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CLUSTERS AND EXOTIC PROCESSES

by

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CLUSTERS AND EXOTIC PROCESSES*

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In my talk I will do two things: first, attempt to present some data which may be construed as indicating that perhaps clusters play a role in high-energy and "exotic" (pion or kaon) interactions with complex ($A \gg 16$) nuclei. In the time and space allotted I cannot do more than mention a few experiments that have captured my imagination. A considerable body of work exists on pion-induced reactions and excellent reviews by Zupancic[1] and Koltun[2] may be consulted for general perspectives. Second, I will attempt to summarize some very recent experimental work on pion interactions with nuclei which may or may not in the end support a picture in which clusters play an important role.

One respect in which pions are different from the more conventional nuclear projectiles is that they can be literally absorbed, giving up the energy of their rest mass to two or more nucleons. And this is a possible place where clusters may play a role, since it is by no means clear whether the two-nucleon correlations required for pion absorption are in fact manifestations of correlations involving larger clusters, perhaps α particles, in nuclear matter.

Complex Fragments from Stopped Pions

One experiment which I find quite suggestive of the importance of clusters is the work of Castleberry et al.[3] They looked at deuterons and tritons emitted from various nuclei with stopped negative pions and the results are shown replotted in Fig. 1. The number of such fragments is rather large even in nuclei such as Ca. In order for deuterons or tritons to emerge from a complex nucleus it is necessary to assume that the primary absorption process of the pion occurred on more than two nucleons. If one were to assume, as an extreme, that all the π^- absorption occurred on α-particle clusters and that the resultant fragments have a mean free path of 1—1.5 fm in nuclear matter, then one can fit the trend of the data of Castleberry et al. reasonably well. Clearly, such data need to be understood in more detail.

Spallation by High-Energy Protons

The work of Poskanzer and Hyde[4] is particularly relevant to a discussion of cluster effects in the interaction of high-energy protons with nuclei. With 5.5-GeV protons on uranium they found surprisingly large cross sections for producing quite heavy fragments. They looked up to Ar and the integrated cross section for all Ar isotopes was 20 mb. The angular distributions are all rather similar: forward peaked. The yield with decreasing A increases first slowly for lighter elements and then rather sharply: 150 mb for oxygen and ~4400 mb for He. Clearly such data are extremely relevant to a cluster picture of heavy nuclei, but we are very far from understanding how to analyze and interpret it. The huge numbers of α particles are especially intriguing.

Gamma Rays from Stopped Kaons

Next I would like to discuss some results on nuclear gamma rays from stopped kaons that a group of us found some years ago.[5] The results are shown in Fig. 2. The clear feature that we see is that strong gamma rays can be identified corresponding to gamma rays in nuclei that differ from the target nuclei by 1, 2 or 3 α particles. The total intensity of these gamma rays was found to be greater than the kaonic X-ray lines and seems to account for 60—70% of the stopped kaons. The nuclides seen change with the neutron excess of the target, which seems to argue against a statistical evaporation process following the absorption of the kaon.

On free nucleons the kaon absorption proceeds in two stages

$$K^- + N \rightarrow \Lambda + \pi$$

$$\Lambda \rightarrow N + \pi .$$

In a real nucleus the process might be the same with the formation of a hypernucleus as an intermediate state or the absorption might occur without producing any real pions and all the energy would be taken up by the nucleons in the nucleus.

Unfortunately, experiments with stopped kaons are difficult. If similar effects could be seen with pions many more experiments could be carried out to understand the relevant mechanism.

Gamma Rays from Fast Pions on ^{40}Ca

A very encouraging result was reported by Lind et al.[6] from the interaction of 220-MeV π^- with ^{40}Ca. They reported very strong lines corresponding to ^{36}Ar, ^{32}S, ^{28}Si, ^{24}Mg and even ^{20}Ne corresponding to α-particle removal, a total of 380 mb as is shown in Table I. This would be truly a remarkable effect. Unfortunately, a recent repetition of this experiment[7] was in drastic disagreement with these cross sections, also listed in Table I. The results are complicated to interpret. The identification of residual nuclides depends on the measurement of characteristic gamma-ray lines, and with Ge-Li detectors of 2—3 keV resolution it is generally not too difficult to make a reasonably unique identification. But in the s-d shell the $2^+ \rightarrow 0^+$ transitions are generally ~2 MeV and fast compared to the stopping time of the recoil nuclei. Thus lines are badly Doppler smeared and the identification is less clear. But even stretching the limits of analysis there seems to be a factor-of-three discrepancy between the LAMPF and SREL experiments. Some results with stopped π^- on ^{40}Ca are reported at this conference.[8]

Since ^{40}Ca is not a very useful region for this type of measurement, the focus of the LAMPF experiment was transferred to some 2p-shell nuclei where the gamma-ray energies are lower and lifetimes longer. This is the same region where the stopped kaon work I just mentioned was done. A number of measurements were made on ^{58}Ni and ^{60}Ni with 220-MeV π^+, π^- and 200-MeV protons and with 100-MeV π^+ on ^{58}Ni. A number of gamma rays were identified and approximately 500 mb of the cross section could be assigned.

Remembering that at this stage we know very little of the fast pion's interaction with the nucleus, we don't even know what fraction of the reaction cross section corresponds to pion absorption, such data may provide a substantial window on these processes.

Since the data are still being analyzed all I have to say is tentative and represents my own perspective at this time. A number of odd as well as even nuclei have been identified as may be seen in Table II. These cross sections are reasonably good estimates for the even nuclei since gamma rays tend to cascade through the final $2^+ \rightarrow 0^+$ transitions. For the odd nuclei the estimates are less reliable, and may be regarded as lower limits. All the even nuclides with a neutron excess of 2 or 4 were seen for Fe, Cr, and Ti.

Various averages may be computed from these data that can, perhaps, give more reliable information. Such is the average number of nucleons removed $\Delta A \equiv \sum_f \sigma_f(A_t - A_f)/\sum_f \sigma_f$ where A_t and A_f are the atomic numbers of the target and the final nuclides and σ_f is the relevant cross section from Table II. These numbers are given in Table III. It is interesting to note that this quantity is remarkably constant with changing pion charge, energy and target at 5.3 ± .1. For protons, on the other hand, one gets 4.1 at 200 MeV, and using similar data from Maryland[9] for 100-MeV protons on ^{58}Ni the result is ~3.2. Thus clearly pions are much more effective than protons in removing nucleons; this points to the likelihood that the rest mass of the pion is absorbed, but in addition, the 100-MeV pions still remove substantially more nucleons than 200-MeV protons, even the pion total energy is used more effectively by the nucleus. This is illustrated in Fig. 3.

The other averages given in Table III reflect the neutron excess of residual nuclides in different ways. We see quite clearly that pions remove more nearly equal numbers of neutrons and protons than do protons. This is illustrated perhaps best in Fig. 4, where the pion vectors are longer, and more nearly parallel than the ones for protons.

Another feature that we see from Table III is the fact that even nuclides with the same neutron excess as the target, in other words those differing from the target by one or more α particles, appear with a substantially larger cross section than other even nuclides.

The question that is difficult to answer at this stage is whether these results are "interesting" or "unexpected" or whether they are the result of a rather dull, predictable statistical process revealing little that is new.

The only recourse we have is to compare to what calculations can be made. Nuclear chemists have long been active in this field and have developed rather elaborate methods using Monte Carlo techniques.[10] They treat the nucleus as a Fermi gas of nucleons from which the pion is allowed to scatter. Any momentum imparted to the nucleon is followed and the cascade is terminated when all the nucleons have either escaped or have energies insufficient to escape above the relevant barriers. At this stage a statistical evaporation of particles is allowed until no more energy is left and all nucleons are bound. The pion-nucleon scattering cross section is taken from free scattering. Absorption is treated through the formation of the (3, 3) resonance, or Δ, which is given a lifetime proportional to it's width and the pion is allowed to annihilate if the Δ encounters a nucleon before it decays. The cross section for this is again obtained from the inverse of the measured $N + N \rightarrow \Delta + N$ process. Calculations of this type had been reasonably successful in fitting radiochemical data. We have been fortunate in obtaining calculations relevant to the present case just a few days prior to this conference from Prof. Ze'ev Fraenkel. The results are not in very good agreement with the data, some of the worst discrepancies are given in Table IV. On the average these cascade calculations predict too few nucleons removed $\langle A \rangle \approx 3.9$ instead of 5.3 and the isotopes tend to be less neutron rich than in the data. On the "α-removal" chain the yield is also off for ^{60}Ni, a factor of ~3 too low, while reasonably correct for ^{58}Ni.

It is clear that the available methods do not do very well in describing the data. Interestingly the same calculation also fails quite badly in describing the energy spectrum of protons from 220-MeV π^+ on Ni, as is reported in a contribution to this conference by Amann, Barnes, and Eisenstein.[11]

It is tempting to speculate that both these failures might be related to the tendency of pions to absorb on clusters of nucleons larger than two, this would tend to lead to more nucleons being removed and the kinetic energy of individual nucleons from the primary process would tend to be lower.

Inelastic Pion Scattering and a Neutron "B(E2)"

There is one feature of pion interactions with nuclei that I find fascinating, it has little to do with clusters but I'd like to mention it nevertheless.[12]

There has been quite a bit of talk of the role of the (3, 3) resonance in quasielastic nucleon removal from nuclei, and recently careful work has been done comparing the $^{12}C(\pi^+,\pi^+n)^{11}C$ to the (π^-,π^-n) cross section.[13] Naively one expected a factor of three, instead the ratio changes from 1.0 to 1.7 as a function of energy. This reduction in the ratio has been explained by invoking charge exchange for the outgoing nucleon.[14]

The arguments for this charge-exchange process are, in fact, analagous to the ones in which neutrons can radiate in an electromagnetic transition by acquiring an "effective charge." The usual inelastic scattering is written in terms of a reduced matrix element that is determined from electromagnetic lifetimes, the B(Eλ) for electric transitions. For a nucleus such as ^{58}Ni, which may be thought of as a doubly-closed shell with two neutrons outside, the $2^+ \rightarrow 0^+$ transition is described by the quadrupole matrix elements connecting the two states, which are pure neutron configurations in the shell model, and then assigning an effective charge to allow for proton core excitations. We had no comparable technique for neutrons up till now, and pions can provide such a technique. If we define the proton matrix element as $\beta_p^2 \equiv B(E\lambda)$ there must be the analagous quantities β_n and $B(''E_n''\lambda)$. The cross sections for inelastic pion excitations may then be written as

$$\sigma^{\text{inel}}_{\pi^\pm} \sim |3\beta_{\substack{p\\n}} + \beta_{\substack{n\\p}}|^2.$$

Thus,

$$\beta_n = \frac{3 - \rho}{3\rho - 1}\ \beta_p, \quad \text{where} \quad \rho \equiv (\sigma^{\text{inel}}_{\pi^+} / \sigma^{\text{inel}}_{\pi^-})^{\frac{1}{2}}$$

or

$$B(''E_n''\lambda) = \left(\frac{3 - \rho}{3\rho - 1}\right)^2 B(E\lambda).$$

To the extent that the kinematics and distortions for π^+ and π^- are similar no details of reaction theory need to enter, and we may have a good handle on a hitherto unexplored nuclear quantity. Unfortunately the inelastic scattering in the data I showed for Ni is plagued by secondary processes (inelastic scattering from evaporation neutrons has a cross section of the order of a barn) in thick targets and it is not possible to use the data in this way. But clearly, it will not be difficult to carry out such measurements.

Summary

To conclude then the present status of pion and kaon interaction with nuclei is still at a rather early stage. Many careful experiments are needed before we can begin to understand even the dominant processes in these interactions, and it is unlikely that any single experiment will provide a clear and unequivocal answer. But the glimpses we are getting suggest interesting possibilities, including the possibility of clusters playing an important role.

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*Work performed under the auspices of the U. S. Atomic Energy Commission.

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TABLE I. Cross Sections for "α-Removal" Nuclides from ^{40}Ca with 220-MeV π^- (mb).

Residual Nuclide	SREL[†]	LAMPF[‡]
^{37}Ar[**]	22[**]	7[**]
^{36}Ar (1α)	138	42–62[*]
^{32}S (2α)	115	15–42[*]
^{28}Si (3α)	66	7–83[*]
^{24}Mg (4α)	36	<15[*]
^{20}Ne (5α)	27	
Total	382	64–202[*]

[†] Lind, Plendl, Funsten, Kossler, Lieb, Lankford, Buffer, Phys. Rev. Lett. 32, 479 (1974).

[‡] Lind et al., Bull. Am. Phys. Soc. 20, No. 4, 662 (1975).

[*] Upper limits estimated by assuming Doppler broadenings of ±~20 keV.

[**] Clean sharp line with no broadening.

TABLE II. Cross Sections from Ni Isotopes[a] (mb).

Target A, E_0 (MeV)	58,220	58,220	58,100	60,220	60,220	58,200	60,200
Projectile / Residual Nuclide	π^+	π^-	π^+	π^{+c}	π^{-e}	p	p
$^{60}Ni^b$				(85)	(99)		(58)
^{59}Ni				51	55		54
$^{58}Ni^b$	(64)	(94)	(57)	8	17	(46)	19
$^{57}Ni^d$	7	11	9			13	
^{59}Co				42	29		8
^{57}Co	61	59	36	55	50	38	38
^{56}Co	30	70	31	≤ 8	~4	34	~10
^{56}Fe	26 ± 8	29 ± 11	26	48	85	22 ± 5	35
$^{55}Fe^b$	87	91	90	79	76	71	48
^{54}Fe	47	43	34	18	14	44	18
$^{55}Mn^d$	≤ 9	≤ 20	14	≤ 12	8	≤ 10	9
^{52}Cr	20	37	20	37	45	17	15
^{50}Cr	40	46	45	28	18	26	11
$^{49}V^d$	28	22	20	24	23	9	6
^{48}Ti	12 ± 4	28	7	14	22	5 ± 2	4
$^{47}Ti^d$	21	32	17	≤ 7	5	10	
^{46}Ti	34	33	23	22	17	9	
$^{45}Ti^d$	7 ± 3	14 ± 6	≤ 4				
$^{42}Ca^d$	10	13	6			< 2	
Total	439	548	382	453	468	310	275

[a] All cross sections are believed to be accurate to ±20% unless otherwise noted.

[b] The secondary gamma rays produced by neutrons may be considerable for (n, n') and (n, α) reactions. A rough estimate indicates that 50—100% of the inelastic gamma rays and 10—20 mb of the ^{55}Fe yield could be of secondary origin.

[c] A gamma-ray line was identified, in this measurement only, which could be assigned to ^{57}Fe with 17 mb. The cautions of footnotes b and d apply.

[d] These assignments are based on the observation of a single gamma-ray line and should be regarded with more caution than the others.

[e] The π^- data on ^{60}Ni are of somewhat lower quality than the rest. The possible errors in assignments are somewhat greater, the errors in cross sections are comparable.

TABLE III. Some Averages Computed for Pions or Protons Incident on Isotopic Ni Targets.

Target A, E_0 (MeV)	58, 220	58, 220	58, 100	60, 220	60, 220	58, 200	60, 200
Projectile	π^+	π^-	π^+	π^+	π^-	P	P
⟨No. of nucleons removed⟩[a]	5.4	5.4	5.2	5.4	5.3	4.1	4.2
$\langle \Delta N\rangle / \langle \Delta Z\rangle$[b]	0.76	0.76	0.77	1.32	1.28	0.70	1.54
$\langle N - Z\rangle$[c]	2.7	2.7	2.7	3.3	3.3	2.7	3.1
$\Sigma\sigma_{(N-Z)=2}$(mb)[c]	131	135	108	67	49	81	30
$\Sigma\sigma_{(N-Z)=4}$(mb)[d]	58	94	53	99	152	44	54
R[e]	0.44	0.70	0.49	1.48	3.10	0.54	1.80

[a] The target atomic weight minus the cross section-weighted average atomic weight of residual nuclides, not counting inelastic scattering.

[b] The ratio of the average number of neutrons removed to protons, computed as in a.

[c] The cross-section-weighted average neutron excess of residual nuclides.

[d] Summed cross sections for even nuclides only, not including Ni, the numbers corresponding to the α removal chains are underlined.

[e] Ratio of the summed cross sections in the previous two lines: $\Sigma\sigma_{(N-Z)=4}/\Sigma\sigma_{(N-Z)=2}$.

TABLE IV. Some Major Discrepancies with Cascade Calculations[a]
(220-MeV pions, π^+ - π^- average)

Target	Residual nuclide	σ(mb)	
		Observed	Calculated
^{58}Ni	^{57}Ni	~10	~80
	^{56}Fe	~25	~10
	^{52}Cr	~30	~ 8
	^{46,47,48}Ti	20, 25, 35	5, 15, 15
^{60}Ni	^{58}Ni	8	63
	^{56}Co	≤8	60
	^{56}Fe	53	17
	^{55}Fe	76	31
	^{52}Cr	37	10
	^{48}Ti	14	5

[a] Ze'ev Fraenkel, private communication.

Figure Captions

Fig. 1. 12788 The fraction of the time deuterons and tritons are seen per stopped π^- on a variety of targets is plotted as a function of target atomic weight. A small correction (~20%) was made for the low-energy cutoff on the detector.

Fig. 2. 12830 Nuclear gamma rays identified from stopped pions on natural Ni and Ca targets. The numbers on the lower left refer to the intensity of gamma rays (per 6 → 5 kaonic x-ray in %) for the Ni target, the ones on the lower right to the Ca target. The probability of seeing this x-ray line per stopped kaon is ~0. 3, thus the total of the gamma-ray lines, per stopped kaon, is ~0. 7.

Fig. 3. 12828 Average number of nucleons removed and average neutron excess of residual nuclides, as defined in the text, displayed as vectors for 220-MeV pions and 200-MeV protons on ^{58}Ni and ^{60}Ni. No appreciable charge dependence was seen for pions.

Fig. 4. 12829 Average number of nucleons removed (as defined in the text) as a function of energy. The energy includes the rest mass of the pions.

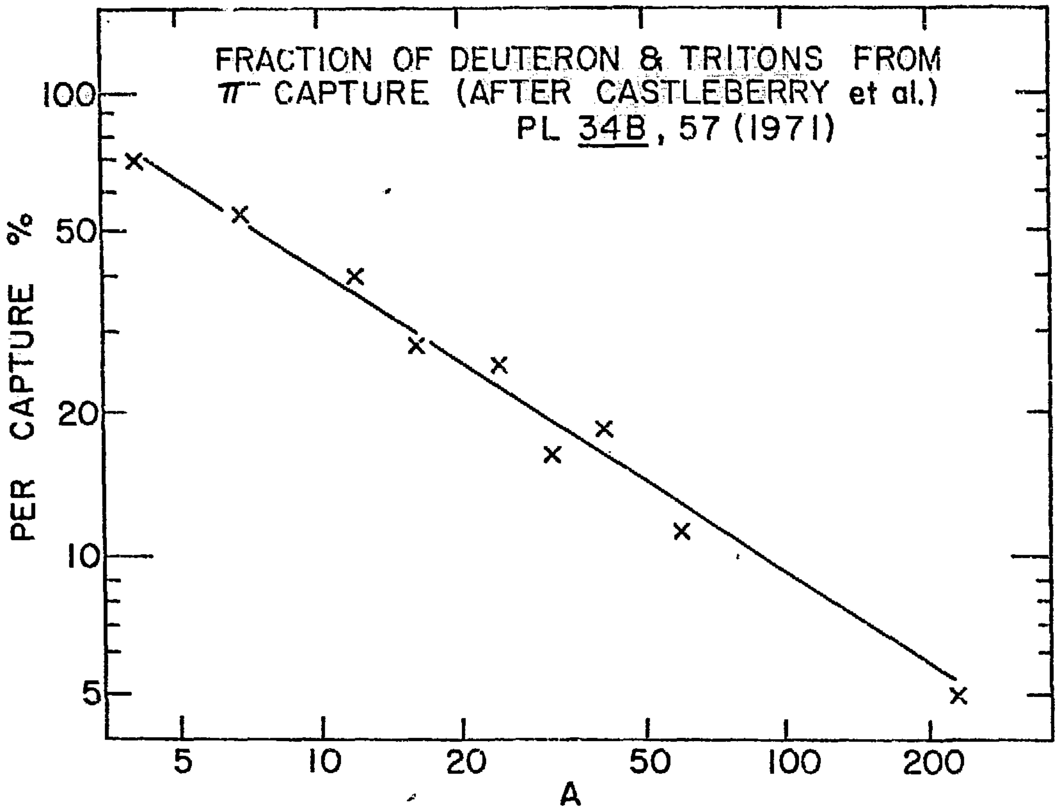
FRACTION OF DEUTERON & TRITONS FROM
π^- CAPTURE (AFTER CASTLEBERRY et al.)
PL 34B, 57 (1971)
PER CAPTURE %
100
50
20
10
5
5
10
20
50
100
200
A

Figure 1

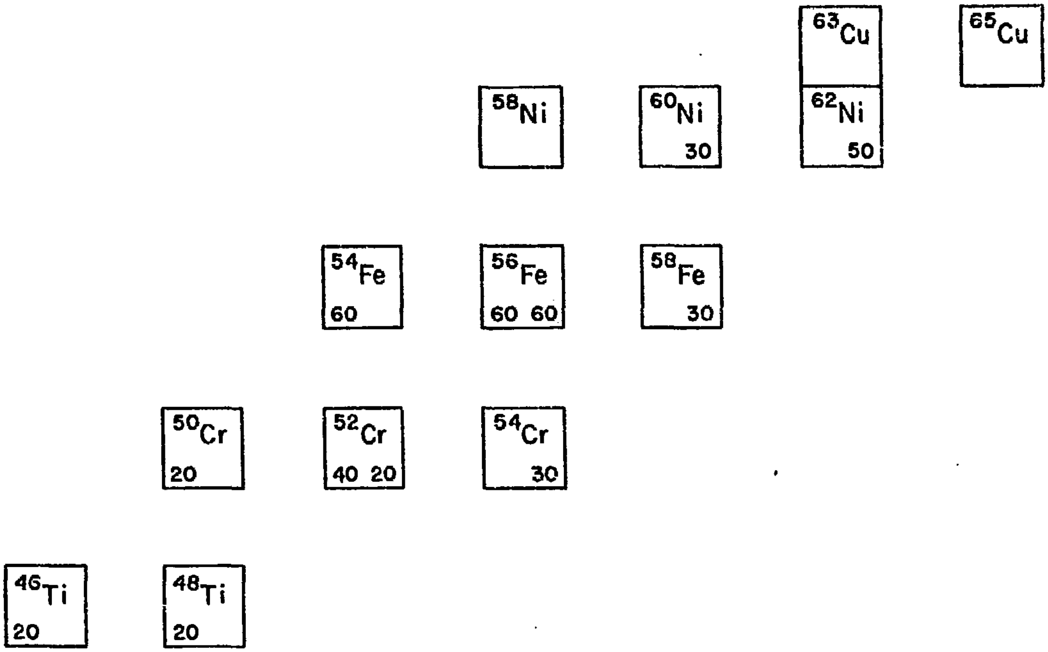
63Cu
65Cu
58Ni
60Ni 30
62Ni 50
54Fe 60
56Fe 60 60
58Fe 30
50Cr 20
52Cr 40 20
54Cr 30
46Ti 20
48Ti 20

Figure 2

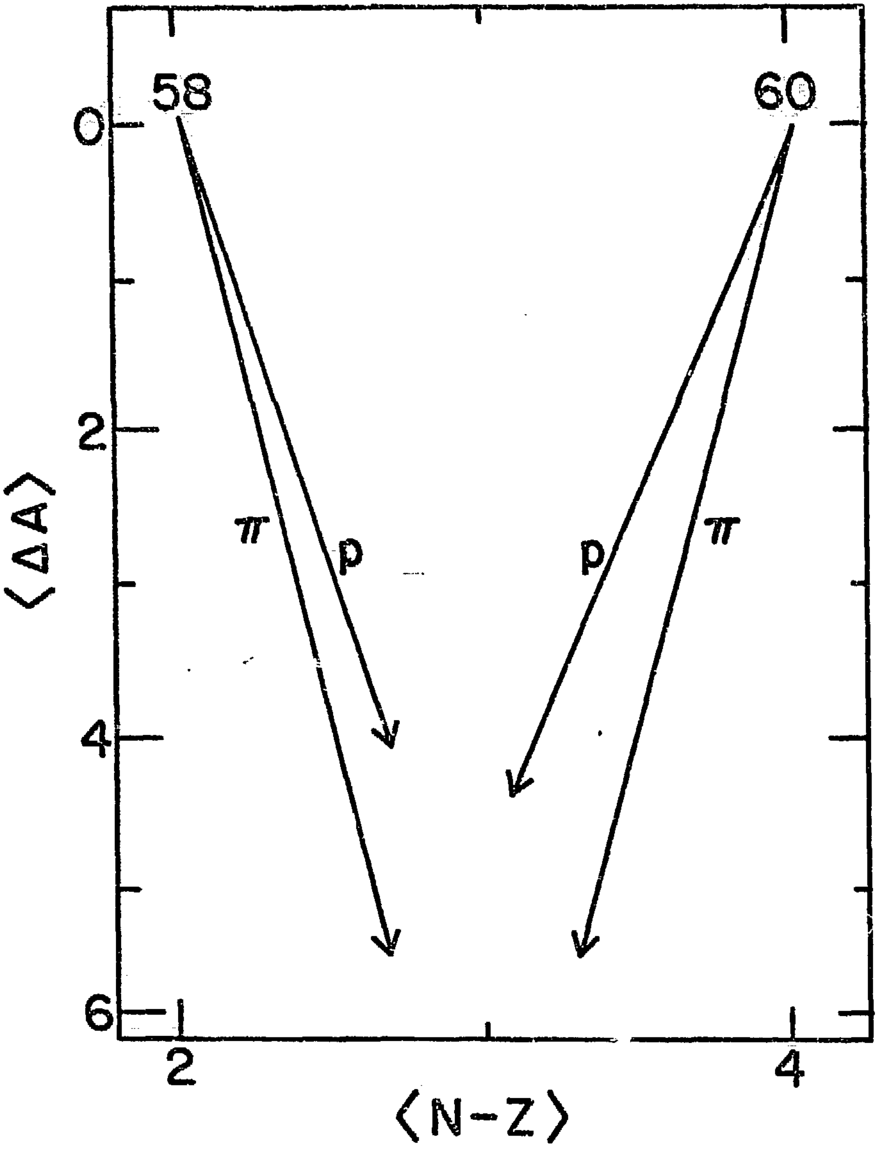

Figure 3

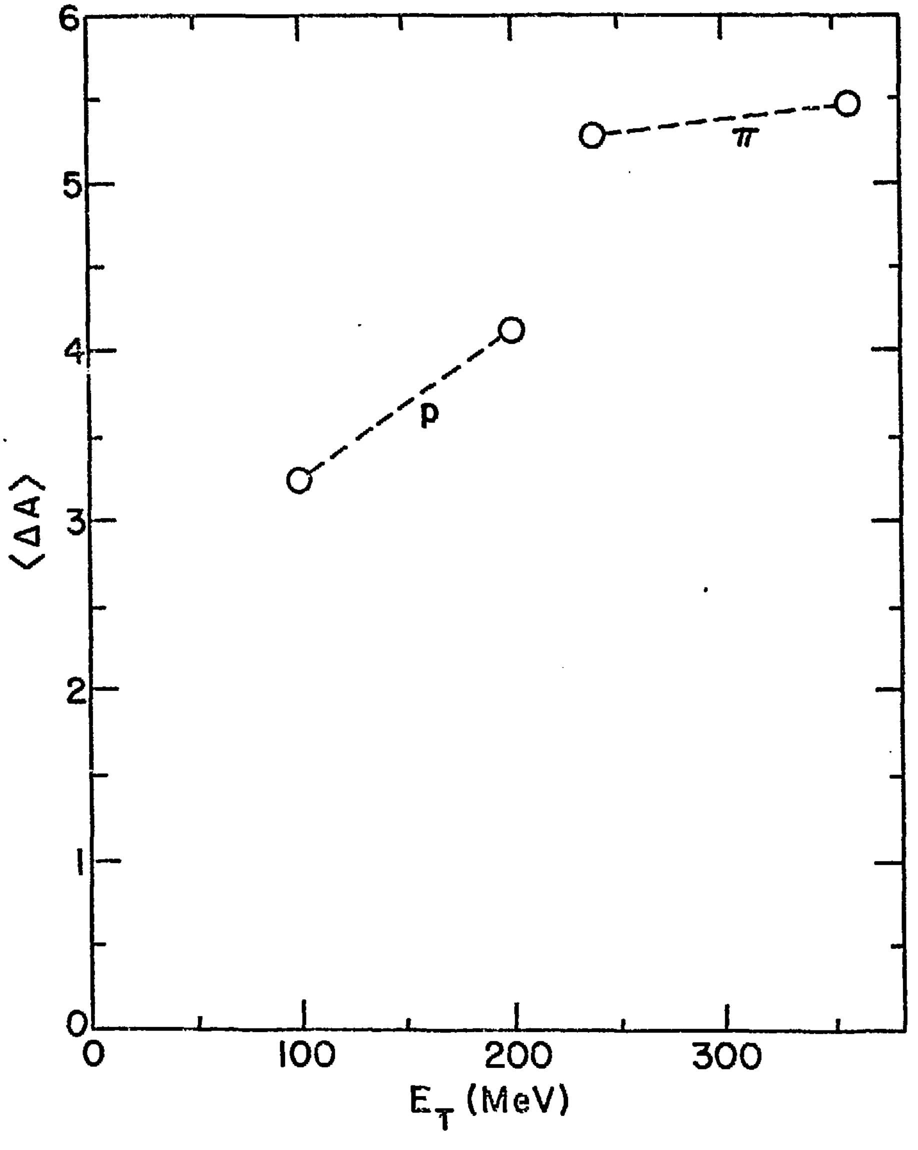

Figure 4