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Study of the continuum in heavy ion inelastic spectra by light particle coincidence measurements[☆]

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The continuum in heavy ion inelastic spectra contains, in addition to the excitation of target nucleus states, contributions from pick-up break-up and knock out reactions. In the case of the $^{40}\text{Ca} + ^{40}\text{Ca}$ collision at 50 MeV/N these contributions are separated and their relative importance assessed by the measurement of light charged particles in coincidence with the inelastically scattered fragments. The pick-up break-up contribution is found to make up less than half of the cross section at high excitation energies, conversely, the knock out process is important.

Recent inelastic scattering experiments have shown that intermediate energy heavy ions are an efficient probe for the study of both isoscalar and isovector giant resonances [1–4]. These states are excited with much higher differential cross sections and larger peak to background ratios than with light hadronic probes. At excitation energies above those of the known giant resonances, low cross-section structures superimposed on a large background have been observed [5,6], which have been attributed to multiphonon excitations built with the giant quadrupole resonance [7]. Heavy ions are also intensively used in the search for other high lying resonances [8]. It is consequently of paramount importance to obtain precise knowledge of the different reaction mechanisms contributing to the continuum in heavy ion inelastic spectra.

In the inelastic channel, the projectile cannot be excited above its particle emission threshold, since it would decay before being detected. Similarly to inelastic α -particle scattering [9], apart from excitations of the target nucleus, two other mechanisms are expected to contribute to the inelastic heavy ion spectra. In pick-up break-up reactions the projectile picks up one or several nucleons from the target, and the resulting excited system subsequently decays, thus populating in certain cases the inelastic channel. Kinematical calculations [10,11] show that this contribution is centered at rather high apparent excitation energies, around the energy per nucleon of the beam. Knock out reactions, in which the projectile knocks out one nucleon or a cluster from the target, are also expected to be present. Inclusive experiments are unable to distinguish directly between the three above processes.

In this letter we present a novel method to separate the effects of the different mechanisms directly. Let us focus on inelastic excitations and pick-up break-up reactions. In the first case the target is strongly excited while the projectile remains below its particle

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emission threshold. Thus all light particles will originate from the decay of the target nucleus, and, assuming statistical decay, will have Coulomb-like velocities in the laboratory frame, since the recoil velocity of the target is small. On the other hand, in pick-up break-up reactions, the projectile-like fragment is excited above its particle emission threshold. In simple transfer reactions at intermediate energies the donor nucleus (in this case the target) remains almost cold [12,13]. Here the light particles originate from the projectile-like fragment and have their laboratory velocity boosted by its velocity. Measurement of the velocity of the light particles emitted in coincidence with the scattered fragment permits to distinguish between pick-up break-up reactions and target excitations.

The experiment was performed by bombarding an evaporated self supporting 0.5 mg/cm^2 ^{nat}Ca foil with the 50 MeV/N ^{40}Ca beam from the GANIL facility. ^{40}Ca was chosen because it decays statistically with a high probability by charged particle emission and its collective states have been extensively studied [14]. The inelastically scattered fragments were measured between $\theta_{\text{lab}} = 1.7^\circ$ and 5° ($\theta_{\text{graz}} = 1.7^\circ$) using the SPEG spectrometer associated with its standard detection system [15]. Unambiguous separation of $^{40}\text{Ca}^{20+}$ was obtained, the total energy resolution was 800 keV , and an excitation energy range of over 150 MeV was covered. Coincident light charged particles were detected in 19 cesium iodide (CsI) elements of the multidetector array PACHA [16], placed at angles between $+55^\circ$ and -80° in the horizontal plane (positive means on the same side of the beam as the spectrometer). Proton, deuteron, triton, and α -particle identification was obtained by comparing the integrated fast and slow components of the CsI pulse read out by a photomultiplier. The energy calibrations were performed by detecting momentum analysed secondary light particle beams in all the counters. The thresholds for particle identification were 1.5 MeV for protons and 5 MeV for α particles. This particle detection ensemble was completed by 5 solid state telescopes ($30 \mu\text{m}$ surface barrier, 3 mm Li-drifted), placed in the backward hemisphere.

In the reaction studied, proton emission dominates and, since the α -particle emission was found to have a low cross section, only proton coincidence data will be discussed. Fig. 1 shows a density plot of the

invariant proton cross-section in the $(V_{\parallel}, V_{\perp})$ velocity plane in coincidence with inelastically scattered ^{40}Ca after correction for different detector solid angles. Random coincidences, which contributed less than 10% of the total counting rate, were subtracted. In the forward direction ($\theta_p = +7^\circ$ and -15° and less intensely at $\theta_p = 20^\circ$ and -22°) an accumulation of fast moving protons is observed which indicates the presence of the pick-up break-up mechanism. At larger positive angles and in the backward hemisphere an almost isotropic component is visible, centered around the velocity of the recoiling target. These features are in good agreement with the Monte Carlo calculation, in which the cross-section for pick-up break-up reactions and inelastic excitations were arbitrarily chosen to be equal and only the one proton pick-up channel was included. The excitation energy distribution of ^{41}Sc was chosen as a gaussian of mean 15 MeV and variance 7 MeV . The decay of the excited nuclei was followed using a modified version [17] of the Monte Carlo evaporation code LILITA [18]. The two characteristic proton rings correspond to the emission from the projectile (pick-up break-up reactions) and the target (inelastic excitations). All protons arising from pick-up break-up reactions are concentrated in a cone of approximately 30° opening in the laboratory frame. The calculated asymmetry of the projectile ring is due to the forward focused primary angular distribution of ^{41}Sc [19] and is clearly also observed in the data. More surprisingly, at negative angles, a strong enhancement of the proton cross-section is apparent in the direction of the recoiling nucleus. Since emission from isolated giant states is symmetric about 90° in the recoil frame, these protons could be attributed to knock out reactions which thus are shown to contribute sizeably to the inelastic cross-section.

In order to examine the contributions to the inelastic spectrum due to the different mechanisms the particle detectors have been separated into four groups as indicated in fig. 1. Group (a) covers the region where the knock out is expected to be maximum. Group (b) corresponds to the domain of protons from pick-up break-up reactions while in groups (c) (CsI detectors) and (d) (solid state telescopes) only protons from true inelastic reactions are present. Fig. 2 displays the inelastic spectra in coincidence with each group of protons, normalized to a

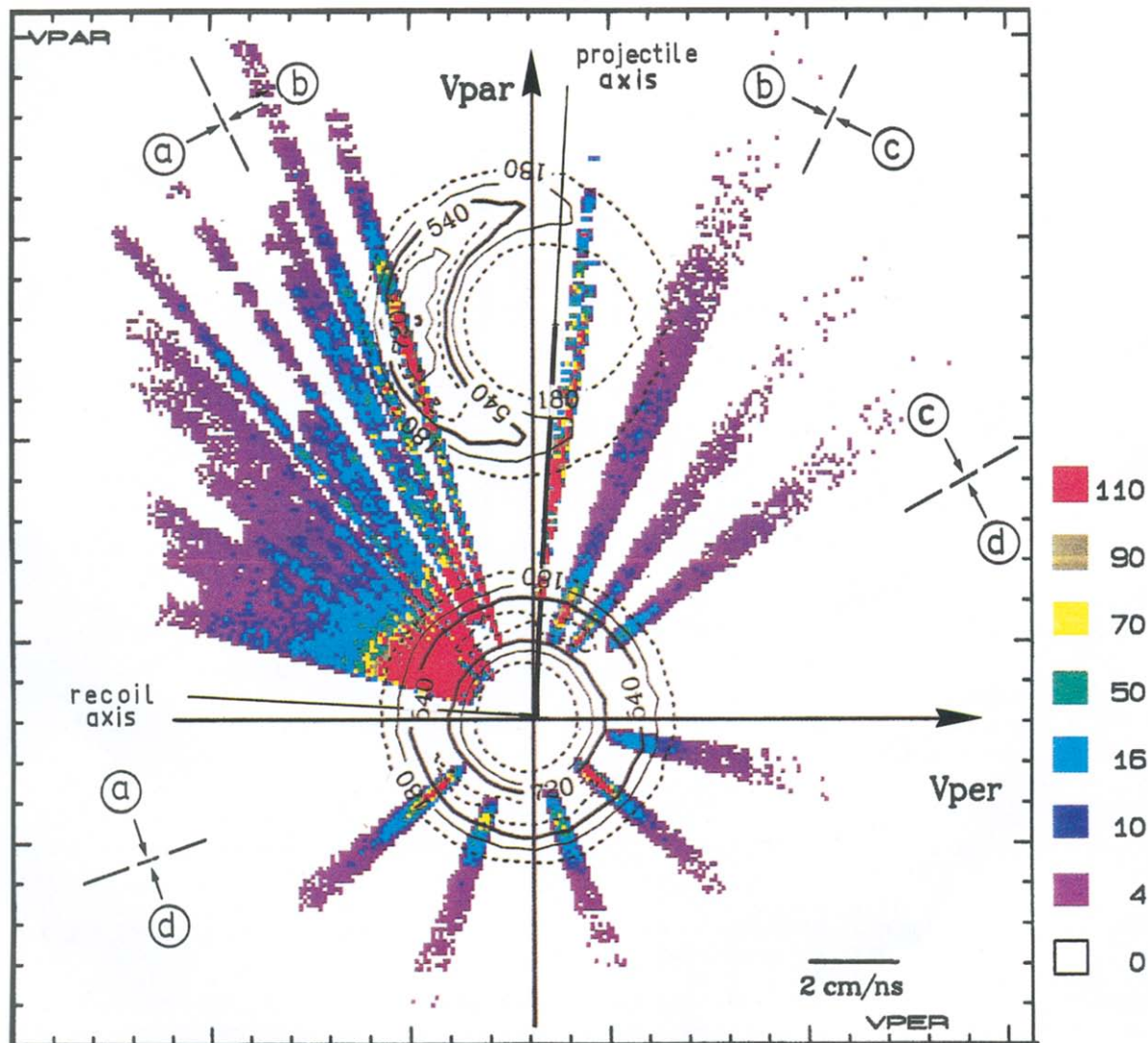


Fig. 1 Experimental invariant proton cross-section represented in the $(V_{\parallel}, V_{\perp})$ plane in coincidence with ^{40}Ca nuclei scattered inelastically into the angular range between $+1.7^{\circ}$ and $+5^{\circ}$. Each cone corresponds to one light particle detector. The red regions correspond to the highest cross-sections and the purple to the lowest. The thick black lines indicate the average velocities of the projectile- and target-like fragments. The defined angular regions (a)–(d) are used for gating the inelastic spectra in fig. 2. Contour plot Monte Carlo simulation (see text) of the invariant proton cross-section in coincidence with inelastic scattering.

fixed solid angle for proton detection. At about 18 MeV the giant resonance bump is clearly visible in all the spectra, reflecting the approximate isotropy of the giant resonance decay. As expected, a broad bump centered around 60 MeV, corresponding to pick-up break-up reactions, shows up strongly in (b) and is much smaller or absent in all the other spectra. The most remarkable feature is the presence of consider-

able cross-section above 20 MeV excitation energy in spectra (c) and (d), where high lying resonances and multiphonon excitations would be expected. These spectra are free from pick-up break-up contributions and from most if not all contributions from the knock out process.

We will now examine more quantitatively the pick-up break-up component. Fig. 3 presents the ^{40}Ca

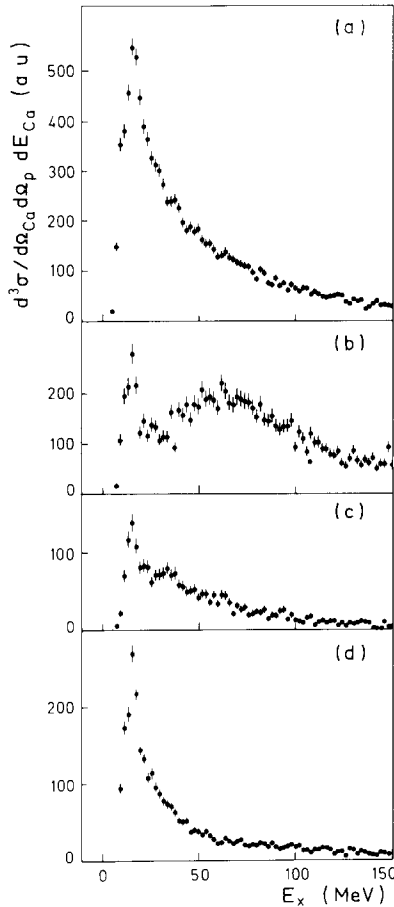


Fig 2 Inelastic ^{40}Ca spectra in coincidence with protons detected in the four angular regions (a)–(d) represented in fig 1 and defined as follows (a) $-80^\circ \leq \theta_p \leq -27^\circ$, (b) $-27^\circ \leq \theta_p \leq +27^\circ$, (c) $+27^\circ \leq \theta_p \leq +60^\circ$, (d) $\theta_p \geq +60^\circ$ and $\theta_p \leq -110^\circ$. All spectra are normalized to a fixed solid angle for proton detection

spectra in coincidence with protons detected at $\theta_p = -15^\circ$ (fig. 3a) and $+7^\circ$ (fig. 3b), where the pick-up break-up process is prevalent. The two spectra exhibit very different shapes, due to the fact that two solutions (forward and backward) are allowed for proton emission at the smaller angle ($\theta_p = +7^\circ$), while at the larger angle ($\theta_p = -15^\circ$), situated on the edge of the proton ring, these solutions are degenerate. The Monte Carlo calculation gives a very good description of the data, using only one overall normalisation coefficient for the two angles. The relative normalisation of the two spectra depends mainly

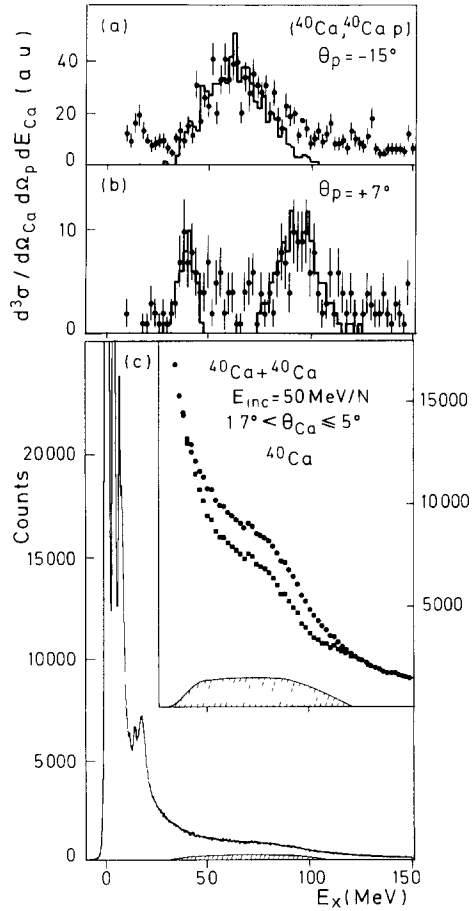


Fig 3 Inelastic ^{40}Ca spectra in coincidence with protons detected at $\theta_p = -15^\circ$ (a) and $+7^\circ$ (b). The solid histograms are the result of the Monte Carlo calculation (c) Inclusive ^{40}Ca inelastic spectrum. The hatched area shows the contribution of proton pick-up break-up reactions. Insert: expanded view of the high excitation energy region. The dots represent the inclusive inelastic spectrum and the squares the inelastic spectrum after subtraction of the pick-up break-up component

upon the angular distribution of the primary transfer products, which was chosen to be equal to the experimental ^{41}Sc distribution. The calculation was performed assuming no excitation of the target nucleus. An excitation energy E_t^* in the target would shift the spectra towards higher apparent excitation energies by E_t^* [10]. The agreement obtained confirms that during the transfer process, the target remains mostly cold. The counts at higher excitation energies which are not accounted for by the simulation could be due

to two-proton and proton-neutron pick-up break-up channels.

In order to assess the contribution of the pick-up break-up process to the inclusive inelastic cross section, we applied the normalisation factor, previously found to fit the data of figs. 3a and 3b, to the calculation performed without any constraint on the proton angle. The result is shown in fig. 3c along with the inclusive experimental spectrum. The proton pick-up break-up reaction accounts for only about 20% of the inelastic cross-section in the region where it is important, between 50 and 90 MeV excitation energy. Since neutrons were not measured in this experiment, the neutron pick-up break-up contribution can only be grossly estimated. DWBA calculations using the code PTOLEMY [20] predict that, for an excitation energy of the projectile-like fragment of 15 MeV, proton transfer is about twice as probable as neutron transfer. Moreover, the statistical decay code CASCADE [21] shows that a ^{41}Sc nucleus excited to 15 MeV will decay with 60% probability by single proton emission, while a ^{41}Ca , produced by neutron transfer, at the same excitation energy, has only a 25% probability of deexciting by single neutron emission. Thus the neutron pick-up break-up cross-section is expected to be about one quarter of the proton one. Even making allowance for a large uncertainty in this prediction, the pick-up break-up mechanism can in no way account for the total cross-section in the high excitation energy region of the inelastic spectrum contrary to previous belief [10]. This conclusion cannot, however, be generalized to other systems since the transfer probabilities are expected to depend dramatically upon projectile-target combination and bombarding energy [22].

In conclusion a new technique has been presented to disentangle the various contributions to heavy ion inelastic spectra, by measuring light particles in coincidence with the ejectile. The pick-up break-up mechanism accounts for at most half of the cross-section in the excitation energy region around 60 MeV in the $^{40}\text{Ca} + ^{40}\text{Ca}$ reaction at 50 MeV/N. Our results indicate that the knock-out process is also important.

A sizeable amount of the cross-section at high excitation energies is due to excitations of the target. This result provides a solid foundation for the use of heavy ions in the search for nuclear collective strength at high energies. Future experiments placing large solid angle particle detectors at angles where the pick-up break-up and knock out contributions are absent will allow to obtain virtually background free spectra of inelastic excitations.

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