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Simulations and developments of the Low Energy Neutron detector Array LENA

C. Langer [a,b,*], A. Algora [c,d], A. Couture [e], M. Csatlós [c], J. Gulyás [c], M. Heil [a], A. Krasznahorkay [c], J.M. O'Donnell [e], R. Plag [a,b], R. Reifarth [a,b], L. Stuhl [c], K. Sonnabend [b], T. Tornyi [c], F. Tovesson [e]

[a] GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany
[b] J.W. Goethe Universität, 60438 Frankfurt a.M., Germany
[c] Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI), P.O. Box 51, H-4001 Debrecen, Hungary
[d] Instituto de Fisica Corpuscular (CSIC-University of Valencia), Aptdo. Correos 22085, E-46071 Valencia, Spain
[e] Los Alamos National Laboratory, Los Alamos, NM 87545, USA

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ABSTRACT

Prototypes of the Low Energy Neutron detector Array (LENA) have been tested and compared with detailed GEANT simulations. LENA will consist of plastic scintillation bars with the dimensions $1000 \times 45 \times 10\ \mathrm{mm}^3$. The tests have been performed with γ-ray sources and neutrons originating from the neutron-induced fission of ^{235}U. The simulations agreed very well with the measured response and were therefore used to simulate the response to mono-energetic neutrons with different detection thresholds. LENA will be used to detect low-energy neutrons from (p,n)-type reactions with low momentum transfer foreseen at the R^{3}B and EXL setups at FAIR, Darmstadt.

1. Introduction

The field of nuclear astrophysics profits strongly from the interplay of experimental and theoretical nuclear physics, stellar modeling, and observations. Unfortunately, in some cases laboratory based measurements cannot be used directly in stellar simulations. This is true for β-decay and electron capture rates, which can be very different from the terrestrial values in the hot plasma of stars or for the extreme conditions during supernova explosions. Electron captures can occur to excited states, which are energetically not allowed on Earth [1]. Also beta-decays from thermally excited states cannot be measured in the laboratory. These effects can sometimes alter the decay rates by orders of magnitude [2,3]. Depending on the stellar environment, different rates can be reflected in different abundance patterns, which allow constraints on stellar parameters [4–6].

For the theoretical calculations of stellar rates, Gamow–Teller (GT) strength distributions $B(GT)$ for low lying states are needed. Charge-exchange reactions, like the (p,n) reaction, allow access to these transitions and can serve as input for rate calculations. In particular, there exists a proportionality between (p,n) cross-sections at low momentum transfer (close to 0°) and $B(GT)$ values:

$$\frac{d\sigma^{CE}}{d\Omega}(q=0)=\hat{\sigma}_{GT}(q=0)B(GT)$$

where $\hat{\sigma}_{GT}(q=0)$ is the unit cross-section for GT transitions at $q=0$ [7].

In order to access the Gamow–Teller distributions for unstable nuclei, charge-exchange experiments have to be carried out in inverse kinematics with radioactive ion beams. Subsequently it is necessary to detect neutrons with low-energies at large laboratory angles relative to the incoming beam.

In general, spin–isospin transitions are important in nuclear processes and in nuclear structure. Another typical example for this is the existing correlation between the cross-section of a spin–dipole resonance and the neutron skin thickness, which is an important input to constrain the density dependence of the symmetry energy. Charge-exchange reactions, like the (p,n) reaction, allow the study of such spin–isospin excitations in unstable nuclei.

At the upcoming R^{3}B (Reactions with Relativistic Radioactive Beams) setup at FAIR [8], Darmstadt, shown in Fig. 1, reactions with exotic nuclei close to the driplines can be studied at medium relativistic energies in the range of up to 1 AGeV [9]. Another experimental part at the FAIR facility will be the EXL (Exotic nuclei studied in Light-ion induced reactions at the NESR storage

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* Corresponding author.
E-mail address: c.langer@gsi.de (C. Langer).

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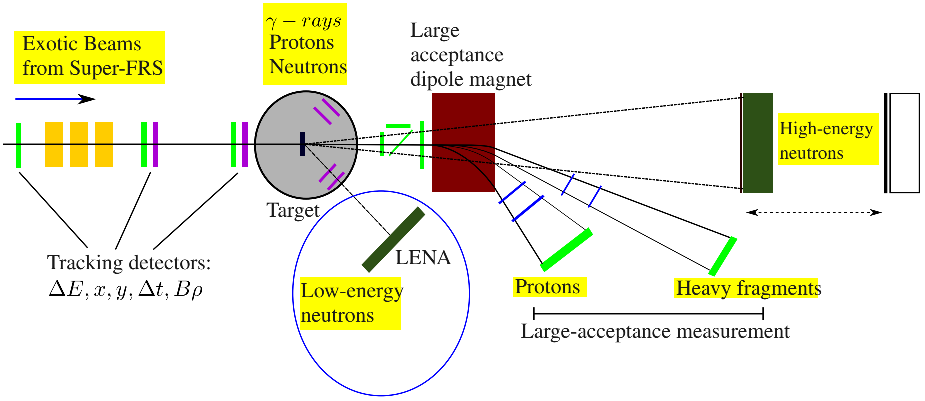

Fig. 1. Main part of the planned R^{3}B setup at FAIR, Darmstadt. LENA is situated downstream of the target and the position is marked in the picture. The distance to the target depends on the kinematical requirements for each experiment and will be around 1–2 m (not to scale).

ring) experiment, which utilizes high target luminosities in a typical storage-ring technique. Both experiments highly profit from kinematically complete measurements in inverse kinematics with the capability to reach the driplines with still sufficient intensities. The R^{3}B and the EXL experiment can be used to carry out charge-exchange experiments with unstable and very exotic beams. Therefore, a new detector is developed for low-energy neutrons stemming from (p,n)-type reactions. A number of detectors with similar techniques and applications are developed and tested at other places too [10–12].

The scope of this article is to describe the developments done so far. Section 2 characterizes the basic properties of the detector and is followed in Section 3 by a description of simulations performed with GEANT3 and measurements with γ- and X-ray sources. In order to understand the detector response to neutrons, an experiment at the Los Alamos National Laboratory with a neutron beam was performed. The results are described in Section 3. Because of the good agreement between the simulations and the experimental data, the simulations are used to study the energy-dependent efficiency of the detector for mono-energetic neutrons. The results are summarized in Section 4.

2. Characteristics

This section describes the basic properties of the detector called LENA (Low Energy Neutron detector Array). A typical experimental motivation for an experiment at the R^{3}B setup is described in the first part. The requirements of the flexible detector setup are derived from the involved kinematics and the geometrical arrangement in the following part.

2.1. Experimental motivation

A typical problem of charge-exchange reactions in normal kinematics is the large background caused by quasi-free charge-exchange processes of the projectile neutrons in thin targets. In inverse kinematics it is possible to use relatively thick targets without disturbing the energy spectrum of the recoiled neutrons to achieve reasonable statistics. An experimental example for a proposed study in inverse kinematics is shown in Fig. 2. The distance of the LENA detector to the R^{3}B target will be between 1 and 2 m.

The calculated kinematics for this particular experiment at two different beam energies is shown in Fig. 3. The respective neutron energies are usually between 0.1 MeV and a few MeV, i.e. a resolution of 10% in the determination of the neutron kinetic energy requires a resolution of 1° in the scattering angle and a resolution of 1 ns for the time-of-flight.

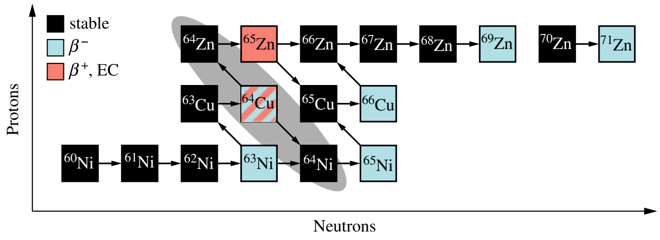

Fig. 2. An example for a proposed measurement utilizing a (p,n)-type reaction at the R^{3}B setup: the reaction network during s-process nucleosynthesis between Ni and Zn. Since the neutron capture branch can be neglected due to the long capture times compared to the decay rate, the (β^+,*EC*)/β^--branch point at ^{64}Cu can be interpreted as a thermometer of the weak s-process, if the β-decay rates under stellar conditions are known [13].

The detector setup and the geometrical arrangement stays flexible and generic. It can be rearranged, depending on the individual proposed study.

2.2. Detector setup

Taking into account the above mentioned constraints several possible detector types were considered for the construction of the LENA detector array. The need to achieve high angular resolution and high detection efficiency at a relatively low cost for neutron energies of up to a few MeVs resulted in two possibilities: (a) a construction of an array of liquid scintillator neutron detectors or (b) the use of an array of plastic scintillator bars. From these alternatives the second option was chosen. The array of plastic bars is safer to handle and provides the necessary angle and position resolution if the light, produced by the neutrons, is read out by fast PhotoMultiplierTubes (PMTs) at both ends of the bars. Another advantage is the possibility of a more compact packing of the detectors using less support material. The detection mechanism for low-energy neutrons is the proton-recoil elastic scattering of the neutrons on the protons in the detector material. A well-known fact is the energy quenching effect which turns out to be the main challenge in building the detector.

LENA is an array consisting of up to 60 single detectors subdivided into smaller arrays. The final arrangement depends case-by-case on the experiment to be performed, see Fig. 3. LENA is mainly build at ATOMKI, Debrecen, Hungary, in collaboration with GSI Darmstadt and the Goethe University of Frankfurt, both Germany. LENA combines high granularity to measure the angle