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PARTITION OF EXCITATION ENERGY IN PERIPHERAL HEAVY-ION REACTIONS *

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Partition of excitation energy in peripheral heavy-ion reactions

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Abstract

The partition of excitation energy between target-like and projectile-like primary fragments from 11-MeV/nucleon ^{20}Ne + ^{197}Au quasi-elastic reactions was determined from kinematic analyses of three-body final states. Projectile breakup following stripping, pickup, and inelastic scattering was studied, and the excitation-energy partition was found to be strongly correlated with the direction of the mass transfer. Results are in quantitative agreement with optimum-Q-value calculations.

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The measurement of the mass, energy, and angle of one of the two complex fragments produced in a binary heavy-ion reaction is sufficient to determine the total kinetic-energy loss in the collision (the two-body Q-value). The amount of kinetic energy that is lost to intrinsic excitation can then be used to classify the reaction (e.g., quasi-elastic or deep inelastic). However, in order to obtain more information on the reaction mechanisms and interaction times, it is important to determine the partition of excitation energy between the two fragments. Studies of deep-inelastic reactions [1-5] initially suggested that the sharing was proportional to the masses of the fragments, the so-called equilibrium or equal-temperature partition. Recent measurements [6,7] indicate that the partition is more-nearly equal over a large range of Q-value. Both sets of results can be understood by employing transport models of nucleon exchange [8]. All such studies have used heavy projectiles (A>50).

Comparable studies have not been made for lighter projectiles ($A \simeq 20$). The division of excitation energy is an interesting question here because the collision geometry and short interaction time associated with peripheral reactions induced by light projectiles would suppress transport processes [9]. Thus one might instead expect a situation closer to that obtained for direct reactions induced by light ions. In this Letter, we report on the first measurements of excitation-energy sharing in such peripheral collisions, for quasi-elastic products from 11-MeV/nucleon ^{20}Ne + ^{197}Au reactions. We find that the energy partition is strongly dependent on the direction of the mass transfer, and find quantitative agreement between deduced excitations and an extended version of the Siemens optimum-Q-value model [15].

The experimental technique involved the coincident detection of a projectile-like fragment (PLF) and a light charged fragment (LF) associated with the charged-particle decay of an excited primary fragment (PF). The PLF's were detected in a three-element silicon telescope located at 28°, slightly forward of the classical grazing angle. The coincident LF's were detected with a large-solid-angle phoswich array [10,11]. This array consisted of eight 20x2.5-cm^2 segments, each a position-sensitive ΔE-E phoswich, and was positioned 25 cm from the target. By centering the PLF detector in front of the array, we were able to cover with almost 100% efficiency the breakup cone associated with those PF's undergoing sequential charged-particle decay. The phoswich array provided information on the charge, energy, and position of the emitted light fragments, as well as the charged-particle multiplicity. When operated as a veto detector, the array could also be used to measure the yield of PF's that were produced in charged-particle-bound states (i.e., two-body final states).

The experiment was performed using a 220-MeV ^{20}Ne beam from the Lawrence Berkeley Laboratory 88-Inch Cyclotron. The reactions ^{197}Au (^{20}Ne; ^{20,21,22}Ne*, ^{21}Na*, ^{18,19}F*, ^{16,17,18}O*) were observed through the proton or α-particle decay of each of the PF's. The α channel is the predominant charged-particle decay mode for all PF's except ^{21}Na, where proton decay prevails. Decays into more than one LF are about two orders of magnitude smaller and, therefore, ignored.

Measurements of the energy and position of the alphas and protons are used to determine the relative velocity between the PLF and LF. This, in turn, gives the excitation in the primary projectile-like fragment via the relation

$$E_x(PF) = E_{rel} + S ,$$

where E_{rel} is the relative energy of the two detected fragments and S is the associated separation energy. This algorithm assumes: (1) the LF is emitted by the PF, (2) the detected fragments are in their respective ground states, and (3) the exit channel is three-body (i.e., with only the target-like fragment undetected). The first of these assumptions is borne out by a variety of measurements [12] of proton and alpha yields in quasi-elastic reactions in this energy domain, as well as by the relative velocities observed in the present work which exhibit energy and angular correlations characteristic of a sequential mechanism.

In Fig. 1, the PF excitations are plotted for primary channels corresponding to α stripping, pn stripping, inelastic scattering, and 2n pickup, respectively. By definition, all distributions are bounded by the alpha-decay threshold (dashed lines); the sub-threshold yields (determined in anti-coincidence mode) are represented as fractions of the total primary yields.

The excitation in primary $^{16}O^*$ is shown in Fig. 1(a). The position of the peak in the ^{12}C-α relative kinetic energy matches the 9.63-MeV state in ^{16}O, the first state above the 7.16-MeV alpha-decay threshold. (The small yield in this sequentially-forbidden region is due to the experimental resolution in the relative kinetic energy.) At higher excitations the yield is found to drop exponentially, indicating that the intrinsic excitation of primary ^{16}O is peaked below the alpha threshold. This steep drop also shows that decays to excited states in the ^{12}C PLF are not significant. A comparison with the charged-particle-bound yield of ^{16}O reveals that 96% of the primary yield is excited below decay threshold, in qualitative agreement with a "cold" ejectile.

The negligible probability that two, or more, light charged fragments are in coincidence with a PLF is an indication that the $^{12}C + \alpha$ channel is a three-body final state. While a neutron in the exit channel would be undetected, such a channel would correspond to excitations in primary $^{17}O^*$ above its αn threshold ($\simeq$ 14 MeV). The excitation in $^{17}O^*$ measured in $^{13}C + \alpha$ coincidences shows that excitations >14 MeV are very weakly populated. Thus, the $^{12}C + \alpha$

channel is a true three-body final state.

Similar analyses can be applied to the excitation spectra of primary ^{18}F and ^{20}Ne [Figs. 1(b),(c)]. In both cases, the sharp drop in yield at excitations above the first alpha-decaying state (or cluster of states) indicates that the primary ejectile is preferentially excited to a particle-bound state. This is also supported by the dominance of two-body channels for primary ^{18}F and ^{20}Ne (84% and >93%, respectively), and is consistent with the observation of Wald et al. [13] that few-nucleon or massive transfer to the target leaves a relatively cold primary ejectile.

The situation is qualitatively different for the pickup channel [Fig. 1(d)]. For primary ^{22}Ne, a conservative estimate places the fraction of primary ^{22}Ne produced in particle-bound states at $\simeq$ 35%, and indicates that the average excitation must be in excess of the 9.7-MeV threshold. This estimate requires a calculation of the neutron-decay yield, which was done by scaling the measured α-decay yield by branching ratios obtained with the statistical-model code STATIS [14]. These branching ratios also suggest that the broad structure in the ^{22}Ne excitation spectrum, though peaked well-above the alpha-decay threshold, may be caused by competition with the neutron-decay channel.

By employing three-body kinematics to the coincidence data, it is possible to calculate the three-body Q-value, Q_3, associated with the breakup channels. This, in turn, can be used to calculate the excitation in the primary target-like fragment (TLF) as

$$E_x(\mathrm{TLF}) = Q_{ggg} - Q_3 ,$$

where Q_{ggg} represents the mass difference in the entrance and exit channels. This construction again assumes that the detected fragments are in their ground states, and that the exit channel is three body.

Fig. 2 shows the target excitation corresponding to the four primary ejectiles considered in Fig. 1. The excitation deduced from the $^{12}C + \alpha$ coincidences [primary ^{16}O, Fig. 2(a)] shows that alpha stripping results in relatively large target excitation, in contrast to the apparently "cold" ejectile. A similar behavior is observed for the TLF associated with primary ^{18}F [Fig. 2(b)]. The TLF excitation for the inelastic channel [Fig. 2(c)] is peaked near zero, so that the average inelastic excitation appear to be low in both primary fragments. However, a "cold" TLF is also observed when two neutrons are transferred to the projectile [Fig. 2(d)], a channel which strongly populates large excitation in ^{22}Ne.

It is instructive to employ an optimum-Q-value model to calculate the excitation generated by mass and charge transfer in peripheral reactions. The model of Siemens et al. [15] considers the direct transfer of nucleons between spectator nuclei. In this prescription, the optimum Q-value for a reaction A(a,b)B can be written as

$$Q_{opt} = V_C(out) - V_C(in) - \frac{[E_{cm} - V_C(in)]}{\mu} \left[n \frac{A-m}{B} + m \frac{a-n}{b} \right] ,$$

for the case where n nucleons are transferred from projectile to target and m nucleons from target to projectile. $V_C(out)$ and $V_C(in)$ are the exit- and entrance-channel Coulomb potentials at contact (evaluated using $r_C = 1.4$ fm), and μ is the entrance-channel reduced mass. The total available excitation energy is then given by

$$E_x(total) = Q_{gg} - Q_{opt} .$$

The predicted total excitation is indicated by the arrow in the TLF excitations of Fig. 2. For the stripping and inelastic channels, the calculated values lie close to the observed most-probable target excitation, indicating that the target-like fragment is absorbing essentially all of this total available excitation. However, there is a large discrepancy for the 2n pickup channel, indicating that most of the excitation is not going into the target.

In the case of the TLF, it is possible to deduce most-probable-excitation values for all primary channels studied. These are plotted in Fig. 3 (solid circles). This set of data clearly demonstrate that the excitation generated in these peripheral reactions is associated with the transfer of mass. To first approximation, the fragment that is donating mass remains cold while the recipient nucleus acquires excitation, illustrating that nucleon exchange is the most important mechanism for dissipating relative kinetic energy in these peripheral collisions. The observed excitation partition is a consequence of the short interaction times associated with peripheral reactions, which does not allow a redistribution of the excitation energy (e.g., towards thermalization) and, thus, preserves the mass-transfer partition. This conclusion is in accord with recent work on quasi-elastic scattering of ^{86}Kr, for which a channel-dependent partition was observed [16]. It is also consistent with the observation of Siwek-Wilczynska et al. [17] that pickup products acquire excitation, as deduced from particle-γ coincidences.

If the Q_{opt} calculations are extended by assuming that the total excitation energy is shared according to the mass captured by each fragment, then it is possible to calculate the most-probable excitations in the PF and TLF via the relations,

$$E_x(PF) = [m/(m+n)]\ E_x(total) \quad , \text{ and}$$

$$E_x(TLF) = [n/(m+n)]\ E_x(total) \ .$$

The PF excitations thus predicted are in qualitative agreement with experiment: stripping products are produced cold, while pickup products are excited. (In the case of ^{22}Ne, the calculated PF excitation of 14.2 MeV is in accord with a deduced excitation in excess of 9.7 MeV.)

Calculations for the target-like fragments are shown in Fig. 3 (open circles), in which a unidirectional mass flow was used (i.e., m=0 for stripping, n=0 for pickup). A cold TLF for the pickup channels is a trivial result of the calculation. More importantly, the channels corresponding to primary ^{16}O and $^{18,19}F$ are well reproduced. The agreement with primary $^{17,18}O$, however, is poor. This can be improved by assuming a bi-directional process corresponding to alpha transfer to the target along with one- and two-neutron transfer to the projectile (open squares). While bi-directional transfer was not needed for the other channels, its use for $^{17,18}O$ is not unreasonable since both alpha stripping from cluster nuclei and neutron pickup from neutron-excess targets are known to have large cross sections. An earlier study of primary yields by Homeyer et al. [18] concluded that neutron pickup was necessary to understand the cluster-stripping yields. It should be noted that the present experiment is more sensitive to the bi-directional component of the $^{17,18}O$ yields since the coincidence technique samples only that portion of the primary cross section that produces excited PF's.

In summary, the partition of excitation energy in peripheral reactions of 11-MeV/nucleon $^{20}Ne + ^{197}Au$ was studied by coincidence measurements of the charged-particle decay of primary projectile-like fragments. The deduced excitation energies of projectile-like and target-like fragments show that the partition is governed by the direction of the mass transfer. Calculations using an optimum-Q-value for the total excitation together with this uni-directional partition provide qualitative and quantitative agreement with reconstructed excitations in the primary projectile-like and target-like fragments, respectively. For the primary $^{17,18}O$ channels, the breakup data appear to be sensitive to the bi-directional component of the transfer, and agreement is achieved only by assuming a complex process.

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Figure Captions

1) Reconstructed PF excitations deduced from α-PLF coincidences via the relation $E_x(PF) = E_{rel} + S_{\alpha}$. The channels shown are (a) α stripping, (b) pn stripping, (c) inelastic scattering, and (d) 2n pickup. Particle-bound yields below threshold (dashed line) are represented as fractions of the reconstructed primary yields. Arrows indicate the positions of the first state (or cluster of states) above threshold.

2) Reconstructed TLF excitations deduced from α-PLF coincidences. Calculations employ three-body kinematics to evaluate Q_3 in the relation $E_x(TLF) = Q_{ggg} - Q_3$. The primary channels are as in Fig. 1. Arrows indicate the total excitations predicted by the model of Siemens et al. [15].

3) Comparison of experimental TLF excitation energies (most-probable values) with calculations based on optimum Q-values. The open circles and squares represent calculations assuming uni-directional and bi-directional mass transfer, respectively.

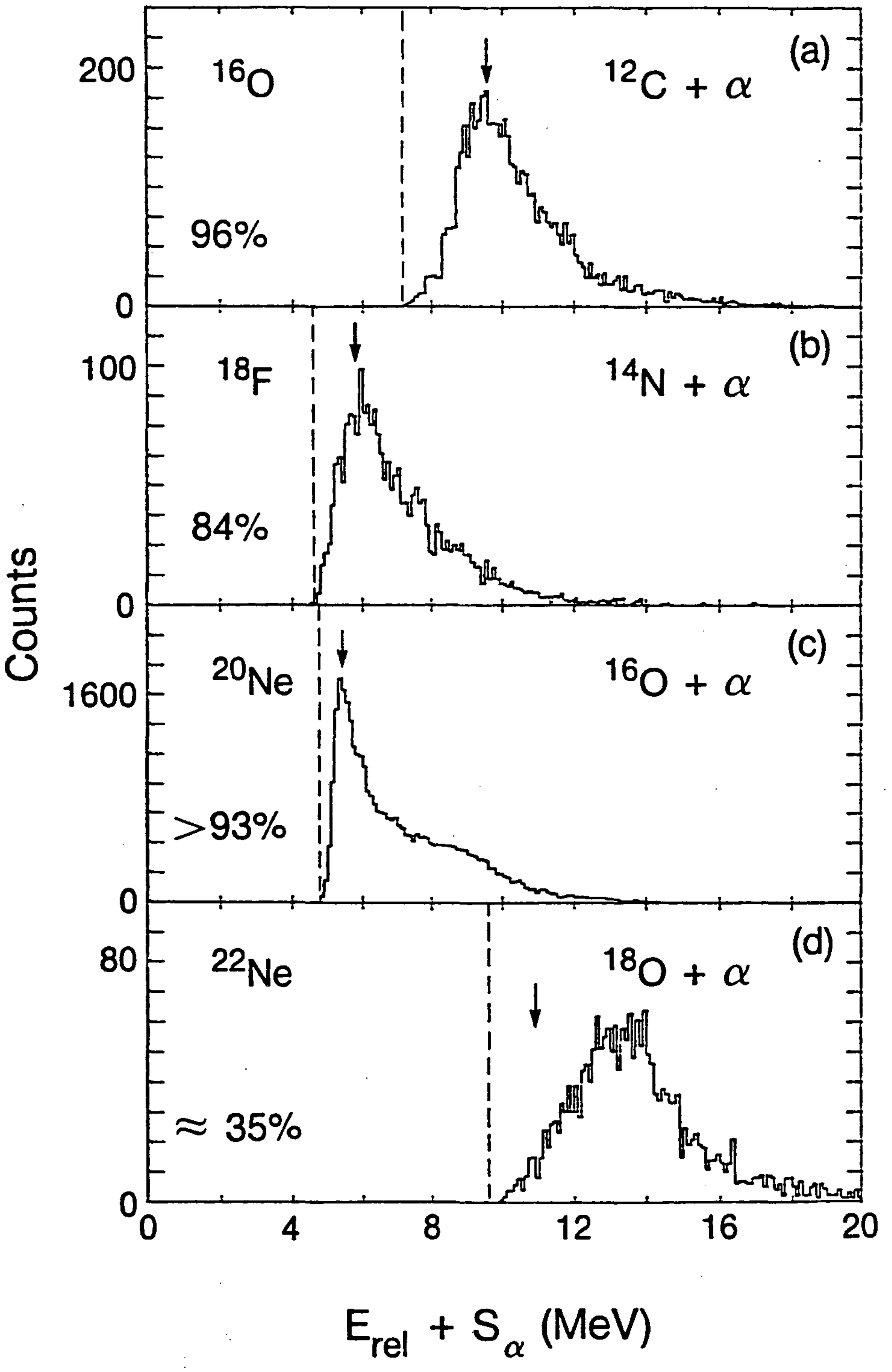
(a)
16O
12C + α
96%
200
0
(b)
18F
14N + α
84%
100
0
(c)
20Ne
16O + α
>93%
1600
0
(d)
22Ne
18O + α
≈ 35%
80
0
0
4
8
12
16
20
Counts
E_rel + S_α (MeV)
XBL 866-10447

Figure 1

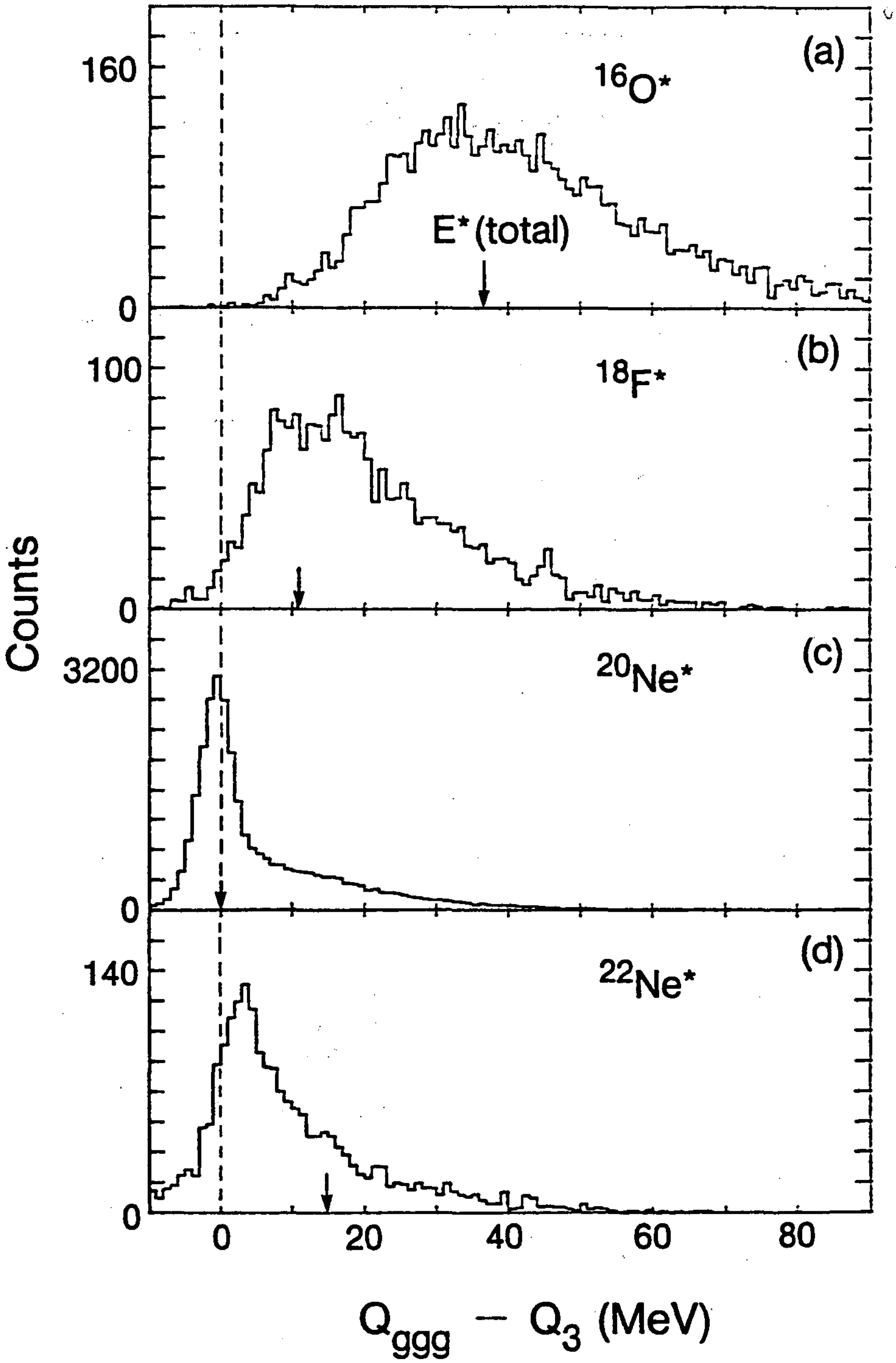

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Figure 2

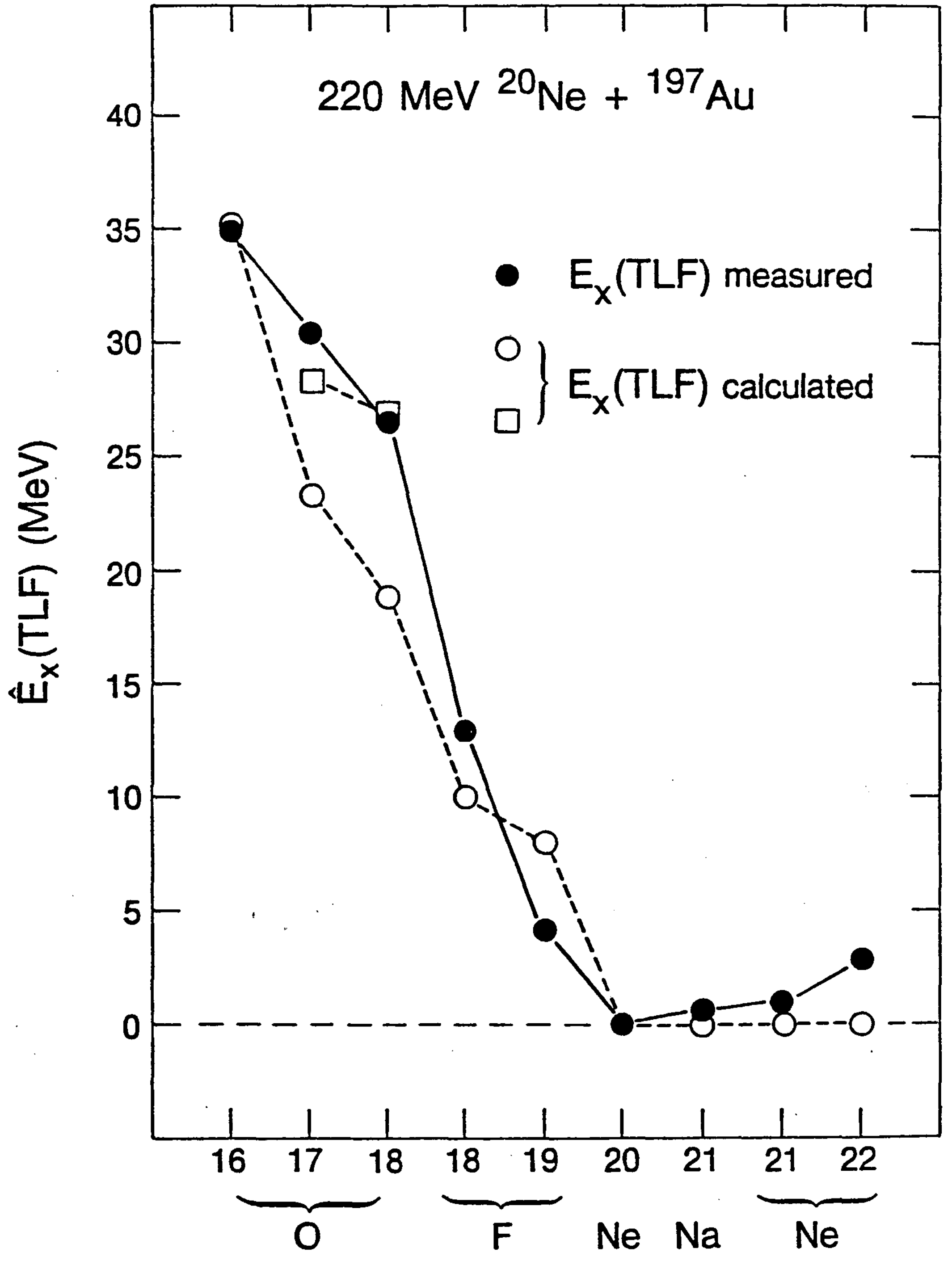

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Figure 3

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