Q-value systematics applied to the absorption of mesons on complex nuclei

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The isotopic yields both from deep inelastic collisions between heavy ions and from fragmentation processes have been successfully described by Q-value systematics. In order to test their range of validity and to investigate correlations with specific reaction mechanisms, the Q-value systematics have been applied to the multinucleon-removal spectra following pion and kaon absorption on complex nuclei. Indeed, the isotopic distribution derived from these spectra shows the following feature: Most of the yields are not strongly influenced by the charge of the pion and can be explained by nuclear evaporation following pion absorption. In contrast, the yields of elements far removed from the target show a better agreement with a Q_{gg} law under the assumption that the pion is implanted in the target. The influence of the pion charge upon the yield distribution is thus evidenced even after the removal of 10–14 nucleons from the target. As a dominant evaporation process would not reproduce this effect, this indicates the importance of direct reaction mechanisms associated with pion absorption. This could support the hypothesis of an absorption on a complex cluster or a very strong final-state interaction. The parameter T extracted from the Q-value systematics appears proportional to the total energy brought by the meson into the system.

[NUCLEAR REACTIONS Q-value systematics; pion and kaon induced reactions; deduced temperatures; reaction mechanism.]

I. INTRODUCTION

The interaction of pions with complex nuclei is the subject of extensive studies.[1,2] The experiments are focused on questions such as absorption on a quasideuteron or on more complex clusters, the balance between fast-particle emission and evaporation processes, the influence of the charge of the pion on the relative yields of the final reaction products, and comparison between reactions induced by pions and by protons. The data obtained so far can only partially resolve these points. A comparison of the data is complicated by the fact that the experiments were carried out at different energies, and the energy dependence of the pion-nucleus interaction is a further component of the puzzle.

In the present article we discuss relative yields of residual products following the absorption of positive and negative pions. Using the data of Refs. 1 and 2 we test in Sec. II the applicability of the Q_{gg} systematics.[3,4] It has been very successful in describing the isotopic distributions from deep inelastic reactions between heavy ions, where it is based on the assumption that the nucleon flow is governed by the available phase space. It applies to binary reactions which have not reached full equilibrium. A very similar Q-value relation has been able to describe the yields after projectile-fragmentation processes.[5] One might ask whether this simple Q-value formula could also be used for other reactions which apparently resemble neither deep inelastic collisions nor fragmentation processes, e.g., the deexcitation following pion and kaon absorption. This questions implicitly whether the Q_{gg} systematics are characteristic of a specific process, and this is discussed in Secs. III and IV. First an evaporation calculation is presented in order to exhibit typical trends owing to evaporation and to reveal deviations from the Q_{gg} systematics. Spallation data with light particles[6] and recently with pions[7] are well described with the empirical Rudstam formula.[8] A possible relation between this formula and the Q_{gg} law is mentioned at the end of Sec. III and derived in the Appendix. Within the discussion (Sec. IV) the significance of the parameter T used in the Q_{gg} systematics, specifically its energy dependence, is investigated.

II. INFLUENCE OF THE PION CHARGE AND THE Q_{gg} SYSTEMATICS

In this section we discuss experimental results of Refs. 1 and 2. In these experiments the isotopic yields were obtained by measuring the prompt γ transitions in the residual nuclei. In the first example, in the absorption of 70 MeV pions on ^{60}Ni

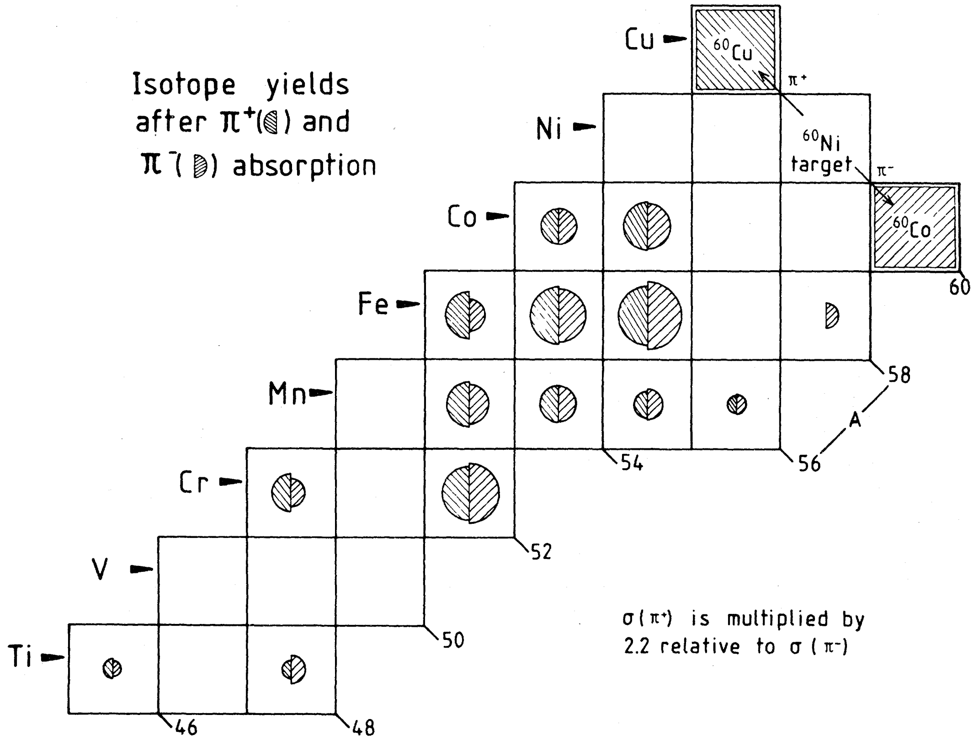

FIG. 1. The relative yields of the isotopes produced after bombarding 70-MeV pions onto ^{60}Ni are represented as areas of half circles. The effect of the charge of the pion on the distribution is rather strong for elements far from the target.

which had been studied at Saclay,[2] the total absorption cross section σ_{abs} for incident negative pions is higher by a factor of 2.2 than for positive pions. This can be understood[9] by the different Coulomb potentials and a velocity-dependent term in the pion interaction, as has been tested in a recent experiment.[10] At higher energies studied at Los Alamos these effects decrease, and indeed at 160 and 220 MeV incident energies no significant differences between $\sigma_{abs}(\pi^+)$ and $\sigma_{abs}(\pi^-)$ is found.[1]

In Fig. 1 we compare the production yields of the residual nuclei. The cross sections for the absorption of π^+ are multiplied by a factor 2.2, as discussed above, in order to evidence the effect of the pion charge on the yields of individual nuclei. The production cross sections of nuclei close to the target (Co, Fe) differ only slightly in the absorption of positive and negative pions. It is interesting to note that the isotopes of Cr and Ti exhibit a more pronounced dependence on the pion charge. The π^--induced reactions favor nuclei with higher N/Z ratios than do the π^+-induced ones. This might suggest that the charge of the pion is implanted into the target nucleus and still governs the yields even after the emission of 10–14 nucleons. This appears in contrast to an evaporation process which would have washed out the initial difference in the total isospin.

Throughout this article we shall focus mainly on these nuclei far from the target, the yield of which represents less than five percent of the total absorption cross section. The production of the nuclei closer to the target exhausting the major part of the absorption cross section was discussed in Ref. 1 and seems qualitatively to be explicable[11] by the quasideuteron model.[12].

In some respect the nuclei obtained after pion absorption might be compared to a deep inelastic collision between heavy ions. In both cases a highly excited, short-lived composite system is formed which decays before reaching an equilibrium. However, the exit channel in the case of pion absorption is not of a binary character as in deep inelastic collisions. On the other hand, π absorption and the subsequent decay could be viewed as a fragmentation process in which only a fraction of the nucleus is "heated" and starts boiling away.

In both cases (deep inelastic collisions and fragmentation processes) the isotopic distributions have been successfully described by relations containing $\exp(Q/T)$ as a dominant factor, where Q is the reaction Q value of the relevant process and T is an effective temperature.

The partial equilibrium reached in a deep inelastic reaction leads to isotopic distributions which seem to be governed by the available phase space. In this view, the residual yields simply depend on the product of the level densities of the two outgoing fragments and the yield distribution can then be written as [3,4]

$$\sigma(A,Z)=f(Z)\exp(Q_{gg}/T). \quad (1)$$

The quantity $f(Z)$ mainly represents the different Coulomb potentials in the exit channels and therefore depends only upon the atomic number. The Q_{gg} is the difference of the binding energies in the entrance and exit channels. It results from this simple expression that isotopic yields are described by straight lines when represented in a logarithmic scale as a function of the Q_{gg} values. The parameter T which is the common slope of these lines in the Q_{gg} systematics bears the character of a temperature. However, its definition is not evident for nonequilibrated systems.

Many examples of the success of the Q_{gg} law in deep inelastic collisions can be given where this simple relation refers to the yield distribution after the deep inelastic process. Subsequent evaporation either has been avoided by detecting the light fragment which is only weakly excited, or has deteriorated the quality of the fit.[13]

It is very interesting to note that for a very different mechanism, the fragmentation process, a very similar relation holds.[5] Here for Q_{gg} the minimum Q value for the separation of the projectile (or target) into two or more fragments is used.

The situation in the case of pion absorption seems quite different from both examples mentioned. A binary character as in deep inelastic collisions is not present. On the contrary, one accepts that various steps from the primary interaction to fast and evaporative particle emission lead to the detected isotopes. On the other hand, the high relative velocities in the fragmentation process yield very short contact times, whereas the incident pion has only little momentum and therefore does not impose such a kinematical constraint. The mechanism following the pion absorption can then be governed by phase space as longer reaction times are possible.

We nevertheless applied Eq. (1). The Q values were calculated:

(i) assuming a binary decay of the complex ($\pi^{\pm}+{}^{60}$Ni) and using binding energies from the liquid-drop model[14] without pairing and without shell corrections. This procedure has been used for heavy ions,[15] too, and is about equivalent to the use of Q values from mass tables corrected for nonpairing effects.[4]

(ii) assuming a fragmentation-type process, and calculating $Q_F^{\min}$ from mass tables, $Q_F^{\min}$ being the lowest separation energy for decomposing the missing part into fragments (see Ref. 5). Here a clear

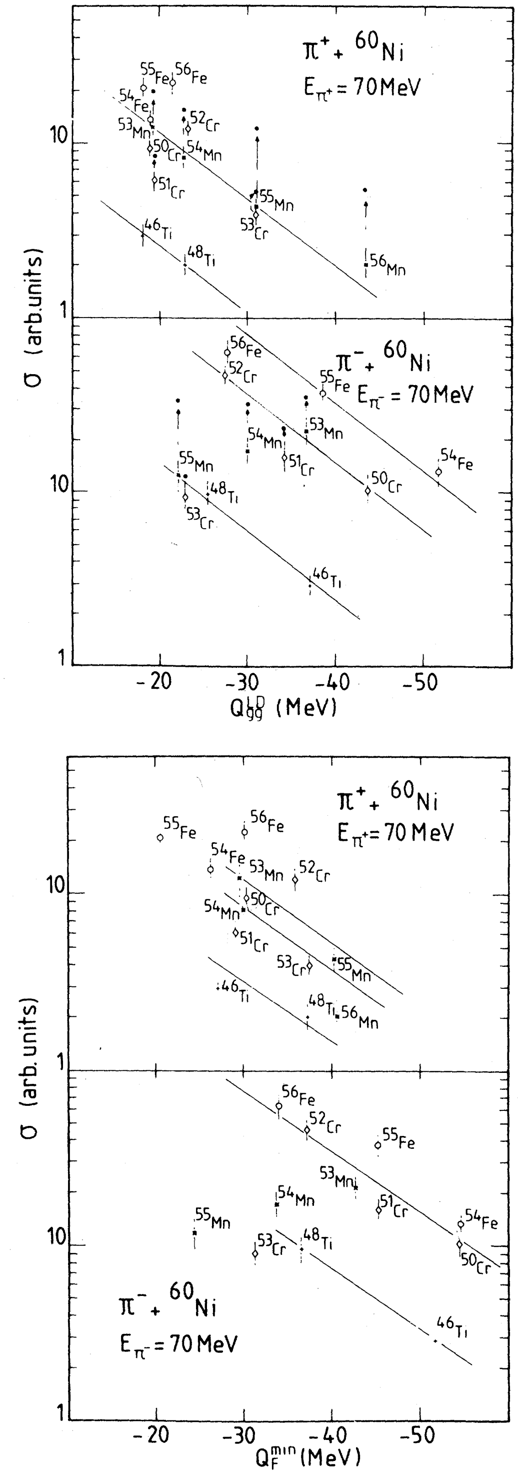

FIG. 2. The isotope yields following the absorption of positive and negative pions of 70 MeV on ^{60}Ni as function of Q value (data from Ref. 2) (a) for binary separation, (b) for fragmentation.

difference from a normal target fragmentation has to be noted: The isospin of the pion is added as π^+- and π^--induced reactions give very different isotopic yields (see Fig. 1).

In Fig. 2 the 70-MeV pion data[2] are given as a function of the Q values; in Fig. 2(a) assuming a binary separation and in Fig. 2(b) assuming a fragmentation-type process. The quality of the descriptions is about equal since the different procedures yield only minor differences in the Q values. Thus no conclusion regarding a binary or nonbinary character can be made; the existence of a binary reaction would indeed be surprising.

Figure 2 illustrates the success of the Q-value law for the isotopes of Ti and Cr (except ^{53}Cr). Parallel lines having about the same slope both for π^+- and π^--induced reactions can be drawn through the isotope yields of the same element. In order to judge the quality of the fit we have to recall that the data were taken using on-line γ detection. Therefore a fraction of the production yield could be missed when its decay proceeds via unknown or unmeasured transitions. The error bars as given in Figs. 2 and 3 are taken from Refs. 1 and 2 and do not include this problem. We preferred to use the original experimental data and not correct them, as the initial level population and decay are not known. In Fig. 2(a) we have added arrows indicating a possible modification of the production cross section assuming a purely statistical decay. The true production cross section will then lie between the measured value and the top of the arrow. Generally, the even-even nuclei (like ^{46,48}Ti, ^{50,52}Cr) are only slightly affected and the corrections do not exceed 5%. We therefore based our conclusions mainly on these even-even nuclei.

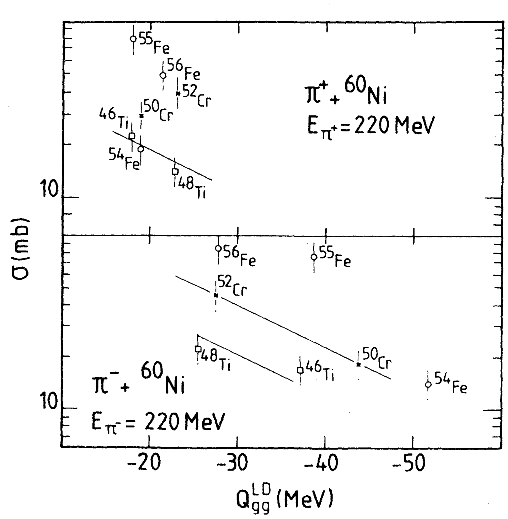

FIG. 3. Same as Fig. 2(a), but for pions of 220 MeV (data from Ref. 1).

The Q_{gg} systematics describe well those cases where different yields show up between π^+- and π^--induced reactions. We would like to draw attention to the fact that the inversion of the yields of ^{46}Ti and ^{48}Ti according to the charge of the incident pion is well reproduced.

Another example is presented in Fig. 3 from the $\pi^\pm$-induced reactions on ^{60}Ni at 220 MeV.[1] As it was shown in Fig. 2 that the way of calculating the Q values does not affect the success or failure of the Q-value systematics, the data are only represented like in Fig. 2 (binary separation). Unfortunately, fewer isotopes have been measured in the multinucleon-removal channels. The data agree with the Q_{gg} concept if one considers the large experimental uncertainties. Again the inversion of the ^{46}Ti/^{48}Ti yield ratio as a function of the pion charge is well described. This is remarkable, as the available total energy has increased from 210 to 360 MeV. The lines are less steep than in Fig. 2, indicating a higher value for the parameter T. This quantity will be discussed in Sec. IV.

From Figs. 2 and 3 it can be concluded that the Q_{gg} systematics seems able to describe the isotopes far from the target. However, before drawing conclusions, the effect of evaporation has to be discussed. In the case of deep inelastic collisions it has been shown that the quality of the fit has deteriorated.[13]

III. THE EFFECT OF EVAPORATION

For simplicity we assume a separation of the reaction mechanisms into two stages, the initial fast interaction and the evaporation. The first refers to the pion absorption on two or more nucleons which might escape immediately or interact rapidly and further fast particles could follow. In the second stage the evaporation takes place starting from an isotopic distribution resulting from the fast interactions. The final distribution after this second stage has been calculated in the statistical-model framework by using the code CASCADE.[16] Let us make some assumptions about the intermediate distribution by starting from $A=58$ nuclei with various excitation energies. Their spins are low and were fixed to $2\hbar$. The trends of the evaporation process, shown in Fig. 4, indicates that the final distributions are concentrated along a line shifted by about 1.5 neutrons from the valley of stability. This region is reached within rather few steps, e.g., the difference of the $N-Z$ values of the two starting nuclei ^{58}Ni and ^{58}Fe being 2 and 6 tends rather rapidly towards a common value of about 3. This behavior is evidenced explicitly in Fig. 5, where the average $N-Z$ values of the residual distribution are presented as a

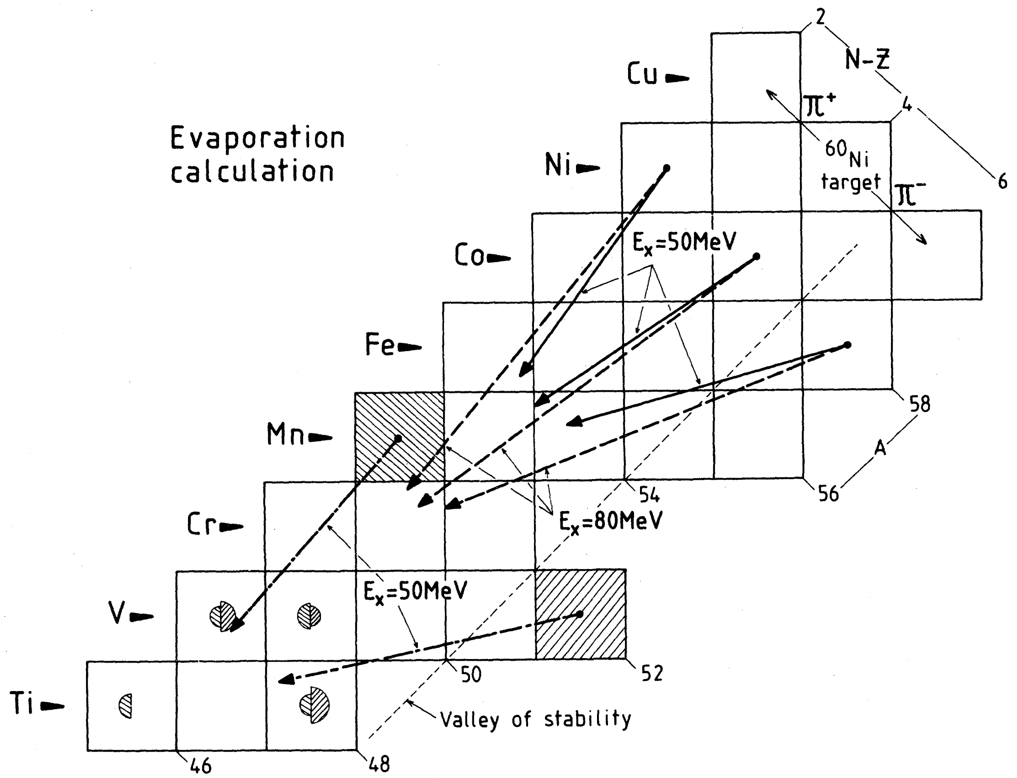

FIG. 4. Isotopic table similar to Fig. 1 showing the trends of the evaporation process as arrows for various starting situations. Additionally the calculated individual yields from emitting $A=52$ nuclei are shown analogous to Fig. 1.

function of the excitation energy, e.g., at 50 MeV excitation energy four nucleons are emitted and the $N-Z$ difference has dropped from four to about one.

The small differences in the relative yields found for isotopes close to the target agree then with a dominant evaporation process which has the effect of washing out the $N-Z$ difference of the various starting points. Of course, this observation is also in agreement with a mechanism in which the charge of the pion is carried away with the first directly emitted particles (see also Ref. 1). In contrast to the residual nuclei close to the target, the yields of the Ti isotopes show a strong dependence upon the charge of the incident pion. Attempts to fit these yields by evaporation are not successful under reasonable assumptions.

As another example we consider the evaporation starting at $A=52$ nuclei. These nuclei could be reached by the direct emission of, e.g., two α particles from the composite systems ^{60}Cu and ^{60}Co which are formed by the implantation of positive and negative pions in ^{60}Ni. Figure 4 presents the individual yield distribution starting from ^{52}Mn and ^{52}V. The excitation energy is assumed to be 50 MeV. The yields of the Ti isotopes are now strongly dependent upon the pion charge and resemble the measured ones given in Fig. 1. From this discussion we conclude that for the nuclei far from the target

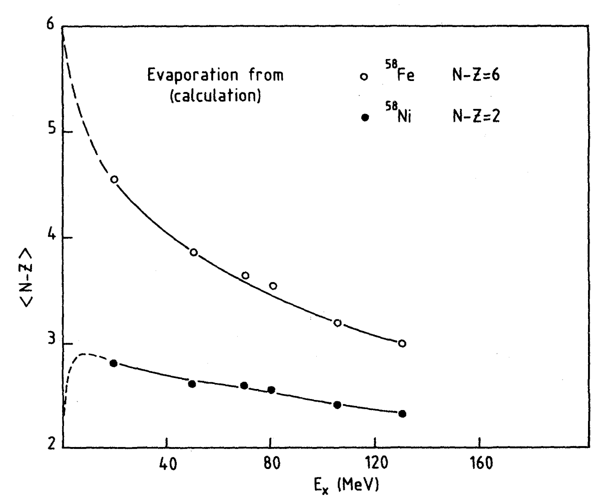

FIG. 5. Trends of the average $N-Z$ values of the residual distribution of an evaporation process as a function of excitation energy.

for which the Q_{gg} systematics work best, evaporation following the deuteron absorption does not give satisfaction.

In the Appendix, we discuss a possible relation between the Q-value systematics and the empirical Rudstam formula[6–8] which fits a large number of spallation data. There exists a purely mathematical analogy between these two formulas, and the essential difference appears in the way in which the most probable isotope A_{max} is determined. In Rudstam's formula it is purely empirical and reflects the dominating evaporation process. In the Q_{gg} systematics A_{max} is given by the most stable pair of outgoing nuclei in a binary process.

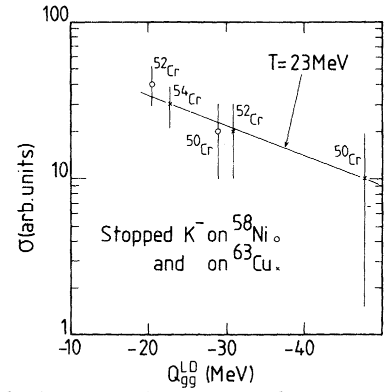

FIG. 6. Same as Fig. 2(a), but for stopped kaons on ^{58}Ni and ^{63}Cu (data from Ref. 21).

IV. DISCUSSION

As discussed in Sec. III, a limit of applicability of the Q_{gg} systematics to pion absorption data is given by the importance of the evaporation process. This can be seen for heavier nuclei. Analyzing, e.g., the Zn-isotope yields following absorption of stopped π^- on ^{75}As (Ref. 17), the yields of neutron-rich isotopes are found too low compared to straight lines in a Q_{gg} plot. This deviation is typical of subsequent evaporation and has been best found in deep inelastic reactions between heavy ions in the same form.[13] The attempt to describe the yield distribution after π^- absorption on Au (Ref. 17) with the Q_{gg} law fails entirely. In these cases evaporation is obviously the dominant process.

The partial success in describing the yields of nuclei far from the target as obtained in the $\pi^{\pm}+{}^{60}$Ni reaction leads us to speculate on processes which preserve the N/Z ratio. This "isospin conservation" suggests direct reactions. In deep inelastic collisions the N/Z ratio of the composite system is roughly preserved. In fragmentation processes, it is the N/Z ratio of the fragmentating nucleus which is preserved. In this respect, the pion data recall more deep inelastic collisions, as the decaying system is not only the target but the target plus the projectile. On the other hand, the decay of the π-plus-target system is not binary, more resembling a fragmentationlike mechanism.

In a recent Letter[18] the addition of an isospin-dependent term made the Q_{gg} law able to describe data both from deep inelastic collisions as well as from fragmentation reactions induced by high-energy protons. An application of this isospin term to the pion data is not evident. A straightforward use yields unsatisfactory results. Even if the elemental distributions exhibit reasonably straight lines, the corresponding temperatures are 3–5 MeV for $\pi^++{}^{60}$Ni and 30–50 MeV for $\pi^-+{}^{60}$Ni at 70 MeV incident energy.

Looking for mechanisms preserving the N/Z ratio, it is very interesting to note that in a recent study based on rapidity plots it was concluded that the pions are absorbed on about four nucleons in this mass range.[19] This contrasts with the traditional view of a quasideuteron absorption,[12] but fits well with our conclusions from the Q_{gg} systematics, suggesting the possibility that a part of the nucleus is "heated" by the pion absorption. Direct α emission or any preequilibrium processes (where proton and neutron emission are about equal), are able to preserve the N/Z ratio, and hence the Q_{gg} systematics work. The positive test of the Q_{gg} law can therefore be used as an indication of fast reaction mechanisms; in the case of pion absorption the rapid particle emission, and in the case of heavy ion reactions the deep inelastic collisions. The slopes found in the Q_{gg} plot (Figs. 2 and 3) are rather flat. The values extracted for the parameter T are about 11 and 18 MeV for 70 and 220 MeV incident pion energy, respectively. Even if it is not evident how one defines a temperature for a nonequilibrated system, as already mentioned, the increase from 11 to 18 MeV well reflects the increase in total available energy. In deep inelastic reactions typical values of 2–3 MeV are found.[4,13,15] The values obtained from high-energy fragmentation data lie around 7–8 MeV for the spectator and exhibit a saturation as a function of the incident energy.[20] If pion absorption seems effectively to "heat" the nucleus, kaon absorption (rest mass =494 MeV) should do it even better. Unfortunately no systematic data are available to test this analogy and only few yields from the absorption of stopped negative kaons on ^{58}Ni and ^{63}Cu are reported.[21] Figure 6 shows a Q_{gg} plot for the Cr isotopes (the only element for which various isotopes are given). The slope indicates a value of 20–25 MeV for the parameter T, in agreement with the increased amount of available energy. A simple relation between the parameter T and the available energy seems to exist for the $A \simeq 60$ nuclei: The total available energy divided by T is nearly 20. This indicates that the concept of the parameter T might be physically meaningful. Such a linear relationship is indeed typical of an ideal gas and may lead to—at the present stage, premature—speculations about the number of participants being about 10–14.

V. SUMMARY

It is shown that the yields of the Ti and partly the Cr isotopes, which are far fom the target, can be described by the Q_{gg} systematics assuming full absorption of the pion, i.e., its charge seems implanted into the target and affects the distribution even after the emission of 10–14 nucleons. This influence of the pion charge is well described by the Q_{gg} systematics. Such an observation is not consistent with a π^- absorption followed by evaporation which would wash out the initial differences in isospin. As nuclei closer to the target are concerned, evaporation could be the dominant process and the Q_{gg} law fails. A fragmentation process of the target alone leads to failure, too: The Q values (binary separation or fragmentation) have to be calculated assuming a decaying pion-plus-target system.

Speculations about a possible mechanism responsible for the loss of 10–14 nucleons, the region where the data agree with the Q_{gg} law, and other experimental observations[19] may lead to the following scheme: The incident pion is absorbed on two or more[19] nucleons. Rescattering or other processes create an excited part of the nucleus tentatively characterized by a temperature of 10–25 MeV. The decay of the "hot" area is dominated by direct emission (preserving the N/Z ratio). Pure evaporation seems to be of minor importance.

The Q_{gg} systematics is, in general, a rather sensitive indicator of nonevaporative mechanisms. As a free parameter, T plays a role analogous to a temperature. Typical values of 2–3 MeV are obtained for deep inelastic collisions between heavy ions[4,13,15] and around 7–8 MeV for fragmentation processes.[5] From pion-absorption data we deduce much higher values ranging from 10 to 20 MeV, and for kaon absorption a value of 20–25 MeV is suggested. These effective temperatures exhibit a linear relationship with the total available energy which is typical of an ideal gas. Yet more data from exclusive experiments are needed before a final conclusion can be drawn. The absorption of mesons appears an interesting tool to study nuclear matter at high excitation energies since only a small amount of linear momentum is brought into the system. "Mesonic heating" seems more effective than "hadronic heating."

We would like to acknowledge J.P. Bondorf for very stimulating discussions and I. Halpern for helpful comments in the early stage of this work.

APPENDIX: THE RUDSTAM FORMULA AND THE Q_{gg} SYSTEMATICS

Proton- and alpha-induced spallation data have been successfully parametrized by the Rudstam formula.[6,8] Recently, it has been applied to π-absorption data too.[7] In this parametrization the isotopic yield distribution is written as

$$\sigma(A,Z) = \text{const. } \exp[pZ - r(A - sZ - tZ^2)^{\alpha}], \tag{2}$$

where α is empirically taken as $\frac{3}{2}$ (or sometimes 2). The parameters s and t describe the location of the most probable mass $A_{\max}$ for each element. These two parameters are independent of the target nucleus and incident energy and describe the line to which evaporation processes lead, as it can be inferred from Fig. 4. It is roughly the valley-of-stability line shifted towards the neutron-poor side since neutrons can be more easily evaporated than charged particles (see Sec. III). Equation (2) can be written as

$$\ln\sigma(A,Z) = pZ - r(A - A_{\max}(Z))^{3/2} + \text{const.} \tag{3}$$

The value $A_{\max}$ is obtained from the universal parameters s and t and the parameters r and p, fitted to a large set of experimental data, show a weak dependence on mass and energy. The width of the distribution around $A_{\max}$ is described by r; p is characteristic of the slope of the elemental distribution.

In order to compare the empirical Rudstam formula and the Q_{gg} systematics law we write Eq. (1) in a way analogous to Eq. (3)

$$\ln\sigma(A,Z) = Q_{gg}/T + \text{const.} \tag{4}$$

If there exists an inherent relation between formulas (3) and (4), the derivative of Eq. (3) with respect to Q_{gg} has to be a constant. This will be evaluated in two steps. In order to express a relation between Q_{gg} and A we use the binding energies from the liquid-drop model.[14] The number of nucleons and the volume term are independent of A. The Coulomb term can be skipped if we keep Z fixed. For simplicity the asymmetry term and the pairing term are neglected too. Using the prominent surface term ($a_s A^{2/3}$) we obtain

$$\partial Q_{gg}/\partial A = -\tfrac{2}{3} a_s A^{-1/3} \left[1 + \left[\frac{A_c}{A} - 1 \right]^{-1/3} \right], \tag{5}$$

where A_c refers to the mass of the composite system.

Combining Eq. (5) and the derivative of Eq. (3) with respect to A gives

$$\partial \ln\sigma(A,Z)/\partial Q_{gg} = \tfrac{9}{4} r/a_s [A - A_{\max}(Z)]^{1/2} \times A^{1/3} + \text{higher order terms.} \quad (6)$$

Thus the derivative $\partial \ln\sigma(A,Z)/\partial Q_{gg}$ is not independent of A.

However, if one would have used $\frac{2}{3}$ instead of $\frac{3}{2}$ as the exponent in Eq. (3), Eq. (6) would read as

$$\partial \ln\sigma(A,Z)/\partial Q_{gg} = r/a_s \left[1 - \frac{A_{\max}}{A}\right]^{1/3} . \quad (7)$$

This demonstrates that a mathematical analogy between the two formulas (1) and (2) exists for this choice of α. The parameter T in Eq. (1) is then equivalent to a_s/r and $f(Z)$ is proportional to $\exp(pZ)$.

The essential difference between these two descriptions is then the way in which $A_{\max}$ is determined. In Rudstam's formula it is purely empirical and reflects the dominating evaporation process, as discussed in Sec. III. In the Q_{gg} systematics $A_{\max}$ is given by the most stable pair of outgoing nuclei in a binary process. Rudstam's formula could be generalized to cover the Q_{gg} law when the parameters s and t are obtained from the contact potential.[22] Then $A_{\max}(t)$ refers to the minima of the potential energy surface. Conversely the Q_{gg} systematics might eventually allow extension to take evaporation into account.[18]

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