STORI24: Constraining Explosive Nucleosynthesis by Indirect Reaction Methods at Storage Rings using unstable beams in batch mode

G. de Angelis[1] F. Recchia[2,3] J. Glorius[4] J. Gerl[4] B. Jurado[5] X. L. Tu (涂小林)[6] J. L. Lou (楼建玲)[7] S. Carollo[2,3] C. Berthelot[5] N. Watwood[8] B. P. Kay[8] P. Aguilera[2,3] M. L. Avila[8] J. Benito Garcia[3] K. Bhatt[8] D. Brugnara[3] K. A. Chipps[9] A. Couture[10] A. Demerdjiev[11] G.D. Dimitrova[11] S. Dutta[12] A. Ertoprak[8] R. Escudeiro[2,3] S. J. Freeman[13,14] F. Galtarossa[3] E. Geleva[11] B. Gongora Servin[1,15] A. Gottardo[1] A. Hall-Smith[8,16] J. Henderson[17] C. Hoffman[8] R. O. Hughes[18] H. Jayatissa[10] M. La Commara[19,2] G. Leckenby[5] S. M. Lenzi[2,3] D. Mengoni[2,3] M. R. Mumpower[10] W. J. Ong[18] M. Paul[21] J. Pellumaj[1] C. Domingo-Pardo[22] R. M. Perez Vidal[1,22] S. Pigliapoco[2,3] A. Ratkiewicz[18] K. Rezynkina[3] S. Rocca[1,2] D. K. Sharp[13] Y. Sun (孙扬)[12] T. L. Tang[23] D. Tonev[11] I. A. Tolstukhin[8] G. Wendell Misch[10] M. Williams[18] B. Wloch[5] F. F. Zeng (曾凡斐)[1]

[1]Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, viale dell'Università 2 I-35020, Legnaro, Italy
[2]Dipartimento di Fisica e Astronomia, Università degli Studi di Padova, I-35131, Padova, Italy
[3]Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy
[4]GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany
[5]Université de Bordeaux, CNRS, LP2I Bordeaux, 33170 Gradignan, France
[6]CAS Key Laboratory of High Precision Nuclear Spectroscopy, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[7]School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China
[8]Physics Division, Argonne National Laboratory, Argonne, IL 60439
[9]Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
[10]Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
[11]Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Science, BG-1784, Sofia, Bulgaria
[12]Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, China
[13]CERN, CH-1211 Geneva 23, Switzerland
[14]Department of Physics and Astronomy, University of Manchester M13 9PL, UK
[15]Dipartimanto di Fisica e Scienze della Terra, Università di Ferrara, Ferrara, Italy
[16]Department of Physics, University of York, Heslington, York YO10 5DD, UK
[17]Department of Physics, University of Surrey, Guildford, GU2 7XH, UK
[18]Lawrence Livermore National Laboratory, 7000 East Ave, Livermore, CA 94550, USA
[19]Farmacy Department, Università degli Studi "Federico II" di Napoli, Napoli 80126, Italy 20Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Napoli 80126, Italy
[21]Racah Institute of Physics, Hebrew University, Jerusalem, Israel 91904
[22]Instituto de Fisica Corpuscular, CSIC-Universidad de Valencia, E-46071 Valencia, Spain
[23]Department of Physics, Florida State University, Tallahassee, Florida 32306, USA

Abstract: Nuclear reaction studies on unstable isotopes can strongly help in improving our understanding of nucleosynthesis in stars. Indirect approaches to determining astrophysical reaction rates are increasingly common-place and undergoing continuous refinement. Of particular interest is the use of such indirect techniques at storage rings, which, among other allow to recycle rare unstable beams. We propose to investigate reaction rates of astrophysical interest using indirect methods (surrogate, Trojan horse….) in reverse kinematics at the IMP-CAS storage ring. Long lived radioactive ion beams, produced remotely, can be accelerated, and made interacting with light targets. Proposed reactions are $^{85}Kr(p,p'\gamma)$, $^{85}Kr(d,p\gamma)$, constraining the neutron flux in an s-process branching point, $^{79}Se(p,p'\gamma)$, $^{79}Se(d,p\gamma)$, constraining the temperature in s-process nucleosyntheses, $^{59}Fe(d,p\gamma)$, constraining core collapse supernovae.

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I. INTRODUCTION

All the elements in the universe heavier than helium were created inside the core of stars by nuclear reactions. Massive stars, that is, stars with eight or more times the mass of the Sun, are believed to have played an essential role in producing the vast number of chemical elements with masses 56 < A < 90. Low mass stars, with one to

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three times the mass of the Sun, are expected to have originated the other elements. The first stars formed after the Big Bang (Population-III/ Pop-III) are believed to have been both massive and short-lived, which makes them exceedingly difficult to be observed today and leaves many open questions about the early history of the universe. As such, the characteristics of the first stars must be pieced together by observing the signatures they impart on the next generation of stars (Pop-II), which preserve the chemical fingerprints of their predecessors. However, large uncertainties in key nuclear reaction rates significantly hinder our ability to reliably compare models with observational data, leaving fundamental questions about the first stars unanswered, such as: How massive were they? How did they evolve? And what was their fate? Many open questions exist related to the origin of the elements, particularly those heavier than iron, and the astrophysical conditions in which they were made. Capture cross sections on many unstable nuclei needs to be provided to the models used to predict s- and r- process nucleosynthesis. An open problem is how to explain abundancies in s/r stars, showing an intermediate composition between s- and r- processes, requiring the so-called i-processes. i-processes show indeed a path involving many unstable nuclei that can be experimentally reached by the existing and forthcoming radioactive ion beam facilities. Unprecedented insight into how the elements were created is gained through combining observations from modern astronomy, isotopic analysis of meteorite samples, and microscopic nuclear physics. However, our predictions as to how stars forged the chemical elements rely critically on our knowledge of the underlying nuclear reactions that made them. Many important reactions involve short-lived radioactive nuclei not found in nature, and so must instead be produced in the laboratory. We are now entering into a golden-era for studies of nuclear reactions on radioactive isotopes, with several new radioactive ion beam (RIB) facilities now coming into operation, such as the HIAF facility in China, the RAON facility in Korea, the Facility for Rare Isotope Beams (United States), the Advanced Rare Isotope Laboratory (Canada), the HIE-ISOLDE at CERN and the SPES facility at LNL (Italy).

Being the reactions of interest neutron-capture or charged particle reactions, and since in most of the cases we are dealing with radioactive species, normal kinematics are not always possible. In the absence of a neutron target, indirect reaction methods become an interesting possibility. Indirect approaches to determining astrophysical reaction rates are increasingly common-place and undergoing continuous refinement, especially as several new rare-isotope facilities around the world are soon to be online. A very promising approach is provided by the so-called surrogate reaction method in inverse kinematics [1−4]. For both (p,γ) (using mirror symmetry arguments [1, 2]) and (n,γ) [3−5] reactions, the (d,p) reaction is often used, coupled with appropriate assumptions. Focusing on neutron captures, the surrogate reaction, like (d,p) or (d,d'), produces the compound nucleus of interest by a different reaction than the pure neutron capture reaction. The idea of the method is to factorize the reaction cross section in two terms, one accounting for the formation of the compound nucleus and the second for the successive decay. The formation can be accurately described by nuclear models. Instead, the difficult decay of the compound nucleus, where different channels are competing as a function of total spin and excitation energy, is investigated experimentally. The measured decay probabilities of the compound nucleus are then used to tune model parameters leading to much more accurate predictions of the desired neutron-induced cross sections. Suitable reactions are exchange reactions with light nuclei, e.g. (d,p) or inelastic scattering reactions like (d,d') or (p,p'). In the (d,p) experiment, an heavy-ion beam is directed onto a deuterium gas target (inverse kinematics). During the particle exchange, the neutron of the deuterium target is passed on to the projectile nucleus and the remaining proton is detected. Another surrogate reaction of interest is the inelastic-scattering reaction of protons or deuterons - denoted ((p,p'), (d,d')) - where the proton/deuteron is scattered leaving the heavy projectile in an excited state for further decay. The detection of charged particles (p,d), (p,p'), (d,d') and gamma rays is used for the identification of the different decay branches. There has been significant progress in the interpretation of surrogate-reaction datasets [5−9].

II. EXPERIMENTAL SET-UP AND DATA ANALYSIS

Many of the cases of interest for the heavy element nucleosynthesis involve radioactive nuclei. The low production rate at RIB facilities combined with the generally low efficiency of the γ detector arrays is therefore a limiting factor for the use of the surrogate method. An interesting possibility is offered by the use of long-lived radioactive species, which can be produced for example in reactor facilities and, after chemical separation, accelerated and made interacting with the target, decoupling in this way the production and the acceleration stages. As an example of surrogate reactions done in the so-called "batch-mode", we have recently investigated the ^{85}Kr(d,p) reaction as surrogate for the ^{85}Kr(n,γ) neutron capture reaction [9]. The precise knowledge of this cross section is indeed relevant for the s-process nucleosynthesis. In the modeling of the s-process, the competition between neutron capture and β-decay offers the opportunity to constrain the physics conditions of the stellar environment, in particular in the so-called "branching points". ^{85}Kr is an important branching point of the s-process, that influences both the ^{86}Kr/^{82}Kr ratio in pre-solar grains and the abundances of heavy Sr isotopes that are produced also by r-process. A better understanding of this branching point can be achieved only if the neutron capture cross section on ^{85}Kr is sufficiently well constrained, but a direct measurement of this cross section is extremely challenging due to the radioactivity of the sample ($T_{1/2}$ = 10.7 yr). However, ^{85}Kr can be accelerated as a pure beam, and the (d,pγ) reaction has been demonstrated to be a reliable indirect probe of the (n,γ)-reaction cross section [5].

The ^{85}Kr(d,pγ)^{86}Kr reaction has been carried out at 10 MeV/u in inverse kinematics at Argonne's ATLAS facility (USA) [9] using the HELIOS solenoidal spectrometer [10] and the Apollo γ-detector array, Figure 1. Excitations from around 2-14 MeV in ^{86}Kr were populated with a Q-value resolution of about 150 keV. γ-rays from ^{86}Kr have been observed in coincidence with protons, which

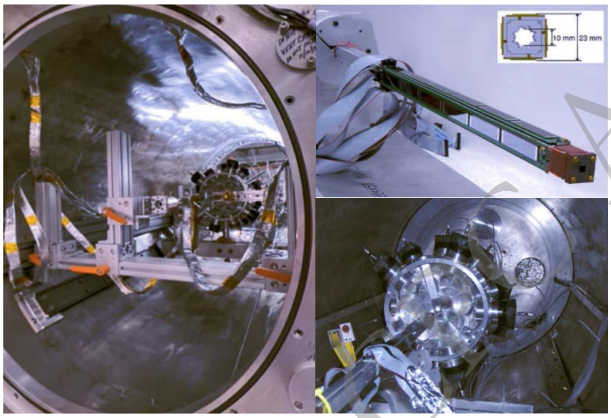

Fig. 1. (color online) HELIOS spectrometer and the Apollo array at the ATLAS facility in Argonne (USA) [10].

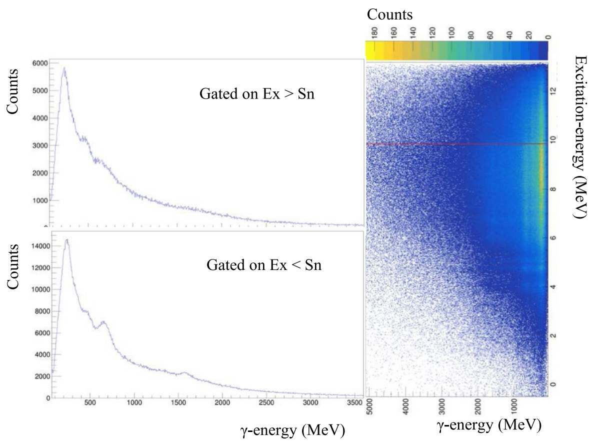

Fig. 2. (color online) γ-rays in coincidence with protons from the ^{85}Kr(d,pγ) reaction at 10 MeV/u [9]. Right: γ-energy versus total excitation energy. Left: gamma spectra gated above (up) and below (down) the neutron binding energy (S_n=9.86 MeV). The 2^+ and 4^+ excitations in ^{86}Kr are clearly visible.

will allow us to determine the γ-ray emission probabilities as a function of excitation energy [$P_\gamma(E_{ex})$]. Figure 2 (Right) shows the γ-ray energy versus the total excitation energy. When gating below the neutron separation energy S_n=9.86 MeV, the $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ γ-rays of ^{86}Kr are clearly visible (figure 2 left), showing the characteristic constant value of P_γ below Sn and a decrease above Sn. These data are used to extract the cross sections for ^{85}Kr(n,γ) reaction, complementing recent direct, high-precision measurements on the stable Kr isotopes. This technique demonstrates significant potential for future indirect studies of the (n,γ) reaction.

III. IN RING EXPERIMENTS

A very interesting alternative for the application of indirect reaction methods is offered by the use of Storage Rings. Storage rings are ideally suited for storing heavy ions at energies between few MeV/u and several 100 MeV/u [11]. The ions revolve in the ring about a million times per second ensuring an extraordinary quality of the beam in terms of purity and emittance and an enhancement in sensitivity of orders of magnitude with respect to single pass experiments. Rings are also equipped with electron coolers, which reduces the longitudinal momentum spread, the energy resolution ΔE/E being improved from typically 10^{-3} in single-pass experiments to 10^{-4}-10^{-5}, and the beam size reduced from about 1 cm to 1 mm diameter.

The stored ions interact with ultra-thin, windowless gas-jet targets located inside the ring, for which thicknesses up to about 10^{14} atoms/cm^2 can be obtained for light gases as H_2, D_2, ^{3}He and ^{4}He. The electron cooler compensates the energy loss of the beam in the gas target. Hence, the ions pass the target always at the same energy – quite in contrast to most single-pass experiments.

Another important advantage of the in-ring experiment is the direct measure of the ions after interaction with the target (and consequent trajectory change), without therefore the need of measuring γ-rays, γ-ray detection systems being characterized by relatively low efficiency [12].

In-ring surrogate reactions of astrophysical interest have been recently performed at the GSI, Darmstadt storage ring using a ^{208}Pb beam [11]. An interesting possibility is also provided by the storage ring CSRe at IMP, Lanzhou, China, where the collection of low energy (25 MeV/u) stable beams has been recently tested [13], see Figure 3. Figure 4 shows the pixelated detector used for proton inelastic scattering (p,p') experiments [14,15]. Of particular interest is the use of radioactive ion beams (RIBs) produced directly inserting long lived activity into the accelerator source, using the so-called "batch mode". The method, somewhat restricted to long lived and commercially available isotopes, allows to produce

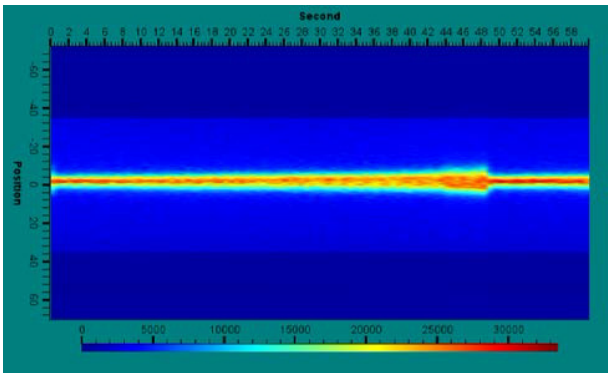

Fig. 3. (color online) Stored $^{56}Fe^{26+}$ at 25 MeV/n at CSRe (corresponding to a magnetic rigidity of 1.5 Tm) [13].

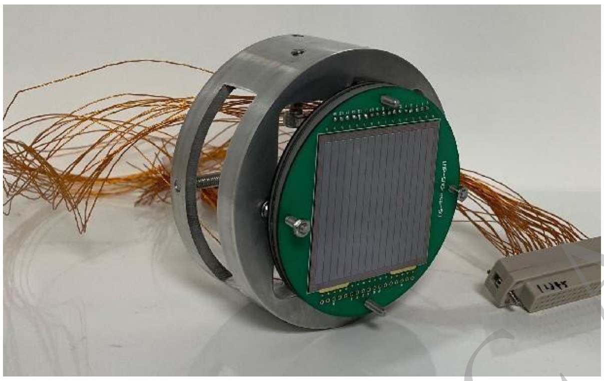

Fig. 4. (color online) Si strip detector for proton inelastic scattering experiments (three layers with 300, 500 and 500 μm thickness) [14, 15].

relatively high intensity beams, overcoming therefore the limited intensity of many secondary beams. In the following we list some of the cases of interest for the determination of neutron capture reactions relevant for stellar nucleosynthesis (s-, r- and i-processes) studied via the surrogate reaction method:

A. ^{86}Kr(p,p'γ) (constraining s-process branching point – neutron flux)

The competition between slow neutron capture by, and β decay of, the radioisotope ^{85}Kr is a source of significant uncertainty in modeling the s-process. As previously discussed, we have recently measured at ATLAS (ANL-USA) the capture cross section with the surrogate reaction method using a >99% pure beam of ^{85g}Kr (T1/2 = 10.7 yr) at 10 MeV/u [8] using the ^{85}Kr(d,pγ)^{86}Kr surrogate reaction. Here we propose to remeasure the same capture cross section using a different surrogate reaction *^{86}Kr(p,p'γ)* as a test bench for in-ring measurements at CSRe IMP, Lanzhou, China, using a stable isotope.

B. ^{80}Se(p,p'γ) ^{79}Se(d,pγ) (constraining s-process branching point – stellar thermometer)

^{79}Se is an s-process branching point, and it is located in a region where two scenarios may contribute, the one from massive stars (weak s-process component) and that of AGB stars (main s-process component). Knowledge of the neutron-capture cross section of ^{79}Se provides a crucial test of our understanding of s-process nucleosynthesis in massive stars, allowing one to assess reliably the thermal conditions and therefore the role of the weak and main s-process components. The ^{79}Se(n,γ) reaction is particularly relevant, since it leads to the production of the s-only ^{80}Kr and ^{82}Kr isotopes, which are shielded from the rapid neutron capture process by their stable (or almost stable) isobars ^{80}Se and ^{82}Se ($t_{1/2} = 10^{20}$ yr). Proposed surrogate reactions are proton inelastic scattering on stable ^{80}Se or (d,p) reaction on a radioactive ^{79}Se, both in reverse kinematics. The results obtained in this experiment could be an excellent complement to the direct measurement performed at n_TOF which extends up to a few keV (only) [16].

C. ^{60}Fe(p,p'γ) ^{59}Fe(d,pγ) (constraining core collapse supernovae)

Ongoing stellar nucleosynthesis in our galaxy is proven by the presence of ^{60}Fe, which, with a half-life of 2.62 Myr, has a lifetime much shorter than the age of the galaxy. ^{60}Fe is produced in massive stars through neutron capture reactions in the high neutron flux reached during C-shell burning and in core-collapse supernovae, the dominating reaction being ^{59}Fe(n,γ)^{60}Fe, a reaction which cannot be presently studied directly. To investigate the production of ^{60}Fe we have gotten approved ATLAS beam time using an enriched beam of ^{59}Fe ($T_{1/2}$=44.5 days) at 9 MeV/u. The goal is to study the ^{59}Fe(d,pγ)^{60}Fe reaction populating states in the proximity of S_n in inverse kinematics using HELIOS Solenoidal Spectrometer. The combined use of a Ge tracking device would allow to constrain the ^{59}Fe(n,γ)^{60}Fe reaction using the surrogate reaction method. The final aim is to improve our knowledge of the core-collapse Supernovae or AGB stars as well as to update the model of the origin of the Solar System.

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