Photoactivation of the p-nucleus $^{92}$Mo with bremsstrahlung at ELBE

M Erhard$^{1,3}$, E Grosse$^{1,2}$, A R Junghans$^1$, J Klug$^{1,4}$, C Nair$^1$, G Rusev$^{1,5}$, K D Schilling$^1$, R Schwengner$^1$ and A Wagner$^1$

E-mail: erhard@pd.infn.it

$^1$ Institut f. Strahlenphysik, Forschungszentrum Dresden-Rossendorf, 01314 Dresden, Germany
$^2$ Institut f. Kern- u. Teilchenphysik, Technische Universität Dresden, 01062 Dresden, Germany

Abstract. In nuclear network calculations especially the p-nucleus $^{92}$Mo is frequently under-produced. Since experimental data of the photodisintegration of $^{92}$Mo so far do not exist, it was necessary to measure the reaction yields with the photoactivation method using the bremsstrahlung facility ELBE at FZ Dresden-Rossendorf. Also the reaction $^{100}$Mo($\gamma$,n) could be tested while irradiating Mo samples of natural composition. The photon fluence was measured with nuclear resonance fluorescence (NRF) of strong and well-known transitions in $^{11}$B. As a normalization standard the photoactivation reaction $^{197}$Au($\gamma$,n) was used. For the 65 s half-life of $^{91m}$Mo a fast pneumatic delivery was used. The photoactivation yields of the ($\gamma$,p) and ($\gamma$,n) reactions are compared to yield integrals of the bremsstrahlung spectral shape folded with the cross sections derived from Hauser-Feshbach nuclear model calculations using the TALYS program and cross sections from earlier experiments.

1. Introduction
There are 35 proton-rich nuclei heavier than iron that cannot be produced by slow or rapid neutron capture since they are blocked by stable isotopes. Originally they were thought to be produced by proton capture but due to the high Coulomb barrier there is no site were temperatures are high enough. In asymptotic giant branch (AGB) stars on the other hand, with temperatures of 2 to 3 GK there are enough photons with energies above the separation energies that can cause photodisintegration reactions. Astrophysical network calculations try to predict elemental and isotopic abundances [1]. Especially the lightest Mo and Ru isotopes are inherently underproduced in p-process networks. Most of the photodisintegration cross sections are not yet measured at astrophysically relevant energies. Therefore network calculations have to resort to Hauser-Feshbach model calculations which may be imprecise.

2. Experimental setup and analysis
Photodisintegration reactions were investigated using the photoactivation method: at the superconducting Electron Linear accelerator with high Brilliance and low Emittance (ELBE) targets of natural isotopic composition are irradiated with intense bremsstrahlung of up to $10^9$ (MeV cm$^2$ s)$^{-1}$ and endpoint energies up to 20 MeV. Afterwards the decay of the radioactive isotopes is measured by $\gamma$-ray spectroscopy with a well-shielded high purity (HP)Ge detector.

$^3$ Pres. add.: Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Via Marzolo 8, 35131 Padova (PD), Italy
$^4$ Pres. add.: Vattenfall Power Consultant AB, Jämtlandsstgatan 99, P.O. Box 527, 16216 Stockholm, Sweden
$^5$ Pres. add.: Dept. of Physics, Duke Univ., Triangle Universities Nuclear Laboratory, Durham, NC 27708, USA
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The activation yield corresponds to the convolution of the bremsstrahlung spectral shape and the real photodisintegration cross section: \( Y_{\text{act}}(E_0) = \int_{E_0}^{E_i} \sigma_{\gamma,x}(E) \cdot \Phi_{\gamma}(E, E_0) \, dE \). At ELBE photoactivation can be studied at two experimental sites:

(A) In bremsstrahlung produced by the electron beam impinging on a 7 \( \mu \)m thin Nb radiator. The setup is located behind a 2.6 m long collimator in a separate cave optimized for photon scattering studies. The photon fluence distribution \( N_\gamma(E_0) \) at photon energy \( E_0 \) scattered off \( ^{111}\)B is measured with 4 HPGe detectors, each two of them at polar angles of 90\(^\circ\) and 127\(^\circ\), respectively. To obtain the photon fluence from a certain transition, the number of counts in the photopeak has to be divided by the number of \( ^{111}\)B target nuclei, the transition strength, the angular correlation coefficient, the full-energy peak efficiency, and the dead-time and pile-up correction factor. Also resonant self absorption in the photon energy region has to be taken into account.

(B) In the bremsstrahlung behind the thick graphite electron beam dump. Here the photon flux is 50 to 150 times higher. Since a direct flux measurement is not possible there, the experimental cross section of the \( ^{197}\)Au(\( \gamma\),n) reaction \([4]\) was used to determine the absolute value of the photon fluence. The reaction \( ^{197}\)Au(\( \gamma\),n) has been investigated as a standard for photoactivation, see \([5]\) and references therein. Mo targets have been activated at both sites with different bremsstrahlung spectral shape to reduce systematic uncertainties. At the target site A only \( (\gamma\),n) \) and \( (\gamma\),p) \) reactions with higher cross sections and half-lives \( T_{1/2} \geq 10 \) min were accessible, while at the site B all photodisintegration reactions of \( ^{92}\)Mo including \( (\gamma\),\alpha) \) have been investigated. The reaction \( ^{92}\)Mo(\( \gamma\),n)\(^{91m}\)Mo \( (T_{1/2} = 65 \) s) was accessible by a fast pneumatic delivery \([6]\). The bremsstrahlung distribution was simulated with the Monte-Carlo N-Particle code MCNP4C2 \([7]\) in realistic geometry for the thin target radiator (site A) and for the thick graphite target (B) \([8]\).

The endpoint energy of the bremsstrahlung \( E_{\gamma,max} \approx 2 \cdot E_p + S_{p,n}(D) \) was determined using the deuteron break-up reaction \( D(\gamma,p)n \). It corresponds approx. to the deuteron separation energy \( S_{p,n}(D) \) plus two times the kinetic energy of the proton \( E_p \), measured with 4 Si detectors perpendicular to the beam and at 45\(^\circ\) to the normal of a 40 \( \mu \)m thick foil of deuterated polyethylene [CD\(_2\)]\(_n\). The proton spectra were Monte-Carlo simulated taking into account the experimental geometry, reaction kinematics and energy loss inside the target foil. By comparison of the measured spectra with the simulated spectra the endpoint energy was determined \([5]\). The total error of the endpoint energy amounts to \( \Delta E_p \approx 40 \) keV.

The photoactivation yield is calculated by the number of counts in the photopeak of the decay measurement by taking into account the number of target nuclei, the photon emission probability, the full-energy peak efficiency of the setup with well-shielded HPGe detectors using GEANT3 simulations normalized by measurements with calibrated sources, corrections for the decay during and in between irradiation and measurement, and eventually summing corrections as well as dead-time and pile-up corrections. The detailed analysis is described in \([5]\).

3. Results and Conclusion
At ELBE we measured for the first time not only the \( ^{92}\)Mo(\( \gamma\),n), but also the \( (\gamma\),p) \) reaction at astrophysically relevant energies. In fig. 1 the activation yields of the photodisintegration reactions on \( ^{92}\)Mo are displayed for irradiation site A and B. They are compared with the yield integrals of H-F model calculations done with the TALYS code based on different nuclear models. The results confirm essentially H-F model calculations of the photodisintegration reactions \( (\gamma\),n) \) and \( (\gamma\),p) \). The underprediction of \( ^{92}\)Mo cannot be explained by imprecise cross sections. The agreement of the measured activation yield for \( ^{92}\)Mo(\( \gamma\),p)\(^{91m}\)Nb with a simulated yield integral using thin and thick target bremsstrahlung spectra as described above, shows that systematic uncertainties related to the bremsstrahlung photon fluence are small.
Photoactivation yields of $^{92}\text{Mo}(\gamma,p)$ are shown as red diamonds, $(\gamma,n)$ as blue points, and $(\gamma,\alpha)$ as green squares, normalized to the photon fluence at 7.3 MeV. At activation site A (panel a)) the photon fluence is normalized with photons scattered off $^{11}\text{B}$ and at the irradiation site B (panel b) to d)) with the activation yield and yield integral of $^{197}\text{Au}(\gamma,n)$. The experimental data are compared with yield integrals based on different nuclear models calculated with TALYS [9]. In the two left panels the effect of different photon strength functions (PSF) is shown (details see text). Different optical model potentials (OMP) are displayed in panel b) and the variation of nuclear level density (NLD) models is given in panel d).

The PSF shows the biggest impact on the yield integral curve. The thin blue solid curves use a standardized Lorentzian with a single resonance for the shape of the giant dipole resonance (GDR) with parameters given by Dietrich and Berman [10]. A novel parametrization of the PSF [11, 6] describes photon scattering data, photoneutron data and averaged resonance neutron capture data (ARC) quite well for all nuclei above $A > 80$. There the PSF is parametrized as function of the ground state deformation parameters taking into account triaxial deformation with up to three Lorentzians were determined. The corresponding yields are shown here as thick green solid lines. The PSF by Kopecky and Uhl [12] is based on a generalized Lorentzian with a $\gamma$-ray energy dependent damping correction (red dashed line). The PSF derived from the Hartree-Fock-BCS model (black dotted curve) and the Hartree-Fock-Bogolyubov model [13] (magenta dash-dotted line) also available in TALYS do not describe our experimental yields very well.

TALYS results using different OMPs do not deviate very much by each other, as can be seen in fig. 1, panel c). The choice of optical model should influence the transmission coefficients for neutron and charged particle emission. TALYS uses by default a phenomenological parametrization of the spherical potential in the optical model of Koning and Delaroche [14] (thick green solid line) which can be adjusted with the $\alpha$-OMP by McFadden and Satchler [15] (red dashed curve). As an alternative the semimicroscopical OMP of Jeukenne, Lejeune, and Mahaux [16] is implemented in TALYS (blue dotted curve). Especially below the neutron separation energy the standard OMP fits best. Five different models of the NLD can be chosen in TALYS and...
are described in detail in the article of Koning et al [17] (and references therein). By default TALYS uses the constant-temperature model at low energies and the Fermi-Gas Model at high energies (thick green solid line). The deviations of the NLD in the yield curves from each other is less than a factor 1.5 over the measured energy region.

The activation yield of the $^{100}\text{Mo}(\gamma,n)^{99}\text{Mo}$ reaction could be compared with the yield integral of the photoneutron measurements of positron annihilation in flight from Saclay [18] (fig. 2). Applying a correction factor of 0.85, suggested by Berman et al [19], they are in excellent agreement with the ELBE data. Also shown are H-F model calculations with TALYS (GDR parametrization of [11]) and the photodisintegration cross section of the NON-SMOKER code [20] which is in very good agreement, too.

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