High-energy target excitations in heavy ion inelastic scattering

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The high-energy continuum from inelastic scattering of 84 MeV/nucleon $^{17}$O by $^{208}$Pb was studied by measuring $^{17}$O-$\gamma$-ray coincidences. The particle spectra in coincidence with $\gamma$ rays above $\sim$1 MeV show structures up to 45-MeV excitation energy that can be explained in terms of the statistical decay of the highly excited target nucleus. The observation in the $\gamma$-ray spectrum of the giant dipole resonance built on excited states in $^{208}$Pb confirms that the continuum up to $\sim$60-MeV excitation energy is dominated by the excitation of $^{208}$Pb and offers the unique possibility of detailed studies of the giant dipole resonance as a function of excitation energy decoupled from the influence of angular momentum.

Inelastic scattering of heavy ions in coincidence with $\gamma$ rays and light particles has become an important tool for study of the decay of giant resonances. In heavy nuclei, the structure in the inelastic spectrum up to $\sim$20 MeV appears to be reasonably well understood in terms of localized (mostly isoscalar) strength. In $^{208}$Pb the decay of giant resonances and the underlying continuum up to 20 MeV is well described by the statistical model. However, there is very little experimental information on the type of target excitations which might contribute to the inelastic continuum above 25 MeV. Most likely broad poorly localized distributions of $I \geq 3$ strength play a major role for most projectiles. Recently, structures in the high-energy continuum have been reported and tentatively interpreted as localized multiphonon strength. Thus, there is a special interest in trying to extend our understanding of the inelastic continuum to higher energies.

In a typical study of giant-resonance excitation by inelastic scattering, the excitation energy of the target is inferred from a determination of the kinetic energy of the scattered particle which is usually detected in a magnetic spectrometer and identified as having the same mass and charge as the projectile. However, the correlation of scattered particle energy loss with target excitation is not unique. For composite projectiles, inelastic projectile excitation or mutual excitation of target and projectile complicates the interpretation, though this problem can be minimized by choosing a projectile with a very low binding energy. A more serious problem, which presumably gets progressively worse with increasing apparent excitation energy, is the occurrence of reaction mechanisms more complex than inelastic scattering which nevertheless produce an ejectile with the charge and mass of the projectile. For example, projectile pickup and sequential decay can be important and can produce structures in the high-energy continuum. Nucleon knock-out reactions which are the dominant contribution in light ion scattering, as well as cluster knock out, can occur with heavy ions; however, they are much less important and do not tend to produce structures in the continuum.

Recently, particle coincidence experiments were performed in order to search for target excitation contributions to the continuum. Assuming that the decay of the excited target can be treated statistically, the number of evaporated particles is a measure of the excitation energy. It is probably reasonable to assume that statistical decay which has been applied successfully below 20 MeV should also describe the decay of higher-lying target excitations very well. The lack of localization of high multipolarity strength implies a large spreading width and consequently rapid damping of the $1p1h$ resonance strength into the more complex compound nuclear states.

If a statistical description is appropriate, coincidence experiments between inelastically scattered particles and high-energy $\gamma$ rays are especially attractive. It is well known from heavy-ion fusion reactions that $\gamma$-ray spectra from the decay of equilibrated compound nuclei exhibit a bump at $\sim 77A^{1/3}$ MeV due to excitation of the giant dipole resonance (GDR) built on highly excited states. If the nuclear continuum in heavy-ion inelastic scattering...
is due to target excitations, a GDR bump should be observable in the γ-ray coincidence spectra at an energy that corresponds to the energy of the GDR in the target nucleus. There should be almost no background of high-energy γ rays, as the reaction dynamical contributions to the continuum (pickup decay, knock out) do not produce highly excited target nuclei.

However, the relatively small cross section of the continuum at high excitation energies and the small γ-decay branch (Γγ/Γν ∼ 10⁻⁴) make these experiments extremely difficult and the use of large γ-ray detector arrays is essential. In the present paper we report results from a γ-ray coincidence experiment that provides a measurement of the γ-ray spectra as a function of excitation energy in the continuum.

The experiment was carried out by bombarding a ²⁰⁸Pb target (3 mg/cm²) with 84 MeV/nucleon ¹⁷O ions from the Grand Accélérateur National d’Ions Lourds (GANIL) cyclotron facility. The choice of a beam with a low particle emission threshold (4.1 MeV) largely eliminates the contributions from projectile excitations. Inelastically scattered ¹⁷O ions were detected and identified in the magnetic spectrograph SPEG (Spectromètre Perde Energie GANIL) at center-of-mass angles between 1.5°–5.0°. The energy resolution was 800 keV. Data were obtained for excitation energies up to ∼60 MeV. γ rays up to 20 MeV in coincidence with ¹⁷O ions were detected in 59 hexagonal BaF₂ scintillators. Two close-packed clusters of 19 detectors (5.19 cm face to face, 20 cm long) were positioned at 110° and 138° with respect to the beam, and three clusters of seven detectors (8.66 cm face to face, 14 cm long) were placed at 110° (two) and 138°. The BaF₂ detectors provided a total solid angle of 22.6% of 4π at a distance of 35 cm. The fast timing characteristics of the BaF₂ detectors and the good time structure beam bursts (1≈800 ps full width at half maximum (FWHM)) allowed for a clean neutron-γ-ray separation. In addition charged particles and high-energy neutrons were rejected via pulse shape discrimination. Particle singles, scaled down by 2⁶ were recorded simultaneously with the γ-ray coincidence events. Further details of the experimental setup are described elsewhere.

Figure 1 shows inelastic ¹⁷O spectra for the entire angular acceptance in which the ¹⁷O energy has been converted to excitation energy of the target. The scaled-down particle singles spectrum (dashed line) shows the excitation of the low-lying 3⁻ (2.61 MeV) and the 2⁺ (4.08 MeV) states. The broad peak around 12 MeV contains the isoscalar giant quadrupole resonance (ISGQR) at 10.6 MeV and the isovector giant dipole resonance (IVGDR) at 13.5 MeV, which are built on the ground state of ²⁰⁸Pb. The continuum slowly decreases in magnitude above 15 MeV and no statistically significant structures are observed.

Both the γ-ray spectrum in coincidence with the particles and the particle spectrum in coincidence with γ rays contain information on the origin of the continuum. The solid curve in Fig. 1 corresponds to the particle spectrum in coincidence with any γ ray above 1 MeV detected in the BaF₂ detectors. The spectral shape differs considerably from the singles spectrum. The apparent shift of the resonance from ∼11 to 13 MeV and the additional peak at 23 MeV can be explained by the statistical decay of the excited target as was previously demonstrated in (α,α'p) experiments. With increasing excitation energy, more particle evaporation channels (in the case of Pb predominantly neutrons) open up. At the threshold for particle evaporation the γ-ray multiplicity is reduced, therefore yielding a smaller coincidence count rate. Increasing the excitation energy further increases the γ-ray multiplicity again until the next evaporation threshold is reached. The ²⁰⁸Pb 2n threshold at 14 MeV is responsible for the dramatic shift of the GQR/GDR peak to higher energies, while the 3n threshold (22 MeV) produces the peak at 23 MeV. The observation of the 23 MeV peak indicates that up to at least 25 MeV a large contribution to the inelastic spectrum is due to target excitations and that the decay of this part of the continuum can be treated statistically in agreement with the statistical analysis of (α,α'n) experiments.

In order to examine the higher-energy continuum in more detail, we show in Fig. 2(a) the particle yield in coincidence with γ rays above 1 MeV divided by the particle singles yield. In this representation additional structure appears in the inelastic continuum up to ∼45 MeV of excitation energy, indicating the influence of higher neutron evaporation thresholds. Statistical-model calculations using the code CASCADE (Ref. 19) were performed to analyze the coincidence spectra at excitation energies above 20 MeV. The entrance channel population was given by the particle singles yield for a given excitation energy bin, the shape of the angular momentum distribution was assumed to be an isosceles triangle ranging from 3 to 7h, with a maximum at 5h. Below 10-MeV excitation energy the level densities were calculated using the parametrization of Dilg et al. and above 20 MeV a constant level-density parameter (a = A/9) was used, with a
smooth interpolation in the intermediate energy range. The GDR built on excited states was included with parameters similar to those for the ground state ($E_{\text{GDR}} \approx 13.5$ MeV, $\Gamma_{\gamma} \approx 3.9$ MeV), with the width slightly increased to $\Gamma_{\gamma} \approx 5.0$ MeV to take into account the finite temperature. Figure 2(b) shows the calculated multiplicity of $\gamma$ rays above 1 MeV, as a function of target excitation, in steps of 1 MeV, corrected for the energy-dependent trigger efficiency of the detectors. The shape of the calculated $\gamma$-ray multiplicity spectrum is in good agreement with the measured coincidence spectrum. Figure 2(c) shows the percentages of the cross sections for the different neutron evaporation channels and illustrates the influence of the neutron evaporation thresholds on the $\gamma$-ray multiplicities. When a new neutron channel opens up, the resulting residual nuclei produced via that channel have very little excitation energy, and produce fewer $\gamma$-rays. This results in a decrease in $\gamma$ multiplicity above each $xn$ threshold where the yield of the newly opened channel is increasing rapidly. The increase in cross section just above threshold for individual $xn$ evaporation channels becomes less steep at higher excitation energies, so that the structures in the $\gamma$-ray multiplicity and therefore in the particle coincidences are washed out. Thus, it is not possible to extract any information on target excitations at energies above 45 MeV from the particle spectrum in coincidence with $\gamma$ rays. The existence of the peak structures up to 45 MeV, however, and the good agreement with statistical model calculations of the $\gamma$-ray multiplicity are strong evidence for large contributions of target excitation.

However, if the continuum is dominated by target excitations, the high-energy $\gamma$-ray spectrum in coincidence with inelastically scattered $^{17}$O ions should contain the $\gamma$ decay of the GDR built on highly excited states in $^{208}$Pb. All other processes likely to be significant here lead to target-like residues at much lower excitation energy, and consequently to little or no yield to high-energy $\gamma$ radiation. Figure 3 shows the $\gamma$-ray spectrum obtained with a coincidence gate on the excitation energy region of 36–60 MeV. An enhancement over the purely exponential dropoff is clearly seen at $\sim 12$ MeV, where the GDR of $^{208}$Pb is expected to be located. The spectrum (solid) calculated using CASCADE reproduces the data very well. In order to emphasize the GDR, a CASCADE calculation not including the GDR strength function is shown as the dashed curve. The calculations were normalized to the data between 7 and 8 MeV. Although the statistics are not sufficient to extract detailed GDR parameters the existence of the GDR is obvious.

It is possible to extract the $\gamma$-ray strength as a function of excitation energy by dividing the coincidence spectrum into smaller excitation energy bins. The $\gamma$-ray yields above 7 MeV at excitation energies between 36–48 and 48–60 MeV show reduced strength relative to the 28–36 MeV bin of 70 and 40%, respectively. We interpret this reduction in strength as an indication of increasing contributions from reaction mechanisms other than inelastic target excitation at these large energy losses. However, even at 60 MeV a large fraction of the cross section can still be accounted for by target excitation. The additional cross section can be explained with pickup-decay reactions, which make essentially no contribution to the $\gamma$-ray spectrum above a few MeV. The maximum contribution of neutron or proton pickup decay is expected at an apparent excitation energy near the beam energy per nucleon (i.e., $\sim 84$ MeV). Calculations using Brink's nucleon transfer model predict a broad distribution centered near 84 MeV and starting to contribute significantly
around 40 MeV of excitation energy, in qualitative agreement with the data.

The observation of the GDR built on highly excited states in coincidence with the inelastic heavy-ion continuum offers an extremely interesting alternative to heavy-ion fusion reactions for studies of the GDR built on excited states. The dependence of the GDR parameters, e.g., energy and width, on excitation energy and angular momentum are of current experimental and theoretical interest. Small-angle inelastic scattering has the advantage of selectively populating states with low angular momentum. In addition, the entire excitation function over a large range of excitation energies can be measured at the same time.

In conclusion, this measurement of inelastically scattered heavy ions in coincidence with high-energy $\gamma$ rays shows that it is possible to observe target excitations in the high-energy continuum. The data show that the statistical decay of highly excited $^{208}$Pb accounts for a large fraction of the continuum cross section up to 60-MeV excitation energy. Although experiments of this kind can determine the presence of high excitations in the target, it is not possible to determine if they were formed via broad giant resonances of higher multipolarity, multiphonon excitations, or other reaction mechanisms. However, the observation, via high-energy $\gamma$-ray coincidences, of the GDR built on highly excited states in heavy-ion inelastic scattering measurements offers the unique possibility of detailed studies of the GDR parameters as a function of excitation energy without the influence of angular momentum.

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