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THE MUNICH ACCELERATOR FOR FISSION FRAGMENTS (MAFF) AT THE NEW REACTOR FRM II*

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In Garching near Munich the new research reactor FRM II is under construction. It is supposed to be commissioned in 2001. The reactor will have a power of 20 MW, a rather small core diameter of 25 cm and a maximum neutron flux of $8 \cdot 10^{14}\,\mathrm{n/cm^2 \cdot s}$. Many new powerful instruments and novel experiments are planned in material science, solid state physics, nuclear physics, fundamental physics, chemistry, biology, medicine and technology. Consequently, the applications will range from material science diffractometers and inelastic neutron scattering over neutron tomography and cancer therapy to fusion producing the heaviest elements using accelerated fission fragments. The acceleration of radioactive isotope beams (RIB) is an important new field in nuclear physics and many new facilities are planned or under construction all over the world. Nuclear fission is the most suitable method to produce neutron-rich isotopes due to the large fission cross sections of thermal neutrons and the high thermal neutron flux in modern research reactors. Consequently, the new facility MAFF (Munich Accelerator for Fission Fragments) is foreseen for the new FRM II reactor. Beams of about 10^{11} atoms/s are expected for ^{91}Kr, ^{132}Sn,^{144}Cs from a ^{235}U source in a graphite cylinder close to the reactor core placed in a through-going beam-tube. Laser ionisation and a linear accelerator with IH and RFQ structures will provide the possibility to accelerate many different isotopes up to about 6 MeV/nucleon. Neutron-rich isotope beams are most interesting, because they will allow the investigation of several exciting new areas: i)Production of heavy and superheavy elements. ii) Atomic physics and chemistry of the heaviest elements. iii) Nuclear structure of astrophysically relevant nuclides and data for the r-process nucleosynthesis. iv) Isospin dependence of nuclear reactions. v) Application of radioactive isotope beams for solid state physics, medicine and radioactive waste management.

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1 The new Munich Reactor FRM II

After more than forty years of very successful operation the Munich Research Reactor FRM will be replaced by the more powerful modern reactor FRM II. Its construction started in 1996. Although the power, core diameter and maximum neutron flux of the FRM II (20 MW, 25 cm and $8 \cdot 10^{14}$n/cm$^2 \cdot$ s), are somewhat lower than the corresponding values of the Grenoble High Flux Reactor of the ILL (57 MW, 42 cm and $1.5 \cdot 10^{15}$ n/cm$^2 \cdot$ s), it is tried to compensate this with most modern, efficient and innovative instrumentation. The FRM II is cooled with light water and moderated with heavy water. For best efficiency the reactor will be operated with highly enriched ^{235}U (93%). The reactor building is nearly finished and has a wall thickness of 1.8 m to protect the reactor against airplane crashes. All safety measures played an important role in the construction. Between 30 and 35 experiments are planned. The reactor is scheduled to be operational in 2001.

2 Instrumentation of the FRM II

The instrumentation will be built and operated by user groups from universities, research institutes and industry. Consequently, dedicated neutron beams will be used for research and education at universities, for testing new ideas and for a large spectrum of applied purposes. Neutrons are very complementary to x-rays, as they mainly interact with the nucleus, not the electron shell. They are easily scattered at light elements including hydrogen. Various precise neutron diffractometers will help to determine the crystal and molecular structure of many technical materials, new compounds and organic, biological and medical substances. Inelastic neutron scattering provides information on dynamic properties of matter. Medical application includes clinical cancer therapy with MeV neutrons, new radiopharmaca and boron capture therapy. The properties of the neutron itself will be investigated with ultracold neutron beams ($\upsilon \approx 5$ m/s). An extremely intense positron source $(10^9 e^+/s)$ will be constructed using pair production with neutron-capture gamma-rays. The most important instrument for nuclear physics will be the Munich Accelerator for Fission Fragments (MAFF) which will be discussed below. Industry is very interested in Si doping with neutron transmutation, irradiation for various tests and analyses and tomography with cold and fast neutrons which is specially suited to see thin layers of organic material.

3 Radioactive isotope beams (RIB)

Research with accelerated radioactive isotopes is a new and exciting development in nuclear physics. Several new facilities are planned and one is already in operation (Table 3). Reactions with extremely neutron-deficient or neutron-rich radioactive nuclei allow the investigation of new regions of the chart of nuclides. Since hot nuclei evaporate mainly neutrons, neutron-deficient nuclei and nuclei close to the proton drip-line have been frequently studied. It is more difficult to produce neutron-rich nuclei which deserve on the other hand special attention, because fusion of neutron-rich nuclei leads to more stable and eventually to the heaviest nuclei. Moreover, neutron-rich nuclides play an important role in the astrophysical r-process. Nuclear fission is the best reaction to obtain neutron-rich nuclei.

Figure 1 shows the cross sections for the production of rubidium isotopes using different reactions [1]. The fission cross sections with thermal neutrons are several orders of magnitude

Table I. European projects on ISOL based radioactive isotope beams.

Place	Primary beams accelerators	Target/ Ion source	Post-acceleration	Energy MeV/u	Beams	Status
ARENAS Louvain-la-Neuve	Cyclone 30 30 MeV p, 200 µA Cyclone 110, 80 MeV p, light ions, 20 µA	solid/molten ECR	Cyclone 110 New cyclotron (1997)	0.56-27 0.2-0.8	A < 40 *close to stability*	operational since 1987
SPIRAL GANIL/Caen	Cyclotrons light and heavy ions 25 - 95 MeV/u, 10^{12} pps	solid targets ECR	Cyclotron	4-40	n-rich and p-rich of many elements *gaseous elements favoured*	under construction target/ECR tests first beams 1999
REX-ISOLDE **CERN**/Geneva	CERN PS-Booster 1 GeV p, 2 µA	solid/molten Surface Plasma Laser	Penning trap EBIS LINAC	**0.8-2.2** upgrade possible	n-rich and p-rich *non refractory elements*	**60 keV beams exist** post accelerator under construction first beams 1999
EXCYT Catania	Super conducting cyclotron light and heavy ions 20 - 100 MeV, 10^{13} pps	molten/solid plasma/ECR surface charge exchange	Tandem 15 MeV	(Q+1) *15 MeV Q < 11	n-rich and p-rich of elements with *negative ions*	under construction 2000?
FRM-II Munich	FRM-II reactor n-induced fission 10^{14} n/cm^{2}s	Uranium-Carbide	ECR-charge state breeder LINAC	3-6	n-rich A = 80 - 150	under construction
SPIRAL-2 GANIL/Caen	LINAC, deuterons 100 MeV/u, 10^{15} pps	liquid U-target ECR	Cyclotron	4-40	n-rich A = 80 - 150	planned
RAL Rutherford Appleton Lab.	proton synchrotron 800 MeV, 200 µA	solid	LINAC	4-15	n-rich and p-rich	target test facility

larger than fragmentation or spallation cross sections. The high in-pile neutron flux of the FRM II makes the fission reaction very attractive.

Table 3 compares the yields of some isotopes from MAFF with accelerator based RIB facilities and demonstrates that MAFF is the most powerful method. P. Armbruster and H. Nifenecker had proposed in 1990 to produce an intense beam of fission fragments from a special uranium target in a beam tube of the ILL reactor in Grenoble and guide this beam 400 m to the SARA accelerator complex of the adjacent Institut des Sciences Nucl*é*aires. This PIAFE project found large international support but was terminated in 1998 due to insufficient funding. Consequently, the interested physicists concentrate their effort now on MAFF. An international workshop took place in October 1996 at Benediktbeuern south of Munich on "Research with Fission Fragments" [2] which provided a comprehensive survey of the new physics to be done and the planned facilities.

4 The MAFF installation at the FRM II

The fission fragment source (Fig. 2) consists of a graphite cylinder (6 cm length, 1.5 cm diameter, with a central bore hole, loaded with $1-2$ g ^{235}U. It is encapsulated in a rhenium cylinder with a 2 mm diameter outlet where the fission fragments diffuse out. An electrical lens system accelerates singly charged ions to 30 keV and guides them to the mass separator and installations in the reactor hall. The source is placed in the highest neutron flux $(1.5 \cdot 10^{14}\,\text{n/cm}^2\cdot\text{s})$ of a through-going beam tube 60 cm from the reactor centre where the flux gradient is rather small.

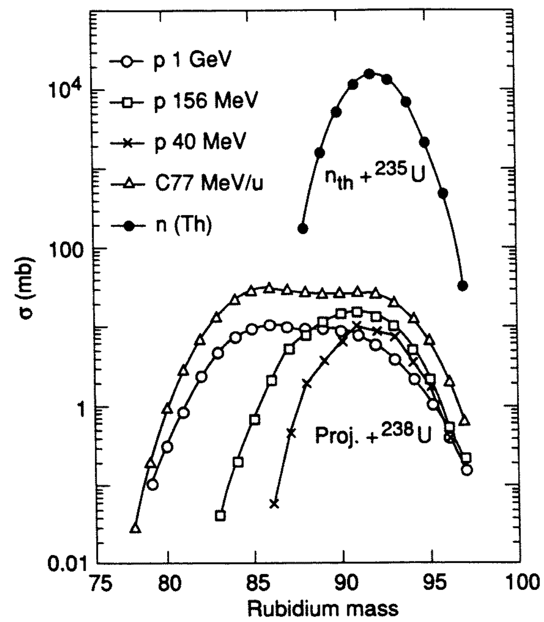

Fig. 1. Cross sections for the production of rubidium isotopes by various nuclear reactions [1].

The fragment beam is extracted on one side while the source mounting and changing and most of the conventional vacuum pumping is provided from the other side. The source temperature of 2400° C will be achieved mainly by the fission process in the source and stabilized by additional electrical heating. A He cryo-pumping system in the beam tube provides the high vacuum and helps to localize gaseous fission fragments at cryo panels.

Singly ionized ions of alkali and alkaline earth elements are produced in the ion source by surface ionization. An efficient way to ionize many elements which are only poorly thermally ionized is the ionization with resonant laser light via one ore more intermediate atomic levels [3]. Two or three laser beams have to be guided into the ion source. This technique is not only element selective already within the ion source, but it might also be used to separate in special cases isotopes and even isomers. Efficiencies of 5-15% can be achieved.

The overall layout of the facility is shown in Fig. 3 with the reactor hall and the special experimental hall for MAFF. The fission fragments enter a magnetic mass separator in the reactor hall and are transferred into the experimental hall. After charge breeding to high ionization levels of $q/A \geq 0.16$ they enter a rather compact linear accelerator consisting of RFQ and IH structures. Energies up to 6 MeV/nucleon are foreseen. The beam can be switched to several experimental areas.

5 Fusion with neutron-rich projectiles

The heaviest elements have recently been produced at GSI, Darmstadt, although the cross sections of these fusion reactions were only a few pb [4]. The systematics of the measured cross

Table II.Yields of prominent isotopes at MAFF compared to accelerator based RIB facilities.

The values given for MAFF assume a total fission rate of $1.0 \cdot 10^{14}$ s^{-1}.

The primary beams of the other facilities are as follows:

SPIRAL: $10\,\mu$A of 1.15 GeV ^{12}C
ISOLDE: $2.5\,\mu$A of 1 GeV protons (600 MeV protons for the SC)
ISL: $100\,\mu$A of 100 MeV protons

Isotope	Prod. rate (s^{-1})	$T_{1/2}$ (s)	Release (%)	Ioniz. (%)	**MAFF** (s^{-1})	SPIRAL (s^{-1})	ISOLDE (s^{-1})	ISL (s^{-1})
^{78}Zn	$2.3 \cdot 10^{9}$	1.47	36	10	$\mathbf{4 \cdot 10^{8}}$	$2 \cdot 10^{6}$	$1 \cdot 10^{6}$ (SC)	$6 \cdot 10^{6}$
^{82}Ge	$1.2 \cdot 10^{11}$	4.6	48	10	$\mathbf{6 \cdot 10^{9}}$		$2 \cdot 10^{5}$ (SC)	$1 \cdot 10^{8}$
^{91}Kr	$3.3 \cdot 10^{12}$	8.6	89	15	$\mathbf{4 \cdot 10^{11}}$	$2 \cdot 10^{9}$	$2 \cdot 10^{9}$	$4 \cdot 10^{10}$
^{94}Kr	$1.1 \cdot 10^{11}$	0.2	16	15	$\mathbf{3 \cdot 10^{9}}$	$3 \cdot 10^{7}$	$4 \cdot 10^{6}$	$6 \cdot 10^{9}$
^{97}Rb	$3.2 \cdot 10^{10}$	0.17	10	80	$\mathbf{2 \cdot 10^{9}}$	$5 \cdot 10^{8}$	$3 \cdot 10^{8}$	$7 \cdot 10^{9}$
^{132}Sn	$7.0 \cdot 10^{11}$	39.7	89	10	$\mathbf{6 \cdot 10^{10}}$	$6 \cdot 10^{6}$	$8 \cdot 10^{7}$ (SC)	$1 \cdot 10^{10}$
^{142}Xe	$5.2 \cdot 10^{11}$	1.24	7	25	$\mathbf{1 \cdot 10^{10}}$	$6 \cdot 10^{7}$	$2 \cdot 10^{8}$	$4 \cdot 10^{10}$
^{144}Xe	$9.3 \cdot 10^{9}$	1.15	7	25	$\mathbf{2 \cdot 10^{8}}$	$1 \cdot 10^{6}$	$5 \cdot 10^{6}$	$2 \cdot 10^{10}$
^{144}Cs	$4.3 \cdot 10^{11}$	1.0	47	80	$\mathbf{2 \cdot 10^{11}}$	$2 \cdot 10^{10}$	$3 \cdot 10^{10}$	$6 \cdot 10^{10}$

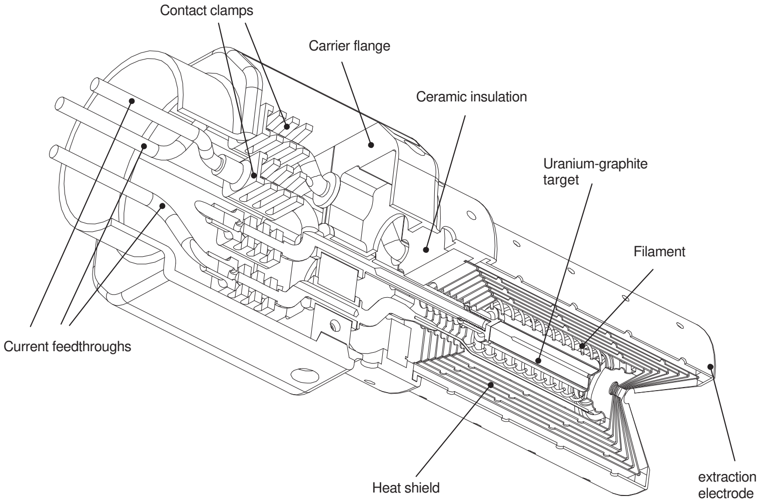

Fig. 2. Fission fragment source.

sections are shown in Fig. 4 [5]. A remarkable result is the increase of the cross section for element 110 from 3.5 pb with ^{62}Ni (^{269}110) to 15 pb with ^{64}Ni (^{271}110).

This fact indicates that the production of element 114 could be feasible with very neutron-

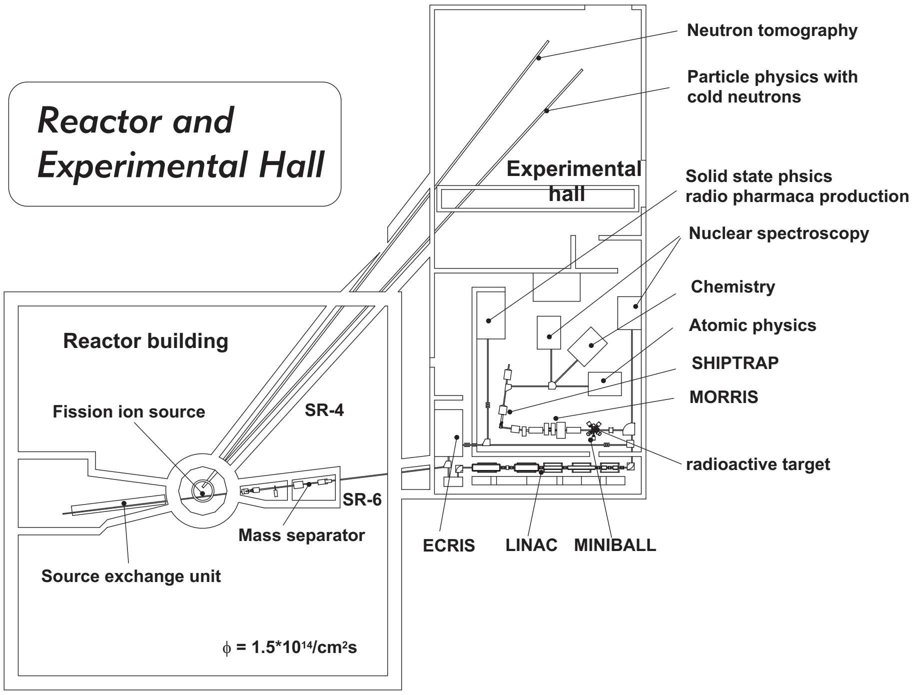

Fig. 3. Overview of the reactor building and the accelerator hall.

rich projectiles [5]. Moreover, careful predictions with shell corrections [6] show that the isotope $^{294}114$ is expected to be more stable (see Fig. 5) and this nuclide can only be produced with projectiles such as ^{144}Xe:

$$^{150}\mathrm{Nd} + ^{144}\mathrm{Xe} \rightarrow ^{294}114. \tag{1}$$

Other similar reactions to superheavy nuclei are for instance [7]:

$$^{150}\mathrm{Nd} + ^{132}\mathrm{Sn} \rightarrow ^{282}110, \tag{2}$$
$$^{208}\mathrm{Pb} + ^{82}\mathrm{Ge} \rightarrow ^{290}114, \tag{3}$$
$$^{208}\mathrm{Pb} + ^{94}\mathrm{Kr} \rightarrow ^{302}118. \tag{4}$$

Another challenging reaction which has not yet been performed until now is ”inverse fission” of uranium or fermium. The understanding of such processes would unify fission and fusion [7], e.g.

$$^{132}\mathrm{Sn} + ^{132}\mathrm{Sn} \rightarrow ^{264}\mathrm{Fm}, \tag{5}$$

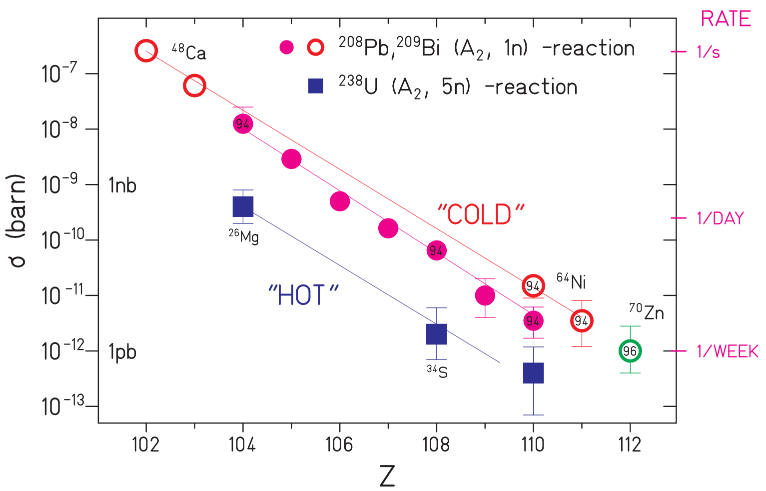

Fig. 4. Systematics of measured cross sections for the production of the heaviest nuclei.

$$^{138}\mathrm{Ba} + ^{94}\mathrm{Kr} \rightarrow ^{232}\mathrm{U}, \quad (6)$$
$$^{100}\mathrm{Mo} + ^{132}\mathrm{Sn} \rightarrow ^{232}\mathrm{U}, \quad (7)$$
$$^{87}\mathrm{Rb} + ^{145}\mathrm{Cs} \rightarrow ^{232}\mathrm{U}. \quad (8)$$

We would like to note that recent investigations showed that fusion reaction with magic target or projectile nuclei are strongly enhanced.

"A compact apparatus for mass selective resonance ionization spectroscopy of transuranium elements in a buffer gas cell" has been developed in Mainz [8]. This will allow laser spectroscopy of the heaviest elements which offers the possibility for the investigation of the unknown atomic, chemical and nuclear properties of these nuclides. The high sensitivity and short extraction time (1.5 ms) opens a large field of new research. For instance, the electron binding energies are known only up to Cf ($Z = 98$) and could be determined for superheavy elements. Single-molecule chemistry with these elements might also be possible.

6 Study of the r-process with neutron-rich nuclides

The fission process produces nuclides which are close to the neutron r-process path and approach the neutron drip-line more than those achieved by other reactions (see Fig. 6). Consequently, all informations on the structure, on masses, on cross sections, on lifetimes, on level densities etc. are very valuable for astrophysical calculations. There are indications that the shell structure known for nuclei close to the valley of stability changes considerably for very neutron-rich nuclei. This fact modifies very much the calculations of isotope abundances. The necessary information can be obtained with various methods: β- and γ-spectroscopy of fission fragments, direct reactions in inverse kinematics [9] such as d(^{132}Sn,p)^{133}Sn or p(^{144}Xe,p')^{144}Xe or Coulomb excitation [10].

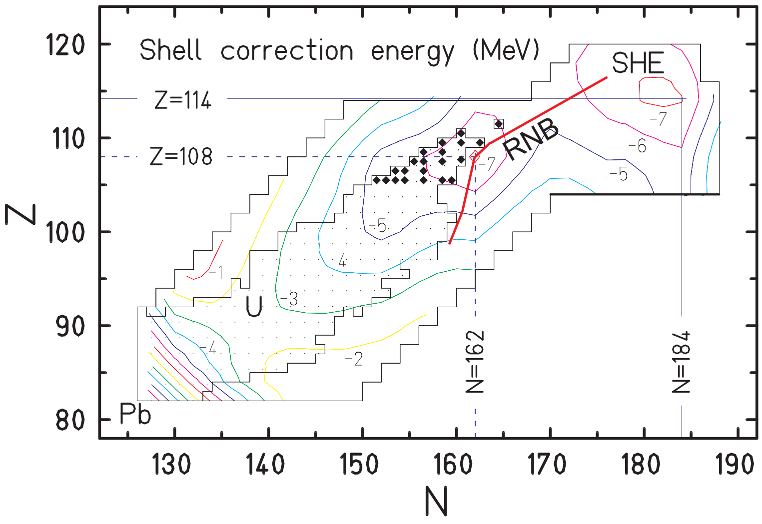

Fig. 5. Contour map of shell corrections to the binding energies. Diamonds denote the heaviest nuclides synthesized up to now.

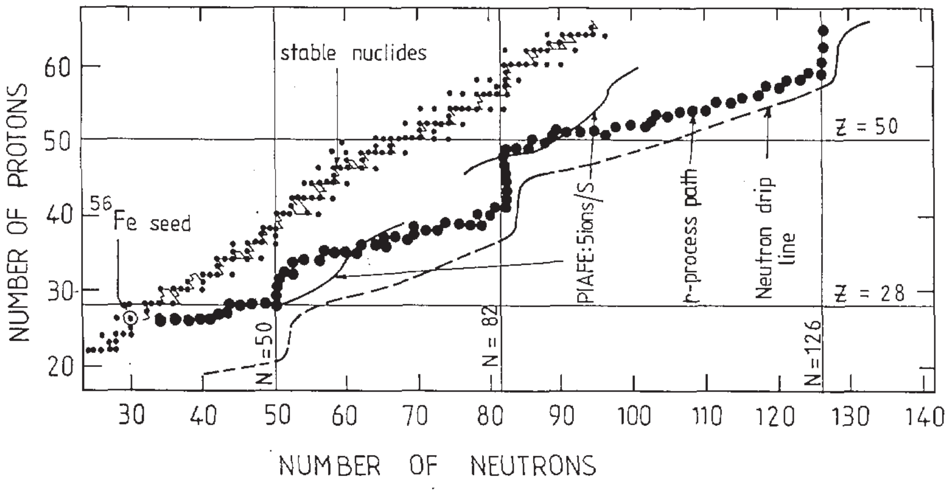

Fig. 6. Comparison of the PIAFE beam (similar to MAFF) at a rate of 5 ions/s with the neutron r-process path and the neutron drip-line.

Atomic masses and nuclear binding energies contain fundamental information on the nuclear structure. However, present mass predictions are still limited and extrapolations beyond the known region show large divergences as shown in Fig. 7 for tin nuclei [11]. Newly improved

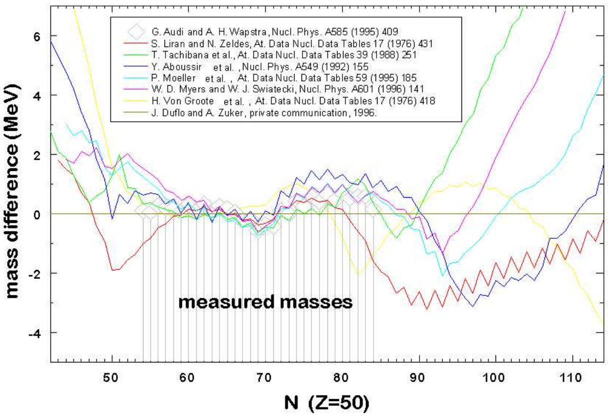

Fig. 7. Differences between various mass models for the tin $(Z = 50)$ isotopes (relative to the values of Duflo and Zuker) [11].

methods such as the Smith spectrometer MISTRAL [11] will allow precisions of $5 \cdot 10^{-7}$.

The predicted and observed neutron skin of neutron rich nuclei and their different isospin can change reaction cross sections and dynamics. Studies of the nucleon exchange in deep-inelastic collisions and of giant isovector dipole resonances are therefore of special interest [12].

7 Applications

There is a wealth of applications for solid state physics which can be done with radioactive fission fragments, such as Mössbauer spectroscopy, perturbed angular correlation, NMR and emission channeling. Other techniques comprise radio-tracers for semiconductor physics, migration and implantation studies. The last methods are also important for storage studies and management of nuclear waste. Also medical applications, e.g. radiopharmaca, could play a role.

8 Summary

The feasibility of the production, extraction, mass separation and acceleration of fission fragments from an ion source in in-pile position has been demonstrated by various careful investigations. Higher yields of neutron-rich nuclei are expected than possible with other methods. The large number of new and exciting experiments justifies the great effort for MAFF. The research with neutron-rich projectiles will substantially enlarge our knowledge of the heaviest nuclei, the fusion process, isospin effects in nuclear structure and reactions, astrophysical processes and even chemistry of heavy elements. Many application in solid state physics and medicine complement the attractivity of this new facility.

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