Photodissociation experiments of astrophysical interest -- Mo isotopes as a test case

Proposal for an experiment at the SIS-FRS-LAND facility

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Astrophysical background

About half of the elemental abundances beyond the Fe-Ni-peak have been produced in explosive events. Such scenarios imply time scales of a few seconds and temperatures of 2 – 3 GK. In principle, these conditions allow to overcome the Coulomb barrier for the production of proton-rich nuclides by proton capture, but on the other hand also trigger photo-dissociation processes in the thermal photon bath. Proton- (and neutron-) captures as well as photo-dissociation processes of type (γ,n), (γ,p), and (γ,α) occurring on *r* and *s* process seed nuclei are important for the origin of the so-called *p* nuclei, stable proton-rich isotopes between Se and Hg, which cannot be made by the *s* and *r* neutron-capture processes [1].

Whereas proton capture is thought to dominate for light *p* nuclei, photo-dissociation of heavier *s* process seed nuclei (the so-called γ-process) most likely prevails in the production of the heavier *p* nuclei [1]. The γ-process sets out as a series of (γ,n) reactions until the p/α separation energies are low enough that (γ,p) and (γ,α) processes start to compete. When the stellar temperature drops, β-decays and neutron captures lead to the final *p* nuclei observed in nature. A theoretical calculation of the isotopic *p* abundances requires a huge reaction network involving thousands of isotopes and correspondingly large numbers of nuclear reactions (e.g. Ref.[1,2]). It is clear that most of the reaction rates have to be calculated, e.g. by the Hauser-Feshbach (HF) statistical model. It is important, however, that as many rates as possible are measured accurately to provide pivot points for the HF calculations.

The present proposal is part of a wider effort to improve the experimental data base for the γ process with different approaches:

1. For *stable* nuclei, many (γ,n) excitation functions have been measured with monoenergetic *real* photons, though data for many neutron-deficient stable targets are still missing; for others, data in the astrophysically interesting energy range up to about 1 MeV above the neutron-emission threshold are not accurate enough [3]. To improve this situation, accurate measurements at low excitation energies have been performed with bremsstrahlung photons, e.g. on ^{197}Au and ^{190,192,198}Pt targets at the S-DALINAC [4,5]. Since the maximum photon energy at S-DALINAC is limited to about 10 MeV, measurements on nuclei with higher binding energies have been started and will be pursued in the future at ELBE [6].
2. For *unstable* nuclei, gases, or many odd-mass nuclei, practically no experimental data exist at all. Here, Coulomb dissociation (CD) of fast radioactive beams in the Coulomb field of a high-*Z* target nucleus (*virtual* photons) is a viable approach to measure (γ,n) cross sections. Such experiments can be performed with the SIS/FRS/LAND facility at GSI [e.g. 7].
3. For (γ,p) and in particular for (γ,α) reactions, the experimental data base is extremely scarce. Input parameters for an accurate theoretical description of (γ,α) reactions have been measured by studying the time-reversed process, (α, γ) on stable targets [8,9]. In the future, such reactions are also envisaged to be performed via CD. Recently, the validity of the CD approach has been

demonstrated for the case of the ^{7}Be(p,γ)^{8}B reaction where very good agreement has been found between direct and indirect methods [10].

The present proposal refers to topics 1 and 2 mentioned above. It aims at verifying that accurate (γ,n) data close to the neutron threshold can be obtained for medium-mass nuclei using the CD method at LAND. An especially interesting region of the nuclide chart in this context is centered around ^{92}Mo. This isotope has one of the highest cosmic abundances of all *p* nuclei. This enhancement, although attracting much attention among theoretical nuclear astrophysicists, has not been explained even by recent nucleosynthesis calculations in massive stars [1,2]: the isotopes ^{92,94}Mo and ^{96,98}Ru are persistently underproduced in practically all state-of-the-art network calculations.

We propose to perform (γ,n) reactions on ^{92}Mo and ^{100}Mo with both, real and virtual photons, the former provided by bremsstrahlung photon beams at ELBE [6] and S-DALINAC [11], the latter provided by accelerating (stable and unstable) Mo beams at GSI/SIS to about 500 *A* MeV and shooting them on thick ^{208}Pb targets. The expected agreement of both results should establish the accuracy of the CD method. Once this goal is achieved, CD measurements on many critical (but unstable) nuclei for the γ-process can be envisaged. As a first example we propose to measure CD for ^{93}Mo, an unstable nucleus that cannot be prepared as a target.

Dissociation experiments with real photons

The irradiation facility at ELBE allows photo-dissociation experiments on stable targets up to about 15 MeV, sufficient to exceed the neutron-separation thresholds of the stable proton-rich nuclei. Together with the new activation/low-level counting set-up [6] rather sensitive measurements can be made by identifying the product nuclei via their γ-decay. For ^{92}Mo, photon absorption above the neutron threshold at 12.7 MeV has been studied by tagged photons at Saclay [3]. Before the onset of the IVGDR the cross section in the first few hundred keV above threshold was measured (with rather large error bars) to range between 1 and 10 mb. New measurements proposed at ELBE aim at improving the accuracy of the data points within about 1 MeV of excitation energy above threshold.

The present nuclear fluorescence resonance (NRF) setup at the S-DALINAC offers the possibility to perform high-precision activation experiments; here the photon energies are limited to about 10 MeV, so that only isotopes with smaller neutron binding energies can be studied. The isotope ^{100}Mo will be studied as a reference case; here an activation experiment has the advantage that the (γ,n) channel dominates and is not contaminated with the (γ,p) channel as is the case for ^{92}Mo. A future tagging facility at Darmstadt will also allow measurements on stable nuclei that are not accessible by activation techniques.

Coulomb-dissociation experiments at FRS-LAND with improved resolution

In CD, it is necessary to measure the cross section near threshold with optimum resolution in excitation energy. In addition, the outgoing nucleus has to be identified with respect to *A* and *Z* to tag the proper reaction channel; this allows to distinguish (γ,n) from other processes like (γ,p) and (γ,α). The masses (A~100) of the Mo isotopes envisaged in this proposal are low enough to provide good mass resolution and, together with a neutron hit in LAND, to tag the reaction channel. The proposed experiments will be performed at 500 *A* MeV. This energy guarantees high neutron detection efficiency in LAND and is sufficiently high to assure dominant dipole excitation.

In CD neutron-removal experiments on heavy nuclei ($A \geq 100$) with the LAND set-up at GSI the excitation energy resolution is mainly determined by the transverse and longitudinal momentum resolution in the neutron detection [7]. For low excitation energies the (very small) recoil momentum transferred to the (*A*-1) residual nucleus can be neglected. In longitudinal direction the neutron momentum resolution is determined by the time resolution of the LAND neutron detector. In transverse direction, the resolution is determined by the position determination of the neutron-induced shower. Assuming a neutron-ToF resolution of σ_t ~250 ps, a flight path of 15 m, and a position resolution of a neutron hit of σ_x ~4.3 cm, one expects an excitation energy resolution of σ_{E^*} ~ 120 keV for E* = 400 keV (see Fig. 1).

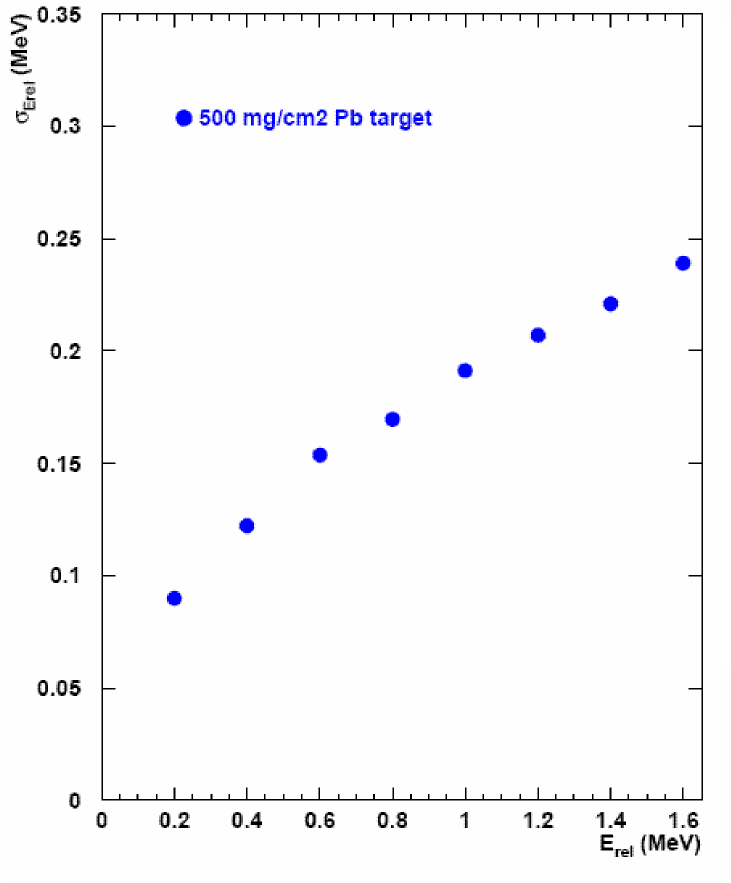

Fig.1: Sigma widths of the invariant-mass resolution close to the neutron threshold for an A~100 fragment, a neutron flight path of 15 m, and a neutron time resolution of σ = 250 ps. A Pb target thickness of 500 mg/cm^2 has been assumed.

Cross sections and rate estimates

CD neutron-removal cross sections can be calculated on the basis of the (γ,n) cross sections from Ref.[3] using Weizsäcker-Williams theory for the virtual photon spectra. As an example, the energy-differential 1n-removal cross section for ^{92}Mo on a ^{208}Pb target is plotted in Fig.2. Close to the threshold, the differential cross section is about 2 mb per 200 keV bin. Using 5x10^4 ^{92}Mo ions per spill, a 500 mg/cm^2 ^{208}Pb reaction target, and an overall LAND efficiency of 0.5, we obtain about 50 counts per 200 keV bin of excitation energy per hour or 400 counts per bin per 8h shift, so two shifts for measuring ^{92}Mo with a Pb target is sufficient.

Nuclear contributions to the CD cross sections will be measured using a ^{12}C target and will be subtracted from the Pb-induced data in the standard way. The measuring time with ^{12}C is about the same as for the Pb target.

For ^{100}Mo, the situation is even more favourable since CD cross sections near threshold of 10 mb/200 keV are expected.

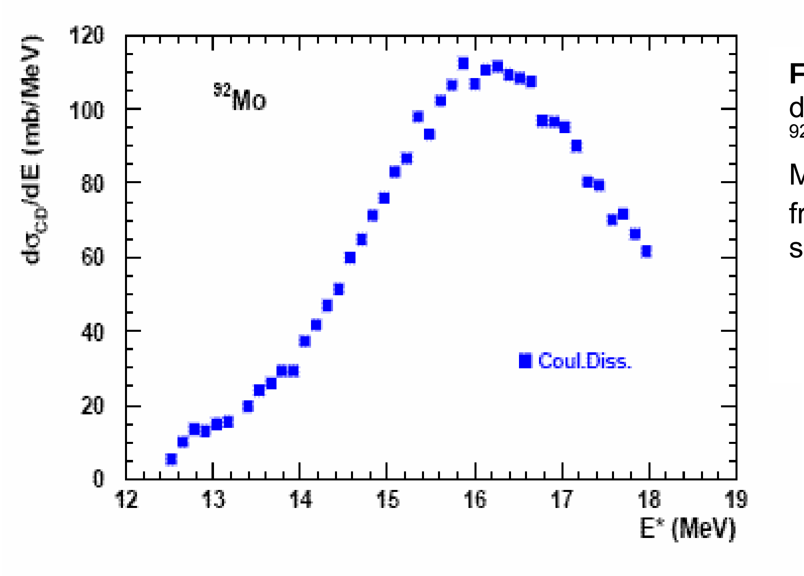

Fig.2: Differential Coulomb-dissociation cross section of ^{92}Mo in a ^{208}Pb target at 500 MeV/nucleon as calculated from measured (γ,n) cross sections [3].

In addition to the two stable isotopes ^{92,100}Mo intended as reference measurements, we propose to measure CD of unstable ^{93}Mo by using a secondary beam from FRS. This isotope can be produced from the primary ^{100}Mo beam with a cross section of 3 mb [12] so that about $8\text{x}10^4$ ^{93}Mo ions per spill can be expected at Cave C, which is more than sufficient to perform the measurements with similar precision as with the stable beams.

Beam time request

With roughly $5\text{x}10^4$ Mo-projectiles per spill about 8 shifts of counting time each for ^{92,93}Mo are needed (evenly distributed between Pb, C-target, and empty-target runs). For ^{100}Mo, 2 shifts in total will be sufficient. This adds up to a total of 18 shifts of production run. FRS setup and calibration and LAND setup and calibration are estimated to take about 1 d each. A parasitic beam time of 2 d is requested to perform tests of the apparatus prior to the production run.

Thus the total beam time requested for this proposal adds up to

- **8 days of main run, and**
- **2 days of parasitic run.**

References:

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[1] M. Arnould, S. Goriely, Phys. Rep. 384 (2003) 1.
[2] T. Rauscher et al., Astrophys. J. 576 (2002) 323.
[3] B.L. Berman, At. Data Nucl. Data Tables 15 (1975) 319.
[4] K. Vogt et al., Phys. Rev. C63 (2001) 241.
[5] K. Vogt et al., Nucl. Phys. A 702 (2002) 241.
[6] M. Erhard et al., Inst. for Nuclear and Hadron Physics, FZ Rossendorf, Annual Report 2003, p.13.
[7] R. Palit et al., Phys. Rev. C68 (2003) 034318.
[8] Zs. Fülöp et al., Phys. Rev. C 64 (2001) 066805.
[9] W. Rapp et al., Phys. Rev. C 66 (2002) 015803.
[10] F. Schümann et al., Proc. 8th Int. Conf. ”Nuclei in the Cosmos”, Vancouver, Canada, 2004.
[11] P. Mohr et al., Nucl. Phys. A718 (2003) 243
[12] K. Sümmerer , B. Blank, Phys. Rev. C 61 (2000) 034607.