# PIANO

## ***P***roton-***I***nduced Reactions for ***A***strophysical ***N***ucle***O***synthesis

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All naturally occurring chemical elements – apart from the primordial H, He, and Li abundances produced in the Big Bang – were and still are synthesized in stars. A clear and quantitative picture of nucleosynthesis in the different stages of stellar evolution constitutes the basis for our understanding of the chemical history of the Universe. In this respect the heavy elements are particularly important because their production can be described by detailed astrophysical models of evolved stars and of Supernovae. Due to the yet uncertain stellar-physics ingredients in these models (e.g. the effects of mixing, rotation, and magnetic fields), the validity of these ingredients must be checked by comparing the predicted abundance distributions with the immense wealth of observational data that are presently collected with ever refined astronomical techniques. The information obtained in this way depends critically on the quality of the underlying nuclear physics data because the model predictions are otherwise obscured by nuclear uncertainties.

The proposed Helmholtz-University Young Investigators Group will be focused on establishing a program for accurate measurements of key nuclear reactions in the fields of stellar and explosive nucleosynthesis. Since the nuclear-physics part of the problem is still far from being fully understood, the program will concentrate on the necessary improvements for characterizing the production processes of the elements to the point where the respective abundance patterns can be interpreted as diagnostic tools for the deep stellar interior. The program covers pioneering work related to explosive nucleosynthesis in Supernovae and to stellar decay rates important to nucleosynthesis in Red Giant stars.

Both aspects will be investigated using proton induced reactions and will make use of the existing and future experimental facilities of the HGF centre GSI Darmstadt, which are unique for the determination of reaction rates in the yet unexplored region of unstable nuclei defining the reaction networks far from stability.

The astrophysical information accessible with the experimental results will be analyzed in collaboration with leading institutes in stellar modeling and astronomical observations.

# 1. Introduction

## 1.1. The nucleosynthesis of the elements

The chemical elements heavier than iron are essentially synthesized by three processes, the slow (s) neutron capture process during stellar He burning, the rapid (r) neutron capture process, and the photo-dissociation (p) process, the latter two being presumably related to Supernovae explosions [1]. A comprehensive and quantitative description of these processes is mandatory for the understanding of stellar evolution, of stellar explosion mechanisms, and of galactic chemical evolution. Isotopic abundance patterns of the elements between Fe and the actinides found in the solar system (Figure 1, [2]) or in meteorites in form of presolar grains [3] carry important information about the stellar production mechanisms and even about the physical conditions at the respective stellar sites. The interpretation of the observed abundance patterns by sophisticated models of stellar evolution can be used as a crucial test for the proper description of the related nucleosynthesis processes. The quality of the underlying nuclear physics input constitutes an essential prerequisite for reliable abundance predictions.

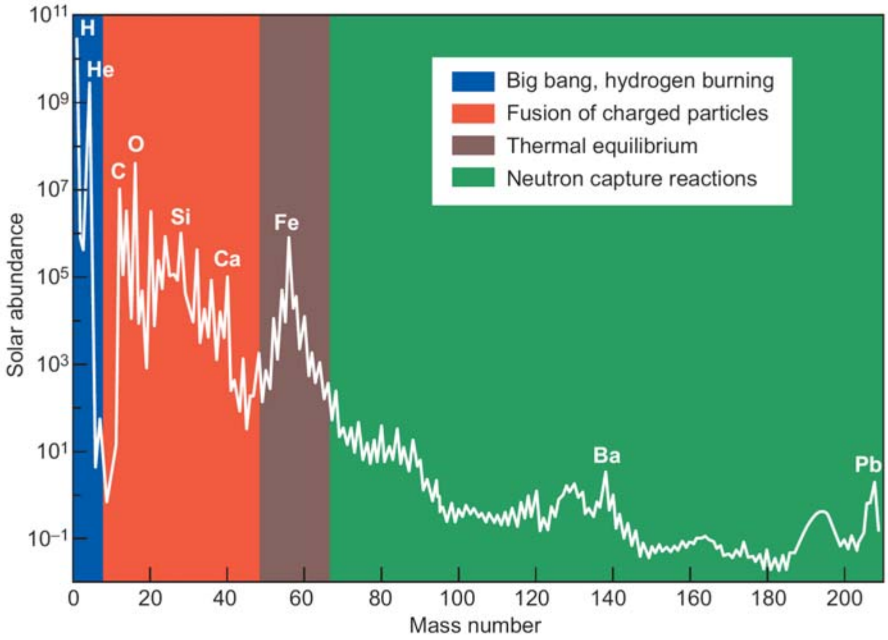

**Figure 1: Solar Abundance Distribution and Production Mechanisms**
The colored backgrounds in this graph of solar abundances vs mass number indicate the most important mechanisms that produced the elements. Blue and red indicate that most of the elements up to titanium are produced by the fusion of charged particles during the different burning stages of stellar evolution. At very high temperature and pressure conditions, as during the various stages of compression preceding supernova explosions, production and destruction reactions occur in equilibrium. The very stable iron group is mainly produced in this equilibrium context, hence its high abundance. For elements beyond iron, the enormous Coulomb barrier all but prevents the fusion of charged particles to make heavier elements. Instead, the elements heavier than iron are mainly produced during nuclear processes induced by neutron capture reactions.

## 1.2. The synthesis of the heavy elements

Most of the elements beyond iron are produced via neutron-induced reactions, mainly neutron captures. About half of them are produced by the s process, which is associated with stellar He burning scenarios [4]. Since the s process is characterized by relatively low neutron densities neutron-capture times are in general much longer than typical β-decay half-lives. Consequently, the s process works its way along the valley of beta stability, starting at the abundant seed nuclei of the iron group elements and ending at the alpha-unstable trans-bismuth isotopes (Figure 2). The abundances of most of the so produced isotopes are inversely proportional to their neutron capture cross sections.

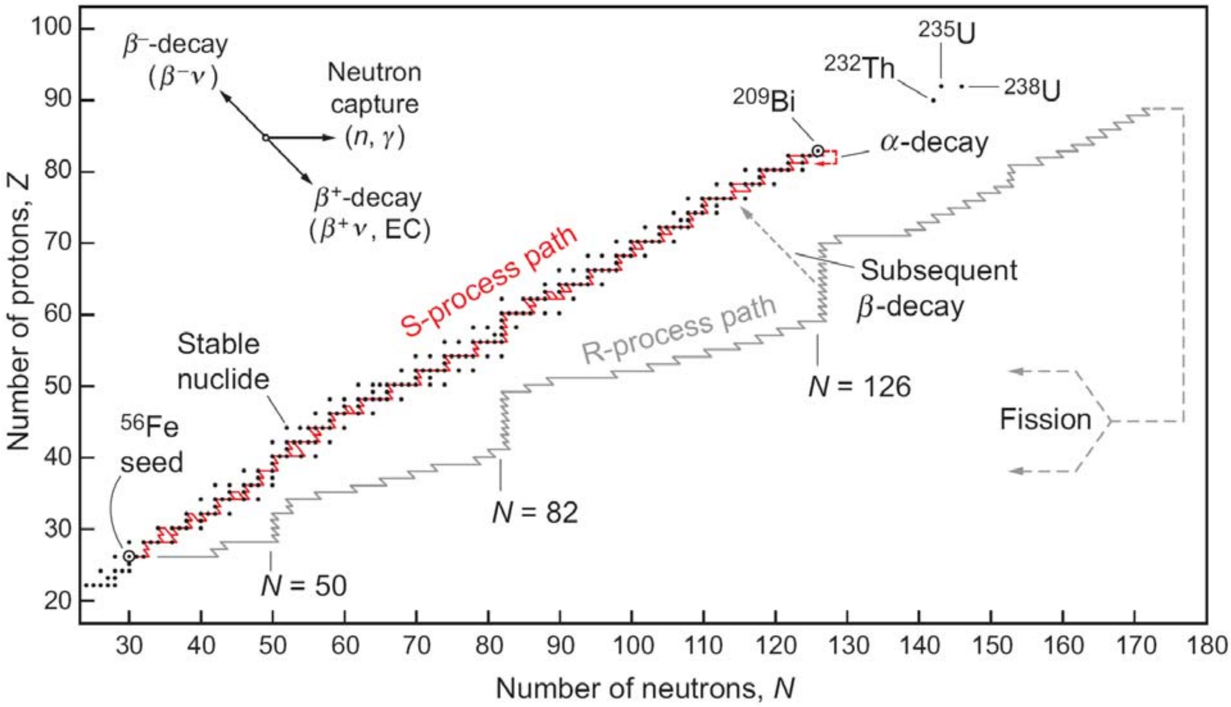

**Figure 2: s-process and r-process synthesis of the heavy elements**
The s- and r-processes start with the iron peak nuclei as seeds. The s-process path follows the nuclear valley of stability until it terminates in the lead-bismuth region. The r-process drives the nuclear matter far to the neutron-rich side of the stability line and upwards until beta-delayed fission and neutron-induced fission occur and recycle the material back to smaller mass numbers. Only a few isotopes on the proton-rich side of the valley of stability get significant contributions from other processes [5].

If the conditions in the star make the rates for neutron capture comparable to the rate of beta decay by a particular isotope, then the s-process path branches at that isotope with some fraction of that isotope transforming via neutron capture, while another fraction transforms through beta decay. The branching ratio, or relative likelihood, for the different reactions depends on the physical conditions in the interior of the star, like temperature, neutron density, and electron density. At higher neutron densities with all other conditions equal, more nuclei of a given isotope would capture a neutron before having the chance to beta-decay than at low neutron densities. Thus, the branching ratios deduced from the isotopic ratios observed in stellar material could provide the tools to effectively constrain modern models of stellar evolution during the He burning phase, where the s process occurs, provided one knows the fundamental rates for neutron capture and beta decay. Better estimates on important beta-decay rates based on experimental data will be produced within this proposal. The details on the scientific method are explained in section 2.2 and the experimental program is outlined in section 3.2.

There are about 35 proton rich nuclei between Se and Hg, which can neither be produced by the s process nor by the r process. These nuclei are attributed to the p process, which requires high temperatures of about 2-3 GK. In such an environment the reaction flow is carried by photo-dissociation processes, i.e. by the (γ,n), (γ,p), and (γ,α) channels. Since high temperatures are needed, the presently favored sites for the p process are the explosively burning O/Ne layers in Supernovae of type II, where temperatures of 2-3 $10^9$ K are maintained for about 1 s at densities of $\approx 10^6$ g cm$^{-3}$ [6]. Under these conditions, especially the heavy proton-rich nuclei are produced by a sequence of (γ,n) reactions, while (p,γ) reactions are most likely dominating for lighter nuclei. When this sequence is halted after about five steps by the increasing neutron-separation energies, the further reaction flow is determined by (γ,p) and (γ,α) reactions. As the temperature decreases after the explosion, the reaction path moves back to the region of stable nuclei. This scenario involves about 2000 nuclei connected by more than 20000 reactions and requires correspondingly large reaction networks to describe the abundance distributions following from these scenarios. Sections 2.1 and 3.1 will illustrate how proton capture measurements performed at GSI will significantly improve the current situation.

## 2. The impact of proton-induced reactions

### 2.1. Proton capture reactions

In view of the huge number of reactions, p-process studies will always have to rely on theoretical results obtained with a Hauser-Feshbach statistical model. Nevertheless, it is of utmost importance to base these calculations on a grid of experimental cross sections spread over the entire reaction network. Such data are crucial since the calculated cross sections exhibit uncertainties of several hundred percent even for stable isotopes. In case of the (n,γ) reactions, sufficient experimental data are available for constraining the model parameters close to stability so that theoretical uncertainties for stable nuclei can be reduced to a level of about 30%. These uncertainties are quickly increasing though, if one moves away from stability. Compared to this rather favorable situation, rate predictions for the (p,γ) and (α,γ) reactions are completely inadequate since only a handful of experimental data for stable isotopes has been determined in the Gamow window of the p process so far. Due to this lack of experimental information the corresponding reaction rates are typically uncertain by factors of two to three even for the stable isotopes.

Due to the uncertain nuclear physics input, p-process models for Supernovae of type II and Ia are capable of reproducing the p-abundances within a factor of about three [7]. Moreover, both scenarios do have problems in describing the light p-nuclei with A < 100 correctly. Since the p process in type II Supernovae is dominated by photodisintegrations from heavy seeds, this model does not account for the relatively large abundances of $^{92}$Mo, $^{94}$Mo, $^{96}$Ru, and $^{98}$Ru. An alternative origin of these nuclei could be imagined via (p,γ)-reactions. The high temperatures and proton densities, which are required for these reactions to proceed with significant rates, are obtained in novae or X-ray bursters [8], where hydrogen is burnt explosively under degenerate conditions, but remixing of synthesized material to the interstellar medium is still in question for these scenarios.

Proton capture rates are, therefore, highly important in this context and can be directly used in p- and rp-process networks [7, 8]. They are also important indirectly for determining (γ,p) rates via detailed balance. Charge exchange reactions like (p,n) are also needed in p-process networks.

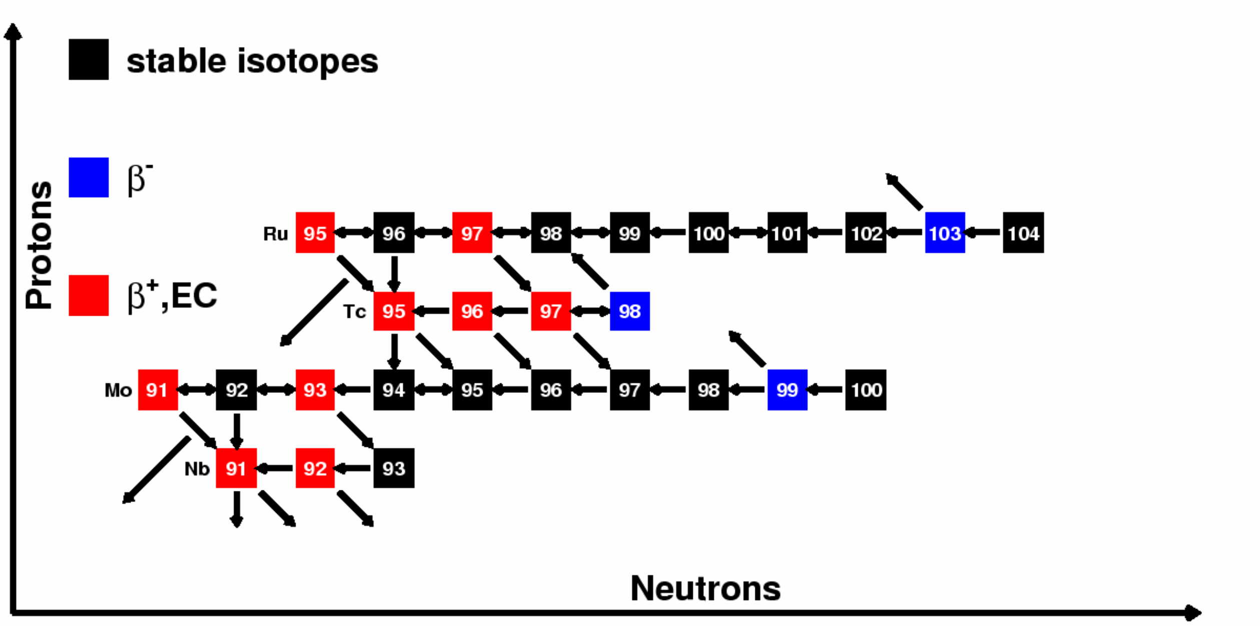

**Figure 3: Reaction network during the p-process nucleosynthesis between Nb and Ru for $T_9$ = 2.4.**
The most important reactions are shown for $T_9$ = 2.4. The p-process network is dominated by (γ,n) reactions. Other reactions are shown, if they are dominating. See [7] for more details.

Such measurements in the astrophysically interesting energy range are already very challenging on stable nuclei, especially for isotopes heavier than iron – the regime of the p- and s-process. Only a minute part of the nuclei involved in p-process networks, however, is stable. The majority of the isotopes crucial for the final p-abundance are unstable. Similarly, the important s-process isotopes, where stellar half-lives are needed, are also unstable under laboratory conditions.

The most promising approach to determine the desired reaction rates is to produce the isotopes in Radioactive Ion Beam (RIB) facilities and to investigate the reactions in inverse kinematics. Bombarding a hydrogen target with the isotopes under investigation has the main advantage that no radioactive sample has to be produced. Since the reaction paths of the p and of the s process are relatively close and even in the valley of stability, the production of the relevant isotopes is significantly facilitated and can be achieved partly in the existing RIB facility at GSI with the in-flight fragment separator (FRS) and the storage/cooler ring ESR and with much improved intensity in the upcoming FAIR facility. At that stage RIBs will be available with unsurpassed intensities [9], enabling the investigation of charged particle induced reactions despite their extremely small cross sections.

## *2.2. Charge-exchange reactions*

In addition to the uncertainties affecting the neutron capture rates, weak interaction properties also face severe theoretical problems. Although all the β-decay and EC rates of relevance in the s-process are known under terrestrial conditions, the contribution of thermally populated excited states, as well as atomic effects in the strongly ionized stellar plasma can drastically modify the laboratory values [10].

The calculated β-rates in stellar environments are subject to nuclear uncertainties, which remain difficult to estimate. The uncertainties in the stellar β-decay and EC rates strongly depend on the relevance of the experimentally unknown transitions at a given temperature and density. So far, the stellar decay rates have been estimated in a systematic study by Takahashi & Yokoi (1987) [10]. In order to illustrate the effect of the remaining nuclear uncertainties Goriely (1999) [11] has reiterated the calculations by Takahashi & Yokoi modifying the unknown transition rates by an error value of log ft = ±0.5. For a typical s-process temperature of $T_8 = 3$ and electron density of $N_e = 10^{27}$ $cm^{-3}$ the final rate was then altered by a maximum value of 3.16. This maximum variation is obtained for many rates.

Under stellar conditions, however, ground state and low-lying excited states are in thermal equilibrium. The combined $\beta^-$decay rates of these states determine, therefore, the $\beta^-$decay probability of the species. Hence, both rates need to be determined in order to understand the important branchings in the reaction path of the s-process. In case of isomeric excited states with sufficiently long half-lives one may attempt to determine their weak-decay rate experimentally.

Charge exchange reactions like (p, n) can be indirectly used to determine beta-decay rates under stellar conditions, which is most valuable for modern s-process networks [12, 13]. Several characteristics of the (p, n) reaction are particularly suited for studies relating weak-decay matrix elements to nucleon-nucleus scattering amplitudes. The natural isospin selectivity of the reaction makes it an ideal probe of isovector excitations. The reaction is spin sensitive and spin selective over a wide range of bombarding energies. Finally, the easy experimental accessibility of 0° scattering makes it possible to observe transitions with quite small momentum transfer. Standard reaction theory and experimental observations support the proportionality between (p, n) cross sections and beta-decay transition strengths [14]. This correspondence derives from the similarity of the operators involved in each type of reaction. The desired energy range is 100 – 500 MeV/nucleon [14, 15], which is easily achievable at GSI.

Taddeucci et al. concluded that the proportionality is well established for transitions between the ground state of the mother nucleus and different states in the daughter nucleus. We would like to test this proportionality for different states in the mother nucleus, namely ground state and isomers, and different states in the daughter nucleus. This proportionality has not been investigated, but would be extremely valuable for astrophysical applications. The half-life of the ground state of the isotopes of interest is typically known and isomers have very often half-lives, which can be investigated via (p,n) reactions in inverse kinematics. If we can prove that the ratio of the (p,n) cross section under 0° is the same the respective beta-decay times, this method can be applied to improve our knowledge about stellar decay times of a huge number of branchpoint isotopes. Within this proposal we want to proof the principle of the described approach and apply it to one of the most interesting branchpoints.

We will approach two different s-process branching regions using this method. Figure 4 shows the s-process reaction network between Te and Cs. The production ratio of the s-only isotopes $^{128,130}$Xe is mainly affected the branchings at $^{127}$Te and $^{128}$I, which are still expected to be comparably weak. Therefore only a small part of the total s-process flow is bypassing $^{128}$Xe. Therefore, the product of the stellar (n,$\gamma$) cross section and the respective s-abundance, which characterizes the reaction flow, is slightly smaller for $^{128}$Xe than for $^{130}$Xe. Since their solar isotopic abundance ratio [16] as well as the stellar cross section ratio are accurately known, the strength of the branching can be determined.
The branching at $^{127}$Te is weak, because the population of ground state and isomer is quickly thermalized in the hot stellar photon bath, leading to a strong dominance of the $\beta$-decay channel of the fast ground state decay. The neutron capture cross section of $^{127}$Te is only theoretically known and may be uncertain by a factor of 2.
The second branching at $^{128}$I with a half-life of only 25 minutes is exceptional, since it originates from the competition between the short-lived $\beta^-$ and electron capture (EC) decays only. In contrast to other branchings, the influence of the stellar neutron flux is negligible in this case, thus eliminating an important uncertainty in the s-process calculation of the isotopic Xe abundances. This provides a unique possibility to better constrain temperature and electron density of the stellar plasma through their effect on the EC rate of $^{128}$I [10].
The branchings at $^{127,129}$Te are very interesting to establish the method of using (p, n) reactions for determining stellar decay rates. See [17] for a detailed discussion in the Te-I-Xe region.

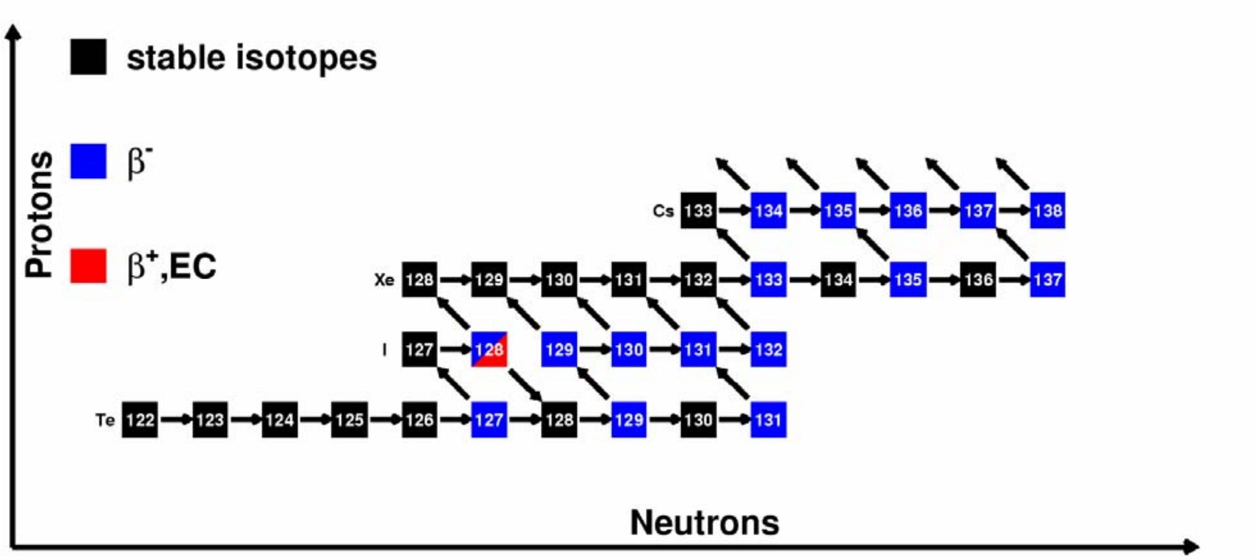

**Figure 4: Reaction network during s-process nucleosynthesis between Te and Cs**
The most important reactions are shown for the hot $^{22}$Ne(α,n) phase of the main component of the s-process. The production ratio of the s-only isotopes $^{128,130}$Xe is mainly affected by the temperature and neutron density dependent branchings at $^{127}$Te and $^{128}$I. See [17] for more details.

Figure 5 shows the s-process reaction network between Sm and Gd. The nucleosynthesis in the Sm-Eu-Gd region is uniquely suited for a detailed analysis of the stellar model parameters. The s-process mass flow at $^{150}$Sm and $^{157}$Gd is unbranched. The Sm-Eu-Gd region is therefore contained and only the reaction rates within this region are important for a branching analysis. With the exception of $^{152,154}$Eu and $^{153}$Gd, neutron capture rates for important branching points in this region have been experimentally determined. $^{151}$Sm(n, γ) has successfully been measured in the stellar neutron energy region [18, 19] and experimental efforts to determine the neutron capture rates of $^{152,154}$Eu are currently underway at the DANCE facility at Los Alamos National Laboratory [20]. It is these branching points that determine the isotopic abundance ratios of the stable Sm, Eu and Gd isotopes in stars. There now exist experimental facilities capable of measuring neutron capture cross sections on these unstable nuclei so it is possible for the first time to complete the nuclear data set for this region. Finally, it is possible to analyze these ratios not only in presolar grains, but the $^{151}$Eu/$^{153}$Eu ratio has also been directly observed in stars [21]. Once the remaining neutron capture rates can be based on experimental data, the stellar β-decay rates of $^{151}$Sm and $^{154}$Eu are the most important unknown pieces in the puzzle of the production of the stable Eu and Gd isotopes.

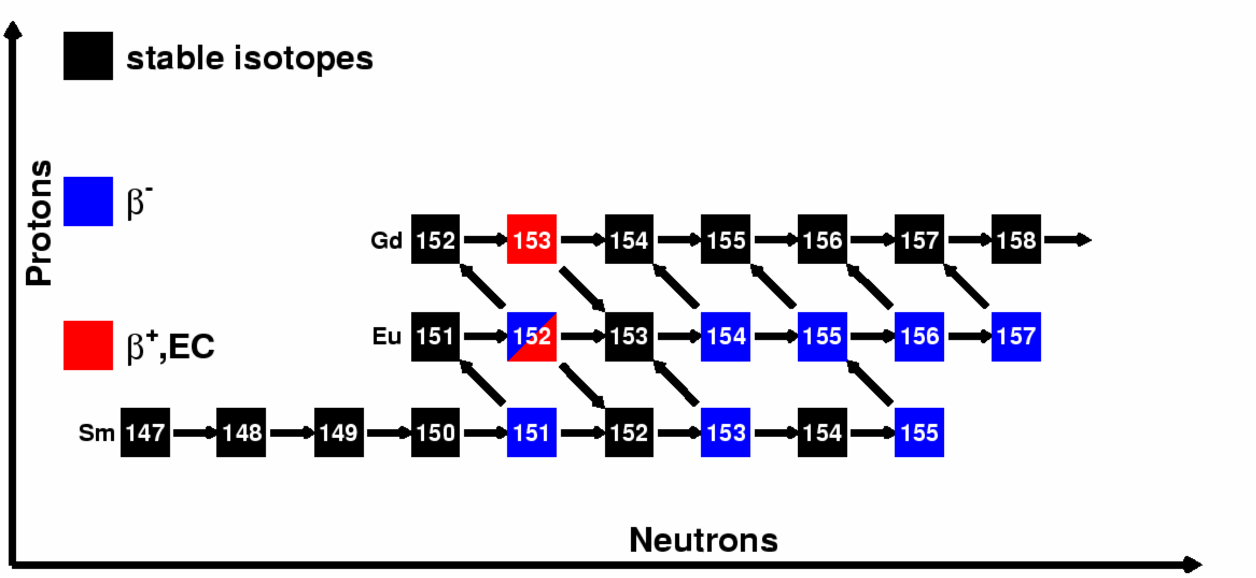

**Figure 5: Reaction network during s-process nucleosynthesis between Sm and Gd**
The most important reactions are shown for the hot $^{22}$Ne(α,n) phase of the main component of the s-process. The production ratio of the s-only isotopes $^{152,154}$Gd is mostly affected by the temperature and neutron density dependent branchings at $^{151}$Sm and $^{154}$Eu. See [18] for more details.

# 3. Experimental program

## 3.1. Proton capture reactions

Within this proposal we intend to establish a (p,γ) program starting at the present GSI facility with stable/long-lived beams and to develop the capability for experiments with short-lived isotopes. We will perform benchmark experiments for high-Z isotopes to show the potential of the described approach and prepare the experimental capabilities for FAIR. With FAIR such measurements will be possible with radioactive species. Additionally we will investigate (γ,p) reactions via Coulomb breakup to benchmark the detailed balance approach used for the p-process reaction networks.

Traditionally stable targets would be irradiated with protons of variable energies. Rare or short-lived radioactive isotopes can typically not be accumulated in amounts necessary to produce a target. Experiments in inverse kinematics are therefore necessary. Apart from the prospects offered by the FAIR facility, existing ESR is ideally suited for inclusive (p,γ) experiments: Stored and cooled bare ions may pick-up a proton whenever they cross (with a frequency of about one MHz) the internal $H_2$ gas jet. This pick-up leads for medium-heavy ions ($A \approx 100$) to a change in the mass-over-charge ratio A/q of less than two percent. Hence, the reaction products still remain in the acceptance of the ESR (except for the lightest ions with $A < 25$), but circulate on new orbits at the inner side of the aperture, and at a significantly altered revolution frequency. They can easily be detected with an efficiency of ~100%, and unambiguously identified either by their Schottky spectrum (Fig. 8) or, alternatively, by a position- and Z-sensitive detector moved into the aperture at the inner side of the ring [22]. It should be emphasized that for bare ions an almost background-free spectrum can be expected in this detector, since there are no disturbing atomic processes, like electron stripping, that might lead to a comparable shift of the orbit within the ring.
The unrivalled combination of sharp ion energy, ultra-thin (as compared to solid-state targets) internal gas target, and simple energy variation by means of the electron cooler, enables precise, energy-differential scans of the (p,γ) cross section and possibly the detection of narrow resonances. The Gamow window for proton reactions on a nucleus with Z=50, A=120, $T_9=3$ (typical p-process temperature) is at $E_{\mathrm{Gamow}}=3.5$ MeV and 6.8 MeV for proton and alpha-induced reactions, respectively. Measurements with 5-10 MeV/nucleon, which have been proven to be possible at the ESR, are not too far away from this window of most probable interaction energies for protons and are actually covering the Gamow window for alpha-induced reactions.

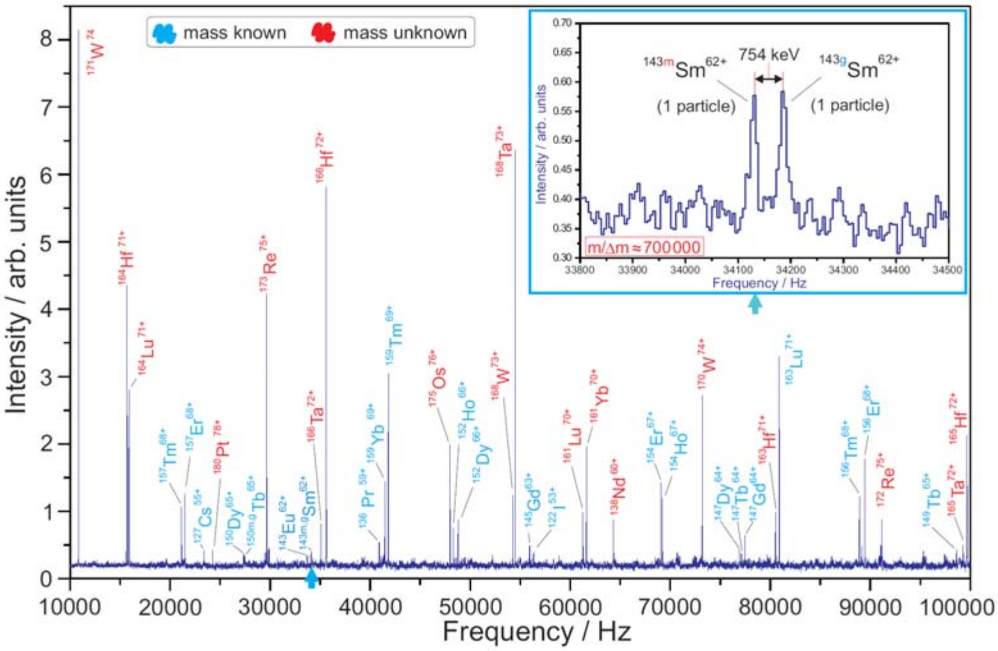

**Figure 6: Schottky spectrum with inset illustrating the separation of ground and isomeric state of $^{143}$Sm$^{62+}$.** Typical Schottky frequency spectrum of cooled bismuth fragments from the FRS injected into the ESR at 370 MeV/u. The inset shows a Schottky frequency spectrum obtained from only two bare $^{143}$Sm ions, one in the ground state, $^{143g}$Sm, the other one in the isomeric state, $^{143m}$Sm. The measured excitation energy is (750 ± 50) keV, to be compared to the literature value of 754 keV. The spectrum illustrates the unique resolving power that allows distinguishing even isomers with small mass differences. Note that the spectrum was obtained from one particle of each isotope only [9].

By combining a jet density of typically $4{\cdot}10^{12}$ $H_2$ atoms/cm$^2$ and a beam intensity of $5{\cdot}10^7$ cooled, decelerated ions with 10 MeV/u at the start of the measurement, we expect a mean luminosity $L{\approx}4{\cdot}10^{25}$ cm$^{-2}$s$^{-1}$ within the measuring phase of each cycle. Assuming a typical (p,γ) cross section of 10 mb in the Gamow window and a measuring time of 40 s per cycle, this translates into an expected rate of about 16 events per cycle, or about 300 events/h for a total cycle length of three minutes. At 5 MeV/u, the lower revolution frequency of 0.27 MHz, the reduced ion intensity, and the shorter measuring time per cycle results in an expected rate of about 30 events/h. These estimates, which are based on the performance of the available hydrogen jet target and the present ESR, confirm that the proposed measurements are feasible in sufficiently fine energy steps and with good statistics.

With the future improvement of the He gas jet the experimental technique will also be used in a similar fashion for measurements of (α,γ) cross sections.

A major advantage of (p,γ) and (α,γ) cross section measurements in the ESR is the universality of the technique. Most of the few existing data in the Gamow window of the p process have been obtained in activation measurements. This method is straightforward and can be pursued even with limited resources. However, it is restricted to few reactions on stable isotopes, because it requires radioactive product nuclei within a certain range of suitable half-lives and with well known γ-decay properties.

No such limits exist for the proposed ESR experiments since the reaction products are identified by their mass-over-charge ratios, regardless whether they are stable or radioactive. The only important condition is the required beam intensity in the ring, which can presently be met only for stable isotopes. Therefore, the proposed program will start by establishing a representative data set along the valley of stability that can serve as a bench mark test for the statistical model. With this information, the theoretical extrapolation into the proton-rich region could already be greatly improved.

In a second step, this approach can be complemented by direct experimental studies of reactions on unstable isotopes as soon as FAIR provides sufficiently high RIB intensities. By then, the technique will be well established and the cooling and deceleration times in the ESR

will be short enough that a grid of experimental reaction rates across the entire p-process network can be established with the ultimate goal to remove the nuclear physics uncertainties from the problem of characterizing the astrophysical site of the p process.
The experimental program in the ESR will naturally concentrate on measurements with stable beams until the higher FAIR intensities become available. The following measurements will be performed:

- The proof-of-principle experiment with the hydrogen jet target will investigate the $^{112}$Sn(p,γ)$^{113}$Sb reaction. Comparison with existing data from an activation measurement [23] will be important to illustrate the potential of the ESR technique.
- After the improvement of the He jet target, a proof-of-principle experiment will also be performed on $^{112}$Sn, again for the possibility to compare the results with the (α,γ) cross section obtained by activation studies [23-25]
- The first part of the extended experimental program will focus on measurements related to the anomalously high p-abundances of $^{92,94}$Mo and of $^{96,98}$Ru. In particular, it is planned to study the $^{93}$Nb(p,γ)$^{94}$Mo, and the $^{92}$Mo(α,γ)$^{96}$Ru cross sections, which are both not accessible by activation.

Important information on related photon-induced reactions will be obtained with the SIS/FRS/LAND setup by measuring Coulomb dissociation reactions. The existing setup is presently used for (γ,n) break-up reactions. In order to perform (γ,p) and (γ,α) measurements large-area drift chambers for light-charged-particle detection have to be implemented. As a consistency check for the results obtained in the capture measurements it is planned to use the SIS/FRS/LAND system for determining the cross sections of

- the $^{94}$Mo(γ, p)$^{93}$Nb reaction and of
- the $^{96}$Ru(γ, α)$^{92}$Mo reaction.

Both reactions are well suited as benchmark experiments since all involved nuclei are stable, hence reliable beam conditions during the experiments are achievable.

## 3.2. (p,n) reactions

Ideally, charge-exchange reactions on isomeric states are performed on secondary beams where all or most of the projectiles are in their isomeric state. Since this may be difficult to achieve, one can perform the (p,n) reaction on a mixture of ground- and isomeric state and subtract the resulting neutron spectra. To this end, the production ratio of isomer to ground state can be tuned within certain ranges by changing the bombarding energy, or, in the case of beams stored in the ESR, measuring at different time intervals to allow the shorter-lived component to decay. In the latter case, Schottky spectroscopy allows to determine quantitatively the relative populations provided the levels are separated by more than about 100 keV.
The best device to perform (p,n) reactions on relatively long-lived isomeric states is the internal target at a storage ring. The EXL equipment presently designed for the NESR at FAIR will serve this purpose. To develop the technique, the present ESR can be used to study benchmark cases; the construction of a neutron detector is under way.
If the isomeric half-life is to short for ESR measurements, the (p,n) reaction can also be measured in complete kinematics at the “external target” of the present ALADIN/LAND facility at GSI or the future R3B facility at FAIR. The external target can be a stable organic compound or a liquid hydrogen target. The program will start with benchmark investigations of the unstable Te isotopes. These isotopes are ideally suited, since they have ground and isomer decays with known half-lives and are close to the valley of stability, which allows

sufficiently intense beams. The experimental program will concentrate on benchmark measurements in the first stage. The second stage will be marked by measurements with high astrophysical impact. The following measurements will be performed:

- The proof-of-principle experiment will be the investigation the $^{129m}Te(p,n)^{129}I$ reaction. The first excited state of $^{129}Te$ at 105 keV is a $11/2^-$ isomer with a known half-life of 33.6 d (35% $\beta^-$, 65% IT). The ground state with $I^\pi=3/2^+$ decays exclusively via $\beta^-$ decay with a half-life of 69 min. Producing $^{129m}Te$ by fragmenting a $^{134}Xe$ beam, a luminosity of about $10^{27}$ $cm^{-2}$ $s^{-1}$ can be assumed.
- Another benchmark experiment will be $^{127}Te(p,n)^{127}I$. $^{127}Te$ has also a low-lying isomer at 88keV with a half-life of 109 d. The $\beta^-$decay rates of ground state and isomer are known.
- After the experiments with the tellurium isotopes have proven the potential of the method, we will investigate the Sm-Eu-Gd region. This branching region is unique in that respect that all neutron capture rates can be determined experimentally with current facilities. The most important branch point in the Sm-Eu-Gd region is $^{154}Eu$. The uncertainty of the stellar $\beta^-$decay rate is a factor of 3 [11], while an experimental program to determine the stellar neutron capture rate is currently underway and an accuracy of approximately 10% is anticipated. $^{154}Eu$ has a long-lived isomer at 160 keV, which lands itself to the method described. In addition, the first excited state of $^{154}Eu$ at 68 keV above the ground state with a half-life of 2.2 μs could be investigated at the external target at LAND/ALADIN. If some of the most important $\beta^-$decay rates in this region can be determined experimentally, a new era of stellar modeling can be opened.

## 4. Summary

It is proposed to use the existing facilities ESR, LAND, and the presently developed EXL for important proton-induced reaction measurements on stable and unstable isotopes related to the p- and the s-process. These experiments contribute to our understanding of the origin of the chemical elements. In parallel, new experimental techniques will be developed to be used at FAIR in an extensive experimental program of measurements on unstable nuclei, which would open a completely unexplored field of Nuclear Astrophysics.

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## 6. Relevance to the Helmholtz Programme

The Helmholtz programme "Structure of Matter" (sub-category "Physics of Hadrons and Nuclei" ) covers "Nuclear Astrophysics" as one of its essential research topics with GSI as a participating Helmholtz institution. Following a recommendation of the HGF Senat, GSI has recently made a considerable effort to strengthen this field by providing additional positions for research related to nuclear astrophysics, both on the experimental and theoretical side.

Experimental studies at GSI were carried on and the experimental methods were further improved, e.g. by increasing the sensitivity of storage ring techniques such as the non-destructive Schottky spectroscopy. Systematic mass measurements and β-decay studies were performed for nuclei relevant in nucleosynthesis processes. Likewise, the experimental devices used in (direct and indirect) capture studies were and are improved.

The Johann Wolfgang Goethe-Universität Frankfurt, together with GSI and other institutions, joined the HGF 'Virtual Institute' VISTARS with common interests in the field of nuclear astrophysics. The University Frankfurt, moreover, established a special program (Universitärer Schwerpunkt – "Schwerionen-Physik") in which nuclear astrophysics plays an essential role. The Institute für Kernphysik at the University Frankfurt is presently planning to install a new accelerator dedicated to produce a neutron beam of high flux, which serves in measuring neutron-capture cross sections for relevant stellar reactions. This would perfectly complement the program of proton-capture studies as proposed here.

It is envisaged to extend the close collaboration between scientists from both institutions beneficial for both sides not only with regard to ongoing activities but also in view of the future facility FAIR. The FAIR facility will provide unprecedented experimental opportunities for experiments in nuclear astrophysics and, as already outlined above, some of the experiments proposed here serve as a demonstration of feasibility for FAIR experiments with nuclei far away from stability, which are presently out of reach. At FAIR, for instance, specific long-lived isotopes can be produced which may be transported to Frankfurt and be exposed to the high-flux neutron beam for neutron capture studies. A collaboration working on this subject was already formed including groups from GSI and the University Frankfurt.

We are convinced that a Helmholtz-Hochschul-Nachwuchsgruppe would considerably contribute to a fruitful collaboration of the two institutes resulting in a very well focused nuclear astrophysics program.In category "Structure of Matter", sub-category "Physics of Hadrons and Nuclei", part "Nuclear Astrophysics" (needs to be expanded by GSI)

## *7. Workpackages and Milestones*

### WP1: Measurements of (p,γ) reactions in the existing ESR at GSI.

Exploratory (p,γ) and (α,γ) measurements will be performed on stable isotopes in the ESR with the aim to establish this technique on firm grounds. The technique can then be used for measurements on unstable isotopes after the transition to FAIR, when the higher intensities will ultimately allow us to directly access the p-process network on the proton-rich side of the stability valley.

The required hydrogen densities can already be reached with the existing jet target. For the (α,γ) measurements the operation with helium has to be improved.

**Milestones:**

- Proof of principle experiment $^{112}$Sn(p,γ) with stable $^{112}$Sn beam and hydrogen jet target
- Improvement of helium jet target
- Proof of principle experiment $^{112}$Sn(α,γ) with stable $^{112}$Sn beam and helium jet target
- Measurement of the (p,γ) cross section of $^{93}$Nb
- Measurement of the (α,γ) cross section of $^{92}$Mo

### WP2: Coulomb dissociation measurements at the existing SIS/FRS/LAND facility at GSI.

It is proposed to measure (γ,n) cross sections of unstable nuclei and gases, which are relevant for the p process and are not accessible by other techniques, e.g by photo-activation with real photons. The experimental setup is already available and the necessary beam intensities for unstable isotopes can be reached with the existing FRS. In order to perform (γ,p) and (γ,α) measurements large-area drift chambers for light-charged-particle detection have to be implemented.

**Milestones:**

- Implementation of telescope for light ions
- Measurement of the (γ,p) cross sections of $^{94}$Mo
- Measurement of the (γ,α) cross sections of $^{96}$Ru

### WP3: Measurements of (p,n) reactions utilizing the LAND facility at GSI.

Exploratory (p,n) on stable isotopes at LAND with the aim to establish this technique on firm grounds. The ultimate goal is to determine the beta decay rate of the isomeric state of $^{154}$Eu with 2.2 μs half-life.

**Milestones:**

- Optimization of the LAND setup including the addition of an auxiliary neutron detector device for the slow neutrons
- Proof of principle experiments: $^{129}$Te(p,n)$^{129}$I and $^{127}$Te(p,n)$^{127}$I at the external hydrogen target
- Measurement of the (p,n) cross section of $^{154}$Eu$^{m}$ (isomeric state)

## *8. Time schedule*

| **WP1 (p,g)** | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 |
|---|---|---|---|---|---|
| 112Sn(p,g) | ■ | ■ |  |  |  |
| He Jet Improvement | ■ | ■ | ■ |  |  |
| 112Sn(a,g) |  |  | ■ | ■ | ■ |
| 93Nb(p,g) |  | ■ | ■ | ■ |  |
| 92Mo(a,g) |  |  | ■ | ■ | ■ |

| **WP2 (g,p)** | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 |
|---|---|---|---|---|---|
| Light Ion Telescope |  | ■ |  |  |  |
| 94Mo(g,p) |  |  | ■ | ■ |  |
| 96Ru(g,a) |  |  |  | ■ | ■ |

| **WP3 (p,n)** | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 |
|---|---|---|---|---|---|
| LAND optimization | ■ | ■ |  |  |  |
| 129Te(p,n) |  | ■ | ■ |  |  |
| 127Te(p,n) |  |  | ■ | ■ |  |
| 154Eu(p,n) isomer |  |  |  | ■ | ■ |

## *9. Publications*

## Refereed Journals

1. “Neutron capture cross section of $^{232}$Th measured at the n_TOF facility at CERN in the unresolved resonance region up to 1 MeV”, G. Aerts et al. (n_TOF collaboration), ***Phys Rev C*** **70** (2006) 034604
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3. „Independent evidence for M1 scissors resonances built on the levels in the quasicontinuum of $^{163}$Dy “M. Krticka, F. Becvár, M. Heil, F. Käppeler, R. Reifarth, I. Tomandl, F. Voss, K. Wisshak, ***AIP conf. proc.*** **819** (2006) 345
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8. „Measurement of $^{139}$La(n,γ) “
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3. „GEANT Simulations of the Karlsruhe 4π $BaF_2$ Detector “ R. Reifarth, R. Plag, M. Heil, F. Käppeler, F. Voss, K. Wisshak, ***Los Alamos National Laboratory Report*** **LA-UR-04-7442** (2004)

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16. „Preliminary background analyses of the first $C_6D_6$ data “ M. Heil, F. Käppeler, R. Plag, R. Reifarth, n-TOF-Collaboration, ***CERN Technical Report*** **n_TOF Note 210504** (2001)
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18. „Sternmodelle im Test: Die Phase der Roten Riesen“ C. Arlandini, M. Heil, F. Käppeler, R. Reifarth, F. Voss, K. Wisshak, ***Nachrichten – Forschungszentrum Karlsruhe*** **33** (2001) 177.
19. „The stellar (n,$\gamma$) cross section of $^{180m}$Ta, the rarest stable isotope in nature“ K. Wisshak, F. Voß, C. Arlandini, F. Käppeler, M. Heil, R. Reifarth, M. Krtička, F. Bečvář, ***Wissenschaftliche Berichte*** **FZKA-6362** (2000)

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## Editorial work

Proceedings of the “1. Workshop on: New opportunities and challenges with DANCE”, February 2-4, 2004, Santa Fe, NM, Editors: R. Reifarth, T.A. Bredeweg, J.L. Ullmann, D.J. Vieira, **http://wnr.lanl.gov/dance/workshop_2004/proceedings.pdf**

## Invited Contributions to Conferences

1. APS Meeting, Tampa, FL, USA, April 2005
2. CAARI 2004 18th International Conference on the Application of Accelerators in Research and Industry, Ft. Worth, TX, USA, October 2004
3. Workshop on “Experimental Nuclear Astrophysics - Challenges and Opportunities”, September 7-9, 2004 at Forschungszentrum Karlsruhe, Institut für Kernphysik, Germany
4. Symposium on „40 Years of Neutron Research at the Karlsruhe Van de Graaff”, September 10, 2004 at Forschungszentrum Karlsruhe, Institut für Kernphysik, Germany

## *10. Curriculum vitae*

# Dr. rer. nat. René Reifarth

Limited Term Staff Member
LANSCE-NS MS H855, Los Alamos National Laboratory, Los Alamos, NM, 87545, USA
Email: reifarth@lanl.gov, Tel.: (505) 667-1053, Fax.: (505) 665-3705
and
Research Assistant Professor at
Department of Physics, Colorado School of Mines, Golden, CO 80401

## Higher education and professional experience:

**Since December 2004**

Research Assistant Professor at the Department of Physics, Colorado School of Mine; supervision of postdoc and graduate students and research within the DANCE collaboration

**Since July 2003**

Limited Term Staff Member at the Los Alamos Neutron Science Center (LANSCE-3), Los Alamos National Laboratory; supervision of postdoc and graduate students within the DANCE collaboration

Research:

- first production runs with DANCE (highlights: $^{237}$Np(n,$\gamma$), $^{151}$Sm(n,$\gamma$) )
- participation at experiments in other international laboratories (highlights: $^{14}$C(n,$\gamma$), $^{62}$Ni(n,$\gamma$))
- member of the n_TOF collaboration at CERN (comissioning of the Total Absorption Calorimeter, $^{151}$Sm(n,$\gamma$))
- RIA R&D (Neutron facility at RIA, (n,$\gamma$) experiments at RIA)

**May 2002 – June 2004**

Directors Funded Postdoctoral Fellow at LANSCE-3, LANL

Research:

- Development and comissioning of DANCE, a 4$\pi$ $BaF_2$ array with 160 crystals at the neutron spallation source in the Lujan Center at LANL)
- (n,$\gamma$) activation experiments on $^{139}$La, $^{14}$C at FZK, Karlsruhe, Germany

**August 1996 – May 2002**

Graduate Student (Diplomand, Doktorand) at the Research Center Karlsruhe, Gemany (FZK)

Research:

- (n,$\gamma$) experiment on Xe with the Karlsruhe 4$\pi$ $BaF_2$ ball at FZK, Karlsruhe, Germany.
- (n,$\gamma$) activation experiments on Te, $^{147}$Pm at FZK, Karlsruhe, Germany and Research Reactor Heidelberg, Germany.
- $^{13}$C($\alpha$,$\alpha$) experiment at University of Notre Dame, IN.
- Experiments during commissioning phase and first runs at n-TOF at CERN, Geneve, CH.
- (n,$\gamma$) activation experiments on $^{34}$S at FZK, Karlsruhe, Germany and Research Reactor Mainz and Garching, Germany.

**October 1992 – August 1996**
Undergraduate Student at the Technical University of Karlsruhe, Germany, Teaching Assistant

## Research Grants:

**2002-2003** LDRD funding (Neutron Capture for Understanding Astrophysical Nucleosynthesis)
$ 30’000 travel, research
**2003-2004** LDRD funding (Probing nucleosynthesis with DANCE)
$140’000 research
**2005-2007** LDRD funding (The s-process in the Sm-Eu-Gd region – a probe for stellar mixing)
$1’000’000 research

## Awards:

**2006** LANLDistinguished Performance Award
**2005** Distinguished Performance Award of the LANL Weapons Program
**2002** Directors Funding for Postdoctoral Fellowship

## Other services or memberships:

Member of the German Physical Society (DPG) and the American Physical Society (APS).

## Conference and committee duties:

- Orgnizer, Editor, Chair: “The physics of the s-process”, Aspen, CO, USA, Juni 2005
- Session chair: International Conference on Nuclear Data for Science and Technology (ND2004), Santa Fe, NM, USA, September/October 2004
- Organizer, Editor, Chair: “1. Workshop on: New opportunities and challenges with DANCE”, February 2-4, 2004, Santa Fe, NM

## Referee Duties:

Nuclear Instruments and Methods A

## 11. Financial Plan

The main costs of the proposed project are:

- 1 group leader position: ~76.000 €/a
- 1 post-doc position: ~53.000 €/a (University contribution)
- 3 PhD positions: ~34.000 €/a each for 3 years (University contribution)
- Investment at GSI: 108.000 €
- Consumables: 109.000 €

**Table 1: Financial plan for the budget of the Helmholtz Young Investigators Group (A)**

| Purpose | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Total |
|---|---|---|---|---|---|---|
| **Helmholtz-Center** | **154.00** | **120.00** | **86.00** | **120.00** | **154.00** | **634.00** |
| Personell | 76.00 | 76.00 | 76.00 | 76.00 | 76.00 | 380.00 |
| Group Leader | 76.00 | 76.00 | 76.00 | 76.00 | 76.00 | 380.00 |
| Postdoc | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| PhD | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Investments | 53.00 | 20.00 | 0.00 | 19.00 | 36.00 | 128.00 |
| Consumables | 25.00 | 24.00 | 10.00 | 25.00 | 42.00 | 126.00 |
| | | | | | | |
| **University** | **96.00** | **130.00** | **164.00** | **130.00** | **96.00** | **616.00** |
| Personell | 96.00 | 130.00 | 164.00 | 130.00 | 96.00 | 616.00 |
| Group Leader | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Postdoc | 62.00 | 62.00 | 62.00 | 62.00 | 62.00 | 310.00 |
| PhD | 34.00 | 68.00 | 102.00 | 68.00 | 34.00 | 306.00 |
| Investments | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Consumables | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | | | | | |
| **Helmholtz+University** | **250.00** | **250.00** | **250.00** | **250.00** | **250.00** | **1250.00** |

Substantial additional contributions are expected from third partners. Collaborations with third partners will be established during the first year.

## 12. Declaration and statement

I am currently empoyed by the Los Alamos National Laboratory as a Limited Term Staff Member. I am responsible for the Nuclear Astrophysics and for the Advanced Fuel Cycle Initiative efforts within the DANCE collaboration. The Detector for Advanced Neutron Capture Experiments (DANCE) is a 160-fold detector array optimized to measure neutron capture cross section between 10 meV and 1 MeV.

I am the Principal Investigator (PI) of the research project "The s-process in the Sm-Eu-Gd region – a probe for stellar mixing", which aims at the measurement of neutron capture cross sections of unstable nuclei and their impact to s-process nucleosynthesis. Furthermore I am Co-PI on 2 other projects aiming at improving the accelerator capapbilities at the Los Alamos Neutron Science Center and the production of new detector materials.

This proposal is not submitted to any other funding agency.