a given transition all other non-directly-coupled channels can be treated through an average absorptive potential. This seems of particular importance in view of the failure of DWBA in many heavy-ion transfer calculations. The *ad hoc* changes made in many cases in optical-model parameters in order to reproduce transfer data through DWBA calculations may find a natural explanation in the phenomenon observed in this work.

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Heavy-Ion Inelastic Scattering to Giant Resonances

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Inelastic ^{12}C and ^{14}N scattering experiments have been performed on ^{90}Zr and ^{208}Pb at $E_{^{12}\mathrm{C}}=120$ MeV, and on ^{40}Ca, ^{90}Zr, ^{197}Au, ^{208}Pb, and ^{209}Bi at $E_{^{14}\mathrm{N}}=161$ MeV. Giant resonances are observed in all spectra. An angular distribution has been measured on a ^{208}Pb target, for which distorted-wave Born-approximation analysis is presented.

The investigation of the nuclear continuum with various probes, including electromagnetic interactions and nuclear scattering, has brought about a great deal of results of major importance[1-3] on the collective modes of oscillation of highly excited nuclei. So far, the scattering studies of giant resonances (GR) have used mostly electrons, protons, and strongly absorbed composite projectiles (d, ^{3}He, ^{4}He).[1] The proper selectivity of the probe, due to the properties of the projectile-target interaction, makes it possible to excite the various (J^π, T) modes[1] in different ways. From this standpoint, inelastic scattering of heavy ions seems to offer interesting prospects. The angular-momentum-matching conditions, favoring large L transfer, can be used to search for new collective modes and to study those already known. It is generally assumed that the background, underlying the resonances in light-particle scattering spectra, is generated by quasifree (projectile, projectile-particle) and precompound emission processes; it could also include some strongly damped giant multipole strength.[4] Heavy-ion inelastic scattering is likely to enlighten this problem as quasifree processes and precompound emission are expected to contribute to a very small extent to the cross section. A consequence of this would be a better GR cross section to background ratio.[5]

Another point of interest for the study of inelastic scattering of heavy ions to the nuclear continuum lies in the possible contribution of giant resonances to the so-called deep-inelastic collision (DIC) mechanism. The recent appearance of a theoretical model[6] describing the supposedly very anharmonic DIC between heavy ions, in terms of coherent excitations of (damped) harmonic modes, makes it highly desirable to search for some experimental grounds. A way of approaching this problem is to look, at first, for GR excitation in the inelastic scattering channel which contains a noticeable part of the reaction cross section, and where the excitation mechanism is still surface-like and likely to excite the surface modes of oscillations of the reaction partners. Recent experiments[7] with 320-MeV ^{16}O revealed that giant-resonance–like bumps are present in the energy spectra of the one-nucleon–transfer reaction channels. In a recent paper,[8] some convincing indications of GR excitation in the ^{12}C + ^{27}Al system have been reported.

In this Letter are presented heavy-ion inelastic-scattering measurements for the excitation of the continuum in a set of standard targets. The experiments were performed at the Institut des Sciences Nucléaires, Grenoble, with 120-MeV ^{12}C (4$^+$) and 161-MeV ^{14}N (5$^+$) beams. Scattered particles were momentum analyzed by means of the QSD (quadrupole-single-dipole) spectrometer, and detected in the focal plane. The detection system, designed and set up for these experiments, was placed in the focal plane and determined position (x) and complete identification of the ions by energy-loss (ΔE) and time-of-flight (T) measurements. This was done by the association of a multiwire porportional chamber (X), and ionization chamber (ΔE) and a fast scintillator detector (T) measuring time of slight relative to rf pulses. This system will be described in detail in a forthcoming paper. No particular effort was made to obtain the best possible energy resolution, which lay between 500 and 800 keV, mostly due to the energy spread of the unanalyzed beam. The targets bombarded with ^{14}N ions were ^{40}Ca (natural target), ^{90}Zr, ^{197}Au, ^{208}Pb, and ^{209}Bi (all thickness ~ 1 mg/cm^2). Each target was studied near the grazing angle. Spectra were calibrated using peaks due to transitions to known low-lying levels and those due to one-neutron transfer. For each spectrum, a background was defined by extrapolating continuously the high-lying continuum down to the bottom of the elastic peak. The difference spectrum was then unfolded into single peaks using Gaussian or Breit-Wigner shapes. All the measured spectra have the same global features: Above a first region ($E \lesssim 5$ MeV), where low-lying collective transitions are observed, most of the spectra show strong enhancement, sometimes with structure in the low-energy octupole-resonance[3] (LEOR) region. Above $E_x \simeq 10$ MeV, the spectra show another bump followed by a flat or gently decreasing background (Figs. 1 and 2). The observed excitation energy of this bump is in good agreement with the average value for the giant quadrupole resonance (GQR).[1]

Figure 1 displays spectra of inelastically scattered ^{12}C from ^{90}Zr and ^{208}Pb targets. Large peaks due to the excitation of the (2$^+$, 4.4 MeV) level in the ^{12}C projectile are seen in both spectra. The 3$^-$ states at 2.75 MeV (unresolved from

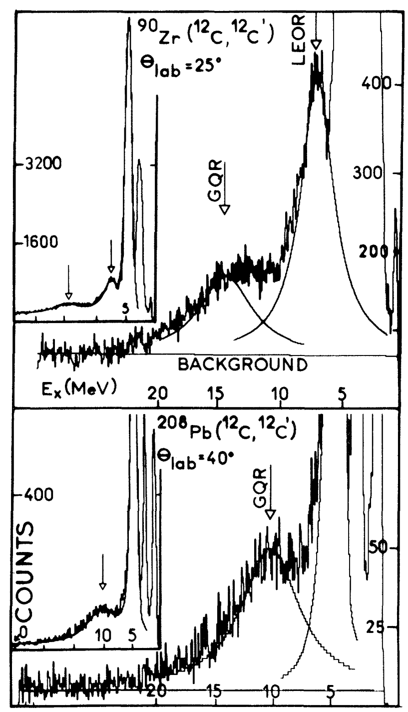

FIG. 1. Energy spectra of inelastically scattered ^{12}C. (The elastic peak was out of the detector.) Expected positions for GQR and LEOR are indicated with arrows. Assumptions for backgrounds and theoretical shapes for the peaks of interest are shown. The insets compare theoretical shapes obtained by summing individual peaks with the experimental spectra.

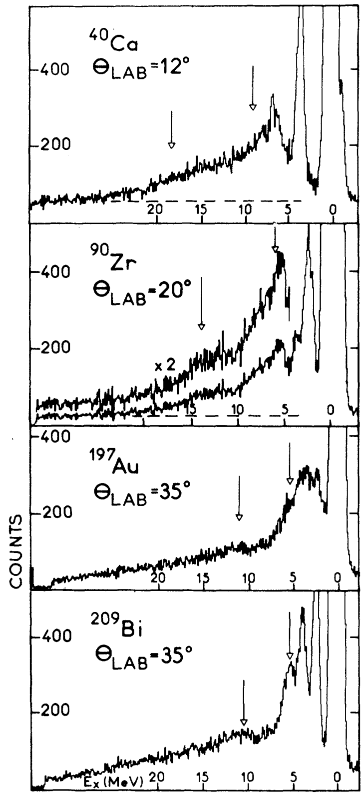

FIG. 2. Energy spectra of inelastically scattered ^{14}N. A horizontal background can be inferred from the high-excitation-energy region of the ^{40}Ca and ^{90}Zr spectra. The same procedure cannot be applied for heavy targets. Arrows indicate the expected positions of GQR at $63A^{-1/3}$ MeV and LEOR at $32A^{-1/3}$ MeV.

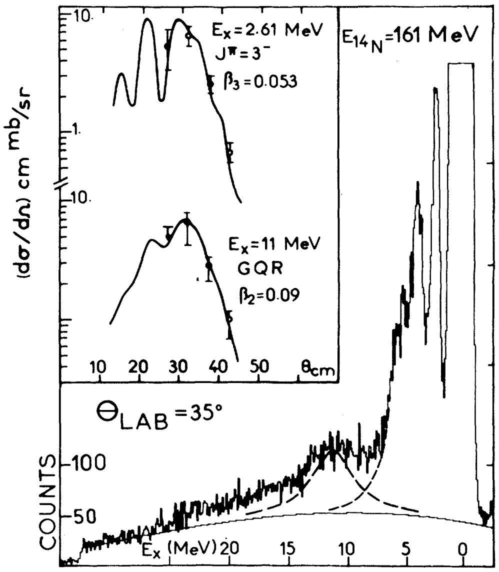

FIG. 3. Typical spectrum from the reaction ^{208}Pb(^{14}N, ^{14}N′). The background assumption is shown together with the GQR theoretical peak and tail of fitted lower peaks. The inset shows experimental angular distributions. The curves are results of DWBA calculations.

its neighbors) in ^{90}Zr and at 2.61 MeV in ^{208}Pb are also seen to be excited. The intermediate-energy region of the ^{90}Zr spectrum is dominated by a single peak with a full width at half-maximum (FWHM) of 3.6 ± 0.3 MeV and centered at $E_x \approx 7.0$ MeV. This is approximately the LEOR excitation energy.[3] The high-excitation-energy bump is found centered around 14 MeV in ^{90}Zr and around 11 MeV in ^{208}Pb, close to the values obtained for the GQR from other experiments. However, the widths deduced from these spectra by fitting the GQR bumps with Breit-Wigner shapes centered at $63A^{-1/3}$ MeV have larger values (5.5 MeV for ^{90}Zr and 6.1 MeV for ^{208}Pb than those measured in light-particle scattering.[1] The corresponding differential cross sections are 1.8 and 4.0 mb/sr for ^{90}Zr and ^{208}Pb, respectively. In relation to the introductory remarks, it is to be noted that the background at excitation energies above the GQR is small and flat. The GQR peak-height to background ratio is about 5 for the ^{208}Pb target and about 2 for the ^{90}Zr target. This is much larger than values observed from light-ion experiments, where typical values are smaller than 1.

The spectra measured with ^{14}N projectiles have quite similar features as can be seen in Figs. 2 and 3. The calibration of the spectra did not reveal a noticeable contribution from the ^{14}N excited states. The low-lying collective states of the target are observed as in ^{12}C scattering spectra. In ^{40}Ca, the intermediate-excitation-energy bump exhibits some structure composed of two main peaks at 6.9- and 7.9-MeV excitation energy. In the same spectrum, the top of the high-excitation-energy bump is located around 15 MeV. This is lower than the expected GQR position (18.4 MeV). This broad enhancement could include contributions from other multipolarities. The ^{90}Zr spectrum is very similar to that measured with ^{12}C projectile. The low-energy bump in ^{197}Au has been observed previously in a (p,p') experiment.[10] All spectra measured on heavy targets have a bump centered at the excitation energy expected for the GQR. However the background (see Figs. 2 and 3) is larger and more difficult to define than in the ^{208}Pb + ^{12}C spectrum (compare Fig. 3 with Fig. 1).

Figure 3 shows the spectrum measured at 35° on ^{208}Pb target, together with the assumed background and the theoretical shape (FWHM = 4.5 MeV) deduced for the GQR. (This spectrum was best reproduced with another smaller peak at a higher excitation energy.) The upper left-hand part of Fig. 3 shows the angular distribution obtained for the (3^-, 2.61 MeV) transition and for the GQR. A simple analysis has been made to be compared to these data: Distorted-wave Born-approximation (DWBA) calculations were performed with the code DWUCK. The optical-model parameters were taken from Ref. 10. It was checked that the corresponding theoretical elastic-scattering cross section reproduced the few experimental values satisfactorily. The inelastic-scattering cross-section calculations included both Coulomb and nuclear contributions, the latter being generated from the standard collective-model form factor. The Coulomb and nuclear-deformation parameters were assumed to be equal although they are known to be markedly different.[11] The calculated angular distribution for the octupole transition at 2.61 MeV fits the data rather nicely (Fig. 3). The value of the deformation parameter deduced from the comparison ($\beta_3 = 0.053$) is close to that extracted from other heavy-ion experiments.[11] The experimental angular distribution for the GQR is shown in Fig. 3 with a calculation assuming $L = 2$ and $E_x = 11$ MeV, leading to a deformation parameter $\beta_2 = 0.09$ (the integrated cross section amounts to 58 mb). This strength exhausts 90% of the energy-weighted sum-rule limit[12] for $E2$ transitions, in reasonable agreement with other determinations.[1] It is gratifying to see that this crude analysis is consistent with the results obtained in other experiments.[1,11]

This investigation of the nuclear continuum by inelastic scattering of heavy ions has shown that giant resonances are excited over a broad range of masses. This provides firmer grounds for the model of Broglia, Dasso, and Winther[6] concerning a giant-resonance contribution to deep-inelastic collisions. It has been shown that DWBA analysis reasonably accounts for the measured GQR cross section, and indications have been obtained that the background underlying the GR can be reduced to a large extent in heavy-ion scattering by suitable choice of the projectile. Discrepancies with light-ion and electron results about excitation energies and widths could indicate contributions due to higher multipolarities. In order to ininvestigate these hypotheses and to extend the knowledge of this reaction channel, more detailed experiments are now in progress.

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