IFIN-HH
Proposal for the TANDEM accelerator
First Campaign of experiments 2018

Searching for shape coexistence in ^{64}Ni

B. Fornal[1], N. Cieplicka-Orynczak[1], L. Iskra[1], A. Maj[1], P. Bednarczyk[1], M. Ciemala[1], M. Kmiecik[1], S. Leoni[2], A. Bracco[2], G. Bottoni[2], G. Benzoni[2], F. Camera[2], F. Crespi[2], G. Gosta[2], A. Mentana[2], S. Ziliani[2], M. Sferrazza[3], N. Mărginean[4], C. Mihai[4], M. Boromiza[4], C. Clisu[4], C. Costache[4], A. Ionescu[4], R. Lică[4], R. Mărginean[4], R.E. Mihai[4], A. Mitu[4], C.R. Niță[4], A. Olăcel[4], S. Pascu[4], P. Petkov[4], L. Stan[4], A. Turturică[4], S. Ujeniuc[4], C.A. Ur[5]
T. Otsuka[6], Y. Tsunoda[6]

[1] *IFJ-PAN, Krakow, Poland*
[2] *Università degli Studi di Milano and INFN sez. Milano, Milano, Italy*
[3] *Université libre de Bruxelles (ULB), Belgium*
[4] *Horia Hulubei National Institute for Physics and Nuclear Engineering, Măgurele, Romania*
[5] *ELI-NP, Romania*
[6] *University of Tokyo, Tokyo, Japan*

Spokespersons: B. Fornal, S. Leoni, N. Mărginean

Abstract

We propose to investigate excited states in ^{64}Ni, focusing on 0^+ states which, according to Monte Carlo Shell model calculations, are expected to exhibit different shapes. This study follows the successful measurements on ^{66}Ni, performed in Bucharest in 2016, which gave evidence for a shape-isomer-like state at 0 spin. In ^{64}Ni, two excited 0^+ states were located, and only for the first one the lifetime has been reported with large uncertainty. Shell model calculations predict the existence of a third excited 0^+ state, in analogy with the case of ^{66}Ni. In a test experiment performed at IFIN-HH in July 2017, we have identified a candidate for a transition de-exciting such a state. In this proposal we would like to pin down the nature of this transition (with energy of 2503 keV) by performing: i) angular distribution, ii) relative yield measurements, by using proton and neutron transfer reactions induced by ^{11}B and ^{18}O beams on ^{65}Cu and ^{62}Ni targets, respectively. Lifetime measurement of the known 0^+ states will be also performed.
For these purposes, two different setups will be used: i) the newly developed setup at the 5th beam line, devoted to angular distribution studies and consisting of a DSSDS detector of annular geometry, coupled to 3 HPGe detectors of clover type, and ii) the ROSPHERE array, for spectroscopy studies and lifetime measurements by DSAM and plunger techniques.

***We request 21 days of beam time, divided as follows**:*
- *7 days: angular distribution measurement (setup at 5th beam line, $^{65}Cu(^{11}B,^{12}C)^{64}Ni$, $E_b = 26$ MeV);*
- *4+2 days: yield measurements (ROSPHERE, $^{65}Cu(^{11}B,^{12}C)^{64}Ni$, $E_b= 26$ MeV, $^{62}Ni(^{18}O,^{16}O)^{64}Ni$ $E_b= 39$ MeV);*
- *8 days: plunger measurements (ROSPHERE, $^{62}Ni(^{18}O,^{16}O)^{64}Ni$, $E_b= 39$ MeV).*

1. Physics Motivation

Nuclear isomers play a key role in understanding nuclear structure physics [1]. Of special interest are shape isomers: they may arise when the nuclear potential energy surface, in the deformation space, has minima associated with different shapes and when a high barrier separates these minima. So far, shape isomers, discovered in the 60's, were known to occur only in the heavy actinide nuclei [2], although, since the 80's, mean-field models predicted their existence also in lighter systems, pointing to ^{66}Ni and ^{68}Ni as the lightest candidates [3-6]. Recently, fully microscopic, state-of-the-art shell-model calculations, based on Monte Carlo Shell Model (MCSM) computational schemes and the use of very powerful supercomputing systems (the Japanese K-computer with 1 million parallel processors) elegantly confirmed shape coexistence in the Ni isotopes and indicated ^{66}Ni as the most promising case [7].

In July 2016, we performed an experiment in Bucharest, in which, by employing the two-neutron transfer reaction induced by an ^{18}O beam on a ^{64}Ni target (at the sub-Coulomb barrier energy of 38 MeV), all three lowest-excited 0^+ states in ^{66}Ni were populated and their γ decay was observed by γ-coincidence technique, as shown in Fig. 1. The 0^+ states lifetimes were assessed with the plunger method, yielding for the 0^+_2 , 0^+_3 , and 0^+_4 decay to the 2^+_1 state the B(E2) values of 4.3, 0.1, and 0.2 Weisskopf units (W.u.), respectively. The retardation of the E2 decay from 0^+_4 was interpreted to arise from a sizable potential barrier between the prolate (secondary) and spherical ground state minima [8]. This result makes the ^{66}Ni nucleus a unique example of a nuclear system, apart from the actinides, in which a shape-isomer like structure exists.

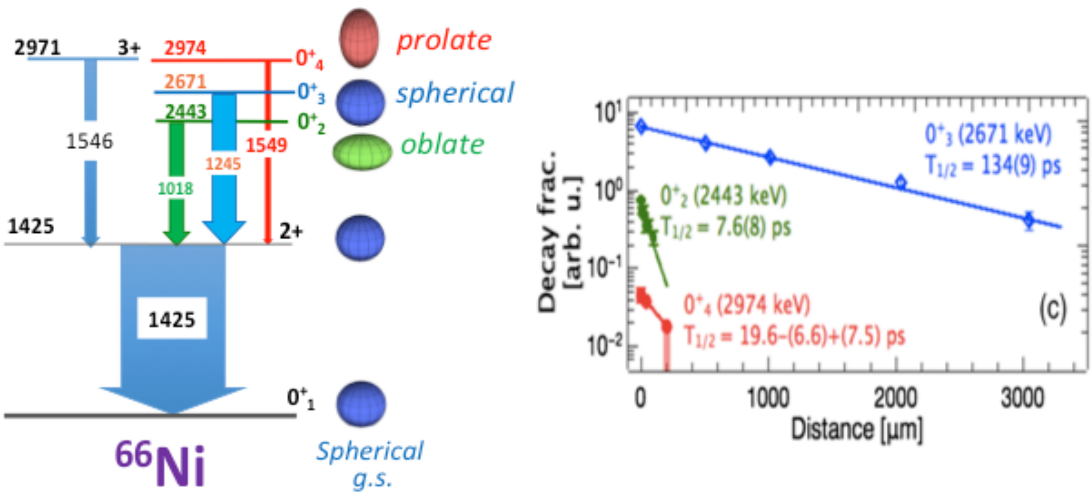

***Fig. 1**: Left: partial level scheme of ^{66}Ni, focusing on the decay of the 0^+ states, associated with spherical, oblate and prolate shapes, as predicted by Monte Carlo Shell Model calculations. Right: decay curves for the excited 0^+ states, measured in Bucharest by plunger techniques [8].*

This experimental discovery shows that shape isomerism is possible not only in very heavy nuclei: it remarkably appears in significantly lighter systems, as correctly predicted by theory. This phenomenon is considered a manifestation of Type II shell evolution: sizable excitations of neutrons in the $g_{9/2}$ orbital causes a reduced proton spin-orbit splitting which favors promotion of protons across the Z=28 shell gap, leading to a stabilization of a deep prolate local minimum [7].

A similar scenario, although at higher excitation energy and with unknown magnitude, is predicted by the MCSM calculations in ^{64}Ni.

In the ^{64}Ni nucleus, the present experimental information is not sufficient to draw meaningful conclusions about coexistence of shapes, therefore a detailed experimental investigation of 0^+ states is needed. What regards 0^+ states, the two lowest ones were located at 2867.3 and 3025.9 keV [9], and only for the first one the lifetime has been reported ($T_{1/2}$ = 0.04(2)) ps) [10], however, as discussed later, this lifetime is expected to be much longer. In analogy with the case of ^{66}Ni, shell model calculations predict the existence of a third excited 0^+ state, as well.

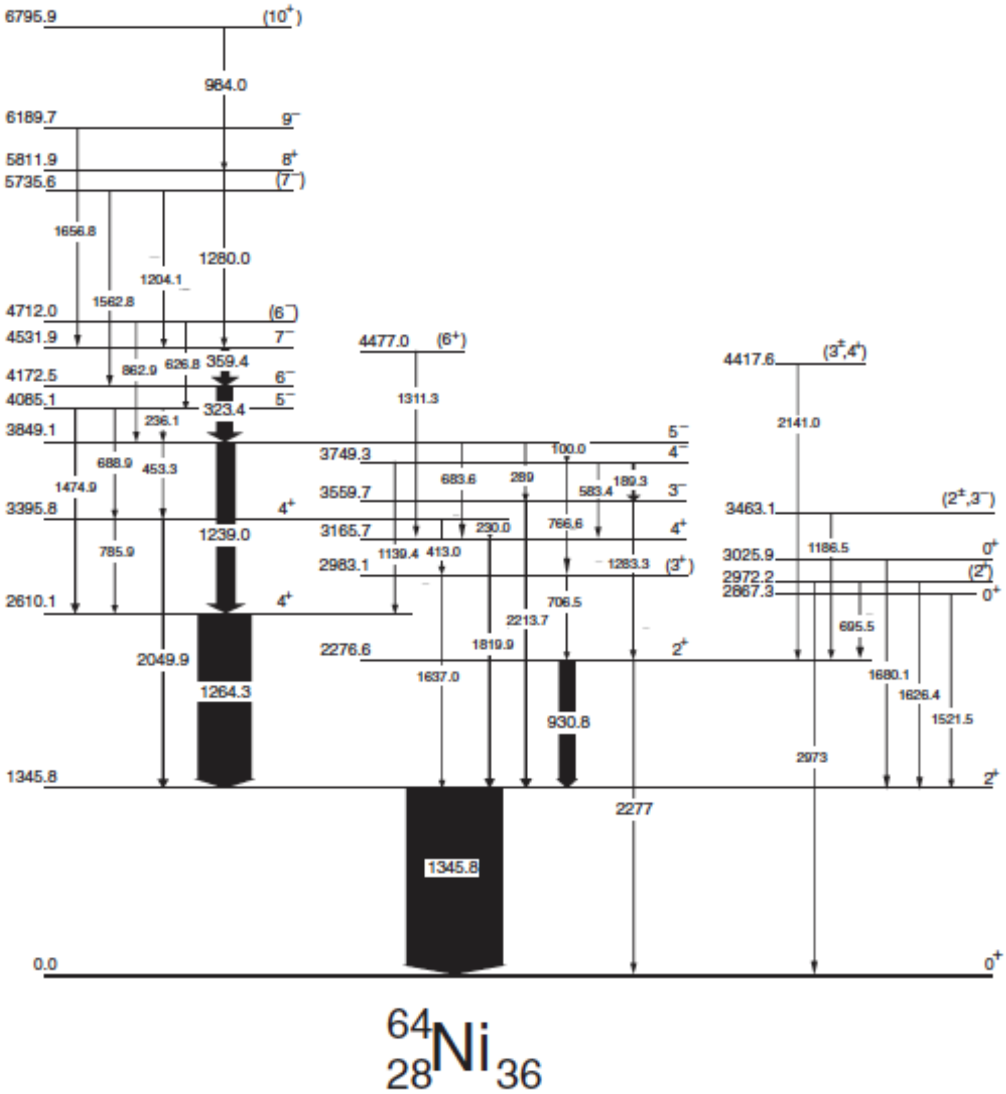

***Fig. 2**: Level scheme of ^{64}Ni, from Broda et al. [9].*

In a test experiment performed at IFIN-HH in July 2017, we have verified the possibility of populating excited states in ^{64}Ni by using proton and neutron transfer reactions induced by ^{11}B and ^{18}O beams (at sub-Coulomb barrier energies) on ^{65}Cu and ^{62}Ni targets, respectively.
Moreover, by comparing the two transfer reactions, we observed a different selectivity in the population of excited states in ^{64}Ni. In particular, the 0^+_2 and 0^+_3 states at 2867.3 and 3025.8 keV were very weakly populated in the one proton transfer as compared to the two-neutron transfer case (the yield ratio is about 0.2). We also noted that the 1521 keV γ ray, depopulating the 0^+_2 state, has a strong stopped component, which implicates lifetimes of at least few ps, contrary to what is reported in literature [10].
An interesting observation was also made: the proton pick-up reaction showed an enhanced population of a new state at 3849 keV, which was weakly populated in the two-neutron transfer case. This new state decays with a 2503 keV transition to the 2^+_1 state at 1345.8 keV,

with a lifetime around 1 ps. We suspect that this 3849 keV state could be the searched for 0^+_4, predicted by the Monte Carlo Shell Model. In literature, Darcey et al., using a (t,p) reaction, observed a level around this energy, but no spin was assigned [10]. In fact, at the energy of 3849 keV, another state has been firmly located later, with 5- spin assignment [9].

In this proposal we would like to perform a spectroscopy investigation of ^{64}Ni, employing the same two neutron and one proton transfer reactions used in the test experiment of July 2017, i.e. induced by the ^{18}O and ^{11}B beams on ^{62}Ni and ^{65}Cu targets, respectively. In particular, we would like to pin down the nature of the newly identified transition (with energy of 2503 keV) by performing an angular distribution study using the p transfer reaction (which shows enhanced yield for this decay), at the new setup being installed at the 5th beam line.
In addition, we propose to perform a detailed relative yield measurement with ROSPHERE, by comparing neutron and proton transfer reactions, using thick targets of ^{62}Ni and ^{65}Cu. This study will also allow estimating the lifetime of short-lived states, by the Doppler Shift Attenuation Method. Finally, lifetimes of the already known 0^+ states will be measured using a plunger and the ^{18}O induced reaction on the ^{62}Ni target, similarly to the previous successful investigation of ^{66}Ni [8].

2. Proposed Experiment

The experiment here proposed will populate excited states of ^{64}Ni using the two-neutron transfer reaction ^{62}Ni(^{18}O,^{16}O)^{64}Ni at E_b = 39 MeV and the one-proton transfer reaction ^{65}Cu(^{11}B,^{12}C)^{64}Ni at E_b = 26 MeV. Both reactions are just below the Coulomb barrier, to hinder the fusion-evaporation mechanism, as successfully done in the ^{66}Ni case [8].

We propose to run the experiment in three steps, as follows:

1) *Angular distribution measurements* to probe the multipolarity of the newly found 2503 keV line, which is a candidate for the decay from the 0^+_4 state.
The reaction will be ^{65}Cu(^{11}B,^{12}C)^{64}Ni at E_b = 26 MeV. A 5 mg/cm^2 thick target will be used.
For this part of the experiment, we propose to use the 5th beam line, where a new reaction chamber will be available [12] to host a S7-type 1049 mm thick Double Sided Segmented Silicon Detector (DSSSD) of annular geometry, placed at a distance of 54 mm from the target. The ^{12}C reaction products, scattered in the backward direction, will be detected by the DSSSD detector (covering an angular range of 147° to 168.5°), in coincidence with the γ rays from ^{64}Ni, measured by three HPGe detectors of clover type.

Based on the test experiment of July 2017, we expect to be able to collect sufficient statistics in the line of interest, at 5 different angles, in **7 days** of beam time.

2) *Thick target measurements* to investigate the population of ^{64}Ni excited states, by using proton and neutron transfer reactions induced by ^{11}B and ^{18}O beams on thick (5 mg/cm^2) ^{65}Cu and ^{62}Ni targets, respectively.
For this part of the experiment, ROSPHERE will be used.

4 days are requested for the one-proton transfer reaction in order to determine the lifetime of the new state at 3849 keV, by DSAM technique. 2 days are requested for the two-neutron transfer reaction for a relative yield comparison.
Total request for this part of the experiment is **6 days** of beam time.

3) *Thin target measurement* to investigate the lifetime, with the plunger technique, of the known 0^+_2 and 0^+_3 states of ^{64}Ni, by using the two-neutron transfer reaction induced by the ^{18}O beam on a 1 mg/cm^2 ^{62}Ni target. This is similar to the previous successful investigation of ^{66}Ni [8].

   For this part of the experiment, **8 days** of beam time are requested with ROSPHERE.

Total beam-time request: **21 days**

References

[1] P. Walker and J. Dracoulis, Nature (London) 399, 35 (1999).
[2] S. M. Polikanov, Sov. Phys. Usp. 15, 486 (1973).
[3] P. Bonche et al., , Nucl. Phys. A500, 308 (1989).
[4] M. Girod, J. P. Delaroche, and J. F. Berger, Phys. Rev. C 38, 1519(R) (1988).
[5] M. Girod et al., Phys. Rev. Lett. 62, 2452 (1989).
[6] P. Möller et al., Phys. Rev. Lett. 103, 212501 (2009).
[7] Y. Tsunoda et al., C 89, 031301(R) (2014).
[8] S. Leoni et al., PRL 118, 162502 (2017).
[9] R. Broda et al., Phys. Rev. C 86, 064312 (2012).
[10] National Nuclear Data Center, Brookhaven, http://www.nndc.bnl.gov.
[11] W. Darcey, R. Chapman, and S. Hinds, Nucl. Phys. A170, 253 (1971).
[12] L.Stan et al, "Measurement of the 3371 keV E3 transition probability in ^{66}Ni", Proposal for the TANDEM accelerator for the period December 2017 - March 2018.