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Emission of intermediate mass fragments using γ-spectroscopic techniques

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Intermediate mass fragments (IMF) and light particles emitted from the ^{58}Ni+^{58}Ni reaction at a beam energy of 375 MeV have been studied. The fragments and light particles were measured in coincidence with 4π γ-ray spectrometer. The $Z=6$ (C) kinetic energy spectra and the distribution of the final nuclei in coincidence with the emitted C are well described by Hauser-Feshbach calculations extended to many channels. A detailed study of C-γ and 3α-γ correlations indicate a strong selectivity of the IMF decay. Our results indicate that the IMF can populate nuclei that are not accessible via multiple light particle ($Z<3$) emission and, thus, are useful for nuclear structure studies.
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The characterization of intermediate mass fragment (IMF) emission in heavy-ion collisions at low and medium bombarding energies (5 to 100 MeV/nucleon) has been an important ingredient in the study of heavy-ion nuclear reaction mechanisms [1,2]. From the early work using light projectiles like ^{3}He [3,4] or ^{4}He [5], it was clear that the IMF cross sections integrated over angles greater than 90° (center of mass) were consistent with statistical model calculations, either the asymmetric fission model variety [6,7] or full Hauser-Feshbach calculations [8]. For the highest energies, it was observed that the angular distributions were not symmetric with respect to 90° because a strong forward peaking occurred even for fragments as heavy as $Z=6$ [4,5]. For heavier projectiles at energies below 15 MeV/nucleon [8–10], also the dominant behavior was that of compound nucleus emission and equilibrium decay. For energies above 15 MeV/nucleon, the emphasis on the IMF studies has been on IMF multiplicity which could provide signs of possible multifragmentation effects [1]. The use of IMF measurements in conjunction with 4π γ-ray detectors has been also

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very useful in determining temperatures of the collision zone by measuring the ratios of the excited states of the IMF populated in these reactions [2,7,8,11,12]. Also, these measurements have been extended to include excited states of the IMFs above particle threshold using particle-particle correlations. A review of this subject has been given recently [2]. Although in many of the studies just mentioned, the compound nucleus decay properties have been deduced from cross-section measurements, angular distributions, or ratios or excited states, no attempt has been made to study the residual nuclei left in excited states after the emission of the IMF. In this regard, the present communication shows for the first time such a measurement where the final nuclei have been studied by their characteristic γ rays. With these measurements, in addition to learning in more detail about the mechanism of the emission process, we may be able to produce nuclei in states of angular momentum and excitation energy than are not normally populated via light particle emission.

The reaction $^{58}\mathrm{Ni}+^{58}\mathrm{Ni}$ was studied at a bombarding energy of 375 MeV, using the beams from the ALPI accelerator facility of the Legnaro National Laboratory in Padova, Italy. The main purpose of these measurements is to complement those done at higher energies of 8 and 11 MeV/nucleon [8,9] and to advance the understanding of the IMF ($3\leqslant Z\leqslant 12$) emission process. The experimental setup consisted of a γ-ray spectrometer (GASP [13]) used to detect the discrete γ rays emitted by the evaporation residues (ER) and IMF and a Si-ball (ISIS [14]) for the detection of charged particles. In this configuration the ISIS consisted of 33, 500-μm-thick ion-implanted silicon detectors that were operated in the ''flipped mode'' that identified the IMF using pulse shape analysis (see Ref. [15]). Seven conventional silicon ΔE-E telescopes completed the ISIS and were used mainly to detect p's and α's at backward angles. A recoil mass spectrometer (RMS) [16] was used to detect the ER emitted in the forward direction. Coincidences between GASP-ISIS and the RMS were recorded and were extremely useful to identify uniquely many of the ER's produced. Due to the low coincidence efficiency between the IMF and RMS, data from the RMs were not used in the present analysis.

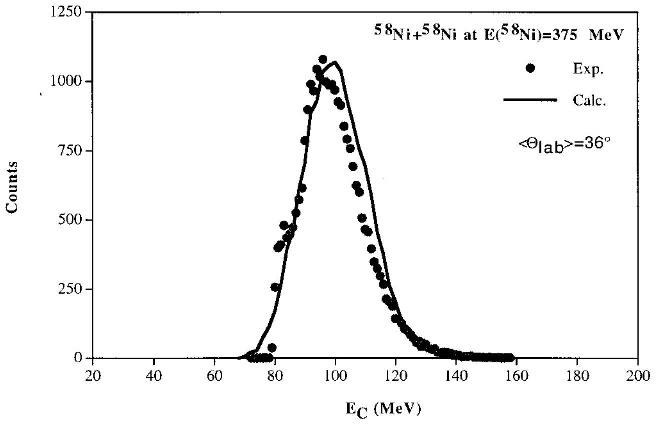

FIG. 1. Energy spectrum of C ions compared to statistical model calculations (solid curve).

The IMF detected by ISIS were identified by the characteristic two-dimensional plot of the rise time of the pulse vs the energy. In this fashion, IMF of Li, Be, B, C, N, and O were clearly identified. The IMF above O and those with energies below ~5 MeV/nucleon were stopped by a cylindrical Cu absorber, 14 μm thick, placed in the center of the chamber and around the target, to stop the elastically scattered Ni nuclei. The energy spectrum for carbon ions shown in Fig. 1 was obtained by projecting on the energy axis the band (corresponding to $Z=6$) drawn in the two-dimensional identification plot. The spectrum in Fig. 1 corresponds to the sum of five silicon detectors placed at an average scattering angle of 36° with an aperture of ±12°. Statistical model calculations were done for the first step of the decay with the code BUSCO (Ref. [8]) and then coupled to the code LILITA (Ref. [17]) for the subsequent steps of the decay. The solid line drawn in Fig. 1 corresponds to the statistical model calculation assuming decay of a fused and completely equilibrated system. The energy loss in the target and Cu absorber as well as the geometry of the detectors are taken into account in the calculations. A maximum critical angular momentum of $68\hbar$ for the compound nucleus [8,9], and a level-density parameter $a=A/10$ were used. The calculations indicate that for the bombarding energy of 375 MeV, 90% of the IMF emission occurs in the first step of the decay processes. Since in the present experiment the absolute cross sections were not measured, the calculations were normalized to the data at the maximum counts. A good agreement between the calculated and experimental shapes of the energy spectra is needed to establish the recoil effects that are used to correct for Doppler broadening of the emitted γ rays.

The γ-ray spectrum in coincidence with C ions, shown in Fig. 2, was obtained by summing the spectra of all Ge detectors of the GASP array. Also, all the Si detectors that had an identifiable carbon group were added together. Doppler broadening corrections were made by determining the velocity vectors of the recoils using the measured carbon energies and angles on an event by event basis. The symbols on some of the γ-ray peaks in Fig. 2 identify several of the residual nuclei produced in this reaction. The residual nuclei produced by the decay via C were identified by placing multiple gates on a γ-γ matrix built in coincidence with C. The γ-ray energy resolution is about 4 keV at 200 keV and 15 keV at 1

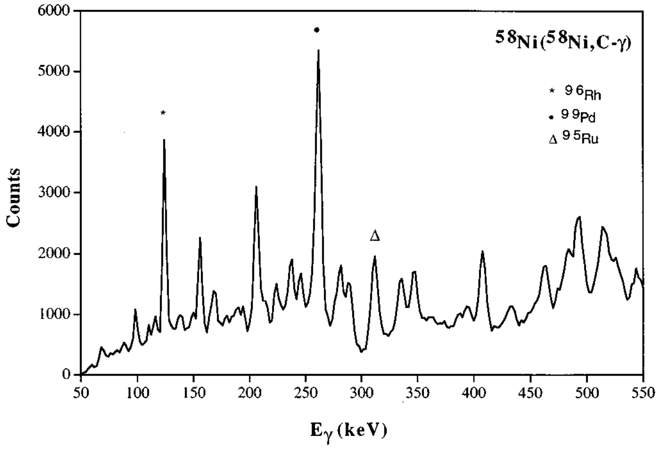

FIG. 2. γ-ray spectrum measured in coincidence with C fragments. The symbols correspond to several of the residual nuclei produced.

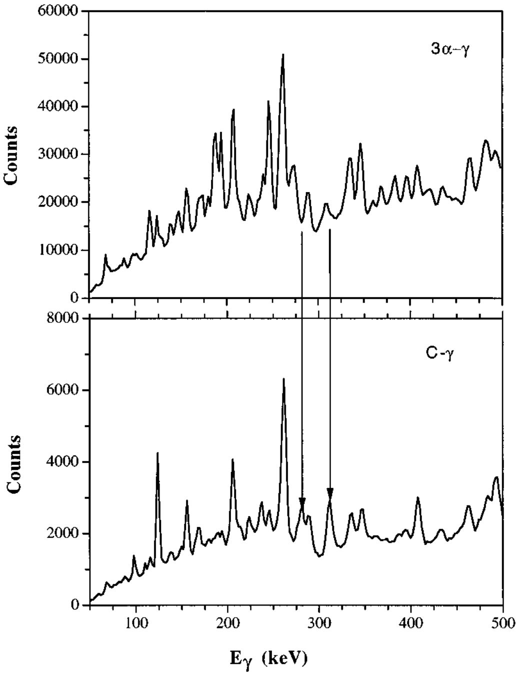

FIG. 3. γ-ray spectrum in coincidence with at least 3α particles (top panel). γ-ray spectrum in coincidence with C (bottom panel). The arrows drawn in the figure indicate γ lines corresponding to the ^{95}Ru nucleus.

MeV and is mostly due to the Doppler broadening arising from the large solid angle subtended by the silicon detectors.

Since most γ-ray spectroscopy experiments use reactions that involve emission of light particles (n,p or α), it is interesting to compare the γ-ray spectra associated with multi-light particle emission to that of the IMF. The relevant comparison to C emission is the emission of 3α particles. The γ-ray spectrum obtained in coincidence with at least 3α particles identified in the ISIS is shown at the top panel of Fig. 3. The bottom panel shows the γ-ray spectrum in coincidence with C ions. As seen in this figure, the C channel shows enhanced selectivity compared to the 3α channel: only a few strong peaks are present in the C channel, whereas the 3α channel shows about twice as many peaks. Also, some of the intense γ peaks in the 3α channel are weak in the C channel and vice versa. The arrows drawn in the figure correspond to γ rays at 281 and 313 keV and belong to the ^{95}Ru nucleus that is populated only by the C decay. The selectivity of the C channels was also confirmed by 3α and C γ-γ coincidences. This fact indicates that the decay of the IMF is a selective tool for spectroscopic studies of residual nuclei. The ^{95}Ru nucleus has been studied previously by (α,xn) (Ref. [18]) and (^{6}Li,pxn) (Ref. [19]) reactions. In the region of excitation energy around 2.6 MeV, the decay schemes reported in Refs. [18] and [19] give conflicting results. In particular, the sequence of γ rays (in keV) of 207, 281, 283, and 313 are clearly seen in the work of Ref. [19], but the 281, 283 doublet is not seen in Ref. [18]. Both works observe an intense line at 255 keV. In the present work, the dominant decay lines in the same region of excitation energy are (in keV) 206, 237, 281, 283, and 313. The relevant γ-ray spectra corresponding to the various gates are shown in Fig. 4. The first comment is that in the present work, we see clearly the 281, 283 doublet, but the most contrasting result with those of Refs. [18] and [19] is the absence of the line at 255 keV. Certainly, this indicates that more work is needed to understand the decay scheme of ^{95}Ru, but many of the differences noted can be due to the fact that our work is the first one that populates this nucleus by a heavy-ion reaction in the entrance channel and, thus, populates higher spin states. With the present statistics, our study of ^{95}Ru cannot go beyond what is presented in Fig. 4.

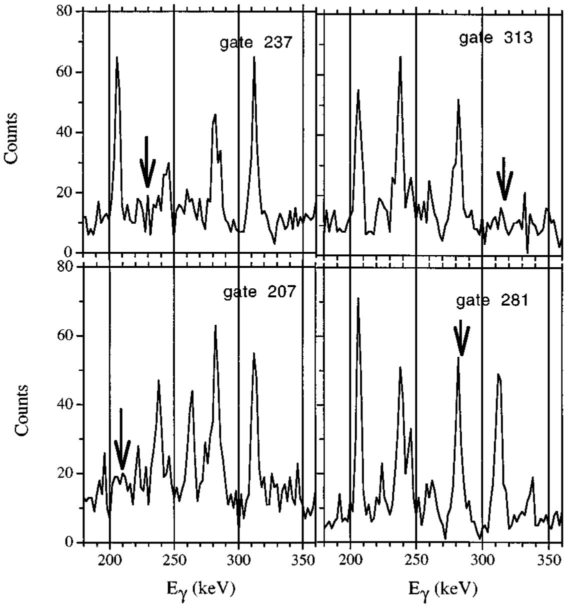

FIG. 4. γ-ray spectra corresponding to the ^{95}Ru nucleus. Each panel shows the spectrum corresponding to the indicated γ-ray energy gate, the arrows show the location of the gate on the energy spectrum. Notice also that the ^{95}Ru nucleus is populated by a ^{12}C α $4pn$ emission.

Another example of identification of residual nuclei is for the case of ^{96}Rh nucleus for which gates were placed on γ-ray energies (in keV) of 99 and 125. The resulting spectra are in good agreement with the known decay scheme [20], in contrast with the ^{95}Ru case. This is perhaps because the study given in Ref. [20] was also done using a heavy-ion reaction (^{64}Zn$+^{40}$Ca) and, thus, populates similar angular momentum states as in our ^{58}Ni$+^{58}$Ni reaction. Also, our decay scheme for ^{97}Pd agrees with the one given in Ref. [20].

Many other nuclei were identified and their relative yields were determined by the intensity of the γ rays of the lowest-lying states. These intensities were corrected for the efficiency of the GASP array. In this analysis nuclei with low lying isomeric states (like ^{94}Ru) were not included because they could not be measured with our experimental setup. In Fig. 5 we show the resulting intensities (open histograms) as a percentage of the total yield measured in coincidence with C. The calculations (hatched histograms) correspond to the statistical model predictions already discussed in connection with the carbon energy spectra (Fig. 1). (In these calculations, a 10% relative yield corresponds to 9 mb absolute cross section). The good agreement between the experimental and theoretical yield distributions indicates that the emitted complex fragments (in particular, $Z=6$) originate from

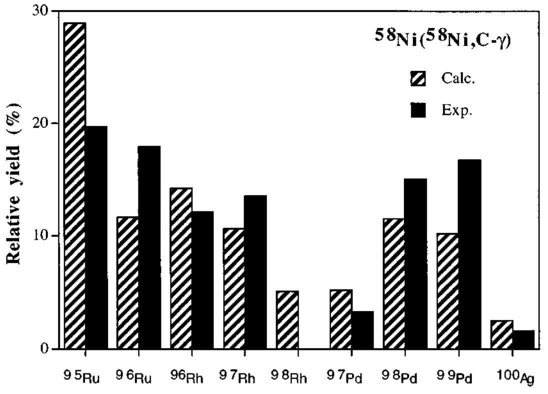

FIG. 5. Distribution of relative yields of the residual nuclei produced by the decay of C. The solid histograms correspond to the experimental distribution and the hatched one to the calculations described in the text.

the decay of a compound nucleus. The calculations given in Fig. 5 are done for the case of coincidences with C. However, the full calculations include, of course, all possible decay channels. From the full calculations, it is possible to make predictions about production rates. For example, the production of ^{95}Ru by the 3α channel (plus $\alpha 4pn$) discussed in connection with Fig. 2 is an order of magnitude smaller than that via the emission of C, explaining why the ^{95}Ru γ lines are not seen in the $3\alpha\gamma$ spectra (see Fig. 3). Also, the calculations indicate that the emission of 3α or multiple-light particles removes more energy and angular momentum than the equivalent cluster (IMF) emission. In view of the present analysis, it would be of interest to investigate in the future some of the predictions of the IMF emission. For example, as a γ-spectroscopic tool, it seems possible that higher angular momentum states are better populated via IMF emission. This is due to the fact that the IMF emission originates from states in the compound nucleus with the highest angular momentum (this could be achieved by studying these or similar reactions at lower bombarding energies to allow the emission, mostly one IMF, and a few light particles). Another interesting study would be to populate nuclei near $N=Z=50$ via IMF emission (for instance, the predicted cross section, for ^{100}Sn at a bombarding energy of 375 MeV is 6.5 μb, which is an order of magnitude larger than the cross section for decay of only light particles).

In conclusion, our results indicate that the emission of complex fragments in the ^{58}Ni+^{58}Ni reaction at 375 MeV bombarding energy is consistent with the decay of a completely fused and equilibrated system. This is supported by the good agreement between the measured kinetic energy spectra for $Z=6$ and the statistical model calculations, as well as the agreement between the measured partial yield distributions of the residual nuclei populated by the carbon emission and the statistical model predictions.

Furthermore, this study establishes the usefulness of IMF emission as a spectroscopic tool. Not only does IMF emission populate the high-spin states, but it also shows a very strong exit-channel selectivity. For example, it may provide a unique tool to reach nuclei in the vicinity of ^{100}Sn.

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