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Giant resonance research: present interests and future perspectives

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In the last decade extensive work has been done to explore and understand various giant resonance phenomena. The research involved the study of the giant dipole resonance as a function of temperature and angular momentum, the study of compressional modes - the isoscalar giant monopole and dipole resonances - and the investigation of their microscopic structures, the study of the charge-exchange modes both in the β^+ and β^- directions, the establishment of the existence of double-phonon giant resonances, in particular those of the isovector GDR and the isoscalar GQR, etc.. A review of some of these advances is discussed and possible future directions in view of the operating and/or planned radioactive nuclear beam facilities will be delineated.

1. INTRODUCTION

In the short time allotted to me to give the concluding remarks of the COMEX 1 conference, I will restrict myself to giving an impression of the research on collective motion in nuclear systems, and in particular on the high-lying giant resonances (GRs), that was presented at this conference and outline the future perspectives for this field. Therefore, this will not be a summary in the strict sense and hence I apologize beforehand for those people whose work will not be mentioned in these concluding remarks. The reader is referred to the various contributions in these proceedings for more details.

2. COMPRESSION MODES AND NUCLEAR INCOMPRESSIBILITY

New data on the compression modes, in particular for the isoscalar giant dipole resonance (ISGDR), have been obtained since the last GR conference in Osaka in 2000. The new results on the ISGDR received special attention because ISGDR systematics obtained earlier resulted in a nuclear incompressibility that was in disagreement with the one derived from the systematics of the isoscalar giant monopole resonance (ISGMR). To reconcile these results, the newly obtained data at RCNP and Texas A&M were subjected to multipole-decomposition analysis (MDA). In this approach, the characteristic angular distributions of the various multipolarities are used to reconstruct from the singles spectra, taken as a function of scattering angle, the excitation-energy distributions of the various contributing multipolarities.

The new singles data and the results of the MDA obtained at RCNP were presented by Garg and Itoh. These data were analyzed without subtracting any continuum background. The results for spherical nuclei, including ^{208}Pb , ^{116}Sn and ^{90}Zr , displayed a double-

humped structure with a low-energy bump increasing in excitation energy from 13.0 to 16.8 MeV and a high energy bump ranging in excitation energy from 22.8 to 26.9 MeV. The results obtained for the Sm isotopes (the spherical ^{144}Sm and deformed ^{154}Sm) indicate that the effects of deformation on the low- and high-energy components of the ISGDR are different. Also, evidence is found for the theoretically predicted coupling of the ISGDR and the high-lying isoscalar octupole resonance (HEOR).

In general, one thinks of the ISGDR as a collective excitation built up of $1\hbar\omega$ and $3\hbar\omega$ 1-particle-1-hole (1p-1h) excitations induced by the operator $\{r^3 - \frac{5}{3}\langle r^2 \rangle r\}Y_{10}$. Theoretical calculations discussed by Colò and Bennaceur, and also those presented in posters in the conference, indicate that the excitation energy of the higher component depends sensitively on the nuclear incompressibility and could thus be labeled compressional, whereas the excitation energy of the lower-energy component does not. The observed low-energy component is still higher in energy than the ' $1\hbar\omega$ ' component of the ISGDR, which has been observed at lower excitation energy by Poelhekke et al. in the early 90's. The low-energy bump observed around 13 MeV appears to be reasonably described by the toroidal mode already predicted by Bastrukov et al. also in the early 90's.

The results of the MDA analysis of the RCNP data on ^{208}Pb yielded an excitation energy for the higher energy component that is in agreement with theoretical calculations, which also reproduce the excitation energy of the ISGMR, thus reconciling the determination of the nuclear incompressibility from the systematics of the ISGMR and ISGDR. However, the width and sum-rule strength for the high-energy component of the ISGDR derived from MDA are much larger than determined from earlier experiments. This seems to be due to a non-decreasing continuum background present in the reconstructed ISGDR excitation-energy spectrum. This in turn results from the huge continuum background observed in the singles spectra. This raises the essential question on the nature of the continuum background observed in inelastic α -scattering and whether it should be included in the MDA.

The Texas A&M group (Lui et al.) presented a new MDA of their published data on ^{208}Pb , ^{144}Sm and ^{90}Zr . In their earlier MDA, they derived excitation energies for the ISGDR that were too low in comparison to other published data. This enhanced the discrepancy for the nuclear incompressibility obtained from ISGDR and ISGMR systematics. In this earlier MDA, they subtracted a continuum background, which may have been overestimated. In their reanalysis, a new choice for the continuum background was made before MDA was performed. The results presented at this conference agree now with the results obtained by others.

Hunyadi presented the neutron and proton decay data obtained at KVI for decay of the GRs excited in inelastic α -scattering at 200 MeV. The neutron and proton detectors were placed at backward angles to suppress the knock-out contributions. It is quite remarkable that the spectra coincident with neutron decay display a large continuum background, indicating that the continuum background observed in the singles spectra has a large statistical neutron decay branch. On the other hand, the proton decay spectra show the high-lying resonances free from any continuum background. Instead of using MDA, Hunyadi et al. used the difference-of-spectra (DoS) method to accentuate the contribution of the ISGDR in the DoS spectrum obtained by subtracting spectra taken at two angles where the ISGDR has a maximum and a minimum. The other multipolarities (other than

$L = 0$) and the continuum, which have a more-or-less flat angular distribution near 0° , cancel out. A few observations could be made:

- The ISGDR excitation energy and width in ^{208}Pb determined for spectra obtained in coincidence with protons and neutrons agree with the main trend of those determined from singles measurements.
- The branching ratios for direct neutron and proton decay amount to several percent, whereas the statistical neutron decay is the main mode. The proton decay branching ratios to low-lying states in ^{207}Tl could be determined and compared to theoretical predictions. The agreement was not that good suggesting that further theoretical efforts are needed.
- In addition to the ISGDR, a new resonance is observed at higher excitation energy which appears to be of quadrupole character. If true, this may correspond to the first observation of the quadrupole compressional mode, i.e. the overtone of the ISGQR which is excited by the operator $r^4 Y_{20}$.

These results emphasize the need to understand the continuum background and to establish whether this compressional quadrupole mode can be observed in other nuclei. Furthermore, more coincidence measurements and theoretical calculations should be made to have a better understanding of the microscopic structure of these collective modes.

3. SPIN AND ISOSPIN GIANT MODES

Charge-exchange reactions have been used as probes of isospin and spin-isospin giant resonances. The first observation and systematic study of the Gamow-Teller (GT) resonance with the (p,n) reaction at intermediate energies ($E_p \geq 120$ MeV) occurred in the early eighties, providing the tools to study the resonances in the β^- direction. The (n,p) reaction with secondary neutron beams at intermediate energies was also used to study the collective modes in the β^+ direction. However, both reactions suffered from bad energy resolution, hindering their use as spectroscopic tools for GT strength distributions in either direction. The availability of intermediate energy ^3He beams ($E \approx 150$ MeV/u) and the high-resolution high-rigidity spectrometer Grand Raiden at RCNP in the 90's allowed a mapping of the GT resonance (GTR) and other spin-flip charge-exchange modes in many nuclei and with a very high resolution reaching recently 30 to 40 keV.

Richter described the high-resolution data taken for the reaction $^{90}\text{Zr}(^3\text{He},t)$ revealing the fine structure of the GTR. A description in the wavelet analysis framework allowed the extraction of the different scales for spreading. Also, high-resolution inelastic electron scattering data taken for ^{58}Ni at 180° and proton scattering data at forward angles allowed the identification of the 2^- twist mode and the correspondence of its fine structure in both reactions.

Frekers described the recent measurements with the ($d,^2\text{He}$) reaction performed with the BBS at KVI. This charge-exchange reaction is by necessity an isospin-flip and also a spin-flip reaction if the two protons of the ^2He are measured at very low relative energy ensuring that the two protons are in a relative 1S_0 state. The first measurements done with a bombarding energy of ≈ 90 MeV/u and a resolution of ≈ 120 keV indicate that

this reaction is a powerful tool to probe GT strength and other spin-flip modes in the β^+ direction. The $(d, {}^2\text{He})$ reaction has been measured for many f - p -shell nuclei because of their importance in astrophysical scenarios.

Charge-exchange ${}^{208}\text{Pb}({}^3\text{He}, t)$ studies ($E = 410$ MeV) of the spin-flip modes in ${}^{208}\text{Bi}$ provided for the first time evidence for the isovector spin-flip giant monopole resonance (IVSGMR). Zegers showed also data for proton decay allowing the delineation of the microscopic structure of the IVSGMR. Interestingly direct proton decay accounts for around 50% of all decay. It is important to study a few more cases to establish some systematics for this mode. Guillot presented some new data taken at KVI for the reaction ${}^{58}\text{Ni}(t, {}^3\text{He})$ with a primary triton beam at around 43 MeV/u. At this energy this reaction favors non-spin-flip excitations. Evidence for excitation of the IV(S)GMR has been found. The IVGMR in the β^+ direction has been observed first in the (π^-, π^0) reaction at Los Alamos and later in $({}^7\text{Li}, {}^7\text{Be})$ at RCNP. The $(t, {}^3\text{He})$ reaction may prove to be easier to apply for the study of these modes and will be the tool of choice because of the high-energy resolution that can be achieved and the simpler reaction mechanism.

Sakai described a new consistent MDA of (p, n) and (n, p) data on ${}^{90}\text{Zr}$ in which more reliable S_{β^+} and S_{β^-} could be derived. The new values further allow the determination of the quenching factor for GTR and the Landau-Migdal parameters. These came out to be different from earlier analysis: $Q = 0.89 \pm 0.04$ (stat. + MDA) ± 0.04 (IVSGMR), the last being due to the uncertainty in the subtraction of the IVSGMR contribution, and $g'_{NN} = 0.6 \pm 0.02$ and $g'_{N\Delta} = 0.17 \pm 0.10$. These have implications on a number of problems that were discussed by Sakai and Suzuki, in particular the critical density for pion condensation and its relevance to neutron stars.

4. COLLECTIVE MOTION AT FINITE TEMPERATURE

A review of the study of the isovector giant dipole resonance (IVGDR) built on highly excited states at finite temperatures was given by Thoennessen. Nuclear shapes as a function of temperature and angular momentum, motional narrowing, fission time scales, reaction dynamics and influence of shell effects were discussed. New data for ${}^{120}\text{Sn} + {}^{17}\text{O}$ were presented. The adiabatic model for thermal shape fluctuations fails to reproduce the data for the width of the IVGDR as a function of temperature. A good fit could be obtained by offsetting the adiabatic model result by about 1 MeV. The possible explanation could be pairing, which leads to a suppression of IVGDR widths at low temperatures. This would be common to all nuclei.

New data were presented by Nanal and Mazumdar on the compound nuclei ${}^{164}\text{Er}$ ${}^{194}\text{Au}$, respectively, where selection was made on temperature and angular momentum. Agreement with systematics of earlier data is found. Kicinska-Habior reported on data taken for reactions in which the nucleus ${}^{32}\text{S}$ is populated via the reaction ${}^{20}\text{Ne} + {}^{12}\text{C}$ feeding the $T = 0$ compound entrance channel. In this channel E1 γ -decay to low-lying $T = 0$ states is isospin forbidden and can only proceed via isospin mixing. By comparing the data to statistical model calculations in which isospin and parity are properly taken into account, and comparing to γ -decay of the $T = 1/2$ compound states populated in ${}^{31}\text{P}$ via the reaction ${}^{19}\text{F} + {}^{12}\text{C}$, it was possible to derive the isospin-mixing coefficient ($\alpha^2 = 0.013$) and the width for coupling between $T_<$ and $T_>$ states ($\Gamma_s = 20$ keV). The Warsaw group

is planning future experiments to study isospin mixing in light and medium-heavy nuclei from low to high excitation energies. This could yield interesting information on the purity of isospin as a function of excitation energy and nuclear charge.

5. MULTIPHONON GIANT RESONANCES

The theory of multiphonon giant resonances was discussed by Hussein and Chomaz. The multistep direct reactions can populate multiphonon giant resonances strongly. Hussein found cross sections of 1–2 mb for excitation of the IVGDR, ~ 200 mb for double IVGDR and ~ 40 mb for triple GDR in Xe scattering from Pb at about 0.5 GeV/u bombarding energy. Data for double IVGDR excitation have been obtained earlier at GSI. These cross sections are in contrast with the data obtained in pion double-charge-exchange (DCX) reactions, which have cross sections in the order of μb . Chomaz studied the structure and excitation of the multiphonon resonances in TDHF and RPA. In his calculations he observed coupling of collective motion in violent collisions of heavy ions leading to strong excitation of double giant resonances. A small splitting between various J-components was found and anharmonicities of $\sim 10\%$.

Very little new data have been presented on multiphonon giant resonances. Scarpaci discussed analysis of the $^{40}\text{Ca} + ^{40}\text{Ca}$ data obtained at intermediate energies. By looking at direct multiple proton decay from the various excitation energy regions and comparing with simulations assuming sequential direct proton decay feeding the $(\text{GR})^{n-1}$ [(n-1)-phonons state] from the $(\text{GR})^n$ [n-phonons state] Scarpaci could identify the isoscalar giant quadrupole resonance (ISGQR), double ISGQR and triple ISGQR. Evidence was even found for the quadruple ISGQR. It would be very interesting to investigate at least one other case to confirm the excitation of these multiple giant resonances. Cinausero found evidence for excitation of the double IVGDR in hot nuclei through analysis of γ -decay spectra from compound nuclei formed in fusion heavy-ion reactions. However, the evidence here is quite weak since the extraction of this information depends sensitively on the parameters used in the statistical-model calculations.

6. SKINS, HALOES AND LOW-LYING COLLECTIVE STRENGTH

Very nice data have been obtained at GSI using the LAND experimental setup. Aumann presented data on excitation of the IVGDR in neutron-rich C, N and O isotopes by Coulomb excitation at relativistic energies. Resolution of around 200 keV at threshold ranging up to 2 MeV at 20 MeV excitation energy was achieved. Low-lying dipole strength was integrated and compared to TRK and cluster (valence neutrons versus core) sum rules. No evidence was found for a collective soft mode.

Zilges reported on the study of the pygmy dipole resonance (PDR) in Ca isotopes and many $N = 82$ nuclei. A white bremsstrahlung spectrum was used to excite the concentrated E1 strength below the IVGDR (i.e. the PDR) and γ -decay was detected with large-volume Ge detectors. The concentrated strength near threshold amounts to about 1% of the TRK sum rule. Its implication for nucleosynthesis was discussed and the nature of the excitation was illustrated on basis of calculations in the quasi-particle phonon model (QPM). Whereas the transition density for the IVGDR shows out-of-phase oscillations of neutrons and protons, the PDR transition density consists of pure neutron

transition density at the surface with in-phase oscillations of neutrons and protons in the interior. Similar results were found by Vretenar et al. in relativistic RPA and QRPA calculations.

Krasznahorkay discussed the various methods that have been used to determine the neutron-skin thickness in nuclei. Elastic electron scattering allows a precise determination of the charge (proton) density distribution. Pion scattering, elastic proton scattering at 800 MeV, elastic α -scattering, anti-protons capture, parity-violating electron scattering and elastic proton scattering at intermediate energy (using the bootstrap method of Kelly) have all been used to determine the radius of the neutron and/or matter distribution. In combination with results from electron scattering the neutron-skin thickness can be evaluated. However, the cross sections for the excitation of the IVGDR by isoscalar probes such as inelastic α -scattering as well as the excitation of the isovector (spin) giant dipole resonance in charge-exchange reactions such as ($^3\text{He},t$) depend sensitively on the neutron-skin thickness. Comparison of the neutron-skin thickness for ^{208}Pb determined from various reactions (elastic proton scattering at 800 MeV, excitation of the IVGDR in inelastic α -scattering and anti-proton capture) indicates agreement with the experimental uncertainties. More precise data are needed, however, to discriminate between various models for calculating the neutron-skin thickness.

7. PERSPECTIVES

Research into giant resonances will receive a boost from the availability of facilities that provide radioactive nuclear beams (RNBs). New phenomena are expected to emerge far from the island of nuclear stability. Some of these studies have already been started at GSI such as the investigation of the IVGDR in neutron-rich isotopes of oxygen as discussed above. These experiments are performed in inverse kinematics where beams of neutron-rich nuclei bombard fixed stable targets. In the future, collider rings which store electron and radioactive nuclear beams will become available at GSI and RIKEN. These will allow the delineation of the various giant resonances and in particular the low-lying dipole strength in light to heavy neutron-rich nuclei. The delineation of this strength is important for the understanding of certain aspects of the nucleosynthesis. Allowing for the storage of proton, deuteron, ^3He and α beams, in addition to electrons, may enrich this field of research tremendously. Of course, one can perform inverse-kinematics in the RNBs ring by bombarding gas-jet targets. However, for the study of the compression modes, the ISGMR and ISGDR, the inverse-kinematics method may face difficulties because of having to detect very low-energy recoils to access the very forward angular region in the center-of-mass frame.

With the availability of high-intensity RNBs at energies where selectivity on the spin, isospin and multipolarity of the GRs can be achieved, one can embark on study of the giant resonance structure in regions far from stability. Aside from the intrinsic interest in the structure of these resonances, excitation of certain modes may yield us information on certain global and bulk properties of nuclei. A few of these are briefly mentioned in the following.

- To fix the isospin dependence of the residual effective nucleon-nucleon interaction, and to determine the dependence of the nuclear incompressibility on the nuclear

asymmetry, $(N - Z)/A$, it would be important to study the ISGMR and the ISGDR in a long chain of isotopes. This may lead to a better determination of the equation of state of asymmetric nuclear matter. Inelastic α -scattering in collider rings is the tool of choice for such studies.

- To determine rates for electron-capture and charged-current ν -scattering reactions, which are important in supernova explosions leading to the formation of neutron stars, GT strength in neutron-rich *sd*- and *fp*-shell nuclei should be determined. Charge-exchange reaction, such as (p,n), (^3He ,t) and (t, ^3He) could be performed in collider rings.
- To have a better understanding of the paths followed in various scenarios of the nucleosynthesis, PDR strength distributions in neutron-rich light, medium-heavy and heavy nuclei should be determined. This could be nicely done with electron scattering in collider rings.
- To determine the neutron-skin thickness in neutron-rich nuclei, the excitation of the IVGDR and IVSGDR in charge-exchange reactions, such as (p,n) and (^3He ,t), is the only suitable and practical method to pursue. These reactions can be performed in collider rings and also in inverse kinematics in storage rings with jet targets of proton or ^3He .