INVERSE-KINEMATIC MEASUREMENTS OF RESIDUES AT GSI

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INTRODUCTION

In the course of the recent discussion on hybride nuclear power plants it has been proposed to destroy nuclear waste in an intense neutron flux produced by high-energy protons [Bowman et al. 1992]. Also an energy amplifier on the basis of spallation reactions with light relativistic ion beams has been considered [Carminati et al. 1994]. For an exact quantitative estimation of the efficiency of this method one needs to know the spallation cross sections of a great number of radioactive nuclei. This knowledge is also mandatory for calculating the activities newly emerging as secondary radioactive spallation products.

The present contribution consists of three parts. First, the advantages of spallation experiments in inverse kinematics are outlined. Secondly, we describe the experimental facilities of GSI which enable to measure essentially all necessary spallation cross sections in inverse kinematics. Thirdly, we will present first experimental results on fragmentation cross sections using radioactive beams.

ADVANTAGES OF EXPERIMENTS IN INVERSE KINEMATICS

There are two possible, principally different methods for performing spallation experiments. In the conventional method targets of the isotope to be investigated are prepared and bombarded with high-energy ions. Most of the reaction products are formed with low kinetic energies, and part of those do not leave the target. The reaction products are analyzed by chemical methods and decay spectroscopy, eventually assisted by mass-separation techniques.

The alternative method proposed here consists of preparing a high-energy beam of the isotope to be investigated which impinges on a light target material. Since the heavy nuclear-reaction products are produced with high kinetic energies, they can be identified in-flight within a few hundred nanoseconds by use of an appropriate detector system.

This second option, namely the experiment in inverse kinematics, offers some important advantages: First, one only needs a microscopic quantity of the isotope to be investigated. Secondly, with the appropriate experimental installation one is free to select almost any isotope as secondary beam, e.g. practically without regard of its half-life. Finally, the observation and the identification of the reaction products is totally independent of their chemical properties and also independent of their β half-lives.

THE GSI RADIOACTIVE-BEAM FACILITY "BRENDA"

Since 1991, Beams of Relativistic Exotic Nuclei from DArmstadt (BRENDA) are available for experimental investigations at GSI. Figure 1 shows the different instruments of this complex installation. S1S beams ($\approx$ 1 A GeV) are converted in a target station into secondary projectile fragments from fragmentation, fission, or any other nuclear reaction. A recoil separator (FRS) selects the unslowed projectile fragments and provides secondary beams of exotic nuclei. These beams can be used for experiments in an experimental area behind FRS, they may be transported to the ESR, or

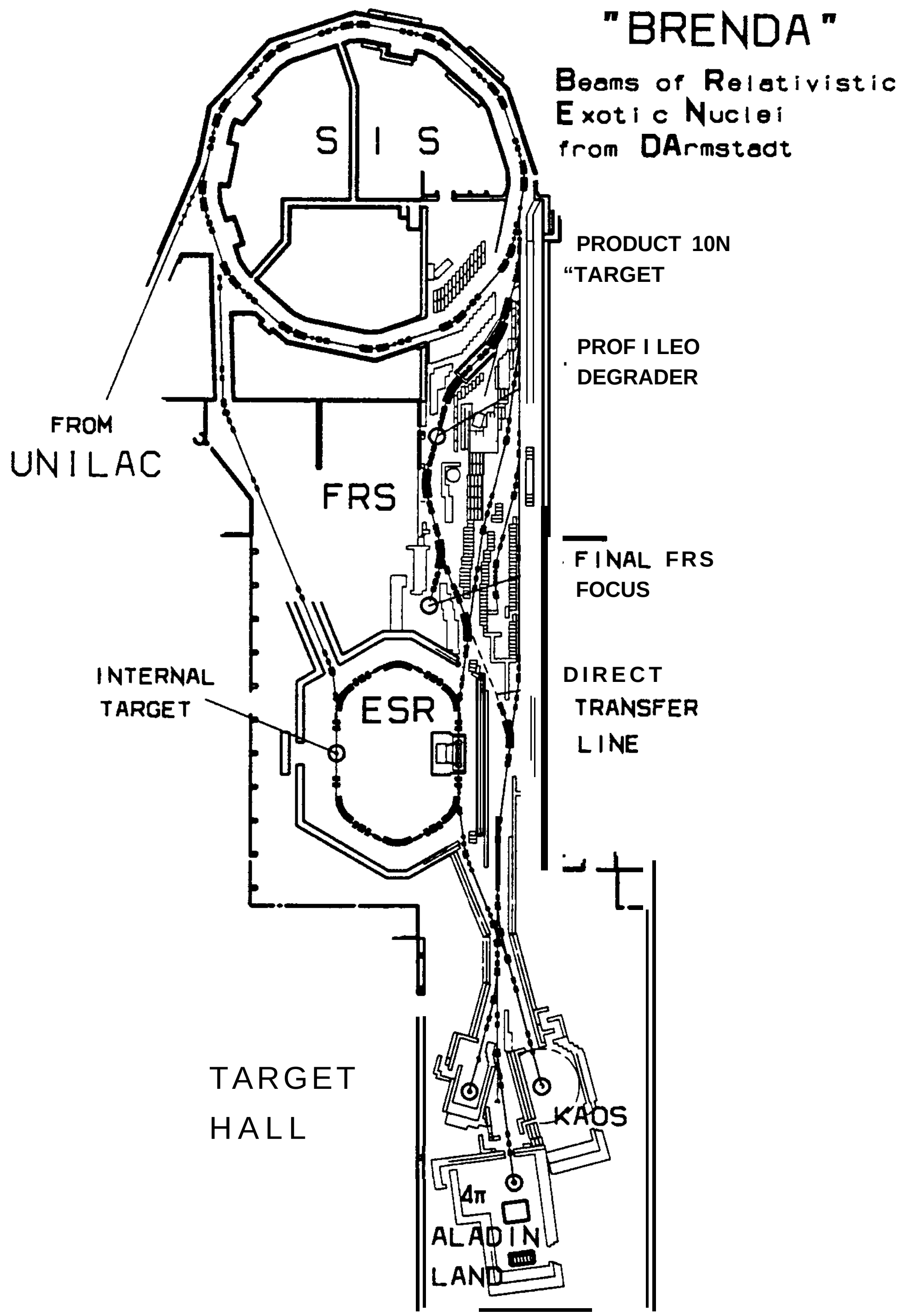

Fig. l: View of BRENDA, theGSI radioactive-beam facility. (See text for details.)

to the large experimental facilities in the Target Hall, as there are KAOS, FOPI and ALADIN, the latter equipped with the large-area neutron detector LAND and the 4-π crystal ball.

Figure 2 shows a global survey on the intensities of secondary beams available from a ^{238}U SIS beam as predicted by a model calculation [Junghans 1994], based on ref. [Gaimard and Schmidt 1991]. The model has been tested with a number of measured cross sections of fragmentation and fission products determined in several experiments [Schmidt et al. 1993, Clerc et al. 1994, Bernas et al. 1994, Schmidt et al. 1994]. Typical intensities in the ridges of the isotopical distributions amount to 10^3 with the presently available primary-beam intensity of 107/s .

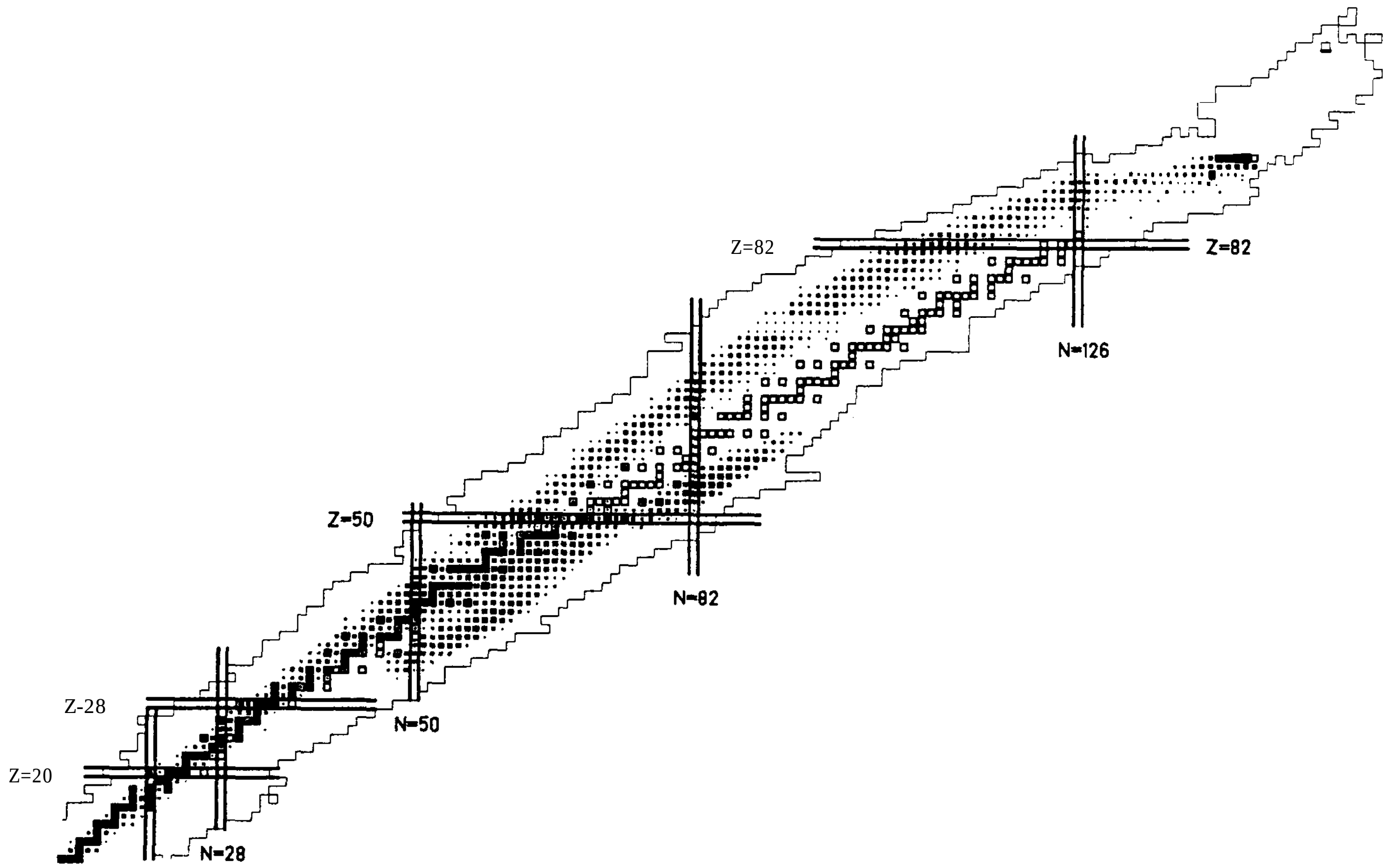

Fig. 2: Formation cross sections of secondary reaction products from a 1 A GeV ^{238}U primary beam in a copper target. The areas of the full clusters are proportional to the cross sections. The primordial nuclei and the limits of the known isotopes are indicated.

First experiments with isotonically identified secondary beams have been performed behind the FRS [Geissel et al. 1992] where the nuclear charge of the secondary reaction products can be measured. Future experiments in the target hall will additionally allow to determine e. g. the mass number of the products as well as the number and the energies of the neutrons formed in the reaction.

FIRST RESULTS OF FRAGMENTATION EXPERIMENTS WITH SECONDARY BEAMS

In a first experiment, we produced secondary beams in the iron region via the fragmentation of a 1 A GeV primary beam of ^{86}Kr [T. Brohm et al., 1992]. A kinematical particle identification (ΔE-ToF-Bρ) was used to identify each secondary projectile. Thus, we were able to investigate 54 secondary beams with only four settings of the FRS. At the exit of the FRS, the secondary beams traversed a reaction target of 3.8 g/cm^2 polyethylene, which was followed by an ionization chamber. This detector was used to determine the nuclear charge Z of the secondary reaction products.

Figure 3 shows the measured total charge-changing cross sections σ_Z for different Fe isotopes at about 650 A MeV. We find that this quantity strongly depends on the N/Z of the projectile. The discrepancy between σ_Z and the total reaction cross section σ_{tot}

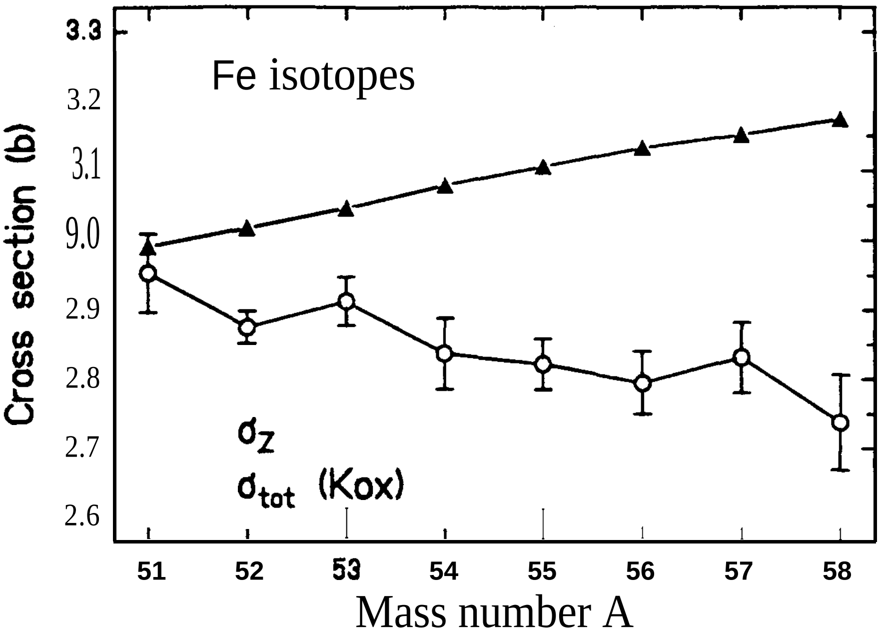

Fig. 3: Measured total charge-changing cross sections (open points) and calculated nuclear-reaction cross sections (triangles) for a series of Fe isotopes.

calculated with the empirical formula of ref. [Kox et al. 1987] which is also given in fig. 3 can be attributed to the reactions that produce isotopes of the secondary projectiles. These neutron-removal reactions are suppressed for the neutron-deficient beams. We conclude that the large body of total charge-changing cross sections measured for stable beams in CH_2 targets, e.g. [Webber et al. 1990], cannot directly be used for extrapolations to reactions involving radioactive nuclei, e.g. from nuclear waste.

In figure 4 we compare the measured element distributions for a ^{51}Fe and a ^{58}Fe secondary beam. In the fragmentation of the neutron-deficient ^{51}Fe , the lighter elements are created to almost equal amounts, while for '*Fe the heavier elements dominate. The yield of cobalt isotopes, for example, differs roughly by a factor of two in this case. This behaviour can qualitatively be understood with the abrasion-ablation calculations [Gaimard and Schmidt 1991], also shown in fig. 4 on a chart of nuclides. For the neutron-deficient ^{51}Fe beam, the ridge of the calculated fragment distribution is curved in the opposite direction than for '*Fe . The projection of these distributions on the Z axis is flat for ^{51}Fe and steep for '*Fe . This means that the amount of a given element created e.g. in bombarding nuclear waste with light ions will sensitively depend on the N/Z ratio of the target material. The complex interplay between the abrasion of nucleons in the nuclear collision and the nucleon losses in the evaporation cascade can be studied in further experiments with radioactive beams.

In other experiments, the fragmentation and the fission of a number of neutron-deficient isotopes from Fr to U in a lead target and of ^{238}U in different target layers [Schmidt et al. 1994, Bernas et al. 1994] have been investigated. It might be interesting in the present context that e.g. for nuclear collisions of 300 A x MeV ^{23}*U with lead for which we calculate a total nuclear cross section of 7.2 barn [Brohm and Schmidt 1994], only a fraction of about 2.4 barn has been measured to end up in fission, while the main part leads to fragmentation. (An additional fission cross section of about 1 barn stems from electromagnetic excitations.) For this fissile nucleus, the measured fission cross section is remarkably low and can only be understood by a large dissipative hindrance of the fission competition in the evaporation cascade.

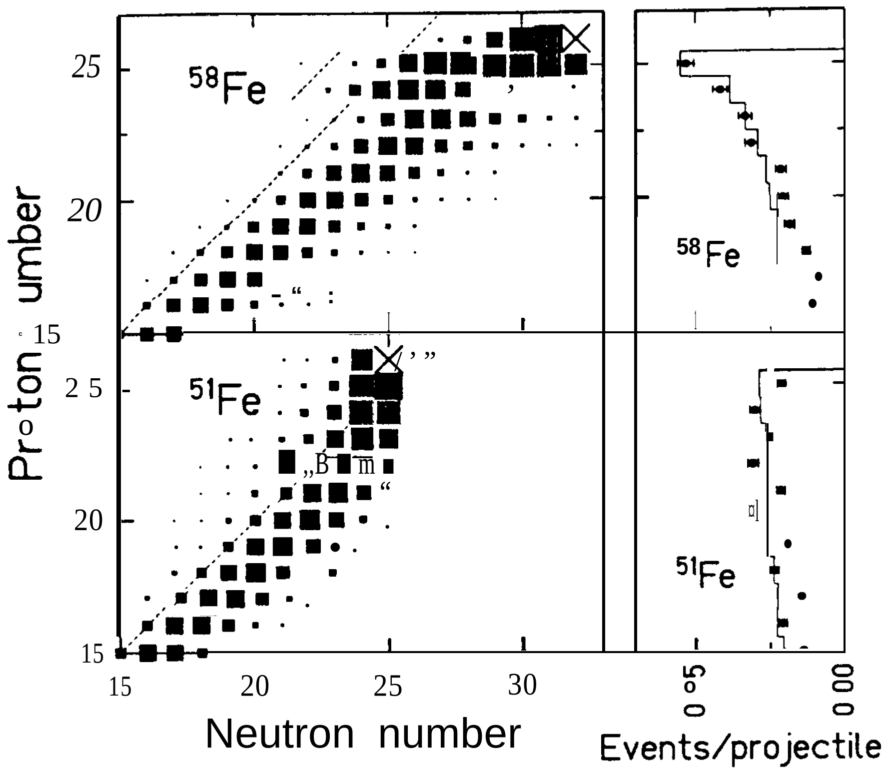

Fig. 4: Measured (data points) and calculated (histogram) element distributions (right-hand side) and corresponding calculated fragment distributions (left-hand side) for two Fe isotopes.

SUMMARY

The radioactive-beam facility of GSI offers unique possibilities to measure thin-target spallation and fission cross sections of a great variety of exotic nuclei in inverse kinematics. First experimental results stress the importance of such data. The data on the fragmentation of neutron-deficient isotopes' revealed that spallation cross sections of radioactive projectiles cannot be extrapolated from available experimental data obtained with stable projectiles by use of simple scaling laws. Moreover, the fission probability of heavy nuclei after high-energy nuclear collisions has been found to be surprisingly low.

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