Investigation of the nuclear continuum by ^{40}Ca inelastic scattering on ^{40}Ca at 160 MeV

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The ^{40}Ca + ^{40}Ca reaction has been studied at 160 MeV incident energy. Low lying peaks are observed in the inelastic channel together with a broad bump at 26 MeV total excitation energy. A comparison is made with results obtained in the same reaction at higher bombarding energy.

[NUCLEAR REACTIONS ^{40}Ca + ^{40}Ca $-E_{\rm inc}=160$ MeV; measured $\sigma(\theta,E)$; angular range 6° to 40°; compared to higher energy results.]

Recent investigations of ^{6}Li, ^{12}C, ^{14}N, and ^{16}O scattering[1–8] have provided clear evidence that giant resonances are strongly excited in heavy ion reactions. Heavy ions are expected to have two advantages over lighter ions for studies of giant resonances with high angular momentum ($L>2$):

(i) angular momentum matching conditions which allow large angular momentum transfers;

(ii) the significant reduction of background due to the fact that quasifree processes and precompound emission reactions do not contribute significantly to heavy ion inelastic spectra.

With the above points in mind, we have chosen to investigate the ^{40}Ca + ^{40}Ca reaction at 160 MeV, a reaction which has been extensively studied at higher incident energy.[9–11] These studies at 400 and 284 MeV have revealed the existence of broad structures at high total excitation energies in the energy spectra of some fragments emitted in the collision. These structures were observed at the same total excitation energies for the two bombarding energies in the energetically allowed excitation energy range. Furthermore, these previous experiments demonstrated that the structures are due to a mechanism with a very short interaction time. Thus, since simple explanations such as effects due to the symmetry of the entrance channel or the opening of evaporation channels have been ruled out,[11,12] the structures have been tentatively associated with giant resonances.

In the present paper, we report on the study of the same ^{40}Ca + ^{40}Ca reaction at 160 MeV. Our interest is divided between the evolution of these structures with incident energy and the observation of details in the energy spectra of the emitted fragments, which is made possible due to the much better energy resolution obtained here as compared to the high energy studies.

A 100 μg/cm^2 target evaporated onto 10 μg/cm^2 ^{12}C backing was bombarded with the ^{40}Ca beam from the Orsay MP tandem accelerator. The reaction products were detected in an ΔE-E detector consisting of an ionization chamber and a position sensitive solid state detector set in the focal plane of a magnetic spectrometer located at an angle of $\theta_{\rm lab}=15°$ which is smaller than the grazing angle ($\theta_{\rm graz}=25°$). With such a setup an unambiguous mass and charge identification of the emitted fragments was obtained together with a momentum measurement in an energy range $\Delta E/E$ of about 3%. The overall energy resolution permitted with this system was less than 1 MeV. Simultaneously, the use of three ΔE-E telescopes consisting of two silicon surface barrier detectors (8 and 500 μm) allowed a large angular range to be measured; however, only a charge identification of the detected fragments could be extracted. Data were taken in 1° steps over an angular range between 6° and 16°, and in 5° steps thereafter to 40°. With these detectors, the overall energy resolution obtained was approximately 1.5 MeV.

Great care was taken to eliminate "spurious" peaks which can arise from target backing and contaminants such as ^{12}C or ^{16}O. To identify the contributions from the light contaminants, the same measurements were repeated with a natural carbon and Mylar targets. These effects can also be easily estimated by the study of the kinematic shifts of the peak position with scattering angles. From these measurements, it was recognized that a small contribution of a Ca beam with a lower charge state was accelerated simultaneously with the main beam.

A striking feature in this experiment is the very low cross section for transfer reactions. The cross section for one nucleon transfer reactions is less than 5% of the inelastic scattering cross section and no deep inelastic events are observed. These results differ markedly from the ones obtained in the study of the $^{40}Ca + {}^{40}Ca$ reaction at 284 and 400 MeV incident energy.[9,10] At these higher energies, the cross section for transfer reactions do not change significantly, although there is 116 MeV difference in the bombarding energies, and thus the general trend of the mass and charge distributions for the quasielastic and the deep inelastic regions depends very little on incident energy.

Figure 1 displays typical laboratory energy spectrum obtained at 15° for the inelastically scattered ^{40}Ca using the magnetic spectrometer. The rather good energy resolution allows for the observation of low lying states in that spectrum. These peaks are located at 3.7, 7.8, 10.7, and 14 MeV (±1 MeV) total excitation energy. Two broad bumps show up at about 17.8 and 26 MeV. Since only inelastic events are observed in this experiment, a direct comparison of this spectrum with those obtained using standard solid state telescopes which allow only a charge identification of the reaction products is possible. Figure 2 displays typical energy spectra for Ca measured using such a setup at two different laboratory angles. These spectra are very similar to the previous one and thus illustrate the fact that the transfer reaction yield is very small in this experiment. Again peaks at 3.7, 7.0, 10.7, and 14.5 MeV (±1.5 MeV) clearly show up. The contribution of the ^{12}C and ^{16}O contaminants is indicated in the Ca energy spectrum at 15° and 16°, and the hatched

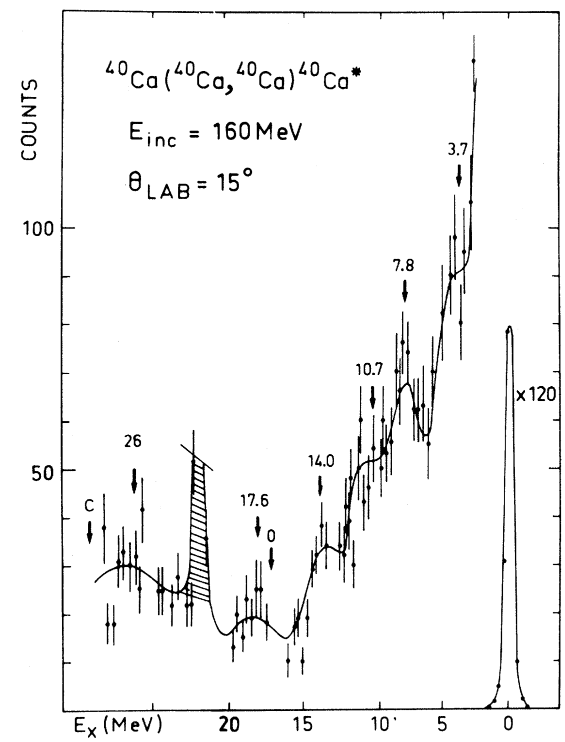

FIG. 1. Laboratory energy spectrum of inelastically scattered ^{40}Ca from ^{40}Ca at $\theta_{lab}=15°$ obtained using the spectrometer setup (see text). The total excitation energy $E_x = Q - Q_{gg}$ is reported. The hatched peak corresponds to a Ca parasite beam (see text).

peak corresponds to a parasite beam of Ca accelerated in the tandem with a lower charge state. At $\theta_{lab}=20°$, the contribution of light target contaminants is kinematically shifted towards the high excitation energy region and a broad bump at 17.6 MeV is clearly observed. Furthermore, at several angles in the Ca spectrum, a small cross-section broad bump is observed at about 26 MeV (see Fig. 2). It should be noted that the possible presence of mutual excitation final states Ca*-$Ca^*_{(3-)}$ would not question the existence of these excited states. Previous inelastic scattering experiments with alpha particles and light heavy ion beams[2,8] on ^{40}Ca have been performed and can provide an interesting comparison. The observation of the 3^- state at 3.74 MeV as well as peaks at 7.0, 10.6, ~14, and 17.7 MeV have been reported. The peak at ~7 MeV was tentatively assigned[2] to be the lower excitation of the octupole resonance (LEOR), whereas the giant quadrupole resonance (GQR) was found at 17.8 MeV.[2,8] Above the GQR region no evidence for any structure was reported. The position of the peaks observed in our experiment are in good agree-

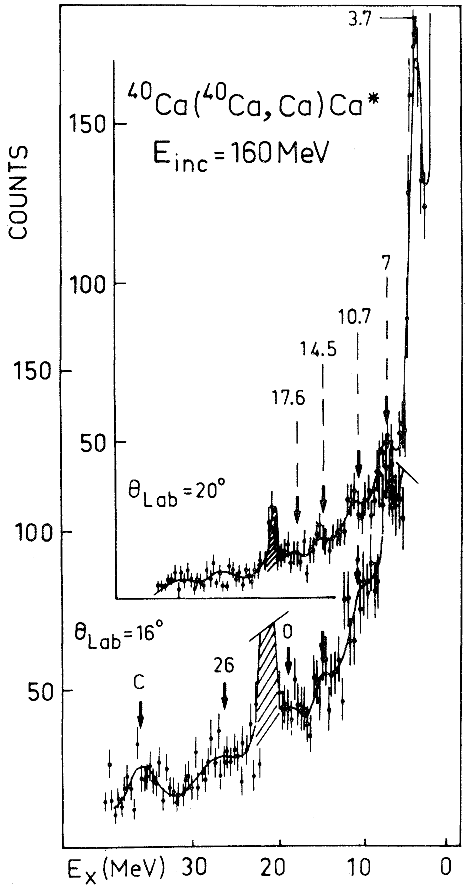

FIG. 2. Laboratory energy spectra of the Ca fragments emitted in the $^{40}Ca + ^{40}Ca$ reaction at two different laboratory angles, obtained using a standard telescope. The hatched peak corresponds to a Ca parasite beam (see text).

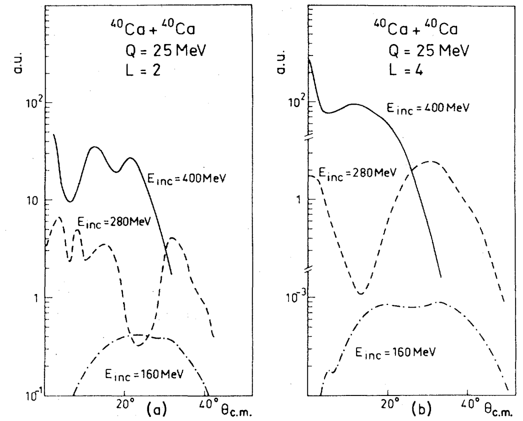

FIG. 3. Energy dependence of angular distributions for inelastic scattering of ^{40}Ca on ^{40}Ca calculated with the DWBA for the $L=2$ and $L=4$ transfers.

ment with these previous observations. Unfortunately, a reliable angular distribution of these peaks cannot be extracted because the presence of peaks due to ^{12}C and ^{16}O contaminants makes their analysis uncertain.

As mentioned above, a broad structure can be seen at ~26 MeV total excitation energy. This position is in good agreement with the position of the first structure (~25 MeV) observed at the higher incident energy experiments.[9,10] However, this structure has an increasing yield with increasing energies.[12] This effect can easily be understood by simple arguments of momentum matching conditions. Tentatively, if one makes the assumption that this bump corresponds to a well defined transition, the increase of the cross section at high energy is well predicted by a distorted wave born approximation (DWBA) calculation.[13] Figure 3 shows the results of such a calculation for a 2^+ state and for a 4^+ state for a total excitation energy $|Q|=25$ MeV for the three studied energies. It is noted that the predicted cross section is considerably larger at 400 MeV in both cases.

In summary, this experiment indicates that even with a heavy ion beam such as Ca, details in the inelastic energy spectrum can be observed. Several peaks are clearly present at positions in good agreement with those observed in previous experiments using lighter projectiles. The most significant result is the observation of a broad bump at 26 MeV total excitation energy in the ^{40}Ca spectrum. This bump can be related to the observations made in the same $^{40}Ca + ^{40}Ca$ reaction at higher incident energy where a structure at 25 MeV total excitation energy was reported.[9,10] The conclusion which can be drawn is that this structure is observed at all the studied incident energies at the same position and appears more clearly at higher incident energies. Although it is difficult to decide on the excitation mechanism of this structure, these features are in complete agreement with the expected evolution of giant resonances.

In that sense, the most revealing step forward would now be to investigate the same reaction at higher incident energies with a good energy resolution permitting the observation of low lying states ($E_x \leq 20$ MeV) in the energy spectra of the detected fragments together with the high excitation energy structures.

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