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Excitation energies in statistical emission of light charged particles in heavy-ion reactions

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Light charged particle emission has been investigated as a function of excitation energy in exclusive experiments on the decay of ^{16}O, ^{24}Mg, and ^{35}Cl projectiles between 25A and 70A MeV. The systematics of excitation energy removed by $Z = 1$ and $Z = 2$ particles were deduced. The results are similar to a previous study of proton and α-particle evaporation in compound nucleus reactions at beam energies below 20A MeV, supporting the idea of a common statistical process.

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Light charged particle (LCP) emission has been widely used at both low and intermediate energies to probe reaction mechanisms and nuclear excitation processes [1,2]. In particular, inclusive measurements of evaporation residue (ER) mass distributions, from studies of compound nucleus (CN) deexcitation at beam energies below 20A MeV, have led Morgenstern *et al.* [3] to a systematic description correlating the excitation energy to the number of evaporated nucleons and α particles. The deexcitation of quasiprojectiles formed in intermediate-energy peripheral collisions has been shown to be a powerful tool in studying nuclear matter because of the feasibility of detecting all charged particles from this source [4]. Such collisions lead to excitation energies as high as 6A MeV for $16 \leq A_{\mathrm{proj}} \leq 40$ [5–13] and are therefore at the threshold for multiple emission of fragments ($Z \geq 3$) for this mass region [12,14]. At the same time, in terms of total excitation energy, the peripheral reactions seem equivalent to CN reactions, which suggests a possible common behavior.

In this paper, we have gathered data from different exclusive experiments on the breakup of projectiles. The data set consists of three projectiles and five beam energies.

(i) 50A MeV ^{16}O on a gold target (2 mg/cm^2). The experiment was performed at GANIL with a rectangular array of 44 phoswich detectors covering from 4° to 20° horizontally and from 4° to 16° vertically [9].

(ii) ^{24}Mg at 50A and 70A MeV impinging on a ^{197}Au target (2.2 mg/cm^2) conducted at GANIL in the Nautilus chamber with an arrangement of 88 detectors, phoswich and time-of-flight scintillators, covering polar angles from 1.5° to 38° [8,15].

(iii) The reaction of ^{24}Mg at 25A MeV with a ^{197}Au target (2.9 mg/cm^2) was studied at the Tandem Super-Conducting Cyclotron (TASCC) at Chalk River with a forward array of 48 phoswich detectors (6.8°–24°) and 32 CsI(Tl) detectors (24°–46.8°) [10].

(iv) Finally, the 30A MeV peripheral collisions of ^{35}Cl with a ^{197}Au target (2.1 mg/cm^2), at TASCC, were detected in 40 phoswich detectors covering polar angles from 6° to 24° [11].

For each system, the reaction products were detected in a forward array (briefly described above) and charges up to the projectile charge were identified along with their emission angles and kinetic energies. Peripheral collisions were selected by requiring that the total charge detected to be equal to the charge of the projectile. In some systems, namely ^{24}Mg at 70A MeV [8], velocity cuts were made to eliminate the intermediate velocity component leading to an excess of LCP emitted backward in the projectile frame [7,16]. More detailed descriptions of the different experimental setups, calibration procedure, and event selection can be found in [8–11].

The sequential and statistical nature of the events in this data set was previously explored through different observables, such as the dependence of the cross sections on the Q value [8,10,11], relative angles [10,11,17], and the multiplicity branching-ratio method developed by Moretto *et al.* [5,8,10,18]. These results are also in agreement with measurements made with 4π arrays at 25A MeV [19] and 94A MeV [6]. This is not to say that possible direct-breakup components are completly elimi-

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nated but, as discussed by Pouliot *et al.* [5], in all cases the bulk of the data presents the characteristics of low-correlation emission processes.

In this work, we look for a systematic trend in LCP emission as a function of the total excitation energy of excited quasiprojectiles, and compare it to evaporation in compound nucleus reactions at lower beam energies. The decay channels of each projectile were identified from the detected fragment charges and a separation energy was given corresponding to the most positive value (Q_{max}) of all isotopic possibilities. The analysis was made on an event-by-event basis by reconstructing the quasiprojectile velocity from the emission angles and kinetic energy of each charged fragment. Then, the velocity of each particle was calculated in the center of mass of the emitter and the total relative kinetic energy, $\sum K_{\text{rel}}$, deduced. The addition of the latter quantity to Q_{max} gives the quasiprojectile (QP) excitation energy [20]

$$\text{E}^*_{\text{QP}} = \sum K_{\text{rel}} + Q_{\text{max}} \ . \tag{1}$$

For the three projectiles, exit channels with 0 or 1 PLF ($Z \geq 3$) and xHelium + yHydrogen were selected, following the classification made by Morgenstern and coworkers [3]. For example Mg → Ne+He (1 PLF + 1He + 0H) or Mg → N+He+He+H (1 PLF + 2He + 1H) are such channels. A total of 54 exit channels, 11 for ^{16}O projectiles, 24 for ^{24}Mg, and 19 for ^{35}Cl, were grouped as a function of the number of emitted Helium ions. Since more than 90% of $Z = 2$ particles are ^{4}He in these reactions [8], we will henceforth treat them all as α particles.

The difference between the projectile mass and the mass of the PLF is plotted for all channels in Fig. 1 as a function of the average excitation energy for 70A MeV ^{16}O and ^{24}Mg and 30A MeV ^{35}Cl. For the sake of clarity, the channels with an even (left) and odd (right) number of alphas were plotted on different graphs. For each Z_{PLF} in a given channel, the corresponding A_{PLF} was chosen to be the one which gave the most positive Q value, Q_{max}, assuming no emission of free neutrons. The error inherent in this particular choice was explored with the statistical code GEMINI [21]. Calculations give an A_{PLF} distribution with an average value that is within 2 mass units of the value used and is strongly correlated with the neutron multiplicities predicted by the code. This error is smallest for channels without hydrogen (1 PLF and α particles) and reaches its maximum for channels with 1 PLF and a large number (4–6) of hydrogens. In this case, the error in A_{PLF} has little effect on $\sum K_{\text{rel}}$ in Eq. 1, but could change the value of Q_{max} to an effective separation energy, and thus changes the excitation energy by a maximum of 30 MeV. The use of a large number of exit channels helps to average out all possible errors.

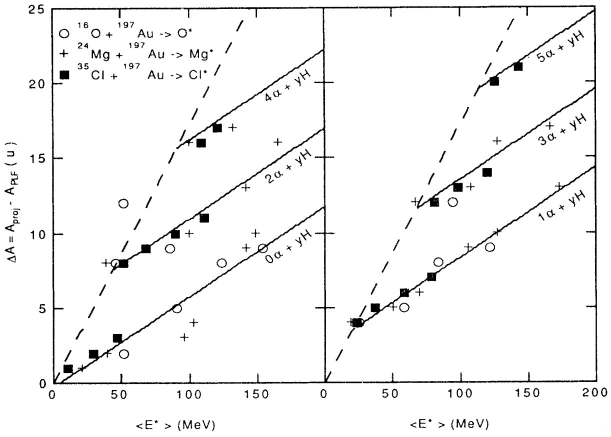

FIG. 1. The difference of the projectile mass and the PLF mass for the groups of channels with 0–5 α particles as a function of the average excitation energy for each channel. Solid lines are given by Eq. (2). Dashed lines represent the 0H (α only) limits. ^{16}O and ^{24}Mg projectiles are at 70A MeV and ^{35}Cl at 30A MeV.

It is interesting to note in Fig. 1 that the channels with 0, 1, 2, 3, 4, and 5 alphas are equally spaced and form distinct groups which can be fitted by straight lines. This dependence is similar to the relation $\Delta A = A_{\text{CN}} - A_{\text{ER}}$ vs E^* of Fig. 9 in [3] and accordingly the linear fits can be written as

$$\Delta A\,(E^*, N_\alpha) = \frac{1}{E^*_H} E^* + N_\alpha \left(\frac{4 - E^*_\alpha}{E^*_H} \right) - \frac{E^*_\gamma}{E^*_H}, \tag{2}$$

where N_α is the number of α particles in a given channel. E^*_H is the average excitation energy removed by the emission of a hydrogen ion and is deduced from the slope of the fits. At constant E^*, the distance between two consecutive lines is given by

$$\Delta A\,(0, 1) = \delta = \left(4 - \frac{E^*_\alpha}{E^*_H} \right) \ . \tag{3}$$

Given δ, one can obtain a measurement of the average excitation energy, E^*_α, for the evaporation of an α particle. The last term of Eq. (2) was necessary to reflect the experimental fit of the group $0\alpha + yH$ which intercepts the ΔA axis at a negative value. E^*_γ is found to be 4.6 MeV. Its physical interpretation is the residual excitation energy of the PLF, after particle emission is complete. This excitation must decay by gamma emission. Therefore at $\Delta A = 0$, the excitation energy is nonzero but small.

The data are well reproduced by Eq. (2) as shown in Fig. 1. The average excitation energy removed by evaporation of a hydrogen ion is 16.6±0.3 MeV; an average of 23.2±6.6 MeV is removed by α-particle evaporation. The uncertainty (±6.6) in E^*_α arises mainly from the measurement of the average distance between the lines. The results are summarized in Table I and compared with those of [3]. The values are in good agreement, showing the common behavior of LCP evaporation in low-energy CN reactions and intermediate-energy projectile breakup.

Our data, however, sample somewhat different systems than those of Morgenstern *et al.* Our work measures light nuclei with high excitation energy per nucleon, while that of [3] considers heavier, cooler systems where decay energies are heavily biased by the Coulomb barriers for emission. It is therefore not surprising that the average energy

TABLE I. Systematics of LCP emission from the data of Fig. 1 compared to the values of [3]. The different values of E^*_H, δ, and E^*_α are shown. The quoted errors are the standard errors of the mean.

System	E^*_H (MeV)	δ (Mass units)	E^*_α (MeV)
This work	16.6±0.3	2.6±0.4	23.2±6.6
Work of [3]	18.3^a	2.65±0.1	22.1±1.5

^{a}Value for proton evaporation. No error quoted.

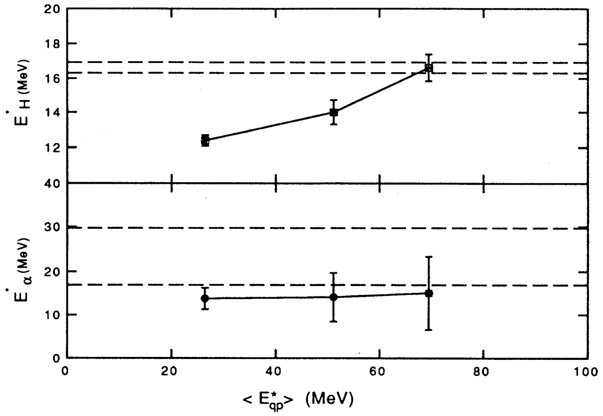

FIG. 2. The parameter E^*_H (upper panel) and E^*_α (lower panel) as a function of the average quasiprojectile excitation energy obtained in reactions with a ^{24}Mg beam at 25, 50, and 70A MeV. The lines between the points are drawn to guide the eyes. The dashed lines indicate the limits of both values from the systematics of Fig. 1.

removed by a charged particle in their work should be relatively independent of excitation energy. Conversely, one might expect that in our lighter, hotter systems, the average energy removed should increase with excitation energy per nucleon.

The effect of the QP excitation energy on E^*_H and E^*_α was explored with ^{24}Mg at 25, 50, and 70A MeV. The average QP excitation energy, $\langle E^*_{\rm QP}\rangle$, is 26.4±0.2 MeV at 25$A$ MeV beam energy, 51.1±0.4 MeV at 50A MeV and 69.4±0.5 MeV at 70A MeV [10]. The previously observed trend in the data was found at all beam energies and linear fits to channels with 0, 1, 2, and 3 α particles were done. The resulting progression of E^*_H and E^*_α is shown in Fig. 2. The values of E^*_H vary from 12.4±0.3 MeV at 26.4 MeV of average excitation energy to 16.6± 0.8 MeV at 69 MeV, showing a linear relation, at least to the first order, between the two quantities. Hence, E^*_H increases when the temperature increases, in contrast to the result from heavier and cooler systems, where E^*_H remains constant. The parameter δ remains nearly constant within the limits of the values of Table I. The values of E^*_α are compatible within the errors with the systematic of Fig. 1 as indicated by the dashed lines. Although excitation energy seems to have a large influence on the slope parameter E^*_H while considering only one system, the use of any one of the three ^{24}Mg beam energies combined with ^{16}O and ^{35}Cl does not change significantly the average excitation energies removed by the evaporation of Z=1 and Z=2 particles, as given in Table I.

In summary, a large data set from exclusive experiments on projectile decay has been examined. Based on previous analysis of the data and on equivalent measurements in the literature, we found enough evidence for a statistical emission process to analyze the data in terms of excitation energy. In this context, the statistical emission of LCP in projectile decay, for $16 \leq A_{\rm proj} \leq 35$, has been investigated as a function of total excitation energy. The average excitation energy removed by Z=1 and $Z = 2$ (α) particles were found to be 16.6±0.3 MeV and 23.2±6.6 MeV, respectively. This behavior is similar to low-energy compound nucleus systematics in the mass region $32 \leq A_{\rm CN} \leq 70$. By using the ^{24}Mg data at different beam energies, we have shown that temperature (or excitation energy per nucleon) governs LCP emission in light nuclei. Aside from Coulomb barrier and temperature effects, we expect that the emission of LCP from a thermalized source in heavy-ion reactions should follow such systematics. New experiments with more complete isotopic resolution are needed to extend the applicable mass region and excitation energy domain.

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