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Coulomb excitation studies at LNL with the SPIDER-GALILEO set-up

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Abstract

Low-energy Coulomb excitation is one of the simplest and most known tools to study the nuclear shape; for this reason it is nowadays widely used at radioactive beam facilities. The Selective Production of Exotic Species (SPES) facility, for the acceleration of radioactive beams will soon provide the first exotic beams at the Laboratori Nazionali di Legnaro (LNL) in Italy. To this end a new particle detector (Silicon PIe DEtectoR) to be used for Coulomb excitation studies has been installed at LNL. SPIDER has been coupled to the GALILEO array of germanium detectors, and a number of experiments have been already successfully performed. This paves the way for future experiments with the radioactive beams provided by the SPES facility.

Keywords: Coulomb excitation, gamma transitions, experimental methods in nuclear physics

(Some figures may appear in colour only in the online journal)

1. Introduction

Coulomb excitation is an ideal tool to study collective properties of nuclear states, since it provides information about key observables such as reduced transition probabilities, quadrupole moments and quadrupole shape invariants. These properties are sensitive to the shape of the nuclear states and their study brings us closer to understand the nuclear many-body problem. In particular it allow to investigate the interplay between the stabilizing effect of shell and subshell closures (which leads to sphericity) and the residual interactions between protons and neutrons outside closed shells (which drives the nucleus to deformation).

The basic assumption of Coulomb excitation is that the excitation of nuclear states is caused solely by the electromagnetic field acting between the colliding nuclei, without

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the contribution of short range nuclear forces. For this assumption to be satisfied, it is necessary that the distance of closest approach for a nucleus-nucleus collision exceeds the so called safe distance usually taken as somewhat larger than the sum of the two nuclear radii (the empirical Cline criterion [1]). The excitation probabilities can be written in terms of the nuclear electromagnetic matrix elements [2] and can be calculated to a high precision by the well-known theory of the electromagnetic interaction. In this way the structure of the involved nuclear states can be studied in a model-independent way.

Coulomb excitation measurements can be performed in a simple way using particle spectroscopy. This method offers a rapid and accurate way to determine the probability of exciting a given state in target nuclei, since it can be directly determined by measuring the relative intensities of the inelastic and elastic peaks of the scattered projectile in the particle spectra. The disadvantage is that it can be applied only to study excited states directly populated from the ground state in nuclei with low level density. Moreover it is limited to light beams (typically $A \leqslant 20$) and requires the use of very thin and pure targets.

In order to study many excited states in Coulomb excitation with heavy-ion beams, γ-ray spectroscopy is necessary. The high energy resolution of germanium detectors allows in principle to disentangle the excitation of levels a few keV apart, but, since they are emitted by the recoiling nucleus and/or the scattered projectile, the energy resolution is to a large extent spoiled by the Doppler effect. To limit this effect the γ-ray-particle coincidence technique is usually employed. A segmented charged-particle detector, measuring the scattered projectile and recoiling target nuclei, is coupled to an array of γ-ray detectors. In this way it is possible to reconstruct the scattering kinematics of the reaction, essential for a precise Doppler correction. The segmentation of the particle detector also permits to exploit the dependence of the excitation probability on the particle scattering angle, thus increasing the precision of the measured transition probabilities and quadrupole moments. In experiments with stable beams, the ion detector is usually positioned at backward angles in order to maximise the multi-step excitation probability and to increase the sensitivity to the reorientation effect, important for the extraction of quadrupole moments.

The excitation probabilities are indirectly determined from the intensities of transitions in the particle-gated γ-ray spectra, since the excitation and the subsequent γ-ray emission are governed by the same set of matrix elements. To extract the electromagnetic matrix elements from Coulomb excitation data, the GOSIA code can be used [3]. The code performs a fitting procedure to the experimental γ-ray yields, using the matrix elements as parameters. To help the fitting procedure, additional spectroscopic data (such as lifetimes, mixing-ratios, together with their experimental uncertainties) can be included in the analysis as extra points to be fitted.

In the following, after a short description of the SPIDER-GALILEO array, a review of the first experiments performed with stable beams will be given. The good results obtained demonstrate the possibility to perform Coulomb excitation measurements with the high-quality stable beams currently available at the Tandem-ALPI-PIAVE accelerator complex at Laboratori Nazionali di Legnaro (LNL), and open the way to future experiments with the Selective Production of Exotic Species (SPES) radioactive beams.

2. The GALILEO and SPIDER arrays

A new segmented heavy-ion detector, the Silicon PIe DEtectoR (SPIDER) [4], has recently been developed in a collaboration among the INFN units of Firenze, LNL and Padova, to be used as a Coulomb excitation ancillary device of the GALILEO γ-ray spectrometer [5] for Coulomb-excitation studies. The new Coulomb excitation set-up, composed of GALILEO and SPIDER arrays is shown in figure 1.

The GALILEO array is, at present, composed of 25 Compton-suppressed HPGe detectors. The measured full width at half maximum (FWHM) energy resolution is below 2.4 keV and the absolute full energy peak efficiency is equal to 2.4% at 1 332.5 keV [5]. The acquisition system is fully digital and can process data with rates up to 50 kHz per detector. A global trigger assures the precise synchronisation of the GALILEO array and its ancillary devices.

The SPIDER array consists of independent, trapezoidal shaped, silicon detectors segmented on the front surface into eight annular strips. The rear surface consists of a unique electrode. Using eight detectors, it is possible to obtain a disk-shaped array. A guard ring is located in the gap between any two adjacent strips to reduce the cross-talk effect and the charge splitting between them. The energy resolution (FWHM) of the SPIDER strips at 5.5 MeV, is about 20 keV when mounted in the test station, and about 50 keV when the array is coupled with GALILEO. To fit the size of the GALILEO vacuum chamber, seven detectors of SPIDER have been assembled in a cone configuration. The array is placed at backward angles, covering a polar angular range from 123 to 161 degrees in the laboratory frame. The polar angle segmentation of the SPIDER array allows to achieve, after Doppler correction, a final FWHM of about 10 keV @ 1 MeV in a typical spectrum acquired with GALILEO.

3. Experiments with stable beams

3.1. Collective character of low-lying states in ^{66}Zn

The interpretation of low-lying states in stable zinc isotopes has been widely debated in the literature, in the framework of both collective and shell models. These nuclei are expected to exhibit collective excitations even at low excitation energies since they have a sufficient number of valence nucleons to develop macroscopic degrees of freedom. Being located not too far from the $Z = 28$ and $N = 28$ shell closures, the stable zinc isotopes have been at first suggested as examples of vibrational nuclei [6]. The excitation energies of the 2_1^+, 2_2^+, 4_1^+, 0_2^+ states are reported as a function of A (from $A = 62$ to $A = 68$) in figure 2. They seem to be in agreement with a

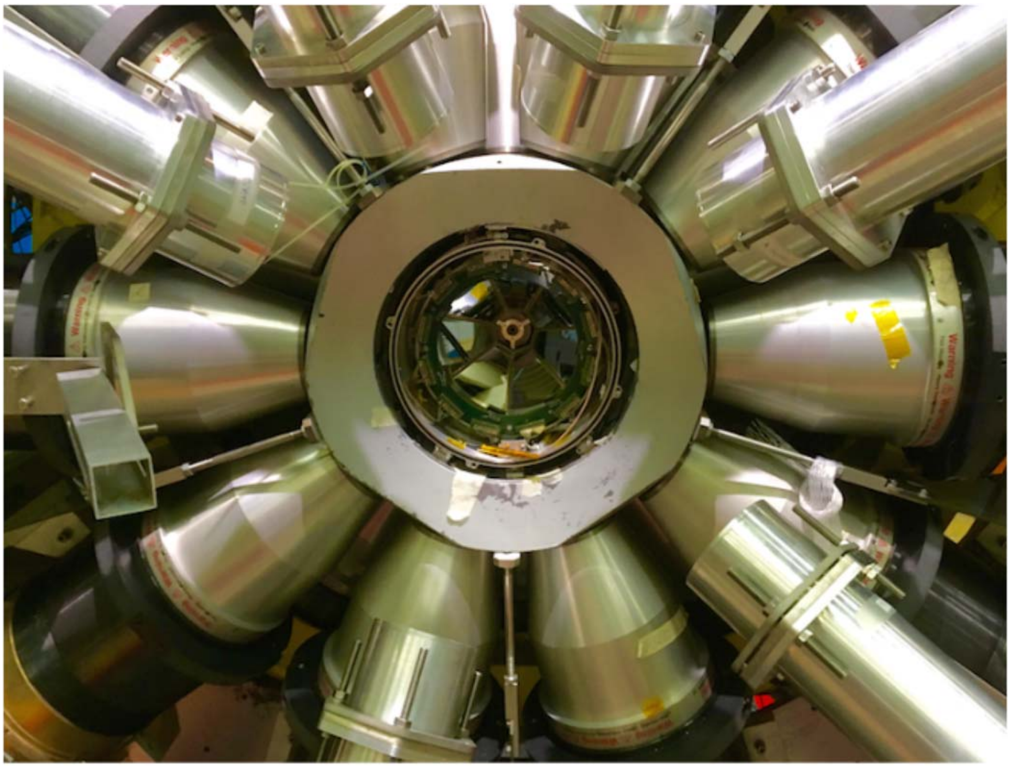

Figure 1. The Coulomb excitation set-up composed of the SPIDER array mounted in the GALILEO vacuum chamber.

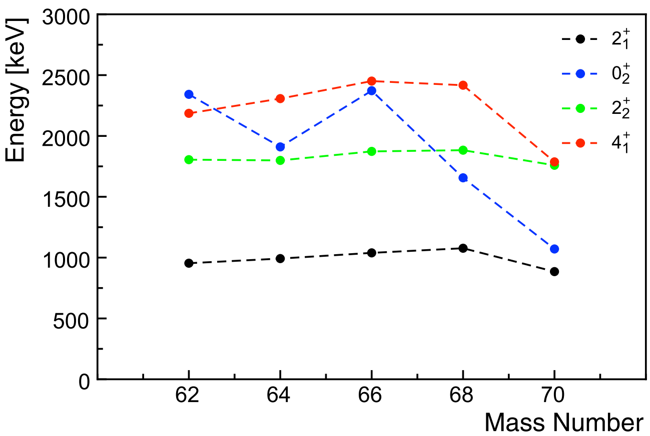

Figure 2. Energy of low-lying states for even zinc isotopes reported as a function of the mass number. Dashed lines are shown only to guide the eye.

multi-phonon picture, with the exception of the excitation energy of the 0_2^+. Other observables, such as transition probabilities and spectroscopic quadrupole moments, indicate a more complex underlying structure. Quasi-rotational bands, built on the ground state and the 2_2^+ state, have been identified in ^{64}Zn [7] and suggested also in ^{66}Zn and ^{68}Zn [8, 9]. Also triaxiality seems to have an important role in these isotopes, even though from the existing data it cannot be determined if it is related to γ-softness or more rigid deformed shapes [8]. Notably, triaxiality has been established in the same mass region for germanium and selenium isotopes, where also indications of shape coexistence exist [10, 11] (a phenomenon not yet clearly observed in zinc isotopes).

The fact that different models are capable of reproducing some features of the low-lying structure of stable zinc isotopes, but not all of them, can be also ascribed to the several discrepancies which are reported in the literature concerning some key measured observables. The case of ^{66}Zn is particularly relevant in this context, since significantly different values are reported for the $B(E2; 2_2^+ \rightarrow 2_1^+)$ and $B(E2; 4_1^+ \rightarrow 2_1^+)$ values, and no $B(E2)$ values are available for transitions from the 0_2^+ state [12]. In addition, the spectroscopic quadrupole moment of the first excited state has been measured some years ago in a Coulomb excitation experiment [8]. Interestingly, its magnitude is reproduced by shell model and beyond-mean-field calculations, but not its positive sign.

In order to provide further information regarding the low-lying structure of ^{66}Zn, we performed a Coulomb excitation experiment at LNL using a 240 MeV ^{66}Zn beam impinging on a ^{208}Pb target (1 mg cm^{-2} thick). The conditions of the experiment were very similar to those reported in [8], thus providing a good benchmark to test the operation of the set-up.

The total Doppler corrected γ-ray spectrum, collected in coincidence with the backscattered ^{66}Zn projectiles, is shown in figure 3. Transitions resulting from the excitation of the 2_1^+, $2_2^+, 0_2^+, 4_1^+$ states are clearly visible. The collected statistics are sufficient to subdivide the number of counts for the observed transitions into eight different angular ranges, thus exploiting the full segmentation of SPIDER in the GOSIA analysis. The yield of the $0_2^+ \rightarrow 2_1^+$ transition is sufficient to extract, for the first time, the corresponding $B(E2)$ value. The $2_3^+ \rightarrow 2_1^+$, $2_2^+ \rightarrow 0_1^+$ and $3_1^- \rightarrow 2_1^+$ transitions have been observed for the

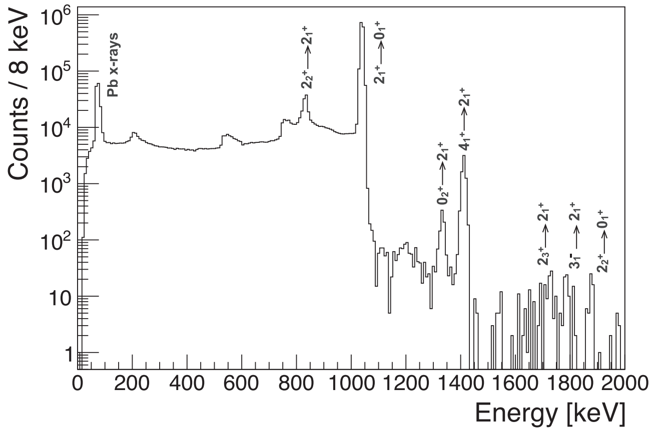

Figure 3. Total γ-ray spectrum acquired by the GALILEO array in coincidence with the backscattered ^{66}Zn projectile detected by SPIDER array.

first time in Coulomb excitation, even though the collected statistics are not sufficient to allow for a full subdivision into scattering angular ranges. The first two transitions are essential to determine the deformation parameters of the ground state, while from the latter a new value for the $B(E3;\, 3_1^- \to 0_1^+)$ can be obtained. The sign and magnitude of the measured spectroscopic quadrupole moment for the first excited state ($Q_{\mathrm{exp}}(2_1^+) = +24(9)$ efm^2) is in excellent agreement with the result reported in [8] ($Q_{\mathrm{lit}}(2_1^+) = +24(8)$ efm^2), providing a validation of the SPIDER-GALILEO set-up. The complete results will be published in a forthcoming paper.

3.2. Shape coexistence in ^{94}Zr

The zirconium isotopic chain has been the subject of both experimental and theoretical investigations, in an attempt to understand how collectivity evolves in the $A \sim 90$ mass region. Indeed, different shapes for the ground state in the zirconium nuclei have been predicted (and in some cases observed), going from a mid-open-shell region (^{80}Zr$_{40}$) to a closed neutron sub-shell (^{96}Zr$_{56}$), through a closed neutron shell at ^{90}Zr$_{50}$. Evidence also exists for coexistence of different shapes within the same isotopes [13–15].

Recently, shape coexistence in even–even zirconium isotopes has been studied theoretically in the framework of the Monte Carlo Shell Model [16], with a focus on the shape transition from $N = 50$ to $N = 70$. Figure 4 shows the excitation energies and the predicted shapes of the $2_{1,2}^+$ and $0_{1,2}^+$ states. The authors also proposed the zirconium isotopes near to the neutron subshell closure $N = 56$ as candidates for displaying type-II shell evolution [17].

In this context the ^{94}Zr isotope is particularly interesting, since existing experimental data suggest a coexistence of spherical and oblate bands in this nucleus [14]. A Coulomb-excitation experiment has been performed at LNL in order to directly determine the quadrupole deformation in the ground state and in the low-lying excited states of the ^{94}Zr nucleus. An energy of 370 MeV for the ^{94}Zr beam, impinging on a 1 mg cm^{-2} thick ^{208}Pb target, was chosen in order to maximise the population of higher-lying states, providing higher sensitivity to spectroscopic quadrupole moments, while fulfilling the safe-energy criterion [1].

The γ-rays de-exciting the populated states were detected by GALILEO in coincidence with scattered beam particles detected by SPIDER, thus allowing to reconstruct the kinematics and to apply an event-by-event Doppler correction of the γ-ray spectra. For the first time, the GALILEO-SPIDER set-up was coupled to 6 large volume 3″ × 3″ LaBr$_3$:Ce detectors [18] in order to increase the γ-ray detection

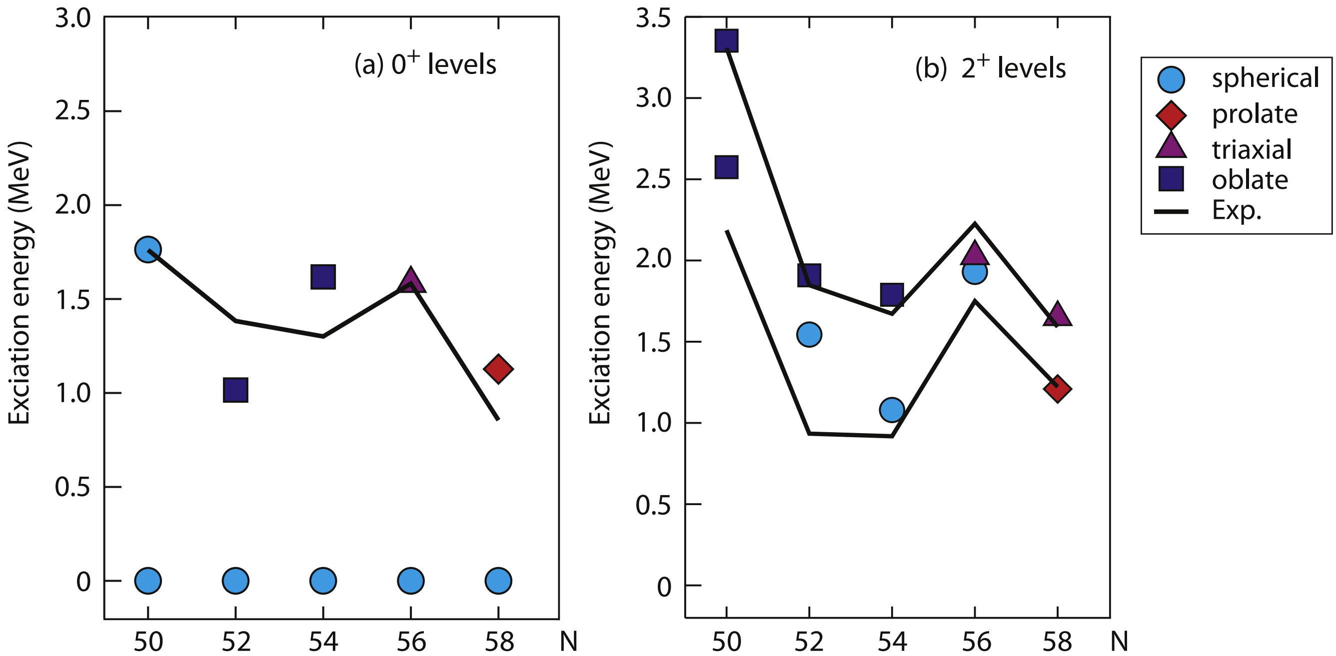

Figure 4. Experimental (continuous line) and calculated excitation energies (symbols) of the $0_{1,2}^+$ (panel a) and $2_{1,2}^+$ (panel b) states in Zr isotopes. The symbols indicate the calculated shape of each state. Figure adapted from [16].

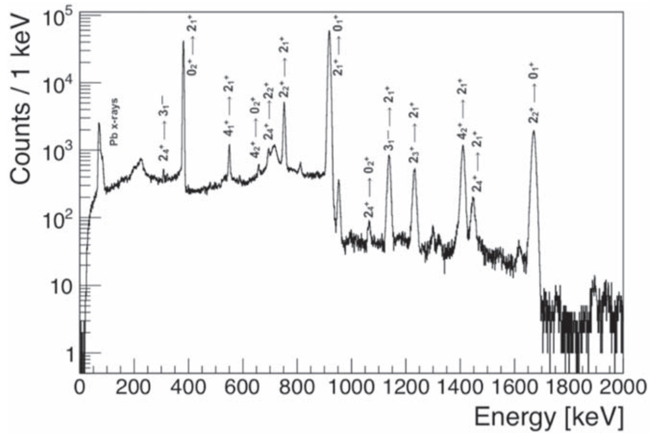

Figure 5. Spectrum of γ-rays acquired by the GALILEO array in coincidence with the backscattered ^{94}Zr projectile detected by SPIDER array.

efficiency, particularly important for the relatively high γ-ray energies involved in the de-excitation of certain key states.

A preliminary γ-ray energy spectrum acquired in coincidence with backscattered ^{94}Zr ions is shown in figure 5. The excitation of the 2_1^+, 2_2^+, 2_3^+, 2_4^+, 4_1^+, 4_2^+ and 0_2^+ states has been observed. We clearly see all the transitions required to obtain the spectroscopic quadrupole moments of the 2_1^+ and 2_2^+ states and to determine the deformation of the ground states and of the 0_2^+ state using quadrupole sum rules [19]. In the spectrum in figure 5, the excitation of the 3_1^- state is also observed. The experimental data are currently being analysed with the code GOSIA [3].

3.3. Shape Coexistence in ^{116}Sn

The tin isotopes ($Z = 50$) offer the excellent opportunity to perform a systematic investigation of the shell evolution as a function of the neutron number, going from the doubly-magic very neutron-deficient ^{100}Sn to the doubly-magic neutron-rich ^{132}Sn. During the last decades, several studies have been accomplished employing both stable and radioactive ion beams (RIBs) in order to measure the reduced transition probabilities between the low-lying states of the Sn isotopes, mainly via Coulomb excitation because of the presence of low-lying isomers.

Within the stable tin isotopes, ^{116}Sn represents an interesting case: on one side the proton shell $Z = 50$ and neutron sub-shell $N = 64$ closure suggests a spherical configuration, while, on the other side, the increasing number of valence neutrons drives the system to the maximum of collectivity. The balance between these two aspects may result in the presence of shape coexistence, which has been already suggested in ^{112,114}Sn [20].

A multi-step Coulomb excitation of a ^{116}Sn target was performed at LNL, in order to investigate the collectivity of both yrast and excited states in this nucleus. A ^{58}Ni beam at the energy of 180 MeV was used. The γ-rays depopulating the Coulomb-excited states were detected by the GALILEO array, in coincidence with the ions detected by SPIDER. Since only back scattered beam ejectiles could be detected by the SPIDER array, a kinematics reconstruction is required to determine the velocity vector of the target recoils. The calculated velocities are then used to perform an event-by-event Doppler correction for the γ-ray lines emitted by the target. In figure 6 a preliminary Doppler corrected γ-ray spectrum for the recoiling target is presented. The detailed analysis of the experimental data is still on-going.

4. Perspectives with the SPES beams

Developments over the last decades in the production and study of RIBs have resulted in techniques that allow to explore the properties of isotopes with large neutron excess and to investigate the density dependence of the effective interaction between the nucleons for exotic N/Z ratios. Coulomb excitation is an ideal tool for studies using the currently available RIBs: The available beam energies of few MeV/A correspond to the maximum probability of multi-step excitation, while the low beam intensities can be compensated by the large cross section of the excitation process.

The facility SPES [21] for production and post-acceleration of exotic nuclei is currently under construction at LNL. SPES is an Isotope Separation OnLine (ISOL) type facility. The ISOL method requires a high-intensity primary beam of light particles from a driver accelerator and a thick hot fissile target, from which the exotic nuclei diffuse and effuse into an ion source, for ionisation and extraction. At SPES, a cyclotron will accelerated a 40MeV proton beam on to a uranium carbide multi-foil target. The proton beam intensity will reach $\sim$200 μA. Neutron-rich radioactive ions will be produced in the target at an expected maximum rate of the order of 10^{13} fissions per second. After the extraction, the reaction products will be isotopically selected using a High Resolution Mass Spectrometer, designed to reach 1/20000 mass resolution. At the exit of the HRMS the transport line will be split: on one side the highly resolved RIB can be sent to the Low Energy Area, on the other side it can be sent towards the superconducting linac of LNL for post-acceleration.

Letters of Intent (47) for experiments with both low-energy and post-accelerated beams have been already submitted to the SPES Scientific Advisory Committee. The topics covered by the LoIs are summarized in figure 7. Several of them require the use of the SPIDER array as an ancillary detector for Coulomb excitation experiments with radioactive beams. These include studies of neutron-rich Kr isotopes and nuclei close to ^{132}Sn, which are among the first-day beams expected at SPES.

5. Conclusions

The GALILEO-SPIDER set-up for Coulomb excitation experiments at LNL was commissioned in an experiment aimed at studying the collectivity in ^{66}Zn. Subsequently, a number of experiments were performed using stable beams available at LNL from the Tandem-PIAVE-ALPI accelerator

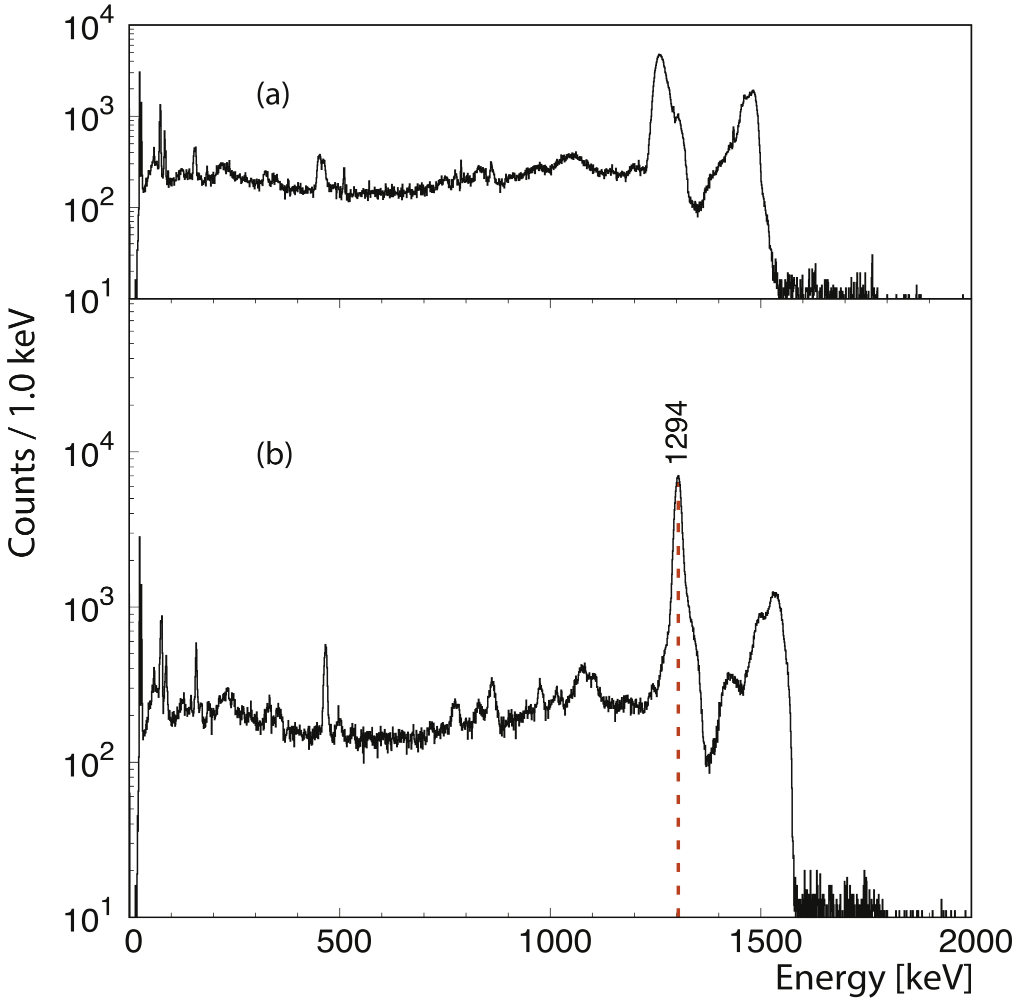

Figure 6. (a) Spectrum of γ-rays detected by the GALILEO array in coincidence with backscattered ^{58}Ni projectile (b) the same energy spectrum Doppler corrected for the recoiling target nuclei. The $2_1^+ \rightarrow 0_1^+$ transition of ^{116}Sn is marked in red.

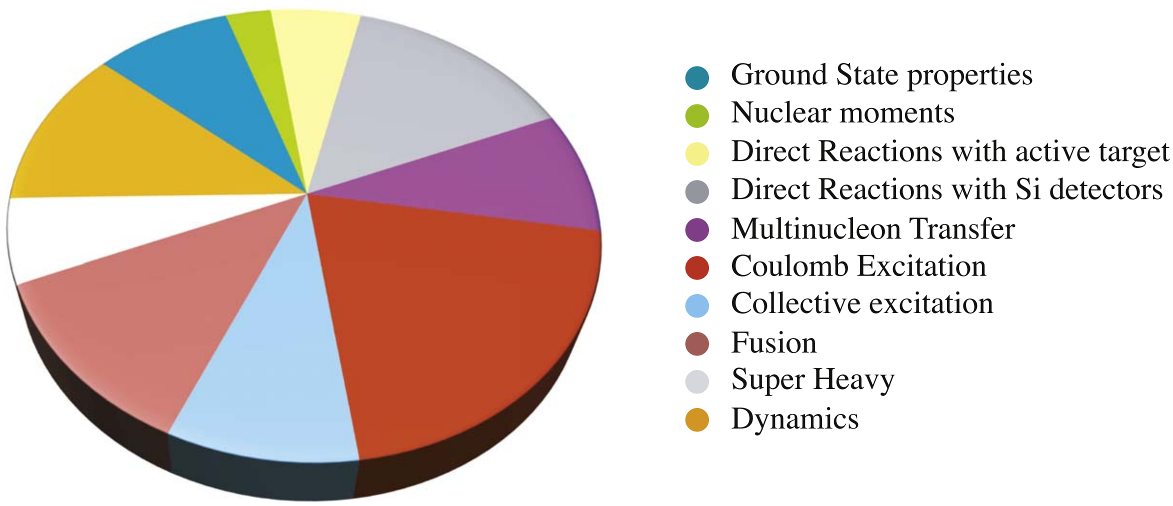

Figure 7. The Letters of Intent presented for experiments with the SPES post-accelerated beams grouped according to their topic.

complex. As an example we report on the ^{94}Zr and ^{116}Sn cases. Other experiments using stable beams are scheduled or planned.

Furthermore, several Letters of Intent have been submitted to use the SPIDER array as an ancillary detector for the future Coulomb excitation experiments with radioactive beams delivered in a near future by the SPES facility at LNL.

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