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Abstract

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 consistent with a previous study of proton and α evaporation in compound nucleus reactions at beam energies below 20A MeV, supporting the idea of a common statistical mechanism for the two processes.

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 quasi-projectiles 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 $16 \leq A_{proj} \leq 40$ [5–12]and are therefore at the threshold for multiple emission of fragments ($Z \geq 3$) for this mass region [12,13]. At the same time, in terms of total excitation energy, the peripheral reactions seem equivalent to CN reactions. In this letter, we look for a systematic trend in LCP emission based on the total excitation energy of excited quasi-projectiles, and compare it to evaporation in compound nucleus reactions at lower beam energies.

The data set consists of three systems: ^{16}O, ^{24}Mg and ^{35}Cl projectiles at beam energies from 25A MeV to 70A MeV, exploring a large part of the intermediate energy domain. The experiments with ^{16}O and ^{24}Mg on a ^{197}Au target at 70A MeV have been performed at GANIL and the ^{35}Cl + ^{197}Au experiment at 30A MeV at TASCC. In the case of ^{24}Mg + ^{197}Au, the effect of the beam energy was studied by also including data at 25A MeV (TASCC) and 50A MeV (GANIL). For each system, the reaction products were detected in a forward array 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]. Detailed descriptions of the different experimental set-ups, calibration procedure and event selection can be found in ref. [8–11].

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 quasi-projectile 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, $\sum K_{r e \ell}$, deduced. The addition of the latter quantity to Q_{max} gives the quasi-projectile(QP) excitation energy [14]

$$\mathrm{E}^*_{qp} = \sum K_{r e \ell} + Q_{max} \tag{1}$$

For the three projectiles, exit channels with 0 or 1 PLF (Z ≥ 3) and xHelium + yHydrogen were selected, following the classification made by Morgenstern and co-workers [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 theses 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 differents 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 [15]. 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 $\sum K_{r e \ell}$ in Eq. 1, but could change the value of Q_{max} to an effective separation energy, and thus change 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.

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 $\Delta A = A_{CN}$ - A_{ER} vs E^* of fig. 9 in ref. [3] and accordingly the linear fits can be written as

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

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 consecutives lines is given by

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

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 0α + 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 $\Delta \mathrm{A} = 0$, the excitation energy is non-zero 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 ref. [3]. The values are in good agreement, showing the common behaviour of LCP evaporation in low-energy CN reactions and intermediate-energy projectile breakup. It is also worth noting that the LCP emitted from the systems considered in this study were independently found to come from statistical emission of an equilibrated source based on the exponential dependence of the cross-sections on the Q_{max} [8,10,11] and on an unambigious method by Moretto et al. [5,8,10,16].

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 ref. [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 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, $< E_{qp}^* >$, is 26.4±0.2 MeV at 25A 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, the statistical emission of LCP in projectile decay, $16 \leq A_{proj} \leq 35$, 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 behaviour is similar to low-energy compound nucleus systematics in the mass region $32 \leq A_{CN} \leq 70$. 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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REFERENCES

[1] W. U. Schröder and J. R. Huizenga in: Treatise on Heavy-Ion Science (vol. 2), ed. D. A. Bromley (Plenum Press, New-York, 1984)115.

[2] D. Guerreau, Nuclear Collisions from the Mean-Field into the Fragmentation Regime in: Proc. of the International School of Physics << Enrico Fermi >> (Varenna, Italy, July 1989), Course CXII, ed. C. Détraz and P. Kienle (North-Holland, Amsterdam,1991) 37.

[3] H. Morgenstern et al., Z. Phys. A313 (1983) 39.

[4] For a recent review see H. Fuchs and K. Möhring, Rep. Prog. Phys. 57 (1994) 188.

[5] J. Pouliot et al., Phys. Rev C48 (1993) 2514.

[6] A. Badalà et al., Phys. Rev C48 (1993) 633.

[7] J. E. Sauvestre et al., Phys. Lett. B335 (1994) 300.

[8] D. Doré et al., Phys. Lett. B323 (1994) 103; D. Doré, Ph. D. Thesis, Université Laval. 1994, unpublished.

[9] R. Laforest et al., Nucl. Phys A568 (1994) 350.

[10] M. Samri et al., Fifth International Conference on Nucleus-Nucleus Collisions, Taormina, Italy, 30 May - 4 June, 1994. To be published in Nucl. Phys. A.

[11] L. Beaulieu et al., Accepted in Nucl. Phys. A.

[12] P. Désesquelles et al., Phys. Rev C48 (1993) 1828; A. Lleres et al. Phys. Rev C48 (1993) 2753.

[13] B. Djerroud et al., to be submitted to Phys. Rev. C .

[14] J. Pouliot et al., Phys. Rev C43 (1991) 735.

[15] R. J. Charity et al., Nucl. Phys. A483 (1988) 371.

[16] L. G. Moretto, D. N. Delis and L. G. Wozniak, Phys. Rev. Lett. 71 (1993) 3935.

TABLES

TABLE I. Systematics of LCP emission from the data of Fig. 1 compared to the values of ref. 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 ref. 3	18.3[a]	2.65±0.1	22.1±1.5

[a] Value for proton evaporation. No error quoted.

L. Beaulieu et al., Phys. Lett. B, TABLE I

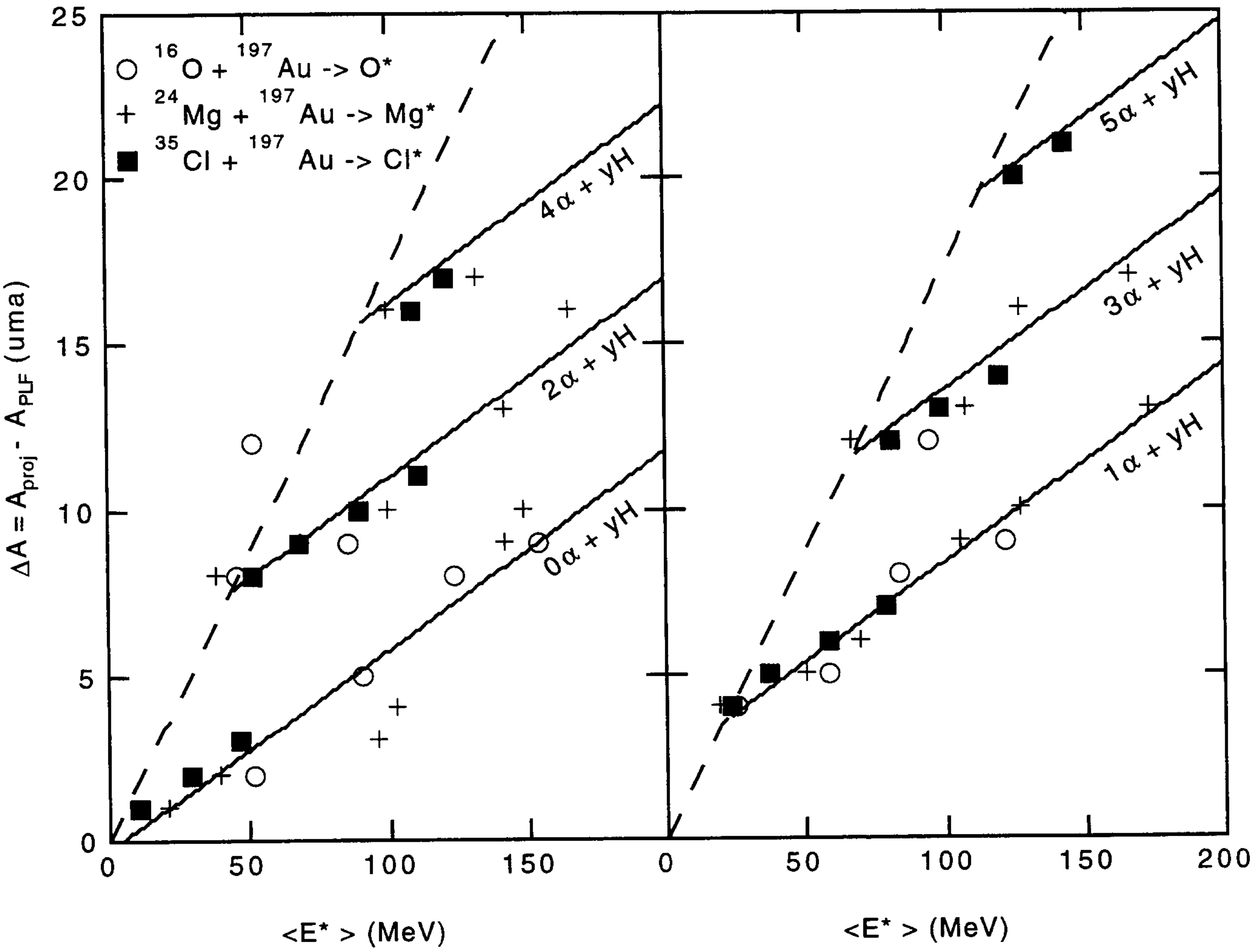

FIG. 1. The difference of the projectile mass and the PLF mass for the groups of channels with 0 to 5 α particles as a function of the average excitation energy for each channel. Solid lines are given by Eq. 2. Dashed lines represent the 0H (α only) limits. ^{16}O and ^{24}Mg projectiles are at 70A MeV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

L. Beaulieu et al., Phys. Lett. B, FIG. 1

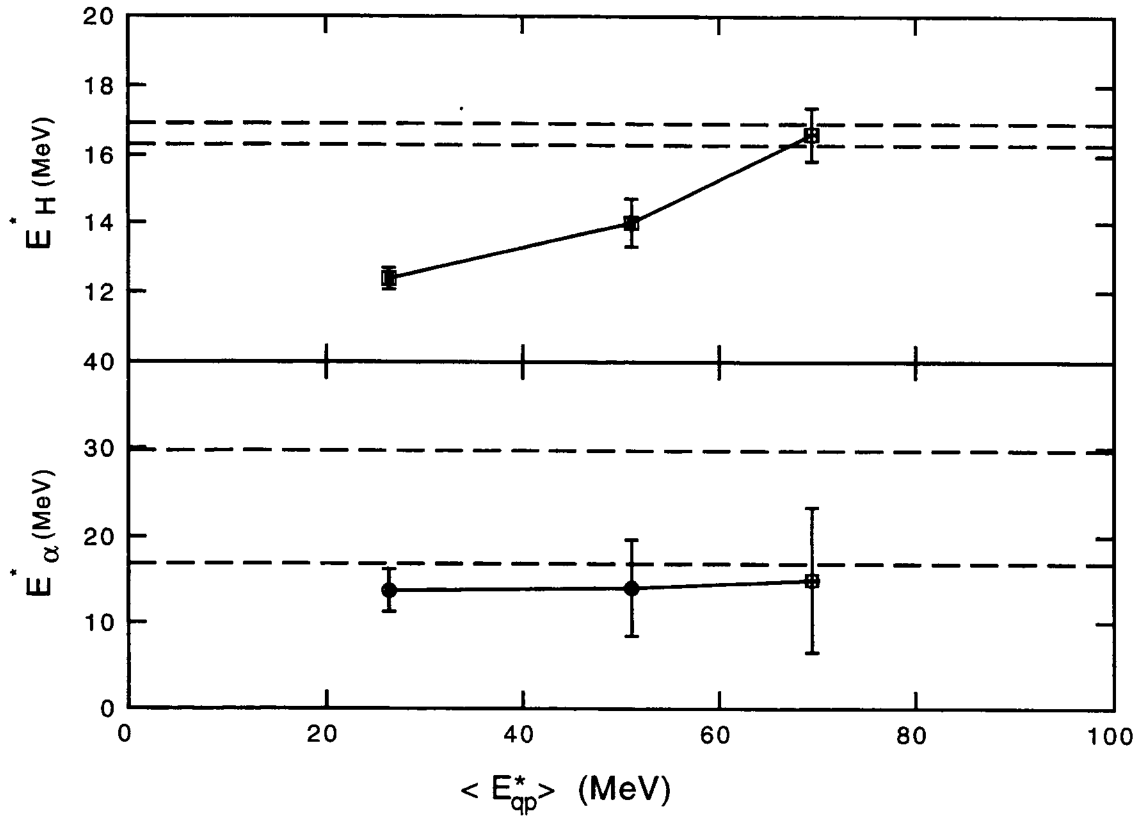

FIG. 2. The parameter E^*_H(upper panel) and E^*_α(lower panel) as a function of the average quasi-projectile excitation energy obtained in reactions with a ^{24}Mg beam at 25, 50 and 70A MeV. The lines between the points are drawn to guide the eyes. The dashed lines indicate the limits of both values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

L. Beaulieu et al., Phys. Lett. B, FIG. 2