ASTROPHYSICAL REACTION RATES STUDIED BY COULOMB DISSOCIATION OF RADIOACTIVE BEAMS

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1 Astrophysical background

In binary stellar systems with a degenerate object (e.g. white dwarfs or neutron stars) mass overflow and accretion from the binary companion can lead to explosive events like e.g. novae (on white dwarfs) or X-ray bursts (on neutron stars). The nuclear energy source is explosive hydrogen burning, ranging from hot CNO-cycles to long sequences of proton captures and beta-decays (rp-process) [Ref.[1] and references therein].

In novae the main energy source, after ignition via pp-reactions, is the hot CNO-cycle. Since present reaction rate information suggests that the gap between the hot CNO-cycles and nuclei beyond Ne can only be overcome by α-capture reactions at temperatures which are unlikely to occur in novae, the observed nucleosynthesis up to $A \sim 40$ can only proceed via proton capture sequences on initial Ne and Mg abundances. To understand and interpret these observations, detailed measurements of low-energy capture reactions on radioactive and stable isotopes in the Ne to Ca range are required.

Among the key nuclear data needed are the reaction rates for proton capture on even-Z, $T_Z = -1$ nuclei like ^{22}Mg, ^{26}Si, ^{30}S, ^{34}Ar and ^{38}Ca. The small reaction Q-values (less than 2 MeV) do not permit the application of statistical-model cross sections, therefore they have to be determined experimentally. At the same time, the low Q-values make them ideal for Coulomb dissociation experiments with radioactive ion beams (see below).

Of special current interest is the nucleosynthesis in the neighbourhood of long lived radioactive isotopes which have been (or probably will be) observed with γ-ray observatories (COMPTEL, INTEGRAL). Two of these nuclei are ^{22}Na and ^{26}Al, where the decay of the latter has already been observed. Both nuclei are also associated with isotope anomalies in meteorites (Ne-E problem and ^{26}Mg anomaly). These nuclei are produced within intricate reaction networks, where the reaction path depends strongly on plasma temperatures, densities (both time-dependent) and burning time scales. At present, a decision on the stellar site(s) of ^{22}Na and ^{26}Al production cannot be made due to the lack of the necessary nuclear physics data. The current nucleosynthesis calculations (outside the valley of stability) are based predominantly on nuclear shell model calculations, sometimes backed by indirect information on the relevant states obtained via transfer reactions or β-decay measurements.

This proposal aims at a measurement of the resonant proton-capture on ^{22}Mg and ^{26}Si. Sizable reaction rates on these nuclei may lead to a bypass of the reaction flow around the long-lived radioactive daughter isotopes, thus having a strong impact on the observable (via cosmochemistry and gamma-astronomy) abundances.

2 Coulomb Dissociation

Coulomb dissociation (C.D.) has proven to be an alternative method for measuring reaction rates of astrophysical proton-capture reactions. Examples for successful studies are e.g. the resonant reaction ^{13}N(p,γ)^{14}O (Ref. [2]) or the direct capture reaction ^{7}Be(p,γ)^{8}B [3] which has both a resonant and non-resonant component. The latter case was the subject of the GSI-experiment S171 of the present collaboration [4] and will be discussed in more detail below. The C.D. method is particularly suited for those cases where

- no stable or long-lived target is available so that the reaction cannot be studied easily in a direct capture reaction;
- the capture process goes to the ground state of the fusion product which is the initial state for C.D.;
- the proton binding energy is small to ensure dominant Coulomb character of the reaction.

The latter condition makes sure that nuclear dissociation plays a minor role at least at forward angles. Another potential source of errors is the different multipolarity composition of the equivalent photon spectrum and/or higher order effects (e.g. "postacceleration"). Theoretical calculations for the C.D. of ^{8}B (see e.g. Ref. [5])

show that for GSI bombarding energies ($\approx 200\ A$ MeV) such effects are less important compared to lower bombarding energies of about 50 A MeV available at GANIL, MSU, or RIKEN. Another advantage of the high energies is that the large-acceptance focussing spectrometer KaoS [6] with its ideal momentum range $p_{max} = 2p_{min}$ can be used which allows an easy discrimination between non-interacting beam and break-up events.

In the following sections, we will summarize the achievements of our previous experiments and propose continued experiments on the C.D. of ^{8}B. We will then discuss the technical feasibility of and the required beam time for the new cases.

3 Further measurements of the Coulomb Dissociation of ^{8}B

In our first C.D. experiment at GSI (Proposal S171) we have measured the Coulomb dissociation of ^{8}B at 254 A MeV using a ^{8}B beam of about 5×10^3 ions/spill from the FRS [4]. The aim of this study was to check the results of a similar RIKEN experiment at $\approx 50\ A$ MeV [3] using a higher bombarding energy and to compare the results to those of the direct (p,γ) reaction. Our preliminary differential cross-section distribution and the deduced S_{17} factors are shown in Figs.1 and 2, respectively. Extrapolating to $E_{rel} = 0$ with the help of theoretical models, we obtain $S_{17}(0) = 20.1 \pm 1.4$ ev b, in very good agreement with the most recent evaluation of the RIKEN C.D. experiment [3] and the most recent (p,γ) experiment of Hammache et *al.* [10]. These results show convincingly that $S_{17}(0)$ is smaller by about 30% than what was deduced from some of the earlier (p,γ) experiments [11, 12] but lies within the (rather generous) error limits of a recent review of the topic [13].

Despite of the apparent success of our first experiment, an important quantity, the angular distribution of the outgoing (^{7}Be+p)-system relative to the incoming ^{8}B projectile, could not be measured due to a failure of the PPAC detectors in front of the Pb breakup target. This prevented (i) a decomposition of the angular distribution into the different multipoles, and (ii) to search for deviations from pure Coulomb interaction due to nuclear overlap. Moreover, such a measurement could allow to study the angular correlations of ^{7}Be (or p) and adress the problem of asymmetric longitudinal momentum distributions of ^{7}Be fragments found in MSU experiments [15].

Another aspect deserves experimental study. In the course of the RIKEN experiments it became clear that C.D. of ^{8}B feeds the first excited state in ^{7}Be with a branching ratio of about 5% on average [3] (these results have been taken into account when extracting the results shown in Fig. 2). Since this ratio is energy-dependent, we will measure γ-rays in coincidence with Coulomb breakup in future experiments. It is foreseen to use a compact CsI array currently being developed by the LAND collaboration.

Due to the rather low ^{8}B intensity from FRS, we had to use a thick ^{208}Pb breakup target with a thickness of 200 mg/cm^2. This led to E_{rel} resolutions of ≈ 140 keV at $E_{rel} = 200$ keV and ≈ 210 keV at $E_{rel} = 400$ keV. With increased primary-beam

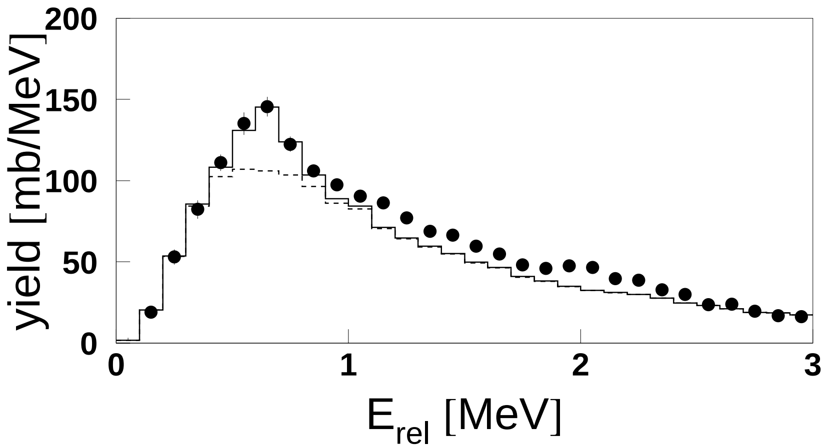

Fig. 1. Differental cross sections $d\sigma/dE$ for the C.D. of ^{8}B from our previous experiment S171 (filled circles). The histograms (from a GEANT simulation) show the decomposition into (E1+M1) and E1 multipolarity, assuming E2 to be negligible. For the M1 resonance at $E_{rel} = 0.63$ MeV we obtain an integrated cross section of about 10 mb when using the experimental value $\Gamma\gamma = 25$ meV [17].

intensity we could reduce the target thickness to about 50 mg/cm^2 and thus improve the resolution to about 85 keV and 120 keV, respectively.

Since ^{7}Be(p,γ)^{8}B is of utmost importance for solar-neutrino physics and since it is an ideal test case for the method of C.D., we propose to perform further measurements of the ^{8}B C.D. and to improve on our previous experiment by the following modifications:

1. PPAC detectors from RIKEN [16] will be inserted at 308 cm and 71 cm, respectively, upstream from the KaoS target. Their position resolution of ≈ 1 mm (FWHM) allows a definition of the ^{8}B incident angle with an accuracy of about 0.6 mrad. Their efficiencies for light ions (e.g. ^{14}Be at 75 A MeV) have been tested at RIKEN and are close to 100% [16].

2. A compact CsI array will be used to measure coincident γ-rays.

3. To improve the E_{rel}-resolution, we will use a thinner ^{208}Pb target of 50 mg/cm^2, which will reduce, however, the C.D. interaction probability to $\approx 4 \times 10^{-5}$.

4. With the primary ^{12}C intensity at the FRS target increased by a factor of about 10 (from an average of 1×10^{10}/spill in the previous run to the space-charge limit of about 1×10^{11}/spill) and twice the measuring time of the previous run (i.e. 7 d), we could nevertheless improve the statistics by a factor of 5 leading to a total of about 1.5×10^5 breakup events, equivalent to about 1500 events in the lowest E_{rel} bin from 100 to 200 keV.

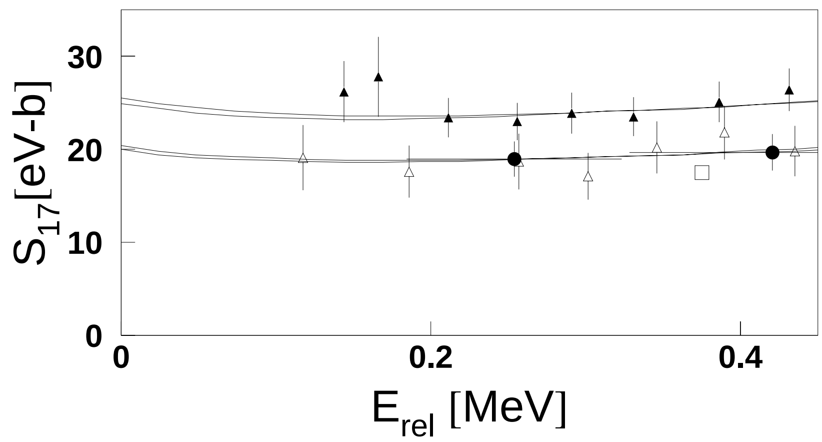

Fig. 2. Low-energy astrophysical S_{17}-factor for the ^{7}Be(p,γ)^{8}B reaction. The filled circles denote the preliminary results of our experiment. The square is from the RIKEN C.D. experiment [3]; lower triangles have been measured in ^{7}Be(p,γ) experiments by Filippone *et al.* [17] which agree well with the most recent study of Hammache *et al.* [10]. All results shown are at variance with the upper triangles from the work of Kavanagh *et al.* [12]. The theoretical curves indicate how the data could be extrapolated to $E_{rel} = 0$ [14].

The improved setup and statistics would enable us to check at which angles nuclear processes start to compete with pure Coulomb breakup and if E2 breakup can be disentangled from E1. The smaller E_{rel} binning below 400 keV will allow a more sensitive comparison with the upcoming high-sensitivity ^{7}Be(p,γ) experiments and thus represent a more stringent test of the obtainable accuracy of the C.D. method than our first run.

4 Coulomb Dissociation of ^{27}P

The astrophysical reaction rate of the ^{26}Si(p,γ)^{27}P reaction, which bypasses the production of ^{26}Al and ^{26}Mg, is believed to be dominated by the resonant capture of protons into the $3/2^+$ first excited state in ^{27}P at E_X=1.18 MeV (corresponding to $E_{rel} = 0.32$ MeV) with a resonance strength of $\omega\gamma = 1.51$ meV, which decays by M1 radiation to the $1/2^+$ ground state of ^{27}P. The $3/2^+$ level energy and strength have only been estimated by shell model calculations [7]. Compared to older estimates [8], which took into account only the E1 direct capture to the ground state, the inclusion of this resonance changes the reaction rate by more than 3 orders of magnitude at the temperature range relevant for novae and x-ray bursts, thus having a strong impact on nucleosynthesis calculations in this mass range [7]. Due to the short half life of ^{26}Si ($T_{1/2} = 2.2\ s$) and the problems of diffusing Si out of a primary target in an ISOL-type radioactive ion beam facility, direct approaches (radioactive target or a ^{26}Si ion beam) can be ruled out. But the relatively low Q-value and the isolated position of the resonance makes it an ideal case for investigation via C.D. of ^{27}P. Due to the amplification of the E2 component in C.D. we also have to consider the

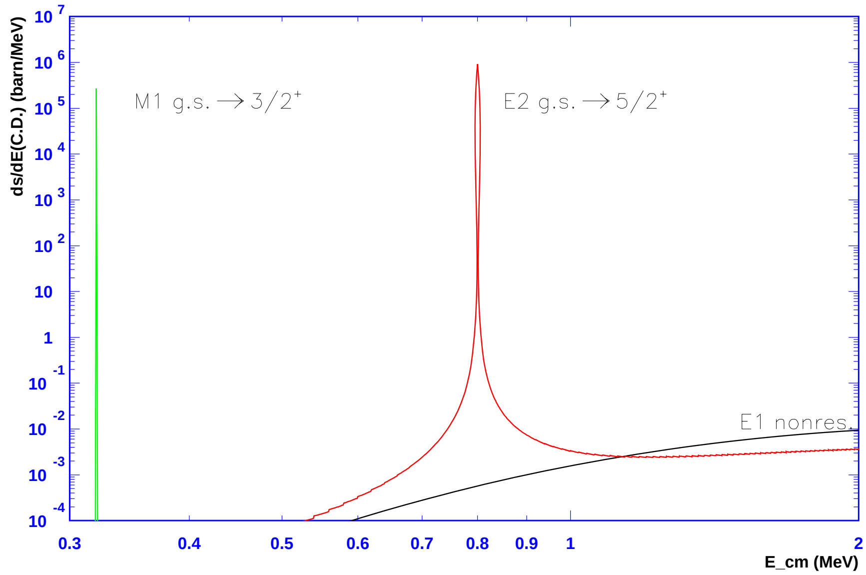

Fig. 3. Predicted differential cross sections $d\sigma/dE$ for the Coulomb dissociation of ^{27}P [7] (neglecting experimental resolution). The M1 resonance at E_{rel} = 0.32 MeV ($\sigma \approx$ 1 mb) and the E2 resonance at E_{rel} = 0.80 MeV ($\sigma \approx$ 140 mb) have sufficient strength to be observed in the C.D. of ^{27}P [7], while the nonresonant E1 contribution is predicted to be too weak to be observed.

$5/2^+$ resonance involving the second excited state at E_x=1.66 Mev (corresponding to E_{cm} = 0.80 MeV) which is connected to the $1/2^+$ ground state via an E2 transition. The calculations are depicted in Fig.3 and show clearly that the contribution of the M1 resonance involving the first excited state and the E2 resonance involving the second excited state dominate the spectrum.

Integrating over the resonances, we obtain $\approx$ 1 mb for the M1 and $\approx$ 140 mb for the E2 resonance. With a primary beam of ^{32}S of 10^{11}/spill (space-charge limit) we calculate a ^{27}P intensity of $\approx$ 8×10^5 after the FRS production target and of $\approx$ 5×10^3 in Cave C yielding about 35 events/day in the M1 resonance with a 100 mg/cm^2 ^{208}Pb breakup target. To obtain an overall accuracy of about 30%, a counting time of about 5 days seems to be appropriate. The rate for the E2 resonance is correspondingly larger and lends itself to a test of the setup with reduced beam intensity (e.g. from the ECR source during the first half of 1999).

5 Coulomb Dissociation of ^{23}Al

In astrophysical scenarios, ^{22}Mg is the product of the reaction ^{21}Na(p,γ)^{22}Mg and can either decay to the long lived ^{22}Na or bypass it via the reaction ^{22}Mg(p,γ)^{23}Al. The reaction rate is believed to be dominated by the resonant capture of the protons into the $1/2^+$ first excited state in ^{23}Al at E_x=0.487 MeV (corresponding to a proton energy of 0.360 MeV) with a very weak resonance strength of $\omega\gamma$=0.25 μeV. The energy of the level has been obtained via a measurement of the ^{24}Mg(^{7}Li,^{8}He)^{23}Al transfer reaction, while the resonance strength has been inferred with the help of shell model calculations [9]. The small resonance strength makes it impossible to measure this reaction directly (this would require more than 10^{12} ^{22}Mg ions/s, much more than the $\approx 10^6$ ions/s available presently from ISOL-type facilities). In C.D., however, this resonance can be populated strongly by the intense flux of E2 photons. The integration over the resonance yields an integrated cross section of approximately 1 mb, identical to the ^{27}P M1 case. The predicted intensity of ^{23}Al is approximately a factor of 5 smaller than that for ^{27}P, however, necessitating a correspondingly longer counting time of about 12 d (assuming a Pb breakup-target thickness of 200 mg/cm^2). This we propose to do in a second experiment after a successful result from the C.D. of ^{27}P.

6 Summary of beam time requests

Summarizing the requests for the above cases, we ask for the following amounts of beam time:

Priority	Topic	Primary beam	Setup/FRS-tuning [days]	Production [days]	total [days]
1	C.D. of ^{8}B	^{12}C	3	7	10
2	C.D. of ^{27}P	^{32}S	2	5	7
	Total 1+2		5	12	17
3	C.D. of ^{23}Al	^{32}S	3	12	15

Priorities 1 and 2 use an identical set-up and should preferentially be allocated in the second half of 1999, but need primary-beam intensities close to the space-charge limit. Due to the lower ^{23}Al intensities available, part 3 will be postponed until a successful completion of parts 1 and 2.

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