Physics Letters B 751 (2015) 371–375

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of isoscalar multipole strengths in exotic doubly-magic ^{56}Ni in inelastic α scattering in inverse kinematics

S. Bagchi [a,*], J. Gibelin [b], M.N. Harakeh [a], N. Kalantar-Nayestanaki [a], N.L. Achouri [b], H. Akimune [c], B. Bastin [d], K. Boretzky [e], H. Bouzomita [d], M. Caamaño [f], L. Càceres [d], S. Damoy [d], F. Delaunay [b], B. Fernández-Domínguez [f], M. Fujiwara [g], U. Garg [h], G.F. Grinyer [d], O. Kamalou [d], E. Khan [i], A. Krasznahorkay [j], G. Lhoutellier [b], J.F. Libin [d], S. Lukyanov [k], K. Mazurek [l], M.A. Najafi [a], J. Pancin [d], Y. Penionzhkevich [k,m], L. Perrot [i], R. Raabe [n], C. Rigollet [a], T. Roger [d], S. Sambi [n], H. Savajols [d], M. Senoville [b], C. Stodel [d], L. Suen [d], J.C. Thomas [d], M. Vandebrouck [b,d,i], J. Van de Walle [a]

[a] KVI-CART, University of Groningen, NL-9747 AA, Groningen, The Netherlands
[b] LPC Caen, ENSICAEN, Université de Caen, CNRS/IN2P3, Caen, France
[c] Department of Physics, Konan University, Kobe 568-8501, Japan
[d] Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DSM-CNRS/IN2P3, Bvd Henri Becquerel, 14076 Caen, France
[e] GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany
[f] Universidade de Santiago de Compostela, E-15706 Santiago de Compostela, Spain
[g] Research Center for Nuclear Physics, Osaka University, Osaka 567-0047, Japan
[h] Physics Department, University of Notre Dame, Notre Dame, IN 46556, USA
[i] Institut de Physique Nucléaire, Université Paris Sud, IN2P3-CNRS, F-91406 Orsay Cedex, France
[j] Institute of Nuclear Research (ATOMKI), Debrecen, P.O. Box 51, H-4001, Hungary
[k] G.N. Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, Dubna, Moscow oblast, 144980, Russia
[l] Institute of Nuclear Physics PAN, ul. Radzikowskiego 152, 31-342 Kraków, Poland
[m] National Research Nuclear Center, Moscow Engineering Physics Institute, Kashirskoe sh. 31, Moscow, 115409, Russia
[n] Instituut voor Kern- en Stralingsfysica, KU Leuven, B-3001 Leuven, Belgium

ARTICLE INFO

Article history:
Received 8 May 2015
Received in revised form 10 October 2015
Accepted 23 October 2015
Available online 28 October 2015
Editor: V. Metag

ABSTRACT

The Isoscalar Giant Monopole Resonance (ISGMR) and the Isoscalar Giant Dipole Resonance (ISGDR) compression modes have been studied in the doubly-magic unstable nucleus ^{56}Ni. They were measured by inelastic α-particle scattering in inverse kinematics at 50 MeV/u with the MAYA active target at the GANIL facility. The centroid of the ISGMR has been obtained at $E_x = 19.1 \pm 0.5$ MeV. Evidence for the low-lying part of the ISGDR has been found at $E_x = 17.4 \pm 0.7$ MeV. The strength distribution for the dipole mode shows similarity with the prediction from the Hartree–Fock (HF) based random-phase approximation (RPA) [1]. These measurements confirm inelastic α-particle scattering as a suitable probe for exciting the ISGMR and the ISGDR modes in radioactive isotopes in inverse kinematics.

Recent developments in nuclear physics involve the studies of short-lived exotic nuclei. New phenomena, such as, neutron halos, neutron skins, and modification of the magic numbers, occur for large neutron-to-proton (N/Z) ratios far from stability. The study of collective modes, the so-called giant resonances, in stable nuclei has been one of the important physics motivations throughout the history of nuclear physics. However, very little information about the collective properties of exotic nuclei is available. Among these collective modes, the ISGMR and the ISGDR are of prime interest as their excitation energies are directly related to the incompressibility of a nucleus, K_A [2,3]. The incompressibility of nuclear matter (K_∞) is defined as the curvature of the energy per particle at the saturation density [4], and can be deduced from K_A [4–6]. It is an important key input to the equation of state (EoS) of nuclear matter which, in turn, is useful in understanding some astrophysical quantities, such as, radii and masses of neutron stars, and also in understanding the mechanism of supernovae explosions.

* Corresponding author.
E-mail address: soumya.bagchi87@gmail.com (S. Bagchi).

http://dx.doi.org/10.1016/j.physletb.2015.10.060

The value of K_∞ obtained from the ISGMR and the ISGDR data in stable nuclei is 240 ± 10 MeV [4,6–8]. Theoretical calculations with effective interactions using this value of K_∞ can reproduce well the centroid energies of the ISGMR for ^{90}Zr, ^{144}Sm, and ^{208}Pb. On the other hand, they overestimate the centroid energies for the ISGMR strength distributions in Sn [9,10] and Cd [11] isotopes, although they can reproduce well the ground-state properties for these isotopes. Nevertheless, the investigation of the ISGMR along the isotopic chains of Cd [11] and Sn [12] helped determine the symmetry energy of the EoS. In spite of significant theoretical efforts to reproduce simultaneously the ISGMR centroid energies in ^{90}Zr, ^{208}Pb, and in Sn/Cd isotopes, the problem remains as to why the isotopes of Sn and Cd are soft [9–11]. It should be mentioned that a recent attempt to fit the centroid energies of soft ^{120}Sn and stiff ^{208}Pb simultaneously [13,14] yielded a smaller value of K_∞ with a large uncertainty, i.e., 230 ± 40 MeV. Therefore, it is useful to study compression modes for another series of isotopes to determine both K_∞ and the symmetry energy parameter of the EoS. Ni isotopes provide such an isotopic series widely ranging over *N/Z* ratios. Therefore, efforts have been put to study in detail the compression modes for several stable and unstable isotopes of Ni from the neutron-deficient to the neutron-rich regions of the nuclear chart.

Measurements of giant resonances in unstable nuclei are particularly challenging. Up to now such measurements have been mainly performed to study the isovector giant dipole resonance in neutron-rich radioactive oxygen [15], neon [16], and tin [17] isotopes, and in ^{68}Ni [18]. These studies have been performed through Coulomb excitation by scattering from a Pb target at relativistic energies. On the other hand, the best probe to study the isoscalar modes in a nucleus is either inelastic α-particle scattering or inelastic deuteron scattering as both the α particle and deuteron have zero isospin. The isoscalar responses have been so far measured for the unstable doubly-magic ^{56}Ni nucleus by inelastic deuteron scattering [19] and for the unstable neutron-rich ^{68}Ni nucleus by inelastic α-particle and deuteron scattering [20,21]. In our experiment, we focused on the study of isoscalar responses in ^{56}Ni via inelastic α-particle scattering. The choice was made because of the fact that, the ^{56}Ni$(\alpha,\alpha')^{56}$Ni* reaction has higher cross section than the ^{56}Ni$(d,d')^{56}$Ni* reaction and the unwanted background due to deuteron breakup can be avoided. Another interesting reason to study the collective modes in ^{56}Ni is because of the important role ^{56}Ni plays in the astrophysical scenarios. ^{56}Ni, a doubly-magic closed-shell nucleus, is one of the waiting point nuclei in the stellar nucleosynthesis and it was found in the ejecta of supernova 1987A [22].

The ISGMR cross section is peaked at 0° in the center-of-mass (CM) frame, which corresponds to the detection of very low-energy recoil α particles in the laboratory frame. To measure the excitation energy ranging from 0 MeV (elastic scattering) to 35 MeV in inverse kinematics, it is necessary to detect the recoil α particles having energies up to 4.5 MeV, which corresponds to 8° CM angle. Detection of such low-energy recoil α particles (including sub-MeV) with a particle telescope would necessitate a very thin target ($\sim$30 μg/cm^2) to allow the α particles to emerge from the target and to minimize the straggling. This would consequently require the radioactive ion beam to have an intensity of the order of 5×10^6 particles/s or above in order to have reasonable yields ($\geq$1000 counts for the ISGMR at 5.5° CM angle for a beam time run of 5 days). Although this is feasible with a storage-ring facility, such as the Experimental Storage Ring (ESR) at GSI [23–25], another alternative is to use an active-target detector. An example of such detector is IKAR [26], developed at GSI, which was used to study the elastic scattering of exotic beams at relativistic energies. Another example is MSTPC [27], built in Japan, for studying fusion reactions and reactions of nuclear-astrophysics interest at low energies. In our experiment, we used the MAYA active-target detector [28]. It is a gas target where the target gas acts also as a detector. In an active target such as MAYA, the target thickness can be increased without severe loss of energy resolution by increasing the gas pressure. In this Letter, we present the results of the first measurement of the isoscalar giant resonances in the doubly-magic ^{56}Ni investigated with inelastic α-particle scattering in inverse kinematics using the MAYA active-target detector.

A secondary beam of ^{56}Ni at 50 MeV/u was produced at the GANIL facility by the *In-Flight* fragmentation technique. The primary stable beam of ^{58}Ni at 75 MeV/u impinged on a 525.6 μm thick ^{9}Be target located at the entrance of the LISE [29] spectrometer. Two dipole magnets and a 500 μm achromatic degrader were used to purify the secondary beam. The average beam intensity of ^{56}Ni was of the order of 2×10^4 particles/s with a purity of about 96%. A plastic scintillator detector, followed by the MAYA detector, was put at the end of the LISE spectrometer. The plastic scintillator was used to count the number of incoming beam particles. The active-target detector MAYA, developed at GANIL, is a time-charge projection chamber with an active volume of $28 \times 25 \times 20$ cm^3. In the presence of an electric field applied across the target volume, electrons produced through ionization of the gas by the incident beam or reaction products, drift towards a set of 32 amplification wires that are parallel to the beam direction. For a two-body reaction, the angle of the reaction plane can be determined by the drift time of the electrons towards the amplification wires. The avalanches on the amplification wires induce signals on a matrix of 32×32 hexagonal pads connected to GASSIPLEX [28] chips. MAYA was filled with 95% helium gas and 5% CF_4, which acts here as a quencher since pure helium cannot be used due to sparking. The pressure of the gas-mixture was maintained at 500 mbar. With the effective length of 20 cm, a luminosity of around 5×10^{24} cm^{-2} s^{-1} was achieved. An electrostatic mask [30] was placed just below the beam trajectory in MAYA. This electrostatic mask helps in reducing the charges due to the highly-ionizing beam particles in comparison to those induced by the very low-energy recoil α particles, thus effectively increasing the dynamic range for charge-detection.

For each event, two observables are measured to reconstruct the reaction kinematics: the range and the scattering angle of the recoil particle. Since MAYA is a time-charge projection chamber, the projected recoil angle is reconstructed using a “global fitting method” as described in Refs. [20,21,31]. In this method, a straight-line trajectory is obtained by minimizing the orthogonal distances of the centers of the pads weighted by the charges on the pads to the fitted trajectory line. The intersection of the fitted trajectories of the beam path and the recoil-particle path determines the vertex of interaction. From the charge projection of the recoil α particle, the Bragg peak is determined and the projected range of the recoil particle is measured from the vertex of interaction. Recoil particles from the quenching gas were rejected on an event-by-event basis using the total charge integral versus the range of the ionizing particles. The third dimension is obtained from the drift times of the electrons towards the amplification wires. The scattering angle is obtained from the projected angle on the pads and the measured drift times. After obtaining the range in three dimensions, the energy of the recoil α particle is deduced using range-to-energy tables in SRIM [32]. The range, energy, and scattering angle of the recoil particle are deduced on an event-by-event basis. A reliable trajectory reconstruction has been achieved for recoil α particles having energies higher than 600 keV.

The reconstructed three-dimensional scattering of the recoil α particles provides the kinematics for the ^{56}Ni$(\alpha,\alpha')^{56}$Ni* reaction as presented in Fig. 1, where the energy of the recoil α particle is shown as function of the scattering angle for all events. The solid