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LETTER OF INTENTION

A RADIOACTIVE-ION BEAM EXPERIMENT FOR THE STUDY OF THE ASTROPHYSICAL RP-PROCESS AT CERN-ISOLDE

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1. Experimental Nuclear Astrophysics with RIB-Facilities

Radioactive ion beam (RIB) experiments offer a unique opportunity to extend the experimental study of astrophysical nucleosynthesis processes towards unstable, short-lived nuclei. These are of extreme importance in explosive environments like type II supernovae (the final collapse and explosion of massive stars), novae (explosive hydrogen burning on the surface of white dwarfs in a binary stellar system), and X-ray bursts (explosive hydrogen burning on neutron star surfaces).

Type II supernovae are the site of the r-process (rapid neutron capture and β^--decay), which produced about half of the heavy elements (beyond the Fe-group) in nature and proceeds 15–35 units away from stability on the neutron-rich side. Explosive hydrogen burning on white dwarfs and neutron stars leads to the rp-process (rapid proton capture and β^+-decay), which can produce elements as heavy as S and Ar in novae, and up to Kr and beyond in X-ray bursts. The understanding of these processes requires a detailed knowledge of the nuclear-structure parameters of the involved isotopes. Because of the substantically different nature of these processes, different experimental approaches with radioactive beams are necessary for the study of the respective nuclear input parameters.

The r-process proceeds on the neutron-rich side of the line of stability and is mainly determined by an equilibrium of neutron captures and (γ, n)-reactions. In that case, the most important features which enter are nuclear masses (or neutron separation energies), β-decay half-lives and β-delayed properties like neutron emission and eventually fission (see e.g. Kratz et al. 1993). However, the r-process develops out of a high-entropy (i.e. low-density) freeze-out of charged particle reactions from a temperature initially exceeding 5×10^9 K. Such a freeze-out at low densities is very rich in α-particles, because the triple alpha reaction to ^{12}C and $\alpha+\alpha+n$ to ^{9}Be are blocked already at high temperatures (about 3×10^9 K). The resulting nuclear statistical equilibrium composition in the Fe-group region will therefore become very distorted by final α-captures (Woosley and Hoffman 1992). In a neutron-rich environment, this Fe-group composition is also neutron-rich and the strongest α-induced reactions are (α, n)-reactions, which can proceed beyond the Fe-group up to $A = 80$–100 with charge numbers $Z = 30$–40. Only after the total freeze-out of charged particle reactions, the transition to an r-process will occur, when these nuclei are exposed to a neutron bath. The onset of the r-process depends on the competition of (α, n)-reactions and neutron captures in this transition phase. It is highly important to understand the change from α-induced reactions to neutron captures, and exactly at which mass number this transition occurs. For that reason, an experimental investigation of the size of α-induced and neutron capture reactions of neutron-rich nuclei in this mass range would be desirable. The latter can be inferred, at least partially, from (d,p)-reactions. Typical reactions of interest would be ^{82}Ge(α, n) and ^{80}Zn(d,p).

The rp-process is determined by a sequence of proton-capture reactions and β^+-decays on the proton-rich side of stability. The understanding of this process requires a detailed knowledge of (p,γ)-, (p,α)-, (α,p)-reactions and β^+-decays. It involves flow impedances due to cyclic reaction sequences (see Fig. 1) and waiting-point nuclei, and undergoes a transition at high densities and temperatures from a process dominated by proton-induced reactions to a process driven by (α,p)-reactions. This has been analyzed in detail in recent studies (van Wormer et al. 1994, Thielemann et al. 1994). Although a multitude of reactions will occur under these conditions, it turns out that the reaction flow is determined almost entirely by only a finite number of reactions. These are up to Ti the proton captures on even-Z, $T_z = -1/2$ nuclei (^{23}Mg, ^{27}Si, ^{31}S, ^{35}Ar, ^{39}Ca, and ^{43}Ti), (α,p)-reactions on even-Z, $T_z = -1$ nuclei (^{22}Mg, ^{26}Si, ^{30}S, ^{34}Ar, ^{38}Ca, and ^{42}Ti), and the competing β^+-decays. The knowledge of these reactions guarantees a description of the reaction flow and corresponding energy generation with high accuracy.

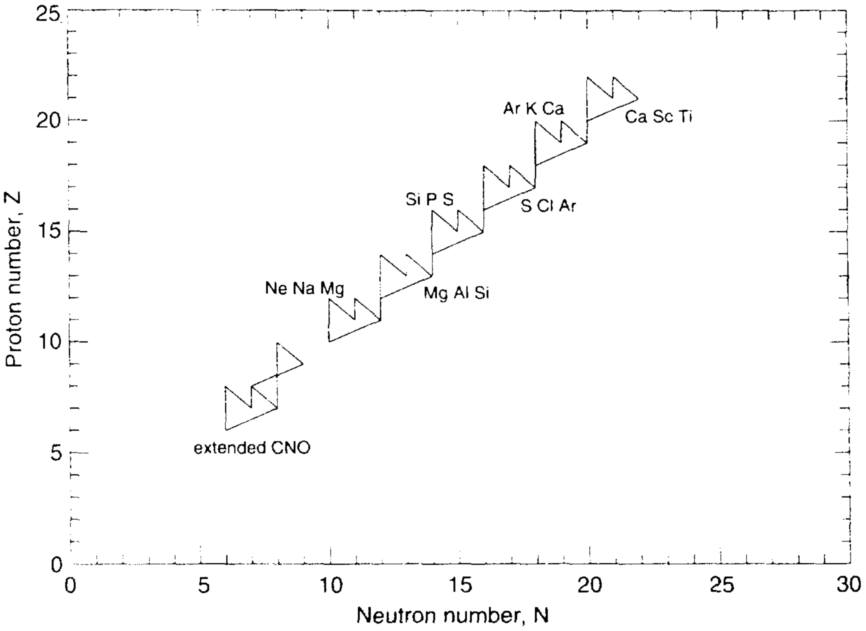

Fig. 1 The hot hydrogen burning cycles from CNO to CaScTi, typically consisting of three proton captures, two β^+-decays, and a closing (p,α)-reaction. Progress towards heavier nuclei occurs only via the $(p,\gamma)/(p,\alpha)$-branching at the cycle closings. No OFNe-cycle exists, connecting the CNO- and NeNaMg-cycles, due to the possibility of a $^{18}F(p,\alpha)$-reaction.

We present in Fig. 2 flows resulting from large scale network calculations, which were performed for temperatures of $T = 0.3$, 0.6, and 1.5×10^9 K (10^9 K $\equiv T_9$) and a density of 10^4g·cm^{-3} starting from solar isotopic abundances. Many of the reaction rates for unstable nuclei involve the best possible application of present experimental knowledge, e.g. from mirror nuclei and charge exchange reactions (see, e.g., Champagne and Wiescher 1992, and references therein), but are not based on actual cross-section measurements, except for ^{13}N$(p,\gamma)^{14}$O (the first reaction cross section analyzed with a radioactive ion beam facility; Decrock et al. 1990). The aim is to develop an understanding of the rp-process, where a few main characteristics give already an accurate description of reaction flows, without having to know *all* involved reaction rates of all unstable nuclei with experimental precision. Such a focussing on a few key reactions is highly advisable in view of the feasibility of radioactive ion beam experiments.

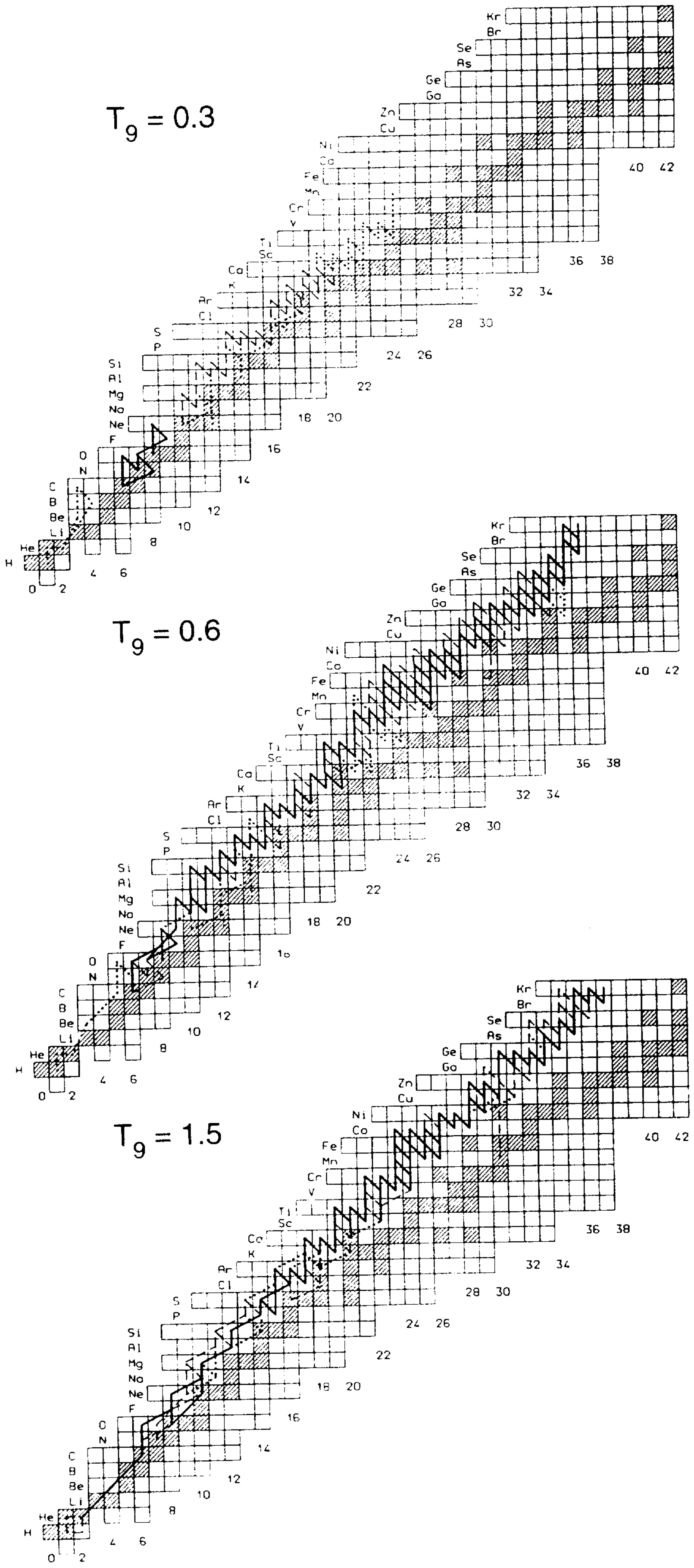

Fig. 2: Reaction flow pattern in explosive hydrogen burning (rp-porcess) for temperatures of T = 0.3, 0.6, and 1.5×10^9 K ($10^9 \equiv T_9$) at a density of $\rho = 10^4 g{\cdot}cm^{-3}$, integrated over a time period of 10^3s. The connecting lines represent the fluxes F_{ij} between the endpoints of the reaction i and j. The thick solid lines indicate the main reaction flows with $F_{ij} \geq 0.1 F_{max}$, with F_{max} denoting the maximum flux of all reactions in a particular calculation. The thin lines indicate flows with $0.01 \leq F_{ij} \leq 0.1 F_{max}$, and dotted lines flows of $0.001 \leq F_{ij} \leq 0.01 F_{max}$.

As can be seen from Fig. 2, for temperatures above $T_9 = 0.3$ the rp-process flux proceeds through the bottle-neck reaction ^{35}Ar(p,γ) which is a break-out point of the SClAr-cycle. This is one of the finite number of reactions discussed above, which determine the working of the rp-process. Because of feasibility arguments, we propose this reaction as a starting point for the investigation of rp-process reactions beyond Ne with radioactive ion beams at CERN-ISOLDE. Fig. 3 summarizes the important reactions in this cycle, which has identical features as all other cycles of the rp-process path based on an even-even nucleus with $T_z = 0$ (in this case ^{32}S).

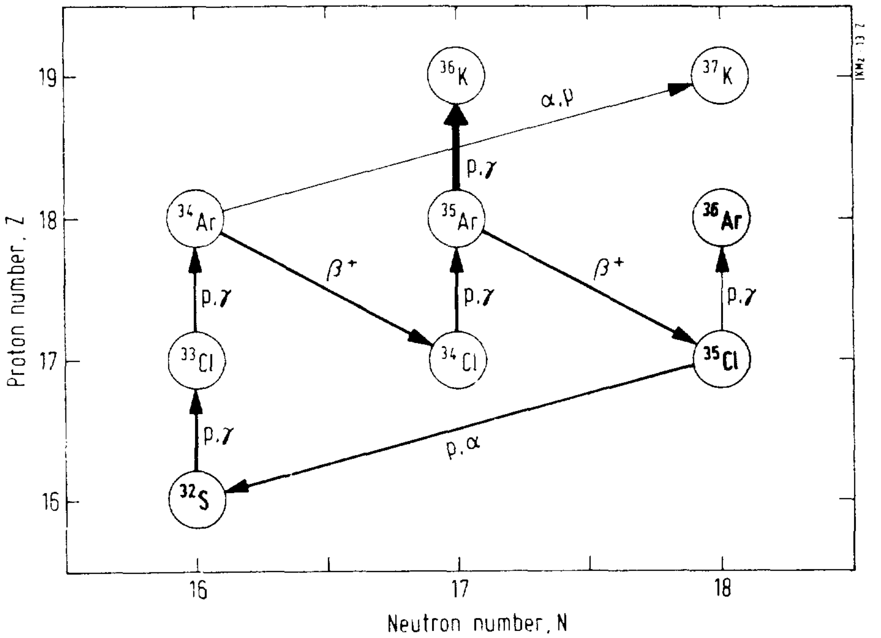

Fig. 3: The SClAr-cycle of the rp-process. Based on ^{32}S, it possesses the typical features of a hot hydrogen burning cycle: two proton captures, a β^+-decay, another proton capture and β^+-decay, and a concluding (p,α)-reaction. Break-out points are with increasing temperature (i) the (p,γ)-reaction competing with the (p,α)-reaction, (ii) the (p,γ)-reaction ^{35}Ar(p,γ) competing with the second β^+-decay, and the (α,p)-reaction competing with the first β^+-decay.

2. Feasibility of the ^{35}Ar(p,γ)-Experiment at ISOLDE

Because of general feasibility arguments (selectivity and yield of isotope production, expected resonance strengths, and total reaction yield), we propose as a first case the measurement of the ^{35}Ar(p,γ)-reaction. According to a recent measurement, the production rate of ^{35}Ar at the PS-Booster ISOLDE is 3×10^8 at/s (at 2.3 μA of proton beam), when using a CaO-target and a FEBIAD ion source with direct heating. The efficiency of the full acceleration cycle (bunching, charge state breeding and acceleration) will be 11 %; hence, a production rate of 3.3×10^7 ^{35}Ar/s can be expected.

The rates of the above mentioned proton capture reactions are dominated by single resonances. The reaction rates depend on the resonance energy E and the strengths $\omega\gamma$

$$N_A < \sigma v > \propto \omega\gamma \exp[-E_r/kT]. \tag{1}$$

While the excitation energies of the resonance levels can in principle be determined by classical nuclear spectroscopy techniques, the measurement of the resonance strengths requires a radioactive beam facility. For the direct measurement of these resonances a beam energy range of 0.2–2 MeV per nucleon is necessary. Because of the fairly low level density at the excitation energy of interest (1.8–2.5 MeV), a beam resolution of $\leq$ 15 keV per nucleon would be sufficient to resolve resonances. The beam energy should be known within 1–2 keV per nucleon to avoid a time consuming search for the resonances. In the specific case of ^{35}Ar, a beam with an energy of 0.8 MeV per nucleon is required.

The expected resonance strengths (Wiescher et al. 1992) were deduced from spectroscopic information of the mirror nucleus ^{36}Cl and range from 3×10^{-4}meV for the $E_r^{cm} = 0.22$ MeV resonance up 6.5 meV for the $E_r^{cm} = 0.74$ MeV resonance. The reaction yield

$$Y = \frac{\lambda^2}{2\epsilon_{cm}}\omega\gamma \tag{2}$$

(λ being the proton wave length and ϵ the stopping power of the heavy projectiles in the center of mass system) calculated for the above beam intensity is 1.5 reactions per hour for the 0.74 MeV resonance. The limiting factor for the measurement of such small reaction yields will be the beam induced background activity. The strengths of the resonances at lower energies, which are weaker than that of the 0.74 MeV resonance, will have to be determined in separate measurements indirectly, using single-particle transfer reactions. This will allow to deduce their strengths relative to the strong resonance at 0.74 MeV. In this way, most of the model dependencies of indirect methods can be removed.

For the direct measurement, either a solid polyethylene or a gas jet can be used as hydrogen target. While the gas target is technically more demanding, its major advantage is its pure H_2 stoichiometry. The presence of carbon in the solid target increases the stopping power ϵ, and therefore reduces the reaction yield by a factor of three [see Eq.(2)]. Nevertheless, for the first experiment we intend to use a polyethylene target because of its simplicity in comparison to a gas target, which would require substantial development time.

Because of the forward focusing in inverse kinematics, the detection of the reaction products (in our case, the heavy recoil ^{36}K) is the most efficient way to measure the reaction yield. The detection efficiency of η = 30–50 % in this case is essentially only determined by the charge-state distribution of the recoil. Assuming a beam rejection ratio of 10^{-10} (Smith et al. 1991), a peak to background ratio of 1:10 is expected. However, this ratio can be substantially increased by a combination of γ- and recoil detection. Best suited for the detection of the γ-radiation from the reaction is a large-angle array of small-size BGO detectors. A total γ-efficiency of about 30 % can be achieved with such a detector system, leading to a total recoil-γ efficiency of 15 %. and an improvement in the peak to background ratio by three orders of magnitude. This results in a total count rate of 5.4 events per day when using the solid target.

Based on the above estimates, approximately 50 shifts of beam time will be needed to accumulate about 100 events for the 0.74 MeV resonance.

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