pn to d and αpn to αd emission ratios in heavy-ion-induced reactions

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The competition between pn and d as well as between αpn and αd evaporation leading to the production of the same residual nuclei has been measured for nine and five heavy-ion-induced nuclear reactions, respectively, each at several bombarding energies. The deduced σ_{pn}/σ_d ratios have been found to be in very good agreement with the predictions of a previously extracted empirical equation. The ratios $\sigma_{\alpha pn}/\sigma_{\alpha d}$ do not seem to depend on either the interacting system or the maximum excitation energy available to the residual nucleus.

I. INTRODUCTION

Considering fusion evaporation reactions, often only p, n, α, and γ-ray emission from the compound nucleus is taken into account, since it is assumed that the emission of other light composite particles is negligible. Convincing experimental evidence on that aspect, however, was not available, mainly because the delineation of the competition between the emission of a cluster and its constituent nucleons is not a trivial experimental problem since all these exit channels lead to the production of the same residual nucleus.

With respect to pn vs d emission, the competition of which has been rather extensively studied,[1-3] the experimental evidence, obtained via charged-particle-gamma coincidence techniques, has demonstrated that in certain instances the evaporation of deuterons may have a quite significant relative importance depending on the interacting heavy-ion system and the energy of the bombardment.

More important has been the observation that the ratio of cross sections for pn and d emission in a series of heavy-ion-induced nuclear reactions, far from being uncorrelated, follows a systematic trend according to which the competition depends only on the maximum energy available for excitation to the residual nucleus. This systematic trend was, furthermore, utilized to extract a phenomenological relationship,[2] according to which the competition between pn and d emission may be predicted. In fact, the predictive formalism and the underlying concepts have already been applied in the literature[4-6] in nuclear reactions of interest for which no relevant experimental data were available.

The applicability of the empirical formalism in describing the competition in reactions widely different from those by which it was derived, however, cannot be safely assumed. In that respect it should be noted that of the nine nuclear[2] reactions previously investigated, that of ^{28}Si(^{12}C, pn/d) deviated significantly from the average trend.[2]

The notation ^{28}Si (^{12}C, pn/d) means that in the bombardment of ^{28}Si with ^{12}C the ^{38}K residual nucleus may be found by pn and/or d emission. The meaning of notation such as (^{16}O, p2n/dn/t) and (^{19}F, αpn/αd), which will be met below, is similar. In such cases, although the entrance channel is the same, the exit channels competing for the production of the same residual nucleus are distinctly different reaction modes, demanding appropriate treatment for either their experimental identification or their theoretical description.

One purpose of the present study is to test the range of applicability of the systematics of the competition between pn and d emission by comparing it with additional relevant experimental evidence. Thus, this competition has been studied in nine previously unreported nuclear reactions, each at several bombarding energies, in which isotopes of neutron excess larger than previously noted, such as ^{13}C and ^{18}O, have been utilized as target or projectile.

The second purpose of this study is to investigate the competition between more massive cluster versus constituent-multiparticle evaporation about which the only relevant, although scant, data are associated with the ^{13}C(^{16}O, p2n/dn/t) nuclear reaction.[1] Specifically, in the present study the competition between αpn and αd has been investigated in five heavy-ion-induced nuclear reactions.

II. EXPERIMENTAL PROCEDURE

Thin, 50 μg/cm^2, targets of different isotopes deposited on Au backing sufficiently thick to stop the heavy-ion beam were bombarded with beams supplied by the Tandem Accelerator of Nuclear Research Centre Demokritos. One of the bombardments at higher bombarding energy was carried out with the Tandem Accelerator of the Brookhaven National Laboratory.

A ΔE-E-A/C counter telescope of silicon detectors was used for light charged particle detection, in a semicircular scattering chamber. The thickness of the ΔE counter varied between 30 and 150 μm in order to observe the effect of the ΔE counter low energy cutoff on the measured relative cross sections. The γ rays were detected with Ge(Li) coaxial detectors with the axis in the reaction plane in perpendicular position with respect to the beam, at 2 cm distance from the target.

Particle identification with pileup rejection and fast coincidence circuitry for particle-γ coincidence were employed. The raw data were stored event by event on magnetic tape by an on-line PDP-11/15 computer.

The light-charged-particle-gamma coincidence technique permitted us to directly observe the competition between exit channels producing an individual residual state. The discrete coincident γ rays were used to identify the heavy residual nucleus.

A particle-γ coincidence between a given kind of light charged particle and of γ rays deexciting a specific residual state can furnish the differential cross section for the production of that residual state as follows:

$$\frac{d^2\sigma}{d\Omega_p d\Omega_\gamma}=0.266\times 10^3\frac{AN_c}{qt\epsilon_p\epsilon_\gamma\Omega_p\Omega_\gamma}\left[\frac{\text{mb}}{\text{sr}^2}\right], \quad (1)$$

where A is the mass number of the target (u), N_c the number of coincidence events, q the beam charge (μC), and t the bombardment duration (sec). Ω_p and Ω_γ are the solid angle for particle and γ-ray detection, respectively, and ϵ_p and ϵ_γ the corresponding detection efficiency coefficients.

Let us consider for simplicity the measurement of competition between pn and d emission producing the same residual nucleus. Because of simultaneous detection, under the same geometry of protons and deuterons in coincidence with a specific γ ray, the detection efficiency and solid angle for p-γ_1 and d-γ_1 coincidence is identical. Furthermore, since neutrons are not detected, the p-γ coincidences correspond to pn events integrated over all angles of neutron emission.

Assuming that particle-γ angular correlation effects are negligible, it is obvious from Eq. (1) that the ratio of the intensity of a discrete γ ray in coincidence with protons to the intensity of the same γ ray in coincidence with deuterons equals the relative differential yields or the ratio of differential cross sections for producing the corresponding residual state by pn and d emission for a given angle of particle detection. That is,

$$(d\sigma_{pn}/d\Omega)/(d\sigma_d/d\Omega)=N_{p\text{-}\gamma_1}/N_{d\text{-}\gamma_1} . \quad (2)$$

Particle-γ ray angular correlation effects should have been washed out in the present measurements due to the large solid angle of the γ-ray detector. Furthermore, the measurement takes into account all reaction events populating the residual state by side feeding or by a prompt γ-ray cascade. This cascade further reduces any particle-γ correlation effect, especially when a low lying state is monitored, as has been the case in almost all the reactions studied.

In order to obtain the angle-integrated relative yields, the dependence of the ratio of the differential cross sections on the angle of charged particle emission should be measured. In some reactions such as $^{12}C(^{16}O,pn/d)^{26}Al$, it was found[1] that, although the individual relative differential cross sections for pn and d emission were forward peaked, their ratio remained approximately constant throughout the measured angular range. In other reactions, such as $^{16}O(^7Li,pn/d)^{21}Ne$, an anisotropy of the ratio $d\sigma_{pn}/d\sigma_d$ as a function of the charged particle angle was observed.[7] After integration, however, it was found that the ratio of angle-integrated cross sections σ_{pn}/σ_d overlapped within the experimental error with the value measured at 0° particle angle.

In either case, it is concluded that the competition ratio of charged particle emission measured at 0° represents the

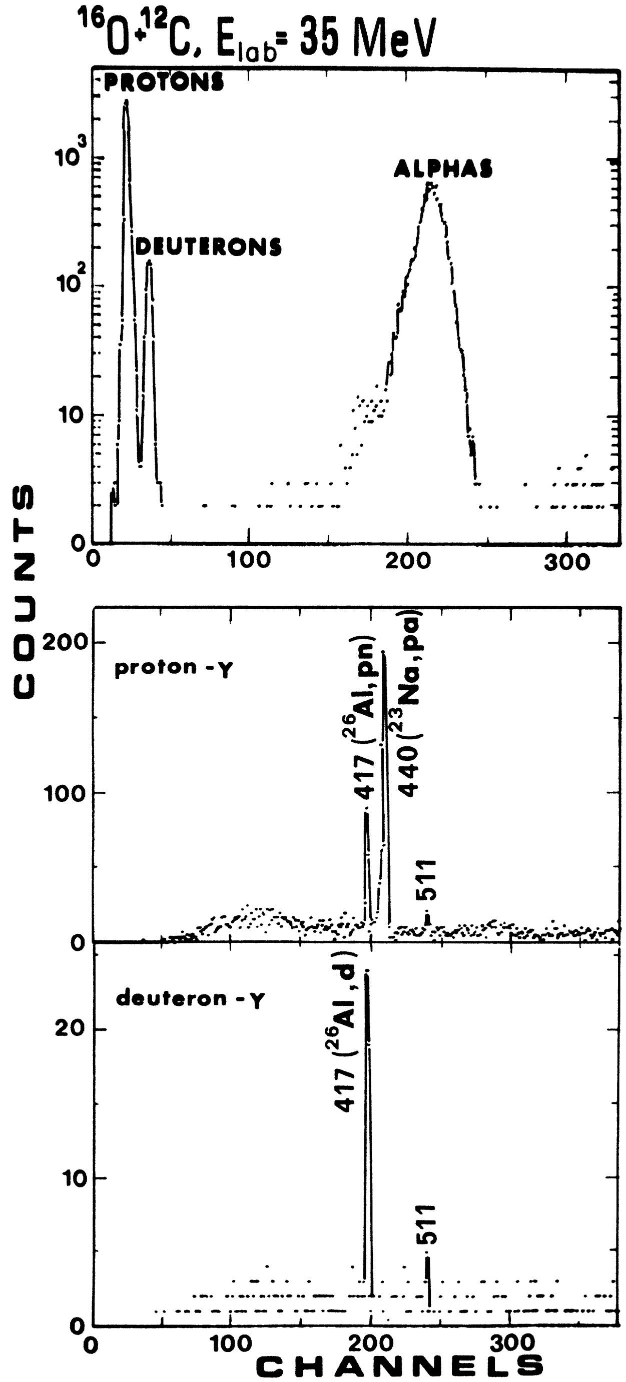

FIG. 1. Mass spectrum and γ-ray spectra in coincidence with protons and deuterons obtained in the bombardment of ^{12}C with ^{16}O at 35 MeV.

ratio of integrated cross sections of the competing exit channels.

We present the data of $^{12}C(^{16}O,pn/d)^{26}Al^*(\gamma)$ coincidence measurements with the help of which we discuss the essential feature of the experimental method. The mass spectrum of particles in coincidence with all γ rays, as well as the lower energy part of the γ-ray spectra in coincidence with protons and deuterons, are shown in Fig. 1. The main discrete γ-ray transitions observed, 417 keV and 440 keV, are associated with $^{26}Al + pn$ or d and $^{23}Na + p\alpha$ exit channels, respectively.

The 417 keV transition appears in coincidence with both proton and deuteron groups, indicating that the corresponding 417 keV state in ^{26}Al is in fact produced by both pn and d emission. As has been previously discussed, the ratio of the intensity of the 417 keV γ ray in coincidence with protons to the intensity of the same γ ray in coincidence with deuterons equals the relative yields for producing the corresponding residual state by pn and d emission.

Another feature of this technique is that the relative yields, instead of using the coincidence intensities of a discrete γ ray, may be equivalently obtained by integrating the energy spectra of the light charged particles which have been measured in coincidence with a specific γ ray.

Charged particle spectra associated with the production of the first three excited states in ^{26}Al via the reaction $^{12}C(^{16}O,pn/d)^{26}Al$ are shown in Fig. 2. The proton spectra show a continuous energy distribution due to the sharing of energy between the two particles of pn exit channel. The deuteron energy spectra, on the other hand, demonstrate the side feeding and cascade modes by which these residual states are produced. From this point of view it is interesting to notice that the 3^+, 417-keV state in ^{26}Al is mainly produced by side feeding, while in the production of the 1^+, 1058-keV third excited state, in addition to the side feeding a significant cascade contribution is present.

The above spectra furthermore permit us to observe the detector cutoff, and, by extrapolating to zero energy, to correct the σ_{pn}/σ_d ratio for the intensity of the low energy protons absorbed by the ΔE detector. The effect of low-energy cutoffs was also investigated by using ΔE detectors of various thicknesses between 25 and 150 μm depletion depths. The corresponding cross section ratio values, obtained under various conditions of measurement or analysis, were overlapping within the experimental error for bombarding energies exceeding the threshold for the competing channels by a few MeV.

The charged-particle-γ coincidence technique may be utilized to study the competition between more massive cluster and multiparticle evaporation exit channels. Measurements of the competition between t, dn, and p2n evaporation have been presented in Ref. 1. This technique has been employed here to study the competition between αpn and αd emission. Relevant data associated with the $^{12}C(^{19}F,\alpha pn/\alpha d)^{25}Mg$ reaction are demonstrated in Fig. 3, where γ-ray spectra in coincidence with protons and deuterons are shown. Prominent transitions correspond-

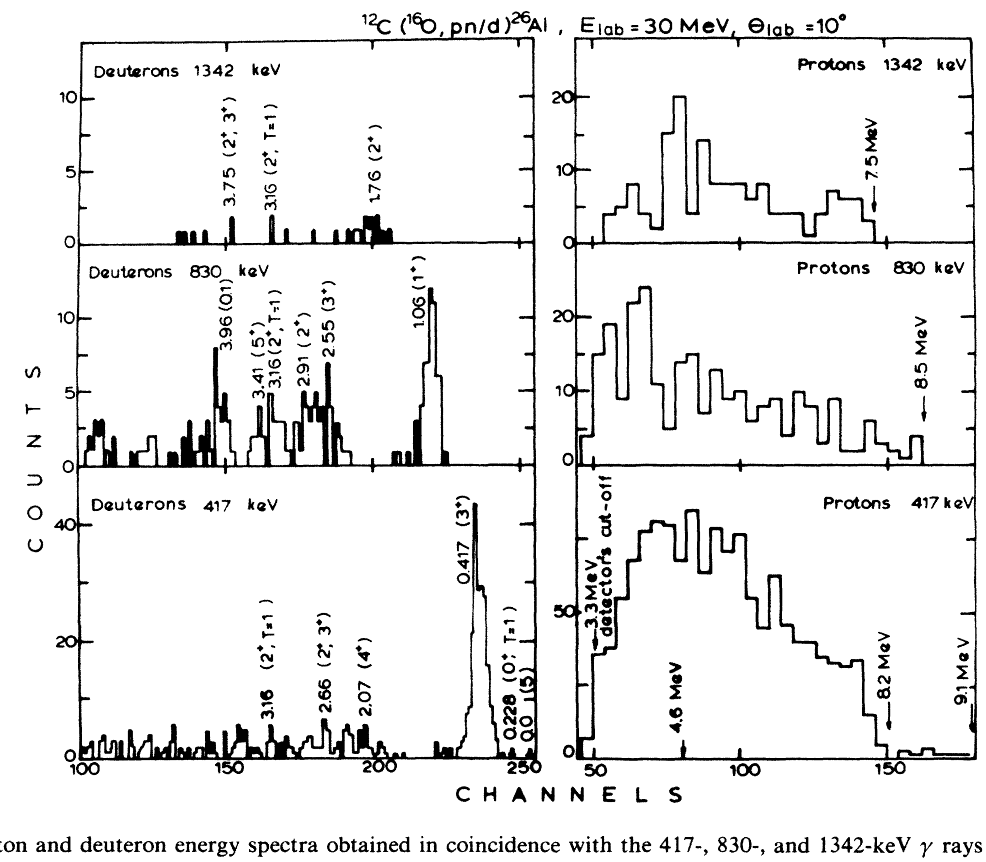

FIG. 2. Proton and deuteron energy spectra obtained in coincidence with the 417-, 830-, and 1342-keV γ rays of ^{26}Al in the reaction $^{16}O + ^{12}C$, at 30 MeV.

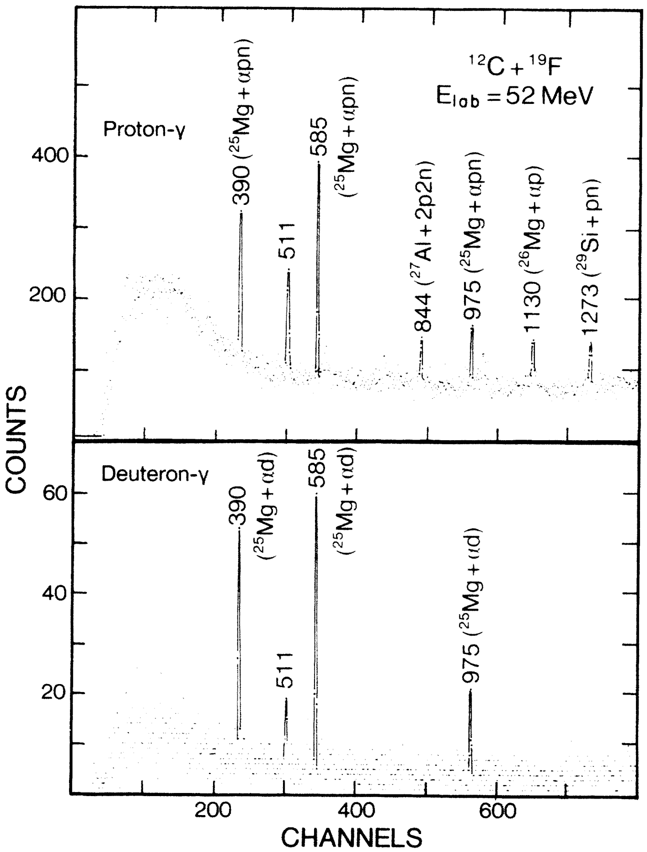

FIG. 3. γ-ray spectra obtained in coincidence with protons and deuterons in the bombardment of ^{19}F with ^{12}C at 52 MeV.

ing to deexcitation of the two lowest excited states of ^{25}Mg are seen at 390, 585, and 975 keV. These transitions appear in coincidence with both proton and deuteron groups, as well as with α-gated groups which are not included in Fig. 3, indicating that ^{25}Mg is in fact produced by both αpn and αd emission. As stated previously, the ratio of the intensity of each of these γ rays in coincidence with protons over the intensity of the same γ rays in coincidence with deuterons gives the relative yields for producing the corresponding residual states in ^{25}Mg by αpn and αd emission. In the above consideration the emitted α particles and neutrons are considered unobserved, and therefore the p-γ and d-γ coincidences correspond to αpn and αd events integrated over all angles of α and neutron emission. In these measurements one has to be very careful with respect to the ΔE low-energy cutoff since the energy available to the αpn and αd exit channels is shared between several particles. For that reason the αpn and αd results considered in the present study are restricted to those reactions associated with bombarding energies corresponding at least to 8 MeV of energy available for particle emission.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Competition between pn and d emission

The nuclear reactions investigated are listed in Table I. The measured cross section ratio for production of the $A-2$ residual nuclei by pn and d emission is given in the third column, corresponding to the bombarding energies listed in the second column. These events demonstrate that for any nuclear reaction the σ_{pn}/σ_d ratio increases progressively with increasing bombarding energy. Apart from this, a correlation between the ratios in the different reactions is not immediately discernible.

A consideration which has been fruitful in understanding the physical origin of the competition is that the ratio σ_{pn}/σ_d is limited by the maximum excitation energy available to the residual nucleus. This hypothesis has been tested[2] by means of a logarithmic plot of σ_{pn}/σ_d vs $E_{c.m.}+Q_{pn}$ whereby a systematic trend emerged, illustrating a nearly linear dependence, thus permitting the description of the competition by the exponential relationship

$$\sigma_{pn}/\sigma_d=0.83\exp[0.19(E_{c.m.}+Q_{pn})]\ , \tag{3}$$

where the quantity $(E_{c.m.}+Q_{pn})$ is expressed in MeV. The predictions of the above relationship are represented

TABLE I. Relative cross sections for the production by pn and d emission of the residual nuclei, commensurate with the indicated reactions at the specified bombarding energies.

Reaction	$E_{c.m.}$ (MeV)	σ_{pn}/σ_d
^{16}O+^{12}C	11.6	1.3±0.2
	12.0	1.8±0.2
	12.9	2.1±0.2
	13.7	2.8±0.2
	15.0	3.0±0.1
	16.1	4.0±0.1
^{16}O+^{13}C	12.1	9.1±1
	12.6	11.5±2
	13.5	13.4±2
	14.3	15.2±3
^{16}O+^{16}O	15.0	4.8±1
	15.5	8.6±2
^{16}O+^{27}Al	18.8	20±4
^{18}O+^{12}C	12.4	8±2
^{18}O+^{16}O	12.9	17.7±4
	14.6	20.0±5
	16.0	35.5±6
^{18}O+^{18}O	13.8	62±20
	15.5	67±20
^{18}O+^{19}F	15.4	72+30
	15.9	pn
^{18}O+^{28}Si	16.7	22±5
	18.9	27±4
	20.7	36±6

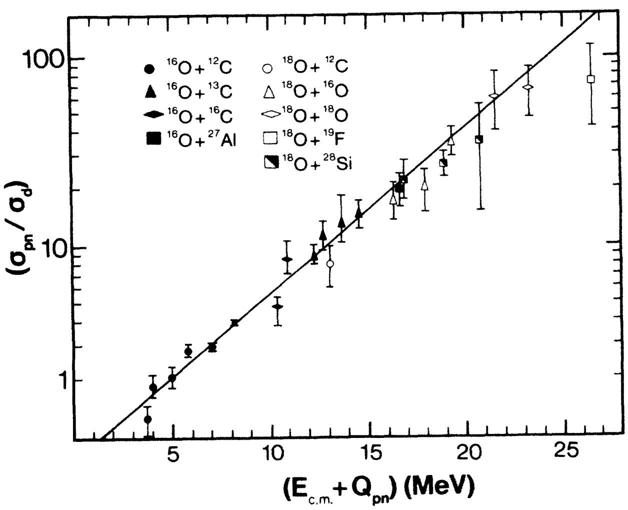

FIG. 4. Comparison between experimental ratios σ_{pn}/σ_d presently measured (data points) and relevant experimental systematics previously (Ref. 2) extracted (solid line).

by the solid line in Fig. 4, where the presently measured competition values are also shown by data points. The error bars represent the statistical uncertainties introduced by the analysis of the coincidence photopeaks.

The very good agreement observed in the comparison of the present results with the previously extracted systematics demonstrates that Eq. (3) accounts remarkably well for the competition between pn and d emission in a total of 17 heavy-ion-induced nuclear reactions. It should be noted that in almost all the investigated reactions relatively light heavy ions are involved, although the results associated with ^{64}Zn(^{7}Li,pn/d), the heaviest system thus far investigated, do not deviate from the rest. Similar satisfactory agreement with the average trend is observed in the reactions induced in the present study with the neutron-rich ^{18}O isotope.

At high values of $E_{c.m.}+Q_{pn}$ the experimental measurement of the ratio becomes problematic, since d emission is relatively rare. This is also reflected in the progressively enlarged statistically uncertainty assigned to the measured ratios at higher energies. Above a certain value of $E_{c.m.}+Q_{pn}$, about 20 MeV, one may assume, therefore, for all practical purposes, that the reactions proceed essentially by pn evaporation. On the other hand, at low bombarding energies the reactions proceed predominantly by d emission.

In conclusion, the present experimental results confirm the applicability of Eq. (3) in predicting the pn vs d emission competition. The deviation from the average trend previously observed[2] in the reaction ^{28}Si(^{12}C,pn/d) constitutes thus far the only exception to the rule.

Finally, it should be noted that statistical-model predictions of pn over d competition previously[2] carried out in the framework of the Hauser-Feshbach theory reproduce rather well the experimental systematics, indicating that the cluster and multiparticle emissions proceed via evaporation from a compound nucleus, as opposed to a direct reaction mechanism.

TABLE II. Relative cross sections for the production αpn and αd emission of the residual nuclei commensurate with the indicated reactions at the specified energies.

Reaction	$E_{c.m.}$ (MeV)	$E_{c.m.}+Q_{\alpha pn}$ (MeV)	$\sigma_{\alpha pn}/\sigma_{\alpha d}$
^{13}C+^{16}O	18.2	8.34	9±4
^{18}O+^{28}Si	16.7	10.21	11±5
^{18}O+^{18}O	15.5	12.04	5±2
^{18}O+^{19}F	15.4	18.30	7±2
^{12}C+^{19}F	31.9	25.79	5±1

B. Competition between αpn and α emission

Competition between αpn and αd emission, which has not been previously identified, was observed in five of the presently investigated reactions listed in Table II. The measured relative cross sections of competing exit channels leading to the same $A-6$ residual nucleus are given in the fourth column of Table II, corresponding to the bombarding energies listed in the second column. The third column demonstrates the commensurate $E_{c.m.}+Q_{\alpha pn}$ quantity which corresponds to the maximum excitation energy available to the relevant $A-6$ residual nucleus, where it can be seen that a rather wide range, about 18 MeV of excitation energy, is spanned by these measurements. The results demonstrate that within the rather large statistical uncertainty, the αpn/αd competition does not seem to depend significantly on either the interacting system or the energy available to the exit channel.

This new competition certainly demands further experimental as well as theoretical investigation.

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[1] A. C. Xenoulis, E. N. Gazis, P. Kakanis, D. Bucurescu, and A. D. Panayiotou, Phys. Lett. **90B**, 224 (1980).

[2] A. C. Xenoulis, A. E. Aravantinos, C. J. Lister, J. W. Olness, and R. L. Kozub, Phys. Lett. **106B**, 461 (1981).

[3] E. N. Gazis, P. Kakanis, and A. C. Xenoulis, Phys. Rev. C **24**, 762 (1982).

[4] J. F. Mateja, A. D. Frawley, L. C. Dennis, K. Abdo, and K. W. Kemper, Phys. Rev. C **25**, 2963 (1982).

[5] R. L. Kozub, J. Lin, J. F. Mateja, C. J. Lister, D. J. Millenev, J. W. Olness, and E. K. Warburton Phys. Rev. C **27**, 158 (1983).

[6] J. F. Mateja, J. Gruvmon, and A. D. Frawley Phys. Rev. C **28**, 1579 (1983).

[7] A. E. Aravantinos and A. C. Xenoulis, Greek Atomic Energy Commission, Tandem Accelerator Laboratory Annual Report, 1979, p. 16.