Giant-resonance studies with radioactive beams: Perspectives

M.N. Harakeh

Kernfysisch Versneller Instituut, Zernikelaan 25, 9747 AA Groningen, The Netherlands

Received: 1 May 2001

Abstract. First-generation radioactive ion-beam facilities have already been in operation for some time. Advanced facilities that will deliver high-intensity radioactive nuclear beams ranging in energy from below the Coulomb barrier to up to several hundred MeV per nucleon (MeV/u) are either starting operation, or under construction or in the planning stage. In this paper the perspectives of using radioactive nuclear beams to study giant resonances in nuclei far from the valley of stability are explored. In particular, emphasis will be made on information on certain nuclear properties that can be gained from such studies.

PACS. 21.65.+f Nuclear matter – 24.30.Cz Giant resonances – 24.50.+g Direct reactions

1 Introduction

With the advent of facilities that provide radioactive nuclear beams, the nuclear-physics research has moved towards new frontiers where new phenomena are expected to emerge from the study of nuclei far from the valley of stability. The study of giant resonances (GRs) in unstable nuclei becomes thus also possible and may strongly contribute to these developments. In fact, the study of GRs in stable nuclei has been one of the major fields of research in low-energy nuclear physics since the first systematic study of the isovector giant dipole resonance (IVGDR) in 1947 [1,2]; the first evidence for a giant-resonance excitation was found ten years earlier [3]. Since then this has proven to be a quite fruitful field of research, which not only taught us about the structure of these fundamental modes of excitation of the nucleus but also about some fundamental bulk properties of nuclei and nuclear matter [4].

The experimental study of GRs in unstable nuclei presents a real challenge. Whereas it has been possible to investigate GRs in stable nuclei by bombarding targets of the nuclei of interest by various probes, chosen depending on the spin and isospin structure of the multipole to be investigated, this will not be possible with unstable nuclei close to the proton or neutron drip line. It will be practically impossible to make targets of sufficient density to be useful for such studies. On the other hand, experiments can be performed in inverse kinematics, where beams of unstable nuclei impinge on a fixed target. This technique is now being developed for radioactive ion beams [5] but has been used with stable beams already in order to investigate the double-phonon excitation in nuclei [6]. This will be discussed in more detail below. Another possibility is to use collider rings where one of the rings is used for accelerating and storing the unstable nuclei and the other for accelerating and storing the beams that will be used as probes for giant-resonance excitation. Plans to build such collider rings with electron beams exist at RIKEN and GSI. Considering that various probes need to be used to disentangle the various multipole strengths and their spin and isospin structure, it is very strongly recommended to have the option of accelerating and storing in one of the collider rings proton, deuteron, ³He, and α beams in addition to the electron beam. Especially for the study of the compression modes, the isoscalar giant monopole resonance (ISGMR) and isoscalar giant dipole resonance (ISGDR), the use of an α beam is imperative [4].

Now that high-intensity radioactive nuclear beams will soon be available at energies where excitation of giant resonances of various multipolarities and spin and isospin structure becomes possible, the following question arises. What new things can we hope to learn from the study of giant resonances in nuclei far from the stability valley, and in particular for the nuclei that are on the neutron-rich side of this valley? Although this question may lead to a wide variety of possible interesting answers regarding various aspects of nuclear structure and properties, I will address here only a few topics on which, I believe, information can be gained in the first stages of research on giant resonances in unstable neutron-rich nuclei. These are:

- The study of the ISGMR in a long chain of isotopes [7-9] in order to pin down the dependence of the nuclear incompressibility on the nuclear asymmetry, \((N - Z)/A\). This is important to fix the isospin dependence of the effective residual nucleon-nucleon interaction, e.g. by reproducing the ISGMR energies in the doubly closed-shell nuclei \(^{100}\text{Sn}, ^{132}\text{Sn}\) and \(^{208}\text{Pb}\), as well as allow a more precise determination of the incompressibility of nuclear matter. Also, the equation of state of asymmetric matter may be better determined.
Determination of Gamow-Teller (GT) strength in unstable neutron-rich sd- and fp-shell nuclei. This has implications on supernova explosions and on the formation of neutron stars.

Use of giant resonances as tools to determine neutron-skin thickness such as in the nuclear excitation of the IVGDR by isoscalar probes, or by the excitation of the isovector spin-flip dipole resonance (IVSGDR) in charge-exchange reactions [10,11].

2 Multipole strength functions in unstable nuclei

There has been a flurry of theoretical activity in the last decade aiming at investigating the structure of unstable nuclei. This was an anticipation of the near-future availability of the radioactive nuclear beams and the wide field of research that would open up. The giant-resonance structure in unstable nuclei, and in particular those with an extreme N/Z value, was studied. These calculations were performed for doubly closed-shell nuclei in order to avoid complications of pairing and deformation effects. The quadrupole (see, e.g., refs. [12–18]) and dipole [19,17] response has been calculated for $^{28}$O, and the monopole response for a number of calcium isotopes [20,21]. All these calculations have been performed in the self-consistent Hartree-Fock (HF) random-phase approximation (RPA) framework using a Skyrme-type interaction. The general feature that emerges from these calculations is the occurrence of low-lying non-collective strength. This is quite pronounced for neutron-rich drip line nuclei, but is also already evident for the less neutron-rich nuclei in the form of the known pygmy resonances.

The new features can be qualitatively understood from the unperturbed response functions of the neutron-rich nuclei. In these nuclei the proton well calculated in HF is much deeper than the neutron one due to the excess neutrons and the n-p interaction which is stronger than the n-n and n-p ones. The results for $^{28}$O [22] indicate that the proton single-particle orbitals are more deeply bound than the neutron ones and that the shell gaps near the Fermi surface are larger for protons than for neutrons. Furthermore, since neutron orbitals just above the Fermi surface are slightly unbound, neutron excitations across the shells near the Fermi surface can lead to the threshold strength. This is observed, for example, in the calculations for the quadrupole response in $^{28}$O [22,12]. In fig. 1, the results of the calculations by Ghielmetti et al. [12] are shown. The dashed curve corresponds to the results of the continuum RPA response for the isoscalar giant quadrupole resonance (ISGQR). The threshold strength displays strong sharp peaks, but low-lying non-collective strength appears in the whole excitation energy region below 10 MeV. The effect of coupling to surface vibrations (the first step in spreading) on the ISGQR is shown by the solid curve. The shape of the main peak is broader and the mean energy is lower. However, the non-collective low-lying strength is hardly affected.

A similar situation occurs for the monopole response in the Ca isotopes. The RPA monopole response has been calculated by Hamamoto et al. for $^{34,40,48,60}$Ca [20,21] using the SkM* interaction. The monopole response for the neutron-rich drip line nucleus $^{60}$Ca is shown in fig. 2. Although the main ISGMR strength is concentrated around 20 MeV, there is clearly low-lying non-collective strength due to neutron excitations in the region $E_x \approx 4$–12 MeV. Similar to the quadrupole case, the threshold strength develops for drip line nuclei.

The variation of the electric dipole response as a function of the neutron excess was calculated in large-scale shell-model basis by Sagawa and Suzuki [23]. The results of these calculations are interesting because for the lighter oxygen isotopes they can already be compared with experiment.

Experimentally there is nothing known about the multipole strength in unstable nuclei except for the recent experiments done at GSI to investigate the giant dipole resonance in neutron-rich oxygen isotopes. In these