PROCEEDINGS OF SCIENCE

Coulomb dissociation reactions on proton-rich Ar isotopes

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A Coulomb dissociation experiment on the proton-rich ^{32}Ar and ^{34}Ar isotopes was performed at the ALADIN-LAND setup at GSI in Darmstadt. Recent RQRPA calculations show a low-lying E1 soft-vibrational mode at an excitation energy $E_x \approx 9$ MeV for proton-rich argon isotopes at the dripline. In a macroscopic picture, this can be understood as an out-of-phase oscillation of a thin proton skin against the isospin-saturated core, similar to the neutron pygmy resonance at the neutron dripline. On the other hand, the measured (γ, p) reactions are interesting for the calculation of reaction cross-sections and radiative proton capture rates for the rp-process. In this hydrogen burning process a lot of nuclear structure inputs are still missing. Especially in the argon region a bottleneck for the reaction flow is assumed at ^{30}S and ^{34}Ar. The impact of the predicted proton pygmy resonance on the reaction flow is not yet clear.

The experimental motivation and the experiment itself are described. Identification plots for incoming and outgoing particles are shown and a tracking algorithm is applied and shows to work succesfully.

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1. Introduction

A key ingredient in modeling and calculating nucleosynthesis processes in stars is a detailed knowledge about the structure and the properties of stable and unstable nuclei. Therefore in the last years a huge effort was taken in theory and experiment to describe and measure exotic nuclei far from stability. Still, only a few percent of the exotic nuclei are measured and upcoming facilities around the world, like FAIR at GSI Darmstadt, FRIB at MSU , RIBF at RIKEN desire to reach more exotic nuclei with high-intensity beams at intermediate relativistic energies. Especially nuclear structure properties of nuclei close to the driplines influence dramatically nucleosynthesis processes in hot stellar environments, like the rapid-proton capture (rp)-process.

The rp-process is a thermonuclear hydrogen burning process taking place on the surface of accreting neutron stars and dependent on the accreting rate, it can be explosive and observed in X-ray bursts. It takes place at extreme temperatures of $T \approx 2 \times 10^9$ K and densities of up to $\rho \approx 10^7$ g/cm^3. This process is extremely fast with timescales in the region of $10 - 100$ s. Under these conditions, it is possible to overcome the huge Coulomb barrier and to capture protons in (p,γ) reactions. Hence, the β-decay rates are low compared to the proton capture rates. The rp-process is initiated by break-out of the hot CNO cycle and ends in a closed Sn-Sb-Te-cycle [1].

It is therefore necessary to understand the properties of proton-rich nuclei close to the proton-dripline. Especially in the low-mass region there is still a lack of nuclear structure information. Statistical models, like the Hauser-Feshbach description, are capable to describe capture cross-sections of nuclei with high level density by forming a compound nucleus. Close to the driplines, where the separation energies are getting low and the capture cross-sections are mainly governed by only a few low-lying resonances, statistical models are not useful anymore and detailed description of level energies, spin-parity assignments, Q-values and reaction cross-sections are needed. Currently, shell-model predictions of individual states in such exotic nuclei are available, but the uncertainties in the level energies are typically in the region of a few hundred keV, which translates to huge uncertainties in the rate calculation.

The region around the proton-rich chlorine and argon isotopes is an example for the above mentioned interesting low-A part of the rp-process flow. There is not much information available about capture cross-sections and deduced rates in this region ([2] and [3]). At the ALADIN-LAND setup at GSI, a Coulomb-breakup experiment in inverse kinematics was performed to study properties of proton-rich argon isotopes close to the dripline, with a focus on ^{32}Ar ($A/Z = 1.77$) and ^{34}Ar ($A/Z = 1.889$). This includes isotopes with similar mass-to-charge ratio, e.g. ^{31,32}Cl, delivered with the same beam to the experimental setup. ^{31}Cl is a very interesting rp-process nucleus. Due to the low proton binding energy of only $S_p = 290(50)$ keV the rp-process reaction flow through that region is assumed to have a waiting point created by the $^{30}S(p,\gamma)^{31}Cl(\gamma,p)^{30}S$ equilibrium. A similar waiting point at ^{34}Ar has been proposed [4].

2. Experiment

Coulomb dissociation experiments in inverse kinematics are a powerful, and often the only available tool to study properties and deduce the capture cross-sections of very exotic nuclei. In particular in this experiment the dipole response of the proton-rich even isotopes ^{32}Ar and ^{34}Ar

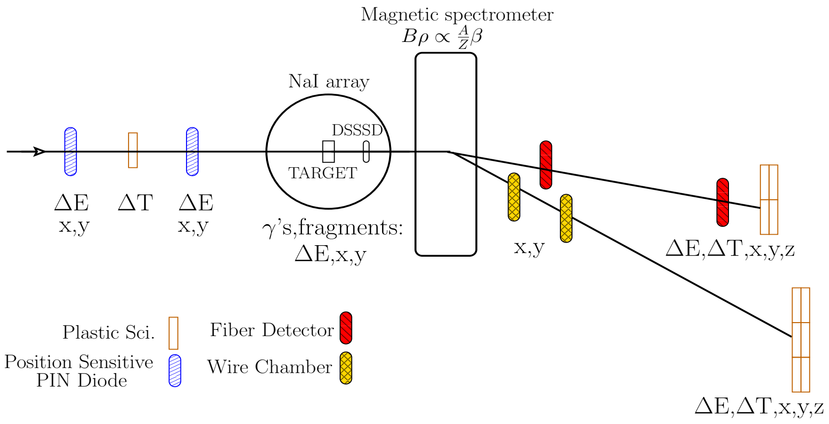

Figure 1: ALADIN-LAND setup. Different detector systems are used for a complete measurement in inverse kinematics.

is investigated. In ^{32}Ar a low-lying E1 strength was recently predicted in various calculations ([5] and [6]). This proton pygmy resonance, in analogy with the well confirmed neutron pygmy resonance, can be understood in a macroscopic picture as an out-of-phase oscillation of a proton skin versus the isospin-saturated core. According to RQRPA calculations [5], the additional strength is situated below the giant dipole resonance at an excitation energy $E_x \approx 8-10$ MeV. For ^{34}Ar a proton pygmy resonance is also predicted, nevertheless, it is not as pronounced as in the case of ^{32}Ar. The role of pygmy resonances in proton-rich nuclei for the rp-process is discussed controversially. A study of the effect of a pygmy resonance for neutron-rich nuclei was performed in an earlier work, cf. [7]. In that case it was found, that a low-lying resonance strength contributes to the overall abundance patterns of the r-process.

The experiment was performed at a beam energy of $E_{beam} = 590$ AMeV. At this energy we profit from the huge flux of virtual photons, generated by the highly lorentz-contracted electromagnetic field of a heavy-Z ^{208}Pb target with energies of up to $E_\gamma = 20$ MeV. From the measured Coulomb dissociation cross-section we deduce the transition matrix element B(E1). The fully exclusive experiment was perfomed at the ALADIN-LAND setup (see Fig. 1). The beam was produced by fragmentation of a 790 AMeV ^{36}Ar primary beam on a 6.347 g/cm^2 Be-target, situated at the entrance of the fragment seperator (FRS) at GSI. The secondary ions were separated by means of energy loss and magnetic rigidity, subsequently transported to the experimental setup and identified event-by-event (see Fig. 2). Due to the measurement of all kinematical variables, it is possible to reconstruct the invariant mass of the desired isotopes after the interaction with the reaction target. To obtain the cross-section for radiative proton capture we will make use of the detailed balance theorem, which connects the measured (γ, p) cross-section with the time-reversed (p, γ) cross-section

$$\sigma_{B+p\to\gamma+A} = \frac{2(2J_A+1)}{2(J_B+1)(2J_p+1)} \frac{k_\gamma^2}{k^2} \sigma_{\gamma+A\to B+p}.$$

where J is the corresponding spin and $k^2 = 2m_{Bp}(E_\gamma - S)$ with S equal to the separation energy and $k_\gamma = E_\gamma/\hbar c$. This method was proven in earlier experiments with a similar setup [8].

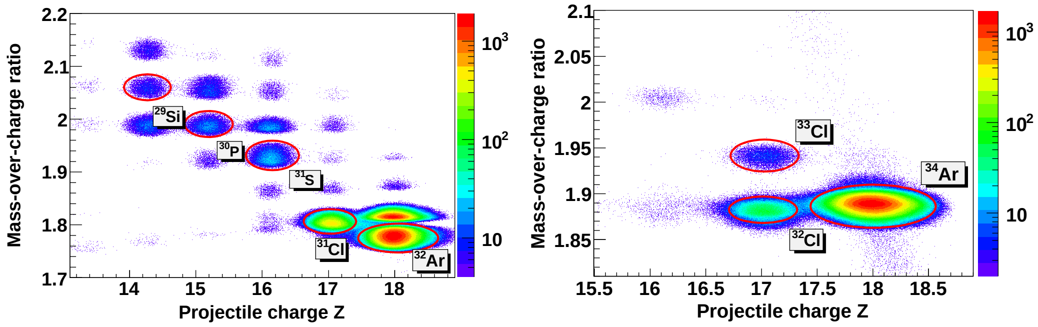

Figure 2: Incoming beam identification with different ion optical settings for achromatic mode of the fragment seperator. Left: setting optimized on ^{32}Ar as main isotope. Right: setting optimized on ^{34}Ar.

Table 1 gives an overview over the identified events and the investigated reactions. Note the low proton separation threshold in case of ^{31}Cl. After identifying the incoming ions the reaction channel of interest has to be chosen. Therefore, a separation of the outgoing particles behind the magnetic spectrometer ALADIN has to be performed. This is done by means of time-of-flight and reconstruction of the charge Z of the ejectiles in a plastic scintillator (see Fig. 3).

Table 1: Identified isotopes, number of events on target, ground state J^P, desired reaction and the Q-value

Isotope	Incident events	J^P	Reaction	Q-value (MeV)
^{32}Ar	3.1×10^7	0^+	$^{32}Ar(\gamma,p)^{31}Cl$	-2.422(50)
^{31}Cl	6×10^6	$\frac{3}{2}^+$	$^{31}Cl(\gamma,p)^{30}S$	-0.2934(6)
^{34}Ar	7.1×10^7	0^+	$^{34}Ar(\gamma,p)^{33}Cl$	-4.662(1)

As an example we choose ^{32}Ar as the main incoming beam (see Fig. 2) and require protons (stemming from the (γ,p)-reaction) in the final state. One can see a lack of expected chlorine ($Z = 17$) isotopes in Fig. 3. Instead of the chlorine isotopes we dominantly find sulfur isotopes ($Z = 16$) and products from other decay channels. This is explained by the low proton separation threshold in ^{31}Cl. Due to phase-space considerations also states above the proton-threshold in ^{31}Cl will be populated. Subsequently, the excited ^{31}Cl will de-excite via proton evaporation to ^{30}S.

2.1 Tracking

As the fragments and the protons get separated by the magnetic spectrometer, it is possible to track the different particles event-by-event. This is done via the magnetic rigidity, time-of-flight and the known charge Z in the outgoing channel

$$B\rho \propto \frac{A}{Z}\beta\gamma.$$

As an example the tracking algorithm is applied to the unreacted ^{32}Ar beam. The expected peak at $A = 32$ proofs the correctly working tracking algorithm and opens the way to reconstruct the

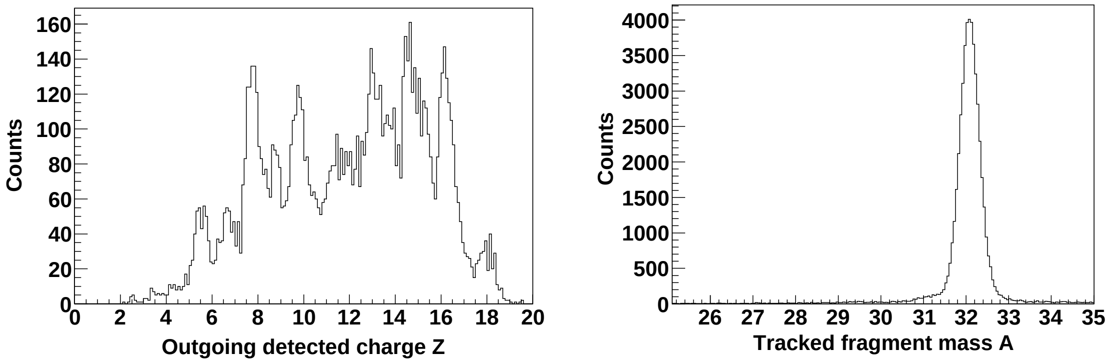

Figure 3: Left: Outgoing fragment identification with a cut on incoming ^{32}Ar. Right: Tracked unreacted ^{32}Ar as a proof-of-principle case.

four-momentum of fragments and protons, stemming from the different reactions. By this reconstruction, it is possible to yield an invariant mass spectrum and to extract the photo-dissociation cross-section σ_γ which is connected to the measured energy-differential cross-section $d\sigma_C/dE$ by the virtual photon spectrum $N_\gamma(E)$ via the relation

$$\frac{d\sigma_C}{dE} = N_\gamma(E)\ \sigma_\gamma(E)$$

3. Outlook and Summary

An experiment with proton-rich argon isotopes was performed at the ALADIN-LAND setup at GSI. The analysis is ongoing, but it is shown, that the tracking algorithm for outgoing fragments works. Therefore, the next step in the analysis will be the reconstruction of the energy-differential cross-section $d\sigma_C/dE$ of different isotopes.

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