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First measurement of isoscalar giant resonances in a stored-beam experiment

J.C. Zamora [a,*], T. Aumann [a,b], S. Bagchi [c,b], S. Bönig [a], M. Csatlós [d], I. Dillmann [b], C. Dimopoulou [b], P. Egelhof [b], V. Eremin [e], T. Furuno [f], H. Geissel [b], R. Gernhäuser [g], M.N. Harakeh [c], A.-L. Hartig [a], S. Ilieva [a], N. Kalantar-Nayestanaki [c], O. Kiselev [b], H. Kollmus [b], C. Kozhuharov [b], A. Krasznahorkay [d], Th. Kröll [a], M. Kuilman [c], S. Litvinov [b], Yu.A. Litvinov [b], M. Mahjour-Shafiei [h,c], M. Mutterer [b], D. Nagae [i], M.A. Najafi [c], C. Nociforo [b], F. Nolden [b], U. Popp [b], C. Rigollet [c], S. Roy [c], C. Scheidenberger [b], M. von Schmid [a], M. Steck [b], B. Streicher [b], L. Stuhl [d], M. Thürauf [a], T. Uesaka [j], H. Weick [b], J.S. Winfield [b], D. Winters [b], P.J. Woods [k], T. Yamaguchi [l], K. Yue [a,b,m], J. Zenihiro [j]

[a] *Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany*
[b] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*
[c] *KVI-CART, University of Groningen, 9747 AA Groningen, The Netherlands*
[d] *ATOMKI, Institute of Nuclear Research, Hungarian Academy of Sciences, 4026 Debrecen, Hungary*
[e] *Ioffe Physico-Technical Institute, Russian Academy of Sciences, St. Petersburg, 194021, Russia*
[f] *Division of Physics and Astronomy, Kyoto University, Kitashirakawa-Oiwakecho, Sakyo-ku, Kyoto 606-8502, Japan*
[g] *Physik-Department E12, Technische Universität München, 85748 Garching, Germany*
[h] *Department of Physics, University of Tehran, P.O. Box 14395/547, Tehran, Iran*
[i] *Department of Physics, University of Tsukuba, Tsukuba, Ibaraki 305-8577, Japan*
[j] *RIKEN Nishina Center, Wako, Saitama 351-0198, Japan*
[k] *Institute for Particle and Nuclear Physics, University of Edinburgh, Edinburgh, EH9 3JZ, United Kingdom*
[l] *Department of Physics, Saitama University, Saitama, Saitama 338-8570, Japan*
[m] *Institute of Modern Physics, Chinese Academy of Sciences, 730000 Lanzhou, China*

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ABSTRACT

A new technique developed for measuring nuclear reactions at low momentum transfer with stored beams in inverse kinematics was successfully used to study isoscalar giant resonances. The experiment was carried out at the experimental heavy-ion storage ring (ESR) at the GSI facility using a stored ^{58}Ni beam at 100 MeV/u and an internal helium gas-jet target. In these measurements, inelastically scattered α-recoils at very forward center-of-mass angles ($\theta_{\rm cm} \leq 1.5°$) were detected with a dedicated setup, including ultra-high vacuum compatible detectors. Experimental results indicate a dominant contribution of the isoscalar giant monopole resonance at this very forward angular range. It was found that the monopole contribution exhausts $79^{+12}_{-11}\%$ of the energy-weighted sum rule (EWSR), which agrees with measurements performed in normal kinematics. This opens up the opportunity to investigate the giant resonances in a large domain of unstable and exotic nuclei in the near future. It is a fundamental milestone towards new nuclear reaction studies with stored ion beams.

Light-ion scattering measurements provide important information about the structure and bulk properties of nuclei. For instance, elastic scattering gives access to nuclear potentials and the radial distribution of nuclear matter [1–3]. Inelastic scattering provides the possibility to study the deformation and collective excitation modes of nuclei [4,5]. In particular, from inelastic α-scattering, compression modes like the ISGMR (isoscalar giant monopole resonance) or the ISGDR (isoscalar giant dipole resonance) are predominantly excited because of the scalar-isoscalar nature of the α-particle. These isoscalar giant resonances are of great interest because their energies are directly related to the

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* Corresponding author.
E-mail address: jczamorac@ikp.tu-darmstadt.de (J.C. Zamora).

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compression modulus K_A for finite nuclei [5]. Microscopic calculations are then usually employed to connect the experimental value K_A and the nuclear incompressibility K_∞. The latter is a key parameter of the equation of state (EoS) for nuclear matter. With relativistic and non-relativistic microscopic models, the nuclear-matter incompressibility has been determined with an accuracy of at most 10% to 20% [6,7]. Part of the uncertainty is due to our poor knowledge of the symmetry energy K_{sym} [7]. Therefore, new experimental data along isotopic chains covering a wide range in N/Z ratios, including neutron-deficient and neutron-rich nuclei, are of paramount importance to determine both the nuclear-matter incompressibility and the symmetry energy more precisely. The knowledge of the EoS of asymmetric nuclear matter is not only fundamental for the understanding of nuclear phenomena, but is also a prerequisite for the understanding of explosive events like supernovae and properties of dense objects in the cosmos like neutron stars.

Over the years, measurements of giant resonances over a wide range of nuclei have been successfully performed in normal kinematics by employing dedicated spectrometers to separate the inelastically scattered particles at small angles in the center-of-mass system (θ_{cm}) [8–10]. However, this technique is limited to stable nuclei because of the difficulty to produce targets of short-lived exotic nuclei. With the availability of radioactive beams, novel techniques have been developed using inverse kinematics [11,12]. One of the major advantages of carrying out this type of experiments in inverse kinematics is that the scattered recoils at small θ_{cm} can be measured at relatively large laboratory angles of up to 50°. This means, inelastically scattered particles are kinematically separated from the beam direction, which in turn is quite favorable for measurements at very forward angles in the center-of-mass frame. However, the experiments are constrained by the low kinetic energies of the scattered recoils that are usually in the order of few hundreds of keV. In this case, straggling and energy loss in the target as well as in the windows of the experimental setup play a critical role in the recoil detection. Therefore, windowless targets and detector systems are preferable for such measurements. Recent experiments with active targets produce successful measurements of the excitation of giant resonances [13–15]. However, such experiments were limited due to detection sensitivity for the recoiling particle to center-of-mass scattering angles significantly above 1°, a region where quadrupole excitations and even higher multipolarities become significant. In this Letter, we report the first measurement of inelastic α-scattering in inverse kinematics covering scattering angles around 1° in the center-of-mass frame (and even below), i.e., in the range where the excitation of the ISGMR is dominant.

A new method which fulfills the previous conditions, besides providing high luminosities, was applied for the present measurements. This method is the stored-beam technique, which is the basis of the EXL (exotic nuclei studied with light-ion induced reactions in storage rings) project [16,17] that is presently being operated at the existing experimental heavy-ion storage ring (ESR) [18] at the GSI facility. In the future, this project will also be a part of the program for nuclear structure, astrophysics and reaction (NUSTAR) studies at the future facility for antiproton and ion research (FAIR) [16] under construction at GSI. A first in-ring experiment with a stored radioactive ^{56}Ni beam was recently reported [19,20]. Also, the experimental procedure and some preliminary results of this work were already reported in Ref. [21].

In this pioneering experiment, a ^{58}Ni beam was produced and accelerated up to the energy of 150 MeV/u by the UNILAC-SIS18 accelerator complex and injected into the ESR which has a circumference of about 108 m and a maximum magnetic rigidity of 10 Tm. With each beam injection, about 10^8 particles were stored in the ring. The ESR magnets and rf system were set to decelerate the stored ^{58}Ni ions to a final energy of 100 MeV/u. This energy results in a beam revolution frequency inside the ring of about 1.2 MHz. The use of the electron cooler enabled a constant beam energy and a small beam emittance (of the order of 0.1π mm mrad). The cooled ^{58}Ni beam interacted with an internal gas-jet target of helium which has an extension of about 5 mm full width at half maximum (FWHM) at the interaction zone. The density of the helium target was about 7×10^{12} part./cm^2. This low target density was well compensated by the beam revolution frequency, which leads to a significant improvement in the luminosity. Luminosities of the order of 10^{25} to 10^{26} cm^{-2} s^{-1} were obtained in our measurements. With the present experimental conditions at the ESR, due to the target densities and the transmission efficiency for radioactive beams, only measurements with stable beams or close to stability radioactive beams are feasible to achieve sufficiently high luminosities that are needed in experiments to study giant resonances. In particular, these measurements are of great importance because they will provide a proof of principle for future experiments with radioactive beams. In the future, radioactive beams provided by Super-FRS at FAIR to the storage ring will increase by a few orders of magnitude in intensity compared to those provided by the present FRS and the detection system EXL will cover almost 4π solid angle [16].

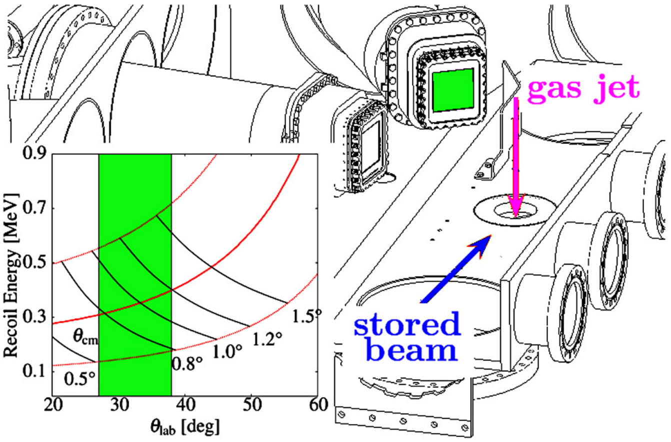

Fig. 1. (Color online.) Schematic illustration of the vacuum chamber installed in the ESR [22]. The stored beam interacts with the gas-jet target oriented perpendicular to the beam. The detectors were assembled at two internal pockets centered at 80° and 32°, with respect to the beam direction. Measurements of isoscalar giant resonances were performed with a DSSD covering angles from 27° to 37°. Kinematics for the excitation of the ISGMR is shown in the inserted plot (for details see text).

As it was necessary for this experiment to measure low energy recoils (above 100 keV), the detector array was designed to be windowless and placed directly inside the ring. As a consequence, the detector setup must be ultra-high vacuum (UHV) compatible and mounted around the internal gas-jet target where a vacuum in the order of 10^{-10} mbar or below is required. An additional constraint is that to achieve such a vacuum condition in the ESR, it is necessary to increase the temperature of the chamber to a value of about 150 °C for several days (*bakeout*) before the experiment. In order to comply with these conditions, the detector array was installed in a vacuum chamber and composed of two internal *pockets* covering the laboratory angular ranges of [74°, 88°] and [27°, 37°], respectively, as illustrated in Fig. 1.

In the front part of each pocket, a DSSD (double-sided silicon strip detector) of 285 μm thickness, (64×64) mm^2 in area and with 128×64 orthogonally oriented strips was installed. Inside these pockets all unbakeable and outgassing elements (e.g., connectors, cabling, etc.) were placed in high vacuum (in the order

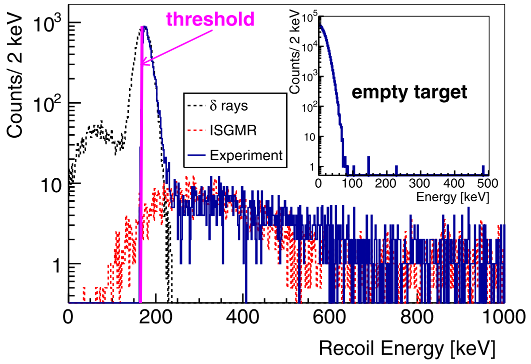

Fig. 2. (Color online.) Energy spectra of a detector strip at a laboratory angle of 27.5°. The solid blue line histogram is the experimental spectrum. The dashed lines are `GEANT4` simulations including δ-ray (black) and ISGMR (red) reactions channels. The spectrum in the insert corresponds to a measurement without gas-jet target.

of 10^{-8} mbar) separated from the UHV of the ring. Such a separation of environments permitted to operate the DSSDs as active windows [22,23]. Additionally, inside the pocket at 80°, two Si(Li) detectors (which cannot be baked) and their respective cooling system were behind the DSSD. This allowed to use the whole system as a telescope for the detection of elastically scattered recoils as was successfully done with the (p,p) reaction in a companion experiment [19,20]. In this work, the elastic α-scattering was employed as normalization for the other reaction channels [24]. The second pocket centered at 32° comprised a single DSSD, which is adequate for the detection of low-energy inelastically-scattered recoils in this angular region. The energy of recoils scattered in the $\theta_{\rm cm}$ interval $[0.5°, 1.5°]$ was calculated from kinematics to be only 100 to 600 keV for excitation energies around 19 ± 6 MeV (ISGMR centroid within $\pm 2\sigma$ [9]), as can be seen in the plot inserted in Fig. 1.

In order to determine the background contribution, measurements without the gas-jet target (empty target run) were performed. Very clean energy spectra for all vertical strips of the DSSD were obtained. However, signals were observed at energies of up to 100 keV, as is shown in the spectrum inserted in Fig. 2, mainly due to electronic noise and to a small part also possibly due to some contributions from the residual gas. In contrast, when the gas-jet target was in operation different reaction channels were observed. These were mainly prominent peaks at energies below 200 keV arising from δ-rays produced in the gas target and broad peaks in the region from 200 to 600 keV where inelastically scattered α-particles following the excitation of the ISGMR are expected to be measured (from the kinematics shown in the insert to Fig. 1). An example of an experimental spectrum from one of the vertical strips is shown in Fig. 2. In the analysis, a threshold at 160 keV was applied to all single spectra of this detector in order to reduce the high event multiplicities. For comparison, a `GEANT4` simulation including δ-ray and ISGMR reactions channels is also shown in Fig. 2. The simulations are in good agreement with the energy positions and widths of the experimentally observed peaks in the different vertical strips that correspond to well-defined laboratory angles.

The subtraction of the δ-rays contribution was performed in all spectra before applying a transformation to the rest frame of the outgoing ^{58}Ni nucleus. Because of the low count rate per strip, the best option was to add all individual strips of the DSSD after performing this transformation. Fig. 3 shows the resulting double-differential cross section as a function of the excitation energy. A clear peak in the energy distribution with a maximum around 18 MeV is seen. The peak is extended towards high energies to almost 40 MeV, but limited to excitation energies higher than 15 MeV due to the δ-ray cut. The background component at high energies is assumed to be produced from direct reactions, mostly knockout reactions. The resulting particles (e.g., p, d, t and α) in this reaction channel can deposit energies from 100 keV up to 3 MeV in the DSSD centered at 32° [24]. Therefore, the parameterization used to describe the present background due to knockout reactions is the one studied in Ref. [25], which comprises a low-energy part arising from 8 MeV (approximately the threshold energy for nucleon separation) and a high energy part that decays exponentially. Such a parameterization was fit to the experimental data in the range above 45 MeV and subtracted from the measured excitation energy spectrum.

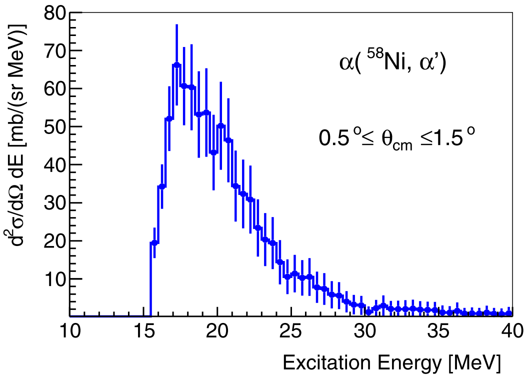

Fig. 3. (Color online.) Double-differential cross section as a function of excitation energy of ^{58}Ni.

The present cross section contains contributions from different multipolarities, mainly $L \leq 2$ which are the most important ones at small $\theta_{\rm cm}$. In order to disentangle the individual resonance modes of this energy spectrum, a multipole-decomposition analysis (MDA) was performed [9,25,26]. Experimental angular distributions were extracted for different energy bins of the cross-section data in the range from 15 MeV to 40 MeV. In this analysis, energy intervals of 1 MeV were chosen in order to reduce statistical fluctuations. Each angular distribution was fit by a linear combination of DWBA (distorted-wave Born approximation) calculations for $L = 0, 1$ and 2 excitations. These theoretical calculations were performed with the code `CHUCK3` [27]. The respective transition potentials were obtained using an explicit single-folding procedure with a density-dependent Gaussian interaction (range $t = 1.88$ fm) for the real part, and an imaginary Woods–Saxon potential [28]. The parameters of these potentials were derived from the fit of the elastic scattering data which were measured with the detectors placed in the region from 74° to 88° [24]. The folding model parameter for the real part was $V = 27.87$ MeV, and the parameters for the Woods–Saxon type imaginary part were: $W = 40.59$ MeV, r_I(reduced radius) $= 1.39$ fm, and a_I(diffuseness) $= 0.69$ fm. The transition densities, sum rules and deformation parameters employed in this analysis are described in Ref. [5]. As the isovector giant dipole resonance (IVGDR) can also be excited via inelastic α scattering [29,30], this small component (below 10% in energies from 16 to 20 MeV) was subtracted from each angular distribution before performing the multipole fit. The IVGDR contribution was calculated on the basis of the Goldhaber–Teller model [5] using the strength distribution $B(E1)$ obtained from an electron scattering experiment [31]. Angular distribution fits for the energy bins centered at 20.5 MeV and 28.5 MeV are shown in Fig. 4 (top).

The monopole strength is dominant for excitation energies smaller than 30 MeV, where the most significant contribution was found around 20 MeV. Also, the angular distribution of the quadrupole component has a slight effect on the total cross section for excitation energies below 20 MeV, in the order of a few

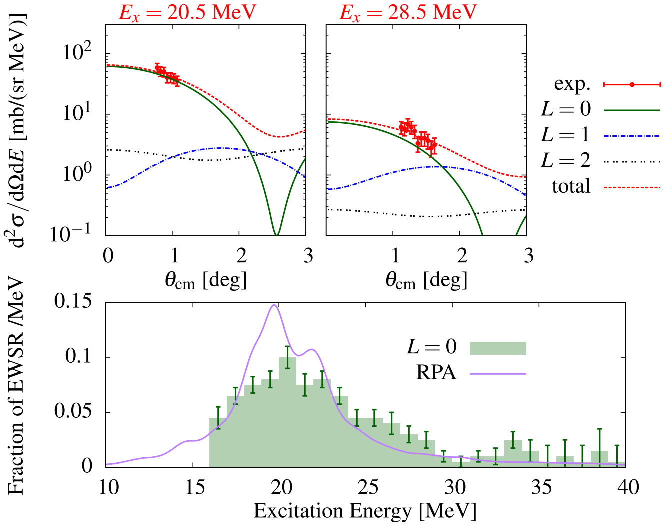

Fig. 4. (Color online.) Multipole-decomposition analysis (MDA). The top panels show angular distributions for two measured excitation energies. The bottom figure shows the result of the MDA for the monopole component. The data are compared with a self-consistent RPA calculation presented with a solid line.

Table 1
ISGMR contribution obtained from multipole-decomposition analysis. The results of this experiment are obtained from a Gaussian fit in the energy range from 15 to 30 MeV.

Reference	Centroid [MeV]	Width$_{RMS}$ [MeV]	EWSR [%]
this work	20.5(6)	4.6(6)	79^{+12}_{-11}
[9]	$19.20^{+0.44}_{-0.19}$	$4.89^{+1.05}_{-0.31}$	85^{+13}_{-10}
[32]	$20.30^{+1.69}_{-0.14}$	$4.25^{+0.69}_{-0.23}$	74^{+22}_{-12}
[26]	$19.9^{+0.7}_{-0.8}$	–	92^{+4}_{-3}

mb/sr MeV^{-1}. Moreover, the dipole contribution increases at high energies and becomes dominant where the scattering angles correspond to the minimum of the monopole angular distribution. The coefficients of such fits are directly related to the percentage of the exhausted energy-weighted sum rule (EWSR) in each energy interval [25]. In the bottom of Fig. 4 the results for the monopole contribution are shown. As was discussed above, because of the cuts in the cross-section data, the sensitivity of this energy distribution is constrained to excitation energies higher than 15 MeV. The monopole strength observed in the range from 15 to 30 MeV exhausts 79^{+12}_{-11}% of the $E0$ EWSR, which is in agreement with results performed in the past in normal kinematics. Table 1 shows a comparison of some of these results with the ones obtained in this work. The centroid and width of the ISGMR contribution in this experiment are obtained from a Gaussian fit of the energy distribution from 15 to 30 MeV.

In Fig. 4, also a theoretical prediction from a self-consistent RPA (random-phase approximation) calculation is presented with a solid line. This strength function was calculated with the code `SKYRME_RPA` [33] by applying the interaction `SkO'` [34]. Lorentzian functions of 2 MeV width were employed for smearing this distribution. The comparison with the experimental data shows a reasonable agreement in the whole energy range, in particular around the maximum of the ISGMR distribution and the exhausted EWSR strength. This is quite remarkable since it also demonstrates the consistency of our experimental results even without availability of data below 15 MeV.

In summary, a new technique developed to perform nuclear reaction experiments using stored ion beams and an UHV compatible detection system have allowed measurements of recoil-like particles at very low momentum transfer. The technique was successfully applied to measure isoscalar giant resonances in a stored-beam experiment for the first time. Experimental results reveal a dominant contribution of ISGMR in the θ_{cm} range from 0.5° to 1.5°. The pure isoscalar giant monopole resonance derived from multipole-decomposition analysis is consistent with the analysis of other experiments performed in normal kinematics as well as with theoretical predictions with RPA calculations applying a Skyrme force. This is a clear demonstration for the feasibility of prospective studies with stored radioactive beams. In particular, the new technique allowed to perform measurements down to below 1° in the center-of-mass system, not feasible for inverse kinematics by other techniques up to date. In the future this experimental method can be applied to investigate the giant resonances of a large domain of unstable and exotic nuclei. New experiments with the EXL program are already planned with an extended detector setup covering larger angular ranges for studies with unstable stored beams at GSI and in the future, at FAIR.

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