EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Shape coexistence in ^{68}Ni and ^{70}Ni

September 25, 2013

F.Recchia[1], S.M. Lenzi[1], D. Bazzacco[1], G. Benzoni[3], A. Bracco[3], F.C.L. Crespi[3], F. Camera[3], G. de Angelis[2], A. Dewald[4], C. Fransen[4], A. Gade[5], A. Gottardo[2], M. Huyse[6], S. Leoni[3], Lunardi[1], C. Michelagnoli[1], R.V.F Janssens[7], P. John[1], R. Menegazzo[1], D. Mengoni[1], V. Modamio[2], D.R. Napoli[2], R. Raabe[6], E. Rapisarda[8], C.A. Ur[1], J.J. Valiente-Dobon[2], P. Van Duppen[6].....

[1] Dipartimento di Fisica e Astronomia, Universita' di Padova and INFN Sezione di Padova, Padova, Italy
[2] Dipartimento di Fisica, University of Milano, and INFN, Sezione di Milano, Milano, Italy
[3] INFN Laboratori Nazionali di Legnaro, Legnaro, Italy
[4] IKP, Universitat zu Koln, Cologne, Germany
[5] National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI, USA
[6] IKS, KU Leuven, Belgium
[7] Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
[8] ISOLDE, CERN, Geneve, Switzerland
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Spokespersons:
Francesco Recchia (recchia@pd.infn.it), Silvia Maria Lenzi (lenzi@pd.infn.it)
Local contact: Elisa Rapisarda (Elisa.Rapisarda@cern.ch)

CERN-INTC-2013-044 / INTC-I-150
28/09/2013

Abstract

Scientific goal of the present letter of intent is the study of the shell structure of low-spin states in ^{68}Ni and ^{70}Ni.

In ^{68}Ni the presence of an high-lying 2^+ state with small transition probability to the ground state are a result of the N=40 harmonic oscillator shell gap between the fp shell and the $g_{9/2}$ orbital. This shell gap is reduced as protons are removed, in Fe and Cr isotopes; both the N=40 isotones ^{66}Fe and ^{64}Cr show a decreased energy of the first 2^+ state and increased transition probability B(E2; $2^+ \rightarrow 0^+$) in contrast to the expected properties of a semi-magic nucleus. The collective behavior is caused by quadrupole correlations which favour energetically the deformed intruder states from the neutron $g_{9/2}$ and $d_{5/2}$ orbitals. Moreover the proton-neutron tensor force, and in particular the strongly attractive monopole part, is expected to modify the shell structure in this region. These potential changes in the intrinsic shell structure are of fundamental interest for testing the validity of modern residual interactions.

The subtle interplay between such shell evolution mechanisms provokes the modification of the magic numbers and gives rise to new region of deformation and shape coexistence. According to a number of theoretical predictions in ^{68}Ni all of these phenomena are expected to express in a relatively narrow excitation energy

range. In order to prove this on a solid experimental basis we propose here to search for deformed structures corresponding to particle-hole excitation across Z=28 and N=40 in the excited states of ^{68}Ni and ^{70}Ni by means of spectroscopy study as well as lifetime measurement.

Beamline: [MINIBALL + T-REX]

Far from the valley of beta stability, the nuclear shell structure undergoes important and substantial modifications. In medium-light nuclei, interesting changes have been observed such as the appearance of new magic numbers, and the development of new regions of deformation and shape coexistence around nucleon numbers that are magic near stability [1,2,3]. In the last few years, particular effort has been put on studying light and medium-mass neutron-rich nuclei where these effects manifest dramatically. In particular, at the magic number N=20, with the promotion of neutrons across the gap intruder configurations come down in energy becoming the ground state for Na and Mg isotopes, giving rise to the so-called Island of Inversion [2]. A similar scenario is predicted for Cr and Fe isotopes when approaching the N=40 subshell closure [4].

The nucleus ^{68}Ni shows properties compatible with a doubly magic nucleus as the energy of the first 2^+ state increases considerably with respect to the neighbouring isotopes and the reduced transition probability for its decay to the ground state is the smallest. However, as soon as few protons are removed from the $f_{7/2}$ shell the collectivity increases very rapidly. This new region of deformation that develops at N~40 can be partially explained in terms of the monopole tensor term of the proton-neutron interaction [1]. The effect is the following: the interaction between $f_{7/2}$ protons with neutrons in both $f_{5/2}$ (attractive) and $g_{9/2}$ (repulsive), weakens when the proton $f_{7/2}$ orbital is not completely full, and therefore the gap between the neutron orbitals $f_{5/2}$ and $g_{9/2}$ decreases. The same interaction makes the neutron occupying the $g_{9/2}$ orbital to induce the lowering of the shell gap between the $f_{7/2}$ and $f_{5/2}$ proton orbitals favouring particle-hole excitations across Z=28 [1,4].

From the theoretical point of view mean field calculations agree in predicting deformed structures in heavy Fe and Co isotopes [5]. The deformation-driving effect of the $g_{9/2}$ orbital has been pointed out in studies of odd-mass Cr, Mn and Fe isotopes [6,7,8]. A Hartree Fock Bogoliubov calculation for ^{68}Ni was performed by Girod et al. [16] using the D1SA interaction. The calculated energy surface predicts the existence of a spherical first minimum while a deformed second minimum is predicted near deformation β=0.3 (see Fig. 2). This minimum could correspond to an excited 0^+ isomeric state.

Shell model calculations can describe satisfactorily the structure of moderately neutron-rich Cr, Mn and Fe isotopes and recently it has been pointed out that to reproduce the quadrupole collectivity in this mass region, the inclusion of the neutron $d_{5/2}$ orbital is needed [12]. This can be understood in terms of the quasi-SU3 approximate symmetry: The deformation can be generated by the interplay between the quadrupole force and the central field in the subspace consisting on the lowest Δj=2 orbitals of a major shell [11]. A new interaction (LNPS) for this model space (fpgd) [12] has been developed and shown to be able to reproduce satisfactorily the different phenomena suggested by the (scarce) available data in this mass region such as collective and single-particle behaviour, including shape coexistence near Z = 28 (^{67}Co, ^{68}Ni).

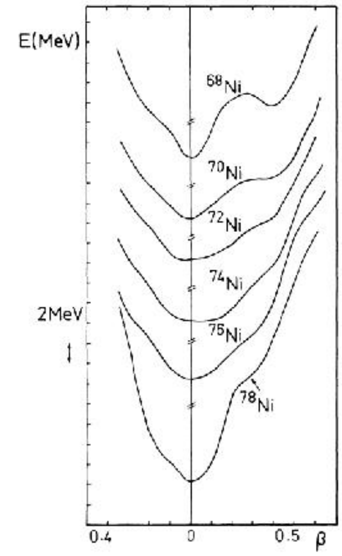

Figure 1 Axial deformation energy curve taken from [16]. A second minimum is present both in ^{68}Ni and in ^{70}Ni.

As reported by Dijon et al. [21] the LNPS shell model calculations, tailored for the mass region and in an extended valence space [12] satisfactorily reproduces experimental data in the mass region. We performed LSSM calculations using the LNPS interaction for ^{68}Ni. In the calculations, a third 0^+_3 state [12] is found at 2.4 MeV (i.e., very close to the proposed (0^+_3)[22]) for which the dominant configuration is a proton (2p-2h), that is, $(f_{7/2})^{-2}$. This intruder state has only normal parity neutron states as neighbours. The 2^+_1 as well as the 0^+_2 wave function is calculated to be a neutron (2p-2h) configuration and hence with a negligible overlap with the theoretical 0^+_3 state.

Calculations performed using Monte Carlo Shell Model were recently presented by Tsunoda et al. [23] predicting a spherical shape for the 0^+_1 g.s. of ^{68}Ni versus an oblated shape for the 0^+_2, 2^+_1, 4^+_1 and 6^+_1 states and a prolate well deformed shape for the 0^+_3, 2^+_2, 4^+_2 and 6^+_2 states.

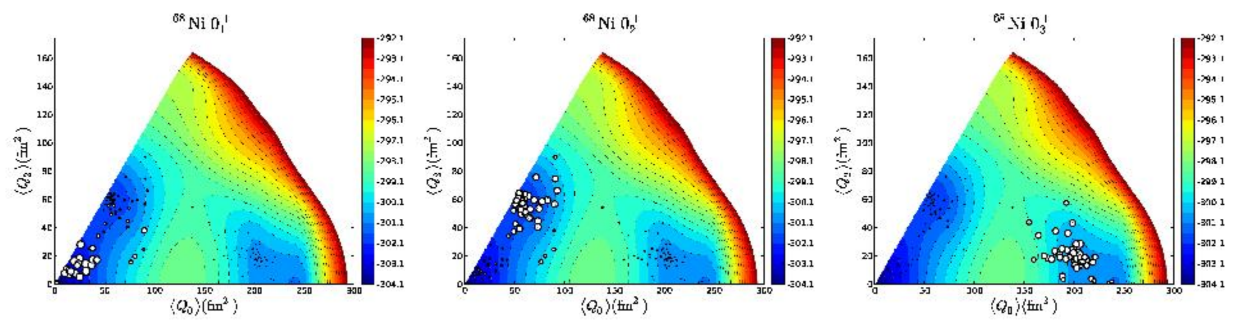

Figure 2 Total energy surfaces of the $0^+_{1;2;3}$ states of ^{68}Ni. The positions of the circles represent quadrupole deformations of the MCSM bases before projection. The areas of the circles represent the overlap probabilities of the bases and the resulting wave function. Taken from [23].

Although so much effort has been spent from the theoretical side to clarify the structure of ^{68}Ni, limited experimental data is available, especially for what concern the lifetime of excited states. Transition probabilities, directly accounting for similarities of the wave-function states, are a broadly accepted signature for defining bands in between excited states of deformed nuclei.

Experimental evidence for deformation effects was drawn from the systematics of a single excited state, deduced from the most intense gamma-ray transition following beta decay [24]. The extent and type of deformation can be established firmly with the observation of additional excited states and the measurement of their transition probabilities.

We intend to investigate

- The s.p. nature of bands built over excited 0+ states in ^{68}Ni via:
    - Spectroscopy of such bands toward higher spins
    - Lifetime measurements, in particular of the 0^+_3 and 2^+_2 states
- The s.p. nature of low spin states in ^{70}Ni:
    - Excitation energy and lifetime of the 0^+_2 state
    - Decay path and lifetime of the 2^+_2 state

Possible reaction for this investigation are ^{70}Zn(^{6}He, ^{8}B)^{68}Ni (Q_{value}: 23 MeV) where the ^{8}B would fission in two alpha particles providing a clear signature for the channel selection. This reaction is also expected to be selective with respect excited states with a configuration of 2p-2h across Z=28. An alternative reaction that will be evaluated is ^{70}Zn(^{10}Be, ^{12}C)^{68}Ni (Q_{value}: 6.5 MeV).

For the investigation of the proton excitations in ^{70}Ni the preferred reaction is ^{69}Ni(d,p)^{70}Ni (Q_{value}: 5 MeV), however alternatives will be evaluated. The neutron transfer to the $(1/2)^-$ isomer of ^{69}Ni (3.5(5) s lifetime, 2p-1h across N=40) is expected to be more favourable for the population of the interesting states, being generally proton p-h excitations correlated to neutron ones.

The present letter of intent will be formulated as a proposal as soon as the plunger coupled to the MINIBALL spectrometer will be available for lifetime measurement.

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