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Role of isospin in neutron- and alpha-induced reactions

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The effects of including isospin in proton-induced reactions have been previously discussed. The effects are most important for heavy nuclei, where a substantial enhancement in proton decay of the compound nucleus is predicted. A comparable study for neutrons and alpha particles shows effects which are largest for light nuclei. The most important consequences are an enhancement in alpha decay and a slight reduction in proton and neutron decay, with some effects persisting for higher stages of multistep reactions.

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The consequences of the inclusion of isospin in Hauser-Feshbach calculations have previously been examined [1–3]. Proton-induced reactions on nuclei with $N>Z$ are found to occur through compound nuclear states with two values of isospin. The higher of these two, $T=T_0+\frac{1}{2}$, where T_0 is the target isospin, has very few neutron channels available for decay, making proton decay the dominant decay mode. States of the lower isospin, $T=T_0-\frac{1}{2}$, are populated with higher probability and have decay widths more consistent with the no-isospin limit. The result of including isospin in a compound nucleus formed by protons is to produce a fraction $1/(2T_0+1)$ of the compound nuclei which are forced to proton decay, enhancing the proton yield.

No similar summary of the effects of isospin on neutron- or alpha-induced reactions has appeared, although inspection of the predictions of Refs. [1] and [2] indicates small effects for $A>50$. A more careful study of the consequences of isospin inclusion for alpha- and neutron-induced reactions indicates that the effects for nuclei with small isospin ($T\leq\frac{1}{2}$) can be substantial.

Table I lists the coefficients for isospin coupling in reactions induced by alpha particles. As can be seen, only one value of isospin characterizes the compound nuclei, but the decay probabilities can be affected substantially. In particular, alpha bombardment of $T=0$ targets result in a reduction of 50% in the proton and neutron decay width. For any target for which the proton and neutron widths were a significant fraction of the decay width, this will enhance the alpha decay by a large factor which can approach 2. For a $T=0$ target, it is also likely gamma-ray decay will also be inhibited, given the fact that $T=0$ to $T=0$ decays are substantially slower than decays between $T=1$ and $T=0$.

In Table II we tabulate the couplings for multistep reactions on ^{24}Mg and ^{25}Mg. For $T=0$ (^{24}Mg), not only are the proton and neutron widths reduced for the compound nucleus, but alpha decay leads to another $T=0$ nucleus, which also will have reduced proton and neutron decay. Also, multiple neutron and proton decays tend to funnel the nucleus back to the $T=0$ region, since nuclei with $N>Z$ have reduced proton decay probability and those with $Z>N$ a reduced neutron decay probability. Thus, multistep reactions would continue the preference for alpha decay. A similar trend is seen for a ^{25}Mg target; the isospin coupling reduces the proton decay width if $N>Z$ and the neutron width if $Z>N$. For a target

TABLE I. Isospin coupling for alpha-induced reactions.

Target	Compound nucleus	Decay channel	Coupling
$T=0$	$T=0$	n	$\frac{1}{2}$
		p	$\frac{1}{2}$
		α	1
$T=\frac{1}{2}$ ($T_Z=\frac{1}{2}$)	$T=\frac{1}{2}$	n ($T=0$)	1
		p	$\frac{2}{3}$
		α	1
		n ($T=1$)	$\frac{1}{3}$
$T=\frac{1}{2}$ ($T_Z=-\frac{1}{2}$)	$T=\frac{1}{2}$	n	$\frac{2}{3}$
		p ($T=0$)	1
		α	1
		p ($T=1$)	$\frac{1}{3}$
$T=1$ ($T_Z=1$)	$T=1$	n ($T=\frac{1}{2}$)	1
		p	$\frac{3}{4}$
		α	1
		n ($T=\frac{3}{2}$)	$\frac{1}{4}$
$T=1$ ($T_Z=-1$)	$T=1$	n	$\frac{3}{4}$
		p ($T=\frac{1}{2}$)	1
		α	1
		p ($T=\frac{3}{2}$)	$\frac{1}{4}$

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with $Z > N$, the couplings to neutrons and protons would be interchanged. For alpha bombardment of ^{19}Ne or ^{23}Mg, neutron decay would be inhibited by a factor of $\frac{2}{3}$ at the first stage. Again, the coupling coefficients tend to focus multistep reactions to $T=0$ nuclei through the inhibition factors for proton and neutron decay.

Table III shows the corresponding couplings for neutrons. If $T_Z \geq 0$, neutron-induced reactions populate only one isospin in the first stage of the reaction. As was seen for alphas, the couplings reduce proton emission if $T_Z > 0$ and neutron emission if $T_Z < 0$, while both are reduced substantially if $T=0$. Note that this tendency will focus emissions in multistep reactions so as to enhance alpha emission by preferentially populating $T=0$ states.

For targets with $Z=N+1$, two isospins are possible for the compound nucleus. This category would include nuclei such as ^{7}Be, ^{19}Ne, and ^{23}Mg which are of astrophysical interest. The $T=0$ states will have reduced proton and neutron decay widths, which enhances alpha decay. The $T=1$ states have no alpha decay width to $T=0$ states and reduced proton and neutron widths to $T=\frac{1}{2}$ states. Allowed decays may also occur to $T=1$ states for alpha decay and $T=\frac{3}{2}$ states for proton and neutron decay.

In general, these analog-to-analog decays should be small. If we use the mass formula of Kümmel *et al.* [4], the coefficient of the $(N-Z)^2/A$ term is 25. Thus, separation between the first $T=0$ and $T=1$ states should be 10, 5, and 2.5 MeV for $A=10$, 20, and 40, respectively. Similarly, separation between the lowest $T=\frac{1}{2}$ and $T=\frac{3}{2}$ states should be 20, 10, and 5 MeV for $A=10$, 20, and 40, respectively. Thus, level density arguments would

TABLE II. Effects of isospin in multistep reactions induced by alpha particles.

Target	Decay nucleus	Decay channel	Coupling
^{24}Mg ($T=0$)	^{28}Si	n	$\frac{1}{2}$
		p	$\frac{1}{2}$
		α	1
	^{27}Si	n	$\frac{2}{3}$
		p ($T=0$)	1
		α	1
		p ($T=1$)	$\frac{1}{3}$
	^{27}Al	n ($T=0$)	1
		p	$\frac{2}{3}$
		α	1
		n ($T=1$)	$\frac{1}{3}$
	^{24}Mg	n	$\frac{1}{2}$
		p	$\frac{1}{2}$
		α	1
	^{26}Si	n	$\frac{3}{4}$
		p ($T=\frac{1}{2}$)	1
		α	1
		p ($T=\frac{3}{2}$)	$\frac{1}{4}$
	^{26}Al	n	$\frac{1}{2}$
		p	$\frac{1}{2}$
		α	1
	^{26}Mg	n ($T=\frac{1}{2}$)	1
		p	$\frac{3}{4}$
		α	1
		n ($T=\frac{3}{2}$)	$\frac{1}{4}$
	^{20}Ne	n	$\frac{1}{2}$
		p	$\frac{1}{2}$
		α	1
^{25}Mg	^{29}Si	n ($T=0$)	1
		p	$\frac{2}{3}$
		α	1
		n ($T=1$)	$\frac{1}{3}$
	^{28}Si	n	$\frac{1}{2}$
		p	$\frac{1}{2}$
		α	1
	^{28}Al	n ($T=\frac{1}{2}$)	1
		p	$\frac{3}{4}$
		α	1
		n ($T=\frac{3}{2}$)	$\frac{1}{4}$
	^{25}Mg	n ($T=0$)	1
		p	$\frac{2}{3}$
		α	1
		n ($T=1$)	$\frac{1}{3}$
	^{27}Si	n	$\frac{2}{3}$
		p ($T=0$)	1
		α	1
		p ($T=1$)	$\frac{1}{3}$
	^{27}Al	n ($T=0$)	1
		p	$\frac{2}{3}$
		α	1
		n ($T=1$)	$\frac{1}{3}$
	^{27}Mg	n ($T=1$)	1
		p	$\frac{4}{5}$
		α	1
		n ($T=2$)	$\frac{1}{5}$
	^{21}Ne	n ($T=0$)	1
		p	$\frac{2}{3}$
		α	1
		n ($T=1$)	$\frac{1}{3}$

TABLE III. Isospin coupling for neutron-induced reactions.

Target	Compound nucleus	Decay channel	Coupling
$T=0$	$T=\frac{1}{2}$	$n\ (T=0)$	1
		p	$\frac{2}{3}$
		α	1
		$n\ (T=1)$	$\frac{1}{3}$
$T=\frac{1}{2}\ (T_z=\frac{1}{2})$	$T=1$	$n\ (T=\frac{1}{2})$	1
		p	$\frac{3}{4}$
		α	1
		$n\ (T=\frac{3}{2})$	$\frac{1}{4}$
$T=\frac{1}{2}\ (T_z=-\frac{1}{2})$	$T=0$ (probability $\frac{1}{2}$)	n	$\frac{1}{2}$
		p	$\frac{1}{2}$
		α	1
	$T=1$ (probability $\frac{1}{2}$)	$n\ (T=\frac{1}{2})$	$\frac{1}{2}$
		$p\ (T=\frac{1}{2})$	$\frac{1}{2}$
		$n\ (T=\frac{3}{2})$	$\frac{1}{2}$
		$p\ (T=\frac{3}{2})$	$\frac{1}{2}$
		$\alpha\ (T=1)$	1

make decay to analog states small. Use of typical level density parameters ($a=A/8$) with these shifts predicts level densities which are smaller by a factor of 3–6 for the analog states.

For particular nuclei, these general systematics may be violated. In the case of ^{26}Al, for example, the lowest $T=0$ and $T=1$ states are very close in energy. This occurs because the $T=1$ states correspond to levels in the nuclei ^{26}Mg and ^{26}Si, which are even-even nuclei. This means the lowest state is depressed by the pairing gap, while for $T=0$ states an unpaired proton and neutron are both present. As the energy is increased, the ratio between $T=0$ and $T=1$ levels increases and presumably approaches the systematics characterized by the semiempirical mass formula. Thus, although at or slightly above threshold the density of $T=1$ states is approximately equal to the density of $T=0$ states, at most energies the density of $T=0$ states is much higher. For some other $T=0$ nuclei, the ratio changes in the opposite direction. If N and Z are even, the pairing gap favors the $T=0$ level density at low energies. For nuclei such as ^{24}Mg, the $T=0$ to $T=1$ ratio would be unusually high at low energies, but again would approach the liquid drop value as E increases.

Table IV presents the results of applying the isospin

TABLE IV. Effects of isospin in multistep reactions induced by neutrons.

Target	Decay nucleus	Decay channel	Coupling
^{24}Mg ($T=0$)	^{25}Mg	$n\ (T=0)$	1
		p	$\frac{2}{3}$
		α	1
		$n\ (T=1)$	$\frac{1}{3}$
	^{24}Mg	n	$\frac{1}{2}$
		p	$\frac{1}{2}$
		α	1
	^{24}Na	$n\ (T=\frac{1}{2})$	1
		p	$\frac{3}{4}$
		α	1
		$n\ (T=\frac{3}{2})$	$\frac{1}{4}$
	^{21}Ne	$n\ (T=0)$	1
		p	$\frac{2}{3}$
		α	1
		$n\ (T=1)$	$\frac{1}{3}$
	^{23}Mg	n	$\frac{2}{3}$
		$p\ (T=0)$	1
		α	1
		$n\ (T=1)$	$\frac{1}{3}$
	^{23}Na	$n\ (T=0)$	1
		p	$\frac{2}{3}$
		α	1
		$n\ (T=1)$	$\frac{1}{3}$
	^{23}Ne	$n\ (T=1)$	1
		p	$\frac{4}{5}$
		α	1
		$n\ (T=2)$	$\frac{1}{5}$
	^{17}O	$n\ (T=0)$	1
		p	$\frac{2}{3}$
		α	1
		$n\ (T=1)$	$\frac{1}{3}$
^{25}Mg ($T=\frac{1}{2}$; $T_z=\frac{1}{2}$)	^{26}Mg	$n\ (T=\frac{1}{2})$	1
		p	$\frac{3}{4}$
		α	1
		$n\ (T=\frac{3}{2})$	$\frac{1}{4}$
	^{25}Mg	$n\ (T=1)$	1
		p	$\frac{2}{3}$
		α	1
		$n\ (T=1)$	$\frac{1}{3}$
	^{25}Na	$n\ (T=1)$	1
		p	$\frac{4}{5}$
		α	1
		$n\ (T=2)$	$\frac{1}{5}$
	^{22}Ne	$n\ (T=\frac{1}{2})$	1
		p	$\frac{3}{4}$
		α	1

TABLE IV. (*Continued*).

Target	Decay nucleus	Decay channel	Coupling
		$n\ (T=\frac{3}{2})$	$\frac{1}{4}$
	^{24}Mg	n	$\frac{1}{2}$
		p	$\frac{1}{2}$
		α	1
	^{24}Na	$n\ (T=1)$	1
		p	$\frac{4}{5}$
		α	1
		$n\ (T=2)$	$\frac{1}{5}$
	^{24}Ne	$n\ (T=2)$	1
		p	$\frac{6}{7}$
		α	1
		$n\ (T=3)$	$\frac{1}{7}$
	^{18}O	$n\ (T=\frac{1}{2})$	1
		p	$\frac{3}{4}$
		α	1
		$n\ (T=\frac{3}{2})$	$\frac{1}{4}$
^{23}Mg $(T=\frac{1}{2};\ T_z=-\frac{1}{2})$	^{24}Mg $(T=0)$	n	$\frac{1}{2}$
	(formed with 50%	p	$\frac{1}{2}$
	probability)	α	1
	^{24}Mg $(T=1)$	$n\ (T=\frac{1}{2})$	$\frac{1}{2}$
	(formed with 50%	$p\ (T=\frac{1}{2})$	$\frac{1}{2}$
	probability)	$\alpha\ (T=1)$	1
		$n\ (T=\frac{3}{2})$	$\frac{1}{2}$
		$p\ (T=\frac{3}{2})$	$\frac{1}{2}$
	^{23}Mg	n	$\frac{2}{3}$
		$p\ (T=0)$	1
		α	1
		$P\ (T=1)$	$\frac{1}{3}$
	^{23}Na	$n\ (T=0)$	1
		p	$\frac{2}{3}$
		α	1
		$n\ (T=1)$	$\frac{1}{3}$
	^{20}Ne	n	$\frac{1}{2}$
		p	$\frac{1}{2}$
		α	1
	^{22}Mg	n	$\frac{3}{4}$
		$p\ (T=\frac{1}{2})$	1
		α	1
		$p\ (T=\frac{3}{2})$	$\frac{1}{4}$
	^{22}Na	n	$\frac{1}{2}$
		p	$\frac{1}{2}$
		α	1
	^{22}Ne	$n\ (T=\frac{1}{2})$	1
		p	$\frac{3}{4}$
		α	1
		$n\ (T=\frac{3}{2})$	$\frac{1}{4}$
	^{16}O	n	$\frac{1}{2}$
		p	$\frac{1}{2}$
		α	1

coupling factors and assuming that decays populate nonanalog $(T=T_Z)$ states. Note that as was found for alpha particles, a tendency to reduce proton or neutron widths is seen, which would enhance alpha decay. This effect is especially surprising for multistep reactions, where the effects of isospin strongly affect $T=0$ states reached by multiple nucleon emission, even though previous analyses found that for protons on targets with $A>50$ isospin effects were profound only in the first stage of the reaction. For a $T=\frac{1}{2}$ target, the $(n,2n)$ reaction populates a $T=0$ nucleus, indicating that substantial enhancement of the $(n,2n\alpha)$ and $(n,2n2\alpha)$ reactions should occur, at the expense of $(n,3n)$ and $(n,2np)$, for example.

These same couplings can be applied to the deuteron, tritium, and helium-3 decay channels, which, from the standpoint of isospin, are analogous to alphas, neutrons, and protons, respectively. As an example, deuteron bombardment of a $T=0$ nucleus would result in an enhanced alpha yield compared to a calculation without isospin. Even in heavy ion physics, a study of $^{32}S+^{32}S$, for example, should find much larger cross sections for multiple alpha decay than would be predicted without isospin.

The present discussion has assumed that the transmission coefficients themselves are independent of isospin. This is approximately true in most cases but could be wrong for some light nuclei. If, for example, a system which does not have compound states of a particular isospin below a certain energy is studied, absorption would be zero until the threshold is reached. Except for very light nuclei, particle-binding energies are large enough relative to isospin splittings that this situation will be unusual. The usual $(N-Z)/A$ terms in proton and neutron optical potentials produce effects on the transmission coefficients of less than 15%, making transmission coefficient effects small compared to the factor of 2 effects for $T=0$ nuclei but not necessarily smaller than the coupling factor effects as T increases beyond 1.

Finally, isospin mixing has not been included. Cases such as the pair of states in ^{8}Be at 15 MeV are known where mixing is substantial, but, in general, isospin is not found to be completely mixed. Arguments based on relative level density [5] indicate that mixing up $(T=T_Z \rightarrow T=T_Z+1)$ is less likely than mixing down $(T=T_Z+1 \rightarrow T=T_Z)$. This would make the present predictions less sensitive to small values of the mixing than are the results for $A > 50$, where the effects require decay of the analog state before mixing. Most of the present results involve decay of nonanalog states, for which mixing is reduced by the ratio of the level densities $[\rho(E,T=T_Z)/\rho(E,T=T_Z+1)]$. The fact that some of the present results are found in multistep reactions, of course, does increase the sensitivity to mixing and may provide a further technique for studying isospin purity of excited nuclear states.

Finally, the present results suggest that the effects of isospin on proton-induced reactions are different for $A \leq 40$ than has been found for $A > 50$. The results for proton bombardment of $T=0$ targets are the same as for neutron bombardment of these targets, while proton bombardment for $T=\frac{1}{2}$ targets can be deduced from the results in Table III by taking the neutron results for the target with the opposite sign for T_Z and interchanging protons and neutrons in the exit channel. As is found for alpha particles and neutrons, alpha emission is enhanced, particularly if energies high enough to allow multiple particle emission are considered.

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[1] S. M. Grimes, J. D. Anderson, A. K. Kerman, and C. Wong, Phys. Rev. C **5**, 85 (1972).
[2] D. Robson, A. Richter and H. L. Harney, Phys. Rev. C **8**, 153 (1973).
[3] A. M. Lane, Phys. Rev. C **18**, 1525 (1978).
[4] H. Kümmel, J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. **81**, 129 (1966).
[5] N. T. Porile and S. M. Grimes, Phys. Rev. C **11**, 1567 (1975).