EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the
ISOLDE and Neutron Time-of-Flight Experiments Committee
for experiments with HIE-ISOLDE

Time-reversal studies of (α,p) reactions in X-ray bursts

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Abstract

The aim of this Letter of Intent is the study of some key (α,p) reactions important for X-ray bursts. It is proposed to study these reactions by time-reversal approach, thus exploiting the higher energies available at HIE-ISOLDE and making use of solid targets (e.g. CH_2) rather than gaseous ones. The cross section of interest for the (α,p) reactions will be inferred from the measured (p,α) ones by means of the detailed balance. Inelastic contributions to the astrophysical reaction rates will be measured concurrently wherever possible by using particle–γ-ray coincidence techniques. The development of relatively intense key radioactive beams is thus required.

1. Introduction

X-ray bursts are driven by a thermonuclear runaway on the surface of an accreting neutron star. The runaway is triggered by the triple-α process and the break-out reactions from the Hot-CNO cycles which cause the feeding of the *rp*-process. Once the break-out has taken place, possibly through the reaction sequence ^{18}Ne(α,p)^{21}Na(p,γ)^{22}Mg(α,p)^{25}Al(p,γ)^{26}Si, a series of alpha- and proton captures (the so-called α*p*-process) may lead up to the Ca-Ti region [1-2]. Subsequent (α,p) reactions, specifically on ^{22}Mg, ^{26}Si, ^{30}S, and ^{34}Ar, are believed to be critical for type I X-ray bursts as they might provide a waiting-point impedance in the reaction flow, as suggested by Fisker *et al.* (2004) [3]. In particular, the effects of experimentally unknown reactions, such as ^{30}S(α,p)^{33}Cl and ^{34}Ar(α,p)^{37}K, might even be directly visible as a double peak structure, as observed in the light curve of some X-ray bursts. These reactions may also affect the nucleosynthesis in these phenomena, which could then affect observable properties of subsequent bursts (energy, recurrence time) through "compositional inertia" [4, 5].

2. Physics case

Unfortunately, sparse or no experimental data are available yet on any of these (α,p) reactions on ^{22}Mg, ^{26}Si, ^{30}S, and ^{34}Ar and conclusions on their role in XRBs are based on statistical approaches such as Hauser-Feshbach calculations. In general, the use of the Hauser-Feshbach approach is appropriate provided the level density in the contributing energy window is sufficiently high to justify a statistical treatment, the critical level density being usually estimated between 5 and 10 MeV^{-1} [6]. However, the level density may fall below critical values in certain nuclei lighter than Fe, at shell closures, and for very neutron-rich or proton-rich isotopes near the drip lines. In these cases, single resonances or direct capture contributions will become significant [3,6] and theoretical estimates may become unreliable.

Recent observations by the BeppoSAX, RXTE and CHANDRA satellites have provided a wealth of new data on X-ray bursts (see for example [7] and references therein). In order to compare model predictions with observations, the models should include accurate reaction rates that need to be determined by laboratory experiments. At present many rates in the *rp*-process are uncertain by several orders of magnitude and invaluable experimental information is clearly needed.

With this LoI, we would like to advocate the need to develop sufficiently intense beams of ^{25}Al, ^{29}P and ^{33}Cl, and ^{37}K at HIE-ISOLDE so that the key reactions ^{22}Mg(α,p)^{25}Al, ^{26}Si(α,p)^{29}P, ^{30}S(α,p)^{33}Cl, and ^{34}Ar(α,p)^{37}K can be studied by the time-reversal approach. We note that these beams (particularly ^{25}Al) would also be useful for studies of (p,γ) reactions relevant for nucleosynthesis in classical nova explosions [8].

3. Methodology and Experimental setup

Direct studies of (α,p) reactions with radioactive ion beams are extremely difficult because they suffer from limitations in beam intensities, target densities, and detection efficiencies. An alternative approach would be to study the reactions of interest, here generically indicated as X(α,p)Y, by their time-reversed Y(p,α)X processes, using a radioactive ion beam Y and a solid CH_2 target.
The time-reversed approach is justified by the fact that the cross-section $\sigma_{\alpha X}$ for reaction α+X → p+Y is related to the cross-section σ_{pY} for the inverse process p+Y → α+X by detailed balance according to the reciprocity theorem:

$$\frac{\sigma_{\alpha X}}{\sigma_{pY}} = \frac{m_p m_Y}{m_\alpha m_X} \frac{E_{pY}}{E_{\alpha X}} \frac{(2J_p + 1)(2J_Y + 1)}{(2J_\alpha + 1)(2J_X + 1)} \tag{1}$$

where E_{ij} refers to the centre-of-mass energy for the direct and inverse reactions involved (here, $E_{pY} = E_{\alpha X} + Q$), m_i are the masses of the respective particles and J_i the nuclear spin of the interacting particles.

As known, the main limitation of the time-reversal approach is related to the fact that only ground-state-to-ground-state transitions can be measured for the reactions of astrophysical interest. Thus, the method only provides lower limits to the direct reaction cross sections as inelastic contributions X+α ⇒ p+Y* to the (α,p) channel, also important for astrophysics, cannot be accessed by time-reversal. However, we have recently demonstrated [9] that the inelastic contribution to the cross section can be estimated by measuring the inelastic proton scattering tagged by the de-excitation gamma rays using the high-efficiency Miniball array. This approach has successfully been adopted to the case of ^{14}O(α,p)^{17}F and would be applicable to the reactions highlighted in this LoI.

Finally, it should be pointed out that, while only natural parity states in the compound system can be accessed by the forward reaction α+X (here spin-less particles) such a restriction does not apply when forming the compound system via the reverse p+Y reaction. However, the kinematic selection of events with both α and X nuclei in their ground states will ensure that only natural parity states have been populated through the p+X channel. This in turn enables a meaningful extraction of cross section $\sigma_{\alpha X}$ from a measurement of σ_{pY} as given by equation (1). The requirement on the kinematic selection can be fulfilled provided that the first excited states for nuclei in the exit channel are sufficiently high in energy (~1 MeV) to allow for experimental discrimination, which is the case for all reactions of interest here. Incidentally, Hauser-Feshbach calculations for this and similar (p,α) reactions have shown that contributions to excited states in the exit channel are negligible with respect to ground state transitions only [6] and thus the ^{22}Mg(α,p)^{25}Al, ^{26}Si(α,p)^{29}P, ^{30}S(α,p)^{33}Cl, and ^{34}Ar(α,p)^{37}K reactions represent excellent candidates for the application of the time-reverse approach.

Concurrently to yield measurements by the time-reversal approach, it is also proposed to investigate the relevant states in the compound nuclei of each reaction by resonant proton elastic scattering. Further details will be provided in due time in a full proposal. Both approaches (time reversal and resonant elastic scattering) are well known and tested and have successfully been used in previous investigations. As such they do not present any major theoretical or technical challenge. Detectors and related instrumentation will be provided by the Edinburgh Group.

The advantages of the proposed time-reversal approach are manifold:

1. Higher beam energies (typically 4-6 MeV/u) are required and are well matched to the accelerator facilities at HIE-ISOLDE;
2. The reaction products are strongly forward focussed and allow for high efficiency detection; and
3. Solid targets are used instead of gas targets.

In addition, the experiment would aim at the coincident detection of both reaction products to fully identify the reaction of interest, thus alleviating any problem associated with isobaric beam contaminations.

Finally, it should be stressed that no published experimental data exists at present for any of the reactions proposed and even partial information would represent a major improvement in the current situation. Recently, a study of the ^{30}S(α,p)^{33}Cl has been carried out [10] at the Argonne Tandem Linac Accelerator using a radioactive ^{33}Cl beam, with typical intensity 5×10^4 pps [11]. The residual ^{30}S nuclei were detected at the focal plane of the split-pole spectrograph, in coincidence with the α particles detected in a double-sided Si detector. No published data are available at present.

The experimental setup will consist of Si detector arrays and γ-ray detector arrays such as Miniball. Measurements of (p,α) reaction cross sections as well as of the inelastic contributions will be carried out using think CH_2 targets in conjunction with ΔE-E Si detector arrays for the coincident detection and identification of alpha-particles and heavy ions.

Resonant elastic scattering measurements for the investigation of excited states in the relevant compound nuclei will be achieved using thick targets (to fully stop the beam) together with ΔE-E Si detector arrays at zero degree for the detection and identification of the scattered protons. Similar setups have already been used successfully at other laboratories for similar studies.

4. Beam requirements

Typically, the beam intensities required for this type of studies are of at least 10^5 pps. At present, the following beams are already available at CERN: ^{25}Al, ^{37}K and ^{33}Cl, whereas ^{29}P is not developed. Some may suffer from significant contaminations and/or may require further intensity upgrades. Thus, significant beam developments may be needed in some cases.

The following table provides an estimate of the required beam-time (in 8-h shifts) for the investigation of the ^{33}Cl(p,α)^{30}S in an energy region (for the direct reaction) slightly above the Gamow window.

Reaction ^{33}Cl(p,α)^{30}S

Q-value: -2.077 MeV

$T_9 = 1.5 \rightarrow E_0 = 2.5 \pm 0.6$ MeV

beam intensity = 10^5 pps

target thickness = 4.3×10^{19} atoms/cm^2 (CH_2 500 μg/cm^2)

Detection efficiency ~ 50% (conservative estimate)

E_{beam} (^{33}Cl) [MeV/u]	E_{beam} (^{33}Cl) [MeV]	E_{cm} dir ^{30}S(α,p) [MeV]	E_{cm} inv ^{33}Cl(p,α) [MeV]	sigma [mb]	counts/h	8h shifts	total counts	stats %
5.7	187	3.4	5.5	4.59E-02	0.36	15	43	15
6.2	204	3.9	6.0	1.98E-01	1.53	7	85	11
6.8	224	4.5	6.6	6.60E-01	5.1	2	80	11
7.4	245	5.1	7.2	1.54	11.9	2	190	7

Total beam time request: **26** (8h) shifts for (p,α) yield measurement
+ **2** (8h) shift for resonant elastic scattering measurement

5. Safety aspects

There are no major safety concerns associated with the proposed experiments other than the usual handling of standard radioactive sources for calibration and high voltage supplies for the operation of the Si and gamma-ray detector arrays.

6. References

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