Photodesintegration experiments in ALBA: A draft proposal

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The feasibility of (γ, p) and (γ, α) reactions in the projected line of hard photons, associated to the Sincrotron facility ALBA is discussed.

I. PHYSICAL MOTIVATION

A source of monochromatic γ-rays has many applications in the study of nuclear structure.

Measurements of the giant dipole resonance has been done previously, and data are available for a large variety of nuclei.

The study of proton-rich nuclei heavier than iron (p-nuclei) has a special relevance for the astrophysical p-process [1]. This process is responsible for the synthesis of neutron-deficient nuclei that are blocked from formation by either the r or s processes [2]. The p process is believed to occur in the oxygen/neon layers of highly evolved massive stars during their presupernova phase or during their explosion. At the temperatures of about 2 to 3 billion degrees, which can be reached in those layers, the p-nuclei are synthesized by (γ, n) photodisintegrations of preexisting more neutron-rich species (especially s-nuclei), possibly followed by cascades of (γ, p) and/or (γ, α) reactions. It has also been proposed that those nuclear transformations could take place in the C-rich zone of Type Ia supernovae as well as in the envelope of exploding sub-Chandrasekhar mass white dwarfs on which He-rich material has been accreted [1].

The p-process is essentially a sequence of (γ, n), (γ, p) or (γ, α) photodisintegrations reactions, possibly complemented by captures of neutrons, protons or α-particles at energies typically far below 1 MeV or the Coulomb barrier in the case of charged particles. Recent experiments have provided direct measurements of some (γ, n) reactions at the low energies of interest for the p-process, i.e close to the photodisintegration threshold. One of the techniques is based on the construction of a quasi-thermal photon spectrum from a superposition of bremsstrahlung spectra with different endpoint energies [3]. As an alternative, a Laser Inverse Compton (LIC) γ-ray source uses a real photon beam in the MeV region produced by head-on collisions of laser photons on relativistic electrons and produces quasi-monochromatic γ-rays in the energy range 1 to 40 MeV [3]. An important advantage of the LIC γ-rays over the bremsstrahlung approach is their more intense peaking in the energy window of astrophysical interest in addition to their better quasi-monochromaticity. The bremsstrahlung and LIC techniques have been used so far to measure the rates of a few (γ, n) reactions. In particular, the latter experimental approach has provided cross sections to the ground and isomeric state for the $^{181}\mathrm{Ta}(\gamma, n)^{180}\mathrm{Ta}$ reaction, which is of special interest in p-process models. These measurements have to be complimented by the determination of the $^{180}\mathrm{Ta}^{\mathrm{m}}(\gamma, n)^{179}\mathrm{Ta}$ reaction rate. Another prime interest in p-process studies is the synthesis of the rare odd-odd p-nuclide $^{138}\mathrm{La}$. This requires the measurements of the $^{139}\mathrm{La}(\gamma, n)^{138}\mathrm{La}$ and $^{138}\mathrm{La}(\gamma, n)^{137}\mathrm{La}$ rates.

Direct determinations of reaction rates for the p-process suffer from two major limitations. The first is the fact that the p-process involves thousands of photoreactions (not to speak of the secondary β^+, electron captures, and (n, γ) reactions) and that most of the involved nuclei are unstable, which means that only a tiny fraction of those reactions can be measured in the laboratory. The second limitation is that in a gas at high temperature, excited levels of the target nuclei are populated according to the Boltzmann statistics, so that photoreactions on excited levels must be taken into account. This thermalization effect is specially important here because of the high temperatures involved in the p-process and because photodisintegrations are specially sensitive to threshold effects. If the direct determination of astrophysical rates at work in the p-process is clearly out of reach, experimental studies of photodisintegration cross sections in the relevant energy range and for nuclei as close as possible to the neutron deficient side of the valley of stability are of crucial importance to test the nuclear reaction models used to calculate the rates. Valuable pieces of information are also obtained, more traditionally, by the measurement of cross sections in the reverse, radiative capture channel. They can indeed be used to constrain the calculation of the rates in the photoreaction channel via the reciprocity theorem. One must keep in mind, however, that such measurements are but a fragment of the information needed for the calculation of the reverse rate. To be correct, such a calculation requires the knowledge of all non-negligible cross sections from any excited state of the target nucleus to any state of the residual one.

Direct measurements of photodisintegration cross sections constitute therefore an independent set of data and the most straightforward way to constrain the calculation of the corresponding astrophysical rate. Improving the theoretical predictions for photodisintegration rates will put p-process nucleosynthesis calculations on a firmer ground. As mentioned before the p-process takes place at very high temperatures but the nuclei involved are in a region of the nuclear chart where basic quantities like masses or β-decay rates are either known or rather reliably estimated. Experimental data on photoreaction cross sections, even scarce, are therefore a very precious ingredient to test the validity of Hauser-Feshbach cross section calculations in the nuclear region of interest. Measurements of (γ, n) reactions on many more nuclei are certainly necessary, but the investigation of (γ, α) and (γ, p) reactions in the energy range of interest is still a challenging prospect. In addition, the E1 and M1 γ strength functions below particle thresholds should be addressed in direct relation to photoreactions on nuclear excited states under stellar conditions.

II. EXPERIMENTAL SETUP

A simple setup to measure (γ, p) and (γ, α) reactions consists in having an array of silicon based telescopes surrounding the target, in order to detect and identify any charged particle (specially protons and α-particles, that are produced due to the absorption of γ-rays.

Considering that the γ-beam can not be as collimated as a beam of particles, and in order to avoid damage in the detectors due to the intense gamma beam, the detectors should not be placed close to the beam direction.

For a beam of polarized photons, the production of charged particles would be maximum along the direction of the electric field, which will be perpendicular to the beam direction.

So, a simple setup would consist in two Double Sided Silicon Strip Detectors (DSSSD), which would be placed perpendicular to the beam, and a target that would be tilted 45 degrees. These DSSSD detectors are avalable from the spanish groups which form the DINEX collaboration (CSIC-Madrid, Huelva and Sevilla). The size of this detector setup should not exceed a cube of $20\times20\times20$ cm^3.

The optimal energy range of the gammas is a compromise of the requirements of the astrophysics (energies in the Gamow window, this is, one or two MeV above the threshold), and the minimum energy needed to go through the $\Delta - E$ detector of the telescope (1.5 MeV for the protons and 6 MeV for the α). This would give a range between 8 and 15 MeV for the gammas. The energy resolution of the beam should be sufficient to allow for particle identification. Probably, 1 MeV could be enough.

To estimate the number of events, we will assume that the photon source, after collimations, produces 10^7 photons/s, in the adequate energy range. As an order of magnitude estimate, we take that the (γ, p) and (γ, α) cross sections will be of the order of 10 mb. The target thickness will be about 100 mg/cm^2. This thickness (about 10-20 μm), should not stop the charged particles coming out, and for a material with $A \simeq 100$, correspond to about 6×10^{20} particles per cm^2 in the target. This estimate will give about 60 charged particle events per second. The efficiency of the detector may be between 50% and 10%, depending on the polarization of the beam and the energy of the outgoing particles. That gives a reasonabe counting rate, which should allow to perform experiments in the time scale of a few days.

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