HINDAS High-Energy Programme:

Main conclusions and implications for spallation neutron sources

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Abstract: The objectives and main results from the HINDAS high-energy programme are presented, as an introduction to the detailed contributions to this conference. Conclusions are drawn, in particular as regards implications of the obtained results for the design of the spallation source of an accelerator-driven system.

I. General motivations

In an Accelerator-Driven System (see the contributions by W. Gudwski, H. Ait Abderhaim, F. Groeschel), high-energy reactions play a major role for the optimisation of the neutron-source performance and assessment of induced radioactivity and material damage in the spallation module. They are induced essentially by the primary proton beam in the target and in the window separating the accelerator vacuum and the target, but also by a few energetic secondary neutrons that can reach the target surrounding.

The source neutrons that will drive the sub-critical reactor are produced by the spallation reactions then multiplied, first by (n,xn) intermediate- and low-energy reactions in the target, and next, by fission in the fissile material. The precise knowledge of the number of neutrons produced in high-energy reactions is therefore important, as are their energy and spatial distributions for the detailed prediction of material damage and thermo-hydraulics in the target and sub-critical core. A few high-energy neutrons also escape the system and have to be taken into account for the shielding of the facility.

Light charged particles (mainly protons and alphas) are produced in spallation reactions with rates much larger than usual in reactors. They will be responsible for radiation damage (as atom displacements) in solid materials and hydrogen and helium bubble formation that can lead to swelling and embrittlement of structural materials. This is particularly important for the prediction of the lifetime of the window.

A large variety of isotopes is produced by spallation reactions. Many of them are radioactive and could be a source of concern for radioprotection. For instance, it is important to know the time evolution of the target activity to determine when it is possible to approach it for maintenance or unplanned intervention. Long-lived isotopes are produced which will be responsible for the long-term radiotoxicity of the target after operation. In addition, the chemical modifications due to the build-up of impurities could lead to corrosion problems on the structure materials in contact with the liquid metal of the target or loss of cohesion of alloys in the window. The recoil energy of the spallation products, which will induce heat deposition and atom displacements, in particular in the window, has also to be known.

For the detailed design of a future ADS, all these quantities, specific for high-energy reactions, will have to be reliably predicted in order to choose the best and most economic configuration and materials, which, in addition, satisfy all the safety regulations. Simulation code packages exist, which make it possible for spallation source designers to predict any of the above-mentioned quantities. They generally

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consist of the coupling of a high-energy transport code, which handles the transport and interactions of the incoming proton and all the produced particles down to 200 MeV, and a low-energy neutron transport code utilizing evaluated nuclear-data files (which are the subject of the intermediate-energy part of HINDAS) below. In the high-energy transport codes, the elementary cross-sections are calculated by nuclear-physics models. It is therefore crucial that the nuclear models be reliable enough, that is, provide correct elementary cross-sections validated on an extensive set of experimental data.

As a step towards the more remote final goal of disposing of a high-energy transport code capable of reliably predicting any quantity related to spallation reactions in ADS, the first objective of HINDAS was to study a limited number of selected key reactions, representative of target (Pb), fuel (U) and structure (Fe) material, in full detail. The second objective was to use these experimental data to benchmark, improve and develop nuclear-reaction codes so that these codes can be used to calculate the reactions occurring in the accelerator-driven system in their full variety. This was realized through the following work:

- Measurements for a few targets (Fe, Pb and U) of experimental data covering all the reaction channels in the whole energy range at the best suited facility
    - Light charged-particle production above 200 MeV at COSY (Jülich)
    - Neutron production (multiplicity distributions and double-differential cross-sections) in thin and thick targets at SATURNE and COSY
    - Residual nuclide production: isotopic distributions in inverse kinematics at GSI and excitation functions measured by γ- and mass spectrometry
- Comparison of the experimental data to nuclear models in order to assess their success and deficiencies, in particular those widely used in high-energy transport codes
- Improvement of nuclear-physics models on the basis of the best possible physics ingredients
- Validation of the models on the new experimental data
- Implementation of the high-energy models into High-Energy Transport Codes
- Assessment of implications of HINDAS results for ADS design

II. Main results obtained in the HINDAS project

II.1. Neutron production

The goal of HINDAS was to collect both thin- and thick-target data on neutron multiplicities by the NESSI collaboration1) (see the contribution by C.M. Herbach et al.) and energy spectra at different angles measured at SATURNE2) (see the contribution by J.C. David et al.).

A comprehensive comparison of the whole set of thin-target data collected within HINDAS with the high-energy models commonly used in high-energy transport codes for applications has been made3-6). In summary, it was shown that the combination of the Bertini7) intra-nuclear cascade (INC) Dresner-Atchison8) evaporation-fission models, which is the default option of most of the codes, presents serious deficiencies, although less important when used in the HERMES9) package. It is clear that the Bertini INC predicts too large excitation energy at the end of the cascade stage, therefore overestimating, especially at high incident energies, the number of evaporated neutrons. The adding of a pre-equilibrium stage improves the prediction of the code, in particular for low-energy neutron multiplicities. However, discrepancies tend to remain for neutrons produced at intermediate kinetic energy for high incident energies and grow larger as the target becomes lighter. The ISABEL10) model was also tried, when possible, and was found to give a good agreement with both the double-differential cross-sections and the multiplicity distributions. Only for iron, the predictions were less good. Finally, it was shown that the use of the Cugnon INC model, INCL211) is able to fairly reproduce the whole bulk of our results.

As an example of obtained results, the neutron multiplicity distributions measured on a large variety of really thin targets at 1200 MeV[12)] by NESSI are displayed in Fig.1 (left). The measured distributions are compared to calculations made with INCL2 coupled to the GEMINI[13)] evaporation model after folding with the detector efficiency (shaded area). The dashed curve shows the distribution before taking into account the detector efficiency. It can be seen that generally the INCL2 calculations agree very well with the measured distributions. For heavier targets and low neutron multiplicities there exists however a discrepancy between experiments and calculations that was ascribed to the sharp cut off modelling of the nuclear density distribution in INCL2. This serious defect makes it impossible to have a correct prediction of the most peripheral collisions and obliges to renormalize the calculations to the correct total reaction cross-section. The influence of the level-density parameterisation and Coulomb barriers (which are suspected of being too low in the Dresner-Atchison (RAL) model leading to too many charged particle emitted) was also tested and found to have an influence on the neutron multiplicities.

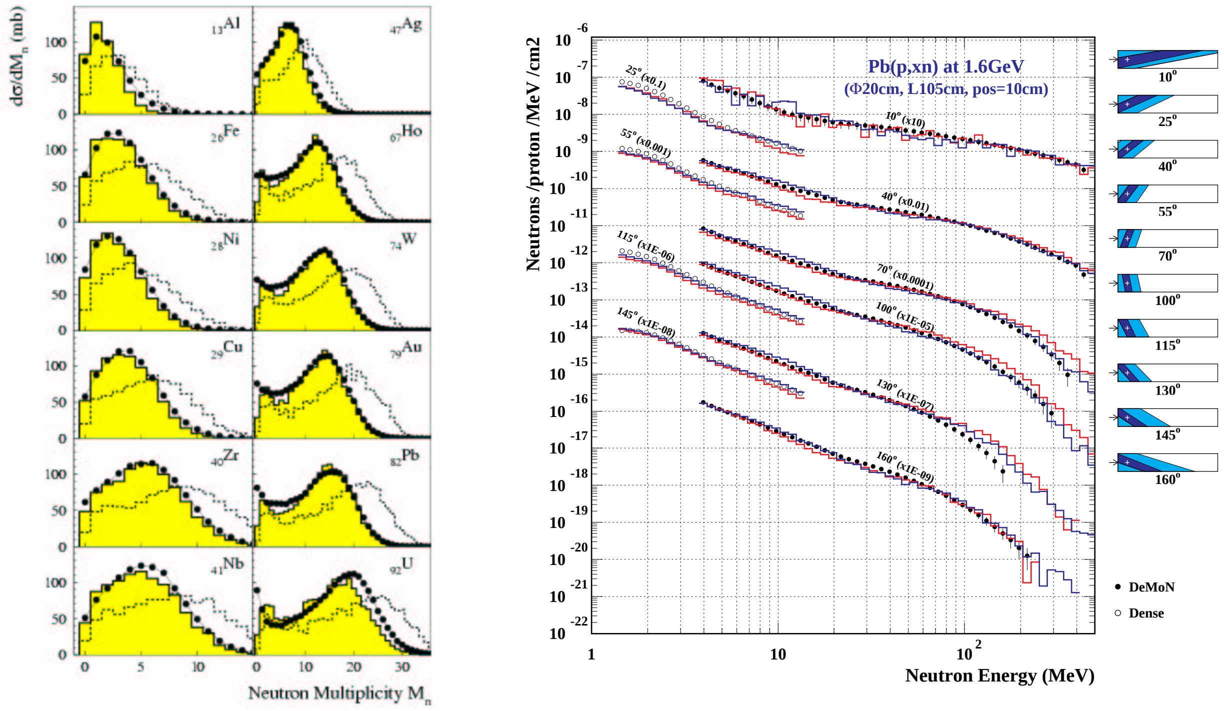

Fig. 1. Left: Experimental (solid points) and calculated (histograms) mean neutron multiplicities as a function of the target atomic number Z_T at 1.2 GeV. The calculated distributions are shown before (dashed line) and after (shaded area) folding with the detector efficiency. From [12)]. Right: Neutron spectra comparisons between SATURNE data[15)] (black points), INCL4/ABLA model[16, 17)] (red line) and Bertini/Dresner[7, 8)] model (blue line) for a lead target at 1.6 GeV.

Both the NESSI and SATURNE experiment allowed not only for studying the neutron production in thin targets, but also the measurement of neutrons produced in thick targets. The NESSI thick-target data[3, 4, 14)] give direct information on the mean neutron number expected from a spallation target, while SATURNE[15)] energy spectra of escaping neutrons are important for shielding. Furthermore, they have been compared also with the old and new models implemented into high-energy transport codes, so that their predictability could be estimated.

In Fig.1 (right), an example of the comparison of the energy spectra measured at SATURNE with the model combination INCL4/ABLA[16, 17)] (red curve), which was developed during HINDAS, can be seen. The data obtained at 1.6 GeV for a lead and an iron target are also compared to the Bertini(+preequilibrium)/Dresner combination (blue curve). Both model combinations are implemented in the high-energy transport code LAHET3[18)]. Actually, whatever the material, diameter or length of the target, or beam energy, the agreement obtained with the two combinations is of similar quality.

Also the neutron multiplicities measured by NESSI are rather well predicted by the standard high-energy transport codes LAHET, MCNPX or HERMES/MC4 with the default. In summary, it can be said that for a spallation target the accuracy of the code predictions can be assessed to be of the order of magnitude of the experimental uncertainties, that is around 10-15% for global quantities, but can be larger in some regions of the angle or energy spectra.

II.2. Light charged-particle production

The NESSI collaboration has also measured with the Berlin Silicon Ball the production cross-sections and the energy spectra of light charged particles, hydrogen and helium[19, 20)]. The measurements in coincidence with the Berlin Neutron Ball also allowed the study of the dependence of this production with excitation energy (see the contribution by C.M. Herbach et al.).

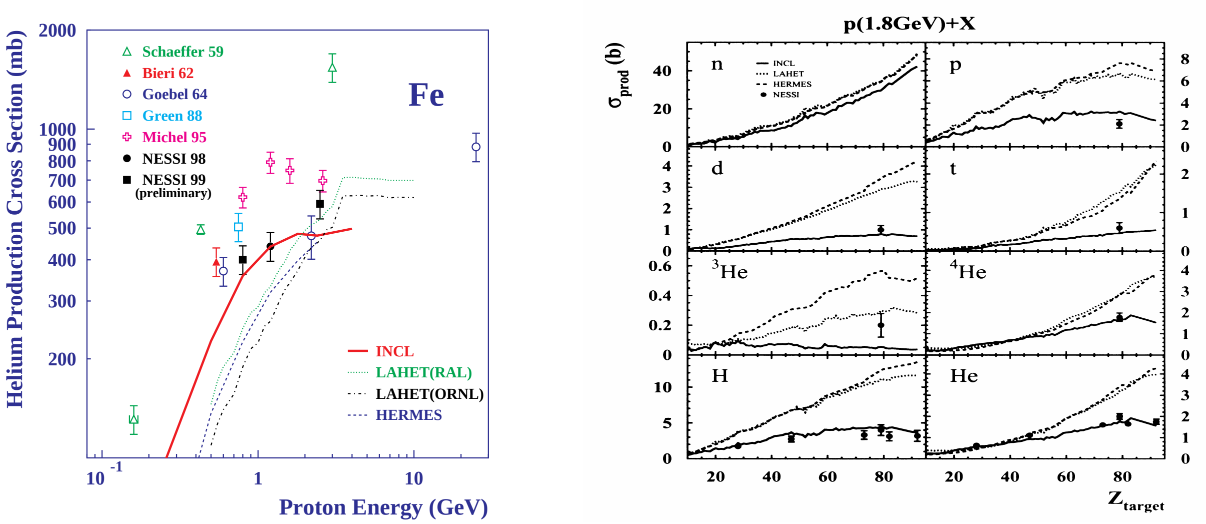

Fig. 2. Right: He-production cross sections for p+Fe as a function of incident proton energy measured by the NESSI collaboration[20)], Michel and data from literature. Comparison with the INCL2 model coupled to GEMINI evaporation and LAHET calculations using the Bertini/Dresner combination with two different options for the Coulomb barrier (RAL and ORNL); Left: Charged-particle production at 1800 MeV as a function of the target charge from[19)] calculated with the same models.

Helium production has also been measured by rare-gas mass spectrometry by the group of R. Michel (see the contribution by I. Leya et al.). While production cross-sections agree with the NESSI results for lead targets, discrepancies of the order of a factor 2 have been found for iron, as can be seen in Fig. 2. Up to now, no satisfying explanation has been found.

As concerns the comparison with codes, it has been found that large deviations also exist between codes, the standard Bertini/Dresner combination generally over-predicting hydrogen and under-predicting the helium production. This is illustrated in both parts of Fig. 2. This has been ascribed to the too large excitation energy remaining in the excited nucleus at the end of the intra-nuclear cascade stage. Different results are also obtained when using different options in the evaporation (RAL in which the Coulomb barrier is lower and ORNL), none of them satisfying (see the contribution by C.M. Herbach). Only the coupling of INCL2 with GEMINI agrees perfectly with the results, both cross-sections and low-energy part of the energy spectra. However, the model is not able to account for the high-energy tail of the composite-particle spectra. Attempts to introduce emission of composites in the INC stage have been done in ref.[21)].

II.3. *Residue production*

One of the most important results of HINDAS was the measurement of isotopic distributions thanks to the reverse-kinematics technique. A total number of 4682 individual nuclide production cross sections and velocity distributions in the reactions of 1 *A* GeV ^{238}U and ^{208}Pb with proton and deuteron target have been studied[22, 23)], covering most elements between oxygen and uranium. The reaction products were fully identified in atomic number *Z* and mass number *A* using the magnetic spectrometer FRS. Moreover, the velocity distribution of each individual nucleus was measured. An example, for U+p is shown in Fig. 3 (Left). Thanks to the measurement of the full isotopic chains, it was possible to produce isobaric cross sections, this means, cross sections summed up over the full isobaric chains. The associated plot is reproduced in Fig. 3 (right), which shows the isobaric distributions for three reactions: ^{238}U + p[23)], ^{208}Pb + p[22)], both at 1 *A* GeV, and ^{197}Au + p[24)] at 0.8 *A* GeV. The isobaric cross section is figured as a function of the mass loss. It can be observed that U behaves quite differently from Pb or Au. This is due to its high fissility, which lead to the fission of the highest mass nuclei while fission occurs only if there is enough excitation energy for the other ones. More details can be found in the contributions from M. Bernas, T. Enqvist and J. Pereira.

The comparison of the predictions of available codes with the measured isotopic distributions has pointed out that the Bertini/Dresner combination was totally unable to predict the isotopic distributions and the fission cross-sections (see Fig. 4 right). This seems due to a wrong competition between neutron, charged-particle emission and fission.

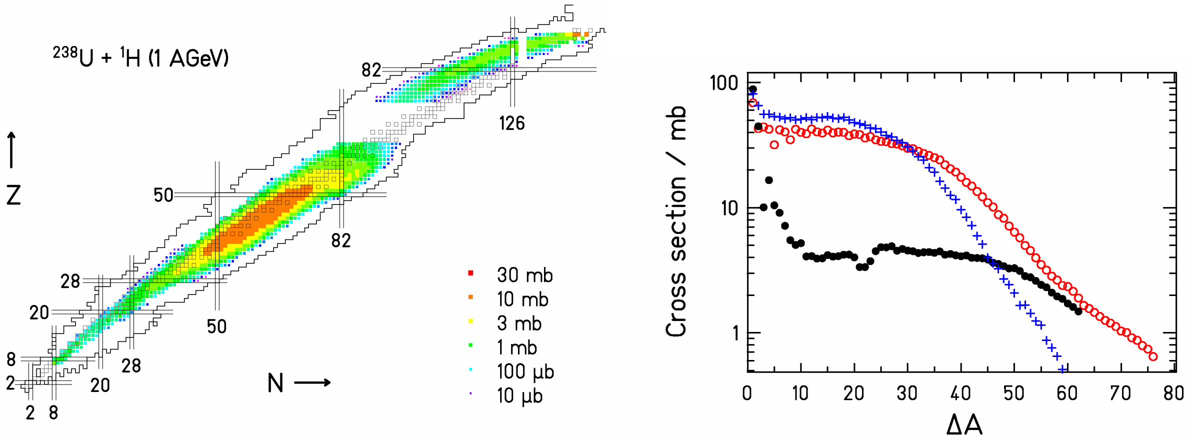

Fig. 3: Left: Residual nuclide cross sections for the reaction ^{238}U + ^{1}H at 1 *A* GeV[23)]. Right: Isobaric cross sections as a function of mass loss for three reactions: The full symbols mark the system ^{238}U + ^{1}H at 1 *A* GeV, open symbols represent the system ^{208}Pb + ^{1}H at 1 *A* GeV[22)], and the crosses result from the reaction ^{197}Au + ^{1}H at 0.8 *A* GeV[24)].

During the HINDAS project, excitation functions of isotope cross-sections were measured by gamma- and mass-spectrometry for the heavy target elements Ta, W, Pb, and Bi[25-27)] and iron. For the target element lead, AMS-measurements of cross sections for the production of the long-lived radionuclides and mass spectrometric measurements of stable and radioactive rare gas isotopes of He, Ne, Ar, Kr, and Xe were also performed. See the contribution by I. Leya. The obtained excitation functions provide complementary information to the reverse kinematics results which is limited to rather high-energies. They allow testing the energy dependence of the models as shown in Fig. 4 right. Production cross-sections for intermediate-mass fragments have also been measured[25-27)], which are under-predicted by orders of magnitude by all the available models. This may be an indication that different reaction mechanisms could be responsible for their production.

II.4. Model development

The comparison of the experimental data to widely used models having shown severe deficiencies, during the HINDAS project, efforts have been devoted to the building of improved INC and evaporation-fission models. Since the previous version of the Liège INC, INCL2, was shown to give encouraging results, a new version, INCL4[16)] was developed in which the known deficiencies were cured. In particular, the diffuseness of the nuclear surface was taken into account, which solved the problems discussed in section II.1, improvements on the implementation of the Pauli blocking, pion production, angular-momentum treatment were brought. More details can be found in the contribution of J. Cugnon.

Concerning the evaporation/fission model, the ABLA[17)] model was adopted, which, in particular, allow to predict correctly the shape of the isotopic distributions of residues, thanks to a consistent treatment of level densities as a function of excitation energy and nuclear shape and realistic Coulomb barriers. The modelling of the fission decay width at high excitation energies takes into account the evolution of the fission degree of freedom as a diffusion process, determined by the interaction of the fission collective degree of freedom with the heat bath formed by the individual nucleons (see the contribution by B. Jurado).

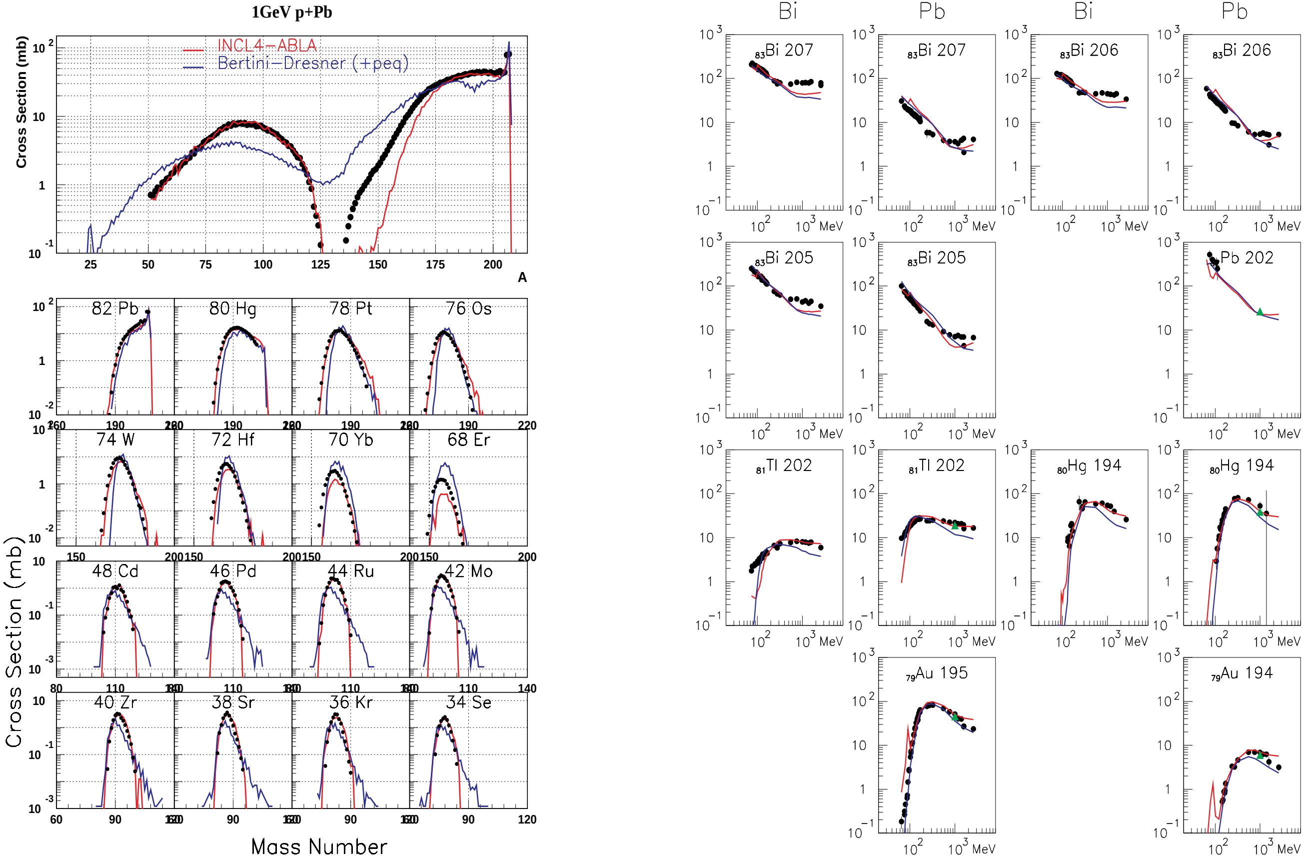

Fig. 4: Left: : Mass and a few isotopic distributions of residues produced in Pb+p at 1 *A* GeV, measured at GSI[22)] compared with the INCL4-ABLA models and also with the Bertini+preequilibrium/Dresner model. Right: Same comparisons but with the production cross-sections (mb) of a few isotopes (which are the main contributors to the activity in a thick Pb-Bi target) measured in p+Pb or p+Bi by γ-spectroscopy[25)] as a function of the incident energy.

The INCL4/ABLA predictions have been tested, during the second year of HINDAS, on a large body of experimental data including total cross-sections, neutron and proton differential cross-sections, neutron and charged-particle multiplicities, residue mass and charge distributions, isotopic distributions, fission cross-sections and distributions, and residue recoil-energy distributions. In particular, they have been compared with many data obtained by the HINDAS collaboration. Two examples concerning residue production are shown in Fig.4. Furthermore, the INCL4 code has also been tested after inclusion in high-energy transport codes. The predictions have been compared with thick-target experiments and have been used for activity calculations and gas production, as explained above in this report.

II. 5. *Implications of HINDAS results for ADS design*

In an Accelerator-Driven System (or a spallation neutron source) spallation target, a large variety of radioactive isotopes is produced by spallation reactions in addition to those created by activation by the low-energy neutron flux. It is therefore important to be able to calculate the activity as a function of time and the quantities of the most annoying radio-isotopes. Thanks to both the experimental data collected within HINDAS and the improvement of the physics models, it is now possible to have a better confidence in the simulations and assess the quality of the prediction power of the codes. As shown in the preceding section (see Fig. 4), the high-energy models used in standard high-energy transport code, in fact the Bertini-Dresner combination, does not correctly predict in particular the isotopic distributions and the fission fragment production measured in GSI. On the other hand, the INCL4 /ABLA model has been shown to give a satisfying agreement with the isotopic distributions of spallation residues in the region of fission and heavy evaporation products. With these models being implemented into the LAHET3 code system[18)], it is now possible to calculate quantities like the activity due to the spallation residues, which as shown in [28)] dominates the total activity, or chemical impurity production for real spallation targets with an improved confidence.

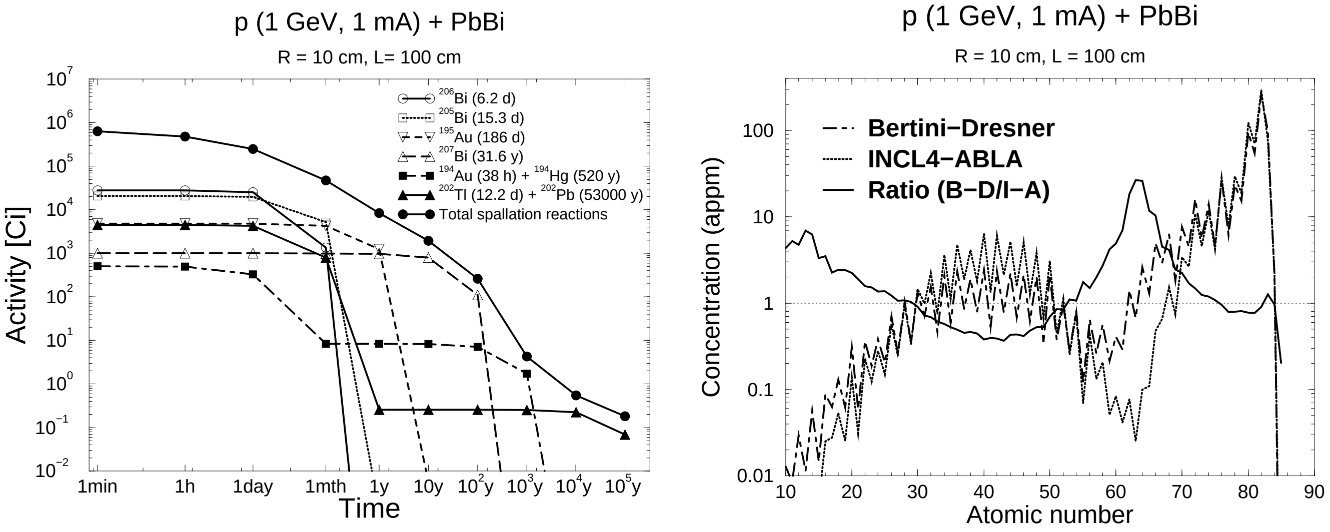

Fig. 5. Left: Main contributors to the activity (in Curies) of a Pb-Bi target as a function of time, after one year of irradiation, calculated with the LAHET3 code system using the INCL4-ABLA models, the line with black circles give the total contribution due to spallation products. Right: Concentration in appm of the different chemical impurities produced by spallation in a Pb-Bi target after one year of irradiation, calculated with LAHET3 using the INCL4-ABLA (dotted curve) or the Bertini-Dresner (dashed-dotted curve) model and ratio between the two calculations (solid line). From Donadille et al.[29)].

Calculations[29)] have been made for 10 cm radius, 1 m long Pb-Bi and Pb targets, supposed to have been irradiated by a 1 GeV, 1 mA proton beam during one year. The evolution of the nuclides concentrations as a function of time has been calculated with the ORIHET3^30) decay code. The neutrons below 20 MeV were transported by MCNP4C. The resulting flux was used to estimate the activation due to low-energy reactions, which was found always smaller than the activity due to spallation^29).

As far as the spallation products are concerned, a large number of isotopes is actually contributing to the total activity. During the irradiation phase, the total activity almost saturates at 5×10^5 Ci after about one month. At this time and up to one day after irradiation, the main contributors to the activity are ^{206}Bi and ^{205}Bi as shown in Fig. 5 (left) in the case of the INCL4-ABLA calculations. For longer decay times the activity is due to a few long-lived nuclides only. For example, after 10 years of decay the nuclide ^{207}Bi represents 60% of the activity, and after 10^4 years the dominant nuclide, representing 50% of the activity, is ^{202}Tl, populated by the beta-decay of the long-lived ^{202}Pb. It can be noticed that only heavy residues close to the target elements contribute significantly. The activity due to the fission products is always less than 10-15% of the total.

When Bertini-Dresner is used instead of INCL4-ABLA, the results are globally the same although the relative contributions of individual isotopes may be different. The maximum differences are actually of the order of ±30%. This is not surprising since actually the models give similar results for residues very close to the target elements (see Fig. 4), with slight differences on the isotopic distributions, the larger discrepancies appearing for lighter isotopes. However, what is new is that we can now rely more confidently on these predictions because we know that the INCL4-ABLA does predict correctly the production of the involved isotopes. As already said, the model agrees totally with the isotopic production at 1 GeV. However, in such thick target, the primary proton induces on average one high-energy and two secondary lower-energy interactions, so it is also important to predict correctly the energy dependence of the production cross-sections. This is the case, down at least to a few tens of MeV, as it can be seen in Fig. 4 (right) where the models are compared to the elementary production cross-sections of the isotopes found to be the main contributors. The discrepancies between the model and the data being at most 30-40%, a similar uncertainty can be assessed for the predicted activity.

As already stated, in a liquid-metal target, chemical impurities produced by spallation reactions, can lead to corrosion problems on the container of the target or on the window if in contact with the metal. We have therefore calculated the concentrations of the different elements generated after one year of irradiation for a Pb and a Pb-Bi target. The results obtained with INCL4-ABLA (dotted curve) and Bertini-Dresner (dashed-dotted curve) are shown in Fig. 5 (right). The ratio between the two calculations (solid line) is also shown. Here the discrepancy between the two models can reach a factor 3 in the region of fission fragments and up to 30 for the very light evaporation residues. Actually, this reflects exactly the differences in the elementary production of the fission fragments at 1 GeV as these fragments are produced only in relatively high-energy reactions. Since it has been established that INCL4-ABLA reproduces much better the fission region, as it can be seen in Fig. 4, this calculation is obviously an improvement compared to the standard codes. For the light evaporation residues that arise in very low concentrations, the situation is not as good since none of the models correctly predicts the elementary cross-sections but this gives an idea of the uncertainty on their production.

Some of the fission products are volatile gases, krypton, iodine and xenon, of which some isotopes are radioactive and can be a concern for radioprotection in case of a containment failure. It is therefore important to investigate more precisely these elements. The element concentrations foreseen by the two models differ by a factor 2 maximum as found in Fig. 4 for these elements. However, for isotopic concentrations the discrepancies can reach a factor 4, due to the fact that the isotopic distributions are different in the two models. Here again, we can stress that with INCL4-ABLA we have a more reliable prediction but also that when using Bertini-Dresner the error on the prediction is certainly not larger than a factor 4 to 5.

Estimations of damage due to gas production and displacement of lattice atoms (DPA) resulting from the collision of the projectile particle upon the target atom or from the recoil energy that the atom receives upon emission of a nuclear particle have also been performed during the HINDAS project[20, 31)]. The damage cross-sections calculated with the standard codes (Bertini-Dresner) and the INCL2 were shown to be very similar despite considerable differences in other observables. The predicted He/DPA ratios, however, differs considerably in absolute numbers as well as in energy dependence. Since the INCL2 calculation was shown to agree with the NESSI helium production data, it was used to assess the life time of an ADS window in some examples of possible configurations.

III. Conclusion and perspectives

The high-energy program of the HINDAS project has permitted the collection of a large amount of new and high-quality experimental data covering all the most important reaction channels (neutron, light charged particles and residue production) in three regions of the periodic table around iron, lead and uranium for proton incident energies above 800 MeV. All the collected data have been compared to well-known nuclear-physics models, in particular those widely used in high-energy transport codes. The following conclusions could be drawn:

- As regards neutron production, there now exists a complete and coherent set of experimental data on double-differential cross-sections and multiplicities on both thin and thick targets that has been used to assess the quality of the predictions of different high-energy transport codes. It can now be stated that total neutron production in an ADS target can be predicted with a precision of 10-15%, which is also the precision of the experiments. General trends of energy, angular or geometry dependence are also well understood.
- Light charged-particle (hydrogen and helium) measurements, for which very few data were available before HINDAS, have been performed at different energies on different targets. While data from different measurement techniques agree for lead targets, not understood discrepancies remain for iron. Comparisons with codes have revealed severe deficiencies in most of the currently used models, in particular for helium predictions.
- The production of some intermediate-mass residual nuclei important for radioprotection, such as ^{7}Be or ^{10}Be, has been measured on a wide energy range and found underpredicted by orders of magnitude by the nuclear models, likely because of a production mechanism not yet well understood.
- For residue production, HINDAS has brought a considerable enhancement of available data thanks both to the reverse-kinematics technique, which has lead to the measurements of thousands of identified isotopes and to excitation functions obtained in direct-kinematics experiments, which allow testing the energy dependence of the production. The comparison of the predictions of available codes with the measured isotopic distributions has pointed out wrong behaviours of the nuclear models concerning the competition between neutron, charged-particle emission and fission.

Meanwhile, an important effort has been devoted to the testing and improving of theoretical models in view of including the best possible physics. This has been possible because the quality of the HINDAS experimental data has often lead to a better understanding of the reaction mechanism and of the reasons for deficiencies in the previous models.

- A new version of the intra-nuclear cascade from Liège, INCL4, has been developed in which the introduction of a realistic nuclear surface diffuseness, better Pauli blocking, angular-momentum

- treatment, among other improvements, have resulted in much better predictions of total reaction cross-sections and peripheral reactions.
- For the de-excitation stage of the reaction, the ABLA model has proved to give a much better reproduction of isotopic distributions and fission yields than other well known models.
- The INCL4-ABLA combination has been compared to the whole set of available experimental data obtained during the HINDAS project but also to earlier experimental results. An overall good agreement has been found out that, it must be stressed, was obtained with the same set of parameters in the models, whatever the system studied, the observable compared or the bombarding energy.
- This INCL4-ABLA combination has been implemented into high-energy transport codes widely used for ADS design, as LAHET3, MCNPX and HERMES/MC4 and are now available to the whole community.
- The MC4 new high-energy transport code, which is written in a modern language and includes the possibility to use different models and analysis tools, has been developed for the HERMES code system.

As concerns the impact of the work done during HINDAS for ADS design, several studies have been conducted:

- simulations of thick Pb and Pb-Bi targets have been performed with the LAHET3 code which have shown that total activity is predicted with a precision of about 30% independently of the choice of models while factors up to 3 of discrepancies can expected for volatile fission-fragment emission when using standard model rather than ours.
- Neutron-leakage energy spectra from thick targets, which are important for shielding, are rather well predicted by INCL4-ABLA.
- Helium production and damage cross-section in ADS window have been estimated: while DPA calculated with the standard models and INCL are rather similar, Helium production varies considerably.

At the end of the HINDAS project, it can be said that the situation concerning high-energy data and models has been largely improved. However, the work performed within HINDAS was limited in the energy range (most experimental results above 800 MeV) and in the studied targets (Fe, Pb and U). Also, a few remaining discrepancies between experimental data and lacks have been pointed out and there are still not well understood (from a physical point of view) deficiencies of the models. If we want that the high-energy transport codes could be able to predict any quantity related to the spallation target and environment, this calls for a pursuing of the work in the future. Among the most important points to be addressed are:

- The large disagreement existing on helium production in iron targets, which may have important consequence for the window life time
- The production of intermediate-mass fragments, for which we need more experimental data and a mechanism to produce them in the models
- The understanding of the under prediction of the light evaporation residues by the models, which could be due either to a too low excitation energy at the end of the cascade or to deficiencies of the evaporation model. For this we need more constraining experiments, in which several observables can be measured simultaneously. During HINDAS, the feasibility of two such experiments, SPALADIN and PISA, has been studied and are now under preparation at GSI and COSY respectively.
- The energy dependence of residue isotopic distributions, which has not been studied in HINDAS, and could help solving the two preceding points.

- Measurements on one element intermediate between lead and iron, since different behaviours in the comparisons with the models have been observed and are not presently understood. Niobium, which is also employed in the superconducting cavities, could be an example.
- Measurements on lighter elements, such as aluminium present in some structure materials, would also be necessary, since the models may be for this system out of their range of validity and new approaches have to be considered.
- Measurements of total fission cross sections for different systems (e.g. U, Pb, W) over a wide range of energy could help to solve discrepancies existing between different experiments performed so far.

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