... They are usually treated by MonteCarlo neutron transport codes relying on evaluated data files for the determination of cross-sections. The transition between the high and the low energy transport codes generally takes place at 20 MeV, present limit of the evaluated data files.

Since all possible configurations cannot be experimentally tested, it is essential to rely on numerical simulations to design ADS target-blanket assemblies. Complex calculation code systems describing all the aspects of particle production and transport as well as time evolution are available [5, 6, 7]. They are all based on the same architecture, an example of which is given on fig.2 showing the SPARTE code system [8]. However, recent intercomparisons [9, 10, 11] of the high energy part of these codes have shown that large discrepancies still remain and that further improvements are needed. In fact, although the spallation mechanism has been known for many years, spallation codes are far from being reliable enough to predict with a sufficient precision all the needed quantities. A large part of the deficiency of the codes comes from the lack of experimental data to test, if necessary improve and finally validate them. Namely, two types of measurement are necessary: elementary cross-sections to improve basic nuclear models or fill nuclear data libraries and integral measurements to validate the transport part and the whole code system. They can be divided into

Figure 2: General architecture of the SPARTE code system developed by the CEA [8] and composed of: a high energy transport code (HETC) using physics models (INC and evaporation-fission) to obtain elementary cross-sections, a low energy neutron and photon transport code (TRIPOLI4) using cross-section libraries and a module (DARWIN) describing the nuclide time evolution and neutron activation.

three main domains: spallation data for the optimization of the target-blanket assembly, low energy cross-sections for the evaluation of the neutronics properties of the sub-critical reactor core and intermediate energy data to extend evaluated data files up to higher energies.

3. NUCLEAR DATA RELEVANT FOR ADS

To design ADS it will be necessary to be able to precisely predict not only the performances of the system in terms of neutron production and transmutation capability but also the behaviour and time evolution of all the device components, including structural materials. Because ADS differ from fission reactors by the use of spallation reactions, which involve much higher energy particles, and by the isotopes present in the system, specific new data are needed. They concern neutron, charged particle and residual nuclide production as well as low energy neutronics cross-sections.

3.1 Neutrons

One of the most important factor in the design of a spallation target is of course the average number of neutrons produced per incident particle which depends on the target material and geometry, and, on the beam nature and energy. It is related to the ratio of the power produced by the system to the power delivered by the accelerator and is thus important for evaluating the profitability of the system. Indeed, in a given multiplicative medium the number of neutrons produced by fission, n_f is:

$$n_f = n_{sp}(k + k^2 + \dots) = n_{sp}\left(\frac{k}{1-k}\right) \quad (1)$$

where n_{sp} is the number of neutrons produced by spallation and k the multiplicative factor of the medium. The thermal power is thus given by:

$$P_{th} = \epsilon_{fiss} I \frac{N_{sp}}{\nu} \left(\frac{k}{1-k}\right) \quad (2)$$

with ϵ_{fiss} the energy liberated for each fission, ν the number of neutrons per fission, N_{sp} the number of spallation neutrons per incident proton and I the beam intensity. The energy gain G , that is the ratio of the thermal power to the power delivered by the accelerator, is then directly proportional to the number of spallation neutrons per incident proton:

$$G = \frac{\epsilon_{fiss}}{E_p} \frac{N_{sp}}{\nu} \left(\frac{k}{1-k} \right) \quad (3)$$

where E_p is the proton energy.

Figure 3: Measured average energy gain as a function of proton beam energy in a device formed of a cylindrical depleted U target surrounded by a sub-critical fuel assembly of natural U moderated by water. From [12].

Fig.3 shows the results from an experiment carried out at CERN-PS [12] in which a sub-critical assembly made of natural U rods moderated by water was irradiated by a proton beam at several kinetic energies from 0.6 to 2.75 GeV and the energy gain was measured by the temperature rise and by counting fission reactions inside the device. It showed that the gain increases with beam energy up to 1 GeV, above which it remains essentially constant, indicating that the optimum energy in this configuration should be around 1 GeV, although other considerations like for instance the energy loss in the window between the accelerator and the reactor have also to be taken into account.

The energy gain also depends on the nature of the projectile and target. Calculations have been performed in [13] for a device simulating the sub-critical assembly above described, as a function of energy. The results for different incident particles (protons and deuterons) and targets (Be and depleted U) are displayed on fig.4 together with experimental data from [12]. It can be seen that, whatever the configuration, a saturation of the gain with increasing energy is always observed. Deuteron projectiles lead to a higher energy gain because they break and make neutrons which penetrate farther. However, the increase is likely not large enough to compensate for the disadvantages of deuteron beams (especially the problem of activation of the accelerator structures by break-up neutrons) except maybe in the case of a low energy device, for which deuterons on a light target surrounded by uranium is the most profitable solution.

The energy spectrum and angular distribution of the spallation particles are important for the optimization of the target geometry. Indeed, it is necessary to maximize the number of low energy neutrons entering the sub-critical blanket while minimizing the back-scattered particles which would hit the window isolating the target from the accelerator vacuum. It is also essential to minimize the escaping high energy neutrons which, in spallation induced reactions, can have much higher energies than in fission or even fusion reactors, potentially leading to severe problems of radiation protection and radiation damage in target (if solid) and structural materials. As an example, fig.5 from [14]

Figure 4: Calculated and measured [12] average energy gain as a function of beam energy, for proton and deuteron induced reactions, in a device formed of a cylindrical Be or depleted U target surrounded by a sub-critical fuel assembly of U moderated by water. From [13].

shows the variation of the number of neutrons emitted from different faces of a cylindrical lead target as a function of the cylinder diameter. It can be deduced that the optimum diameter, at this energy, is around 25cm.

Figure 5: Number of low (left) and high (right) energy neutrons emitted through the forward, backward and cylindrical faces of a 80 cm long cylindrical lead target, at $E = 1000$ MeV, as a function of the target diameter. From [14].

3.2 Charged particles

A lot of light charged particles, mainly protons and alphas, are produced in the evaporation stage of spallation reactions. Since the production rate of light charged particles is strongly enhanced at these energies, the amount of hydrogen and helium formed in ADS could be one or two orders of magnitude larger than in fission reactors possibly leading to swelling (because of bubble formation) and embrittlement of structural materials. Energetic charged particles emitted during spallation reactions also undergo secondary reactions and therefore are important to estimate radiation damage due to atom displacements (DPA).

3.3 Residual nuclides

Figure 6: Evolution with time of the activity of a lead-bismuth target supposed to have been irradiating during one year with a 15 mA, 1 GeV proton beam. From [15].

Spallation reactions on a heavy target like Pb lead to the production of a wide range of residual nuclei, from heavy evaporation residues to fission fragments and light nuclei. The determination of the production rate of all these isotopes is very important since some of them are radioactive. Indeed, in an ADS the activity due to short-lived nuclei would have to be low enough to ensure access in case of failure and maintenance of the spallation target, and the radiotoxicity caused by long-lived isotopes would have to be kept as low as possible. For instance, fig.6 from [15] shows the evolution with time of the activity of a lead-bismuth target supposed to have been irradiating during one year with a 15 mA, 1 GeV proton beam. It can be noticed that the activity level is quite high and mainly due to spallation residues. Nuclei, such as ^{210}Po , formed by neutron activation are not the major contributors.

Also the production of all the chemical elements has to be known since some of them, even in very low concentration, could be responsible for embrittlement of solid materials (the window between the accelerator and the target for instance) and, in the case of liquid metals could enhanced chemical corrosion problems. See the paper by G.S.Bauer in this conference for more details.

The knowledge of the recoil velocity of the spallation fragments is also very important for DPA estimation.

3.4 Neutronics data

Nuclear data concerning the isotopes of interest for nuclear industry, i.e. main actinides, most important fission products and standard structural materials, have been thoroughly investigated in the past and are now very well known and well documented in nuclear data libraries. The situation is much less favorable for some isotopes of minor actinides or fission products that are considered for possible transmutation in ADS. The value of their capture and fission cross-sections that will directly influence the transmutation capabilities and neutronics properties of an accelerator-driven incinerator, are sometimes not known with a sufficient precision or show large discrepancy between different data libraries. It is even worse in the case of the thorium cycle, for which some of the fundamental cross-sections are poorly known. As an example, fig.7 from [16] shows the evolution with time of the k_{eff} of the Rubbia's Energy Amplifier calculated using JEF-2 and ENDF/B-VI data libraries, which happens to be drastically different. The deviation is attributed mainly to differences in ^{232}Th capture cross-section.

Figure 7: Evolution with time of the k_{eff} of the Rubbia's Energy Amplifier calculated using JEF-2 and ENDF data libraries. From [16].

4. EXPERIMENTAL STUDIES

4.1 Spallation neutron studies

4.1.1 Neutron multiplicity measurements

Figure 8: Number of captures in the manganese per incident proton obtained by manganese bath technique (symbols) as a function of the beam energy for different targets compared with calculations performed with the code TIERCE from Bruyères-le-Châtel. From [18].

A collaboration between Bruyères-le-Châtel and Los Alamos has conducted average neutron multiplicity measurements in various targets at SATURNE between 800 MeV and 2 GeV, using the manganese bath technique [17]. The cylindrical targets were placed inside a lead blanket surrounded by a water moderator tank containing $MnSO_4$. The neutrons produced in the target are thermalized in the water and captured by the manganese to form radioactive ^{56}Mn , the activity of which is measured. Fig.8 from [18] shows the number of captures in the manganese per incident proton as a function of the beam energy for different targets ($\Phi = 25$ cm Pb, $\Phi = 15$ cm W and a series of separated W plates) compared with calculations performed with the high energy transport code TIERCE from Bruyères-le-Châtel [19]. It can be noticed that in W the number of captures is much lower than in the Pb target although the numbers of neutrons produced in the tungsten and lead targets are of the same order of magnitude. This is due to the large capture cross-section of W for

low energy neutrons. This can be solved by using separated plates as it can be seen in fig.8. It is also shown that the TIERCE calculations agree quite well with the experimental results. However, experiments without the lead blanket surrounding the targets were also performed. Then, the calculations overestimate the experimental results, especially at high energies and for smaller targets, by up to 24%. This could be ascribed to problems in the high energy transport code or to a bad prediction of the angular distribution of secondary particles produced in the intra-nuclear cascade model.

Figure 9: Mean neutron multiplicity for incident particles on 35 cm long 15 cm diameter Pb and 40 cm long 8 cm diameter depleted U targets. From [21].

Neutron multiplicity measurements have also been made using 4π liquid scintillator detectors loaded with gadolinium, which captures the neutrons after they have been thermalized. This type of detector has been used by the collaboration GANIL-Berlin on several facilities (SATURNE, CERN, COSY) to obtain the number of neutrons emitted from thin targets event by event inclusively or in coincidence with charged particles and fission fragments [20]. The neutron multiplicity is indirectly sensitive to the excitation energy of the nucleus heated after the intranuclear cascade and, coupled to other observables, makes it possible to have a deep insight of reaction mechanisms. The same apparatus was also employed to get mean neutron multiplicities on thick targets with different projectiles. Results concerning 35 cm long, 15 cm diameter Pb and 40 cm long, 8 cm diameter depleted U targets [21], are summarized in fig.9. Globally, the total number of neutrons produced from a thick target continuously raises with the beam kinetic energy and depends only on the target and on total available energy of the projectile.

4.1.2 Neutron energy and angular distribution measurements

A program aimed at measuring the production of neutrons induced by protons and deuterons on various thin and thick targets, has been carried out at the SATURNE accelerator in Saclay. Two different experimental techniques were used for these measurements: for the low energy part of the neutron spectrum [22] (namely from 2 to 400 MeV) time-of-flight is employed between a NE213-scintillator sensitive to neutrons and a small plastic scintillator detecting the tagged incident particle. High energy neutrons, from 200 MeV to the beam energy, were measured using (n, p) diffusion on a liquid hydrogen target and reconstruction of the proton trajectory in a magnetic spectrometer [23]. A special attention was paid to the determination of detector efficiency, which is a critical problem in neutron detection techniques. Quasi-monoenergetic neutron beams from 100 MeV to 1600 MeV coming from deuteron breakup on a *Be* target were used to directly determine the response function

Figure 10: Neutron production double-differential cross-sections measured in proton induced reactions on a 2 cm thick Pb target at 1200. The histograms represent TIERCE calculations [19] using Bertini [24] (full line) or Cugnon [25] (dotted line) cascade model followed by the same evaporation model. From [28].

of the detection systems. The neutron scintillator efficiency was completed at lower energies by measurements on the Tandem of Bruyères-le-Châtel and in Uppsala.

Measurements were performed with protons and deuterons between 0.8 et 1.6 GeV on various thin targets representative of different parts of the periodic table of elements and corresponding to materials used in targets or in structures of ADS. Fig. 10 from [28] presents neutrons cross-section distributions in Pb(p,xn)X reactions at 1200 MeV. The histograms are numerical calculations, taking into account the actual geometry and composition of the target, performed with the TIERCE [19] code system developed at Bruyères-le-Châtel. Within HETC two different intranuclear cascade codes followed by the same evaporation model [26] have been used: Bertini [24] (full line) and Cugnon [25] (dotted line) codes. At 0°, the more realistic parametrization of the $NN \rightarrow N\Delta$ reaction angular distribution [27], introduced in the code from Cugnon et al. [25], solves the problem of the pathologic behaviour obtained with the Bertini cascade. At higher energy, both models are in quite good accordance with the data between 10° and 85° but Bertini underpredicts the backward angles. Whatever the angle, calculations with the Bertini cascade overestimate the production cross-sections below 20 MeV while the Cugnon model generally leads to a much better agreement. This is due the larger excitation energy left in the nucleus after the INC phase in the Bertini than in the Cugnon code.

While double-differential cross-sections measurements on thin targets allow to test the validity of the physics models, thick target data provide information on the transport part of the codes. The same experimental setup has also permitted the measurement of energy spectra of neutrons coming out from thick targets. A broad programme of measurements with various lengths and diameters of cylindrical targets has been conducted with 0.8, 1.2 and 1.6 GeV protons and 0.8 and 1.6 GeV deuterons on lead, tungsten, iron and aluminium targets. The collimators and the possibility to longitudinally translate the target allowed to select neutrons coming from different emission zones, thus enabling to test the propagation of the cascade along the target.

As an example, fig.11 displays some of the results [29] obtained with a lead cylinder of 20 cm diameter and 65 cm length, at longitudinal position 10 cm, for 1200 MeV and for different angles. The results are compared with calculations performed with two versions of the code HETC: TIERCE from

Figure 11: Results obtained on a lead target of 65 cm length, 20 cm diameter, at longitudinal position 10 cm, at 1200 MeV, compared with two different versions of the HETC codes (see text): TIERCE [19] and NMTC [30]. From [29].

Bruyères-le-Châtel [19] and NMTC from JAERI [30], followed by MCNP. They differ mainly in the nucleon-nucleon cross-section used in the INC phase (the free $N-N$ cross-section in TIERCE but an in-medium corrected one in NMTC) and in the evaporation model. It can be seen that there are large discrepancies between the data and the predictions of the models: TIERCE generally underestimates the data, especially for high energy neutrons and at large angles. Actually, the estimation of the high energy neutron flux at large angles is important since it corresponds to neutrons back-scattered towards the window which would separate the target from the accelerator in a spallation source.

4.2 Residual nuclide production

A large amount of data on the production of nuclides in spallation reactions, measured by radiochemical methods and γ -spectrometry, have been collected by Michel et al.[31] for several years, on several facilities. Excitation functions from a few tens of MeV to several GeV have been obtained on nuclei relevant for astrophysics and more recently for ADS. Results from mass spectrometry analysis were also obtained at PSI [33] on Th and U targets which lead to the measurement of complete mass distribution of residues at 600 MeV. A group from Bruyères-le-Châtel [32] has also conducted, at SATURNE by γ -spectrometry, thick target experiments in which the production of the residual nuclides is studied by analyzing activation products in thin foils placed at different longitudinal and radial positions inside a lead cylinder.

These kind of experiments suffers from the fact that the isotopes are identified after a radioactive decay chain. This makes the interpretation of the results rather difficult. A more direct measurement is possible using the heavy nucleus as a projectile on a hydrogen target in so-called reverse kinematic experiment. The various produced isotopes are then emitted in the forward direction with a velocity close that of the beam and can thus be directly identified with a magnetic spectrometer. A collaboration between GSI Darmstadt, LNS Saclay, SPhN Saclay, IPN Orsay, and CENBG is undergoing such experiments at SIS accelerator in Darmstadt [34]. The use of reverse kinematics and of the fragment separator FRS allows the precise (N,Z) determination of all residues, as shown in fig.12, with production cross-sections larger than 0.1 mb and ranging from fission fragments to beam isotopes. So far, experiments with ^{197}Au , ^{238}U and ^{208}Pb beams of about 1 GeV/A on a liquid

Figure 12: Identification of isotopes in the fission fragment region obtained using the fragment separator FRS in Darmstadt, from [34].

hydrogen target are being carried out.

4.3 Intermediate energies

Figure 13: Comparison between MINGUS (left), HETC (right) and experimental data measured at 113 MeV on Pb. From [35].

Up to now, the evaluated data files used by the low energy transport codes were limited to 20 MeV. This implies that the microscopic nuclear models entering the high energy transport codes have to be used down to energies where their validity may become questionable. For instance, the intra-nuclear cascade model rely on the assumption that the interaction can be described with a good approximation by hard collisions between individual nucleons inside the target heavy nucleus. This is true as far as the incident particle associated wavelength is smaller than the nucleon mean free path inside the target, that is definitely not below 50 or 100 MeV. On the other hand, there exists sophisticated fully quantum-mechanical microscopic model codes able to predict rather precisely all the different reaction channels [35]. An example can be seen on fig.13 where the MINGUS code system, combin-

ing direct, pre-equilibrium and compound nuclear models and a HETC code using an intra-nuclear cascade model are compared with experimental results on (p, xn) cross-sections on Pb. It clearly shows that the use of MINGUS lead to a better prediction of the data. However, these codes are too much time consuming to be thought to be included in transport codes. The solution that has recently been proposed is to validate such models on a series of experimental results and then use them to generate evaluated data files up to 150 or 200 MeV. For this purpose, a high priority nuclear data request list for intermediate energies has been established by the OECD/NEA [35]. It concerns reactions on a elements which enter either as a spallation target material or a structural material. New experimental programs aiming at measuring double-differential cross-sections are being started on several European facilities to fill part of the requests: (p, xp) , $(p, x\alpha)$ at Louvain-la-Neuve and KVI Groningen, (p, xn) at Louvain-la-Neuve, (n, xp) , $(n, x\alpha)$ at Louvain-la-Neuve and TSL Uppsala and (n, xn) TSL Uppsala [36].

4.4 Neutronics data

4.4.1 TARC experiments

It has recently been proposed [37] to use Transmutation by Adiabatic Resonance Crossing (TARC) to destroy long-lived fission products. This could be achieved using lead as the moderator material, because of its high atomic mass and very low neutron capture cross-section. In lead, the kinetic energy of a highly energetic neutron decreases by successive elastic collisions in a very smooth (adiabatic) way, because of the Pb high atomic mass. This ensures that the neutron will be captured in any resonance of an isotope placed as a small sample inside a lead block. In fact, in such a medium, there is a nearly one-to-one correlation between the neutron slowing down time and the energy. Therefore, it is possible to deduce neutron energy from time measurements and, if transmutation rates are measured, to determine capture cross-sections as a function of energy. This has been done at CERN and ISN Grenoble where large lead blocks have been installed and transmutation rates determine by γ -spectrometry. An example of the γ energy spectrum obtained in the TARC experiment [38] in the case of a ^{99}Tc sample. This method allows the measurement of capture cross-sections on very small quantities of material but however with a modest accuracy.

Figure 14: Typical γ energy spectrum obtained in the TARC experiment, showing all the characteristic lines of ^{100}Tc coming from neutron capture on ^{99}Tc . From [38]

4.4.2 Transmission and capture measurements at Geel

A programme for measuring radiative capture and total reaction cross-sections have been started

at the white pulsed neutron source GELINA in Geel [39] (collaboration IRMM-CEA) for measuring ^{237}Np , ^{99}Tc and later ^{129}I cross-sections in the resonance region with the time-of-flight method. These measurements permit a very precise determination of all the resonance parameters, but need large samples, in the order of grams, to be carried out. An example is shown on fig.15 of the transmission factor of ^{99}Tc .

Figure 15: Transmission factor as a function of neutron energy, measured at GELINA. From [39]

4.4.2 Measurements at ILL (Grenoble)

Studies on the transmutation of ^{241}Am in different neutron spectra have underscored a large discrepancy in the value of the capture cross-section of $^{242g.s.}\text{Am}$, at thermal energy, between JEF2 ($\sigma_{cap} = 5000 \text{ barns}$) and ENDF-B/VI ($\sigma_{cap} = 252 \text{ barns}$) evaluated data libraries. This cross-section plays a major role in the transmutation of americium in a high superthermal flux as proposed by [2]. This is illustrated on fig. 16 where the number of neutrons required to destroy one isotope by fission, D , is shown in the case of a mixture of minor actinides obtained after reprocessing. Incineration can be achieved if D is negative, with an absolute value larger than 0.3 to compensate for neutron leakage. This is the case for reasonable neutron fluxes, only if the $^{242g.s.}\text{Am}$ capture cross-section is low enough.

A measurement of this cross-section was recently carried out at ILL where a high thermal neutron flux is available. Small samples of ^{241}Am oxide were placed into two different reactor channels, corresponding respectively to 5×10^{14} and $3 \times 10^{13} \text{ n/s/cm}^2$ neutron fluxes, and irradiated for different periods of time. The samples were then analysed off-line by mass spectrometry (TIMS and ICPMS). This has led to the determination of the $^{242g.s.}\text{Am}$ capture cross-section which is compatible with the ENDF-B/VI value.

5. Conclusion

A lot of work is still needed before being able to assess in detail the performances, possible problems and cost of Accelerator-Driven Systems, which seems attractive innovative options in the field of nuclear waste transmutation. Part of this work regards the optimization of the target-blanket assembly in which intense neutron fluxes are produced and used for transmutation. To do this, new specific nuclear data are needed to build evaluated data libraries, test and validate nuclear physics models

Figure 16: Neutron consumption per fission as a function of the superthermal flux in different reprocessing scenarii with the value of the capture cross-section of $^{242g.s.}\text{Am}$ from JEF2 or ENDF-B/VI.

and transport codes. With the above described new set of studies, although still to be completed, and other researches, not cited in this paper, performed elsewhere, it is expected to have, within a few years, calculation tools precise enough to design realistic target-blanket assemblies for ADS.

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