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Rapid Communications

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Comparison of (^{3}He, π^-) and (^{3}He, π^+) exclusive reactions on ^{7}Li and ^{12}C

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Differential cross sections of (^{3}He, $\pi^{\pm}$) exclusive reactions have been measured for ^{7}Li and ^{12}C targets at 235 MeV and 20° laboratory scattering angle. Several levels of the final nuclei have been observed for π^+ as well as π^- production. Simple assumptions for the reaction mechanism are considered for explaining the ratio of π^- to π^+ production.

For a long time, pion production reactions have been expected to provide interesting information on nuclear wave functions at very high momentum transfer. Unfortunately, most of the theoretical models have partially failed to explain the large amount of (p, π^+) and (p, π^-) experimental data on cross sections, excitation functions, and asymmetries.[1] This is due in part to the complexity of the reaction mechanism and the sensitivity of the calculations to the theoretical hypotheses, approximations, and nuclear structure ingredients. In order to clarify experimentally the mechanism involved, new experiments have been performed at Saclay and Orsay[2] with complex light projectiles, mainly deuteron, and ^{3}He beams. Some general experimental trends have already been identified,[3] including the dependence of the cross sections on incident energy, projectile mass, and target number A.

The steep falloff of the cross sections from $A=4$ to $A=6$ (from tens of nanobarns to tens of picobarns) does not allow us to make systematic studies of (^{3}He, π) reactions on numerous heavy targets, since the low counting rate leads to very long run times (typically 40 h). But it is important to know if this behavior is a general feature of the reaction mechanism or if it reflects a structure effect such as that observed, for example, in recent (p, π^-) studies at Indiana,[4] where unexpectedly large cross sections were measured for narrow excited states, compared to the low yield ground-states cross sections.

In order to complement the existing data on $A>6$ nuclei we have performed new measurements of the ^{7}Li(^{3}He, π^+)^{10}Be and ^{12}C(^{3}He, π^+)^{15}N reactions. Theoretical arguments based on the model proposed by Germond and Wilkin[5] also lead us to explore the ^{7}Li(^{3}He, π^-)^{10}C and ^{12}C(^{3}He, π^-)^{15}F reactions. Comparison of π^+ to π^- production on the same target should provide a valuable test on the reaction mechanism as outlined later in this Rapid Communication.

The experiment was performed at the Orsay Laboratory with the synchrocyclotron 235 MeV ^{3}He beam. The standard experimental arrangement has been described in previous papers.[2] Background rejection by two time-of-flight measurements and by trajectory reconstruction behind the spectrometer was efficient enough to allow measurements of 20 pb/sr (c.m.) π^- cross sections. Considering the large ^{3}He intensities available (up to 600 nA) target thicknesses of 50 mg/cm^2 were chosen to give reasonable counting rates and energy resolution. The latter is dominated by energy losses of ^{3}He and $\pi^{\pm}$ in the target. The solid angle of the spectrometer was 6.0 ± 0.2 msr.

The (^{3}He, π^+) and (^{3}He, π^-) spectra, at $\theta_{\text{lab}} = 20°$ are presented in Fig. 1 for $T_{^3\text{He}} = 235$ MeV on ^{7}Li. The values of the corresponding cross sections are quoted in Table I. The ground state of the final nuclei was found to be so weakly excited that only upper limits of the corresponding cross sections could be extracted. The ^{7}Li(^{3}He, π^+)^{10}Be differential cross sections are of the same order of magnitude as the ones for (^{3}He, π^+) reactions[2] induced on ^{6}Li and ^{10}B (100 of pb/sr). This confirms our earlier finding that π^+ production from p-shell nuclei is almost three orders of magnitude smaller than from s-shell nuclei. Moreover, excitation of the final nucleus ground state is even more suppressed.

Concerning the (^{3}He, π^-) reaction on ^{7}Li, the cross sections are seen to be smaller, by about an order of magnitude, than for (^{3}He, π^+) on the same target. The ratio of π^- to π^+ production can only be calculated for the first 2^+ excited state of the two mirror final nuclei. The obtained

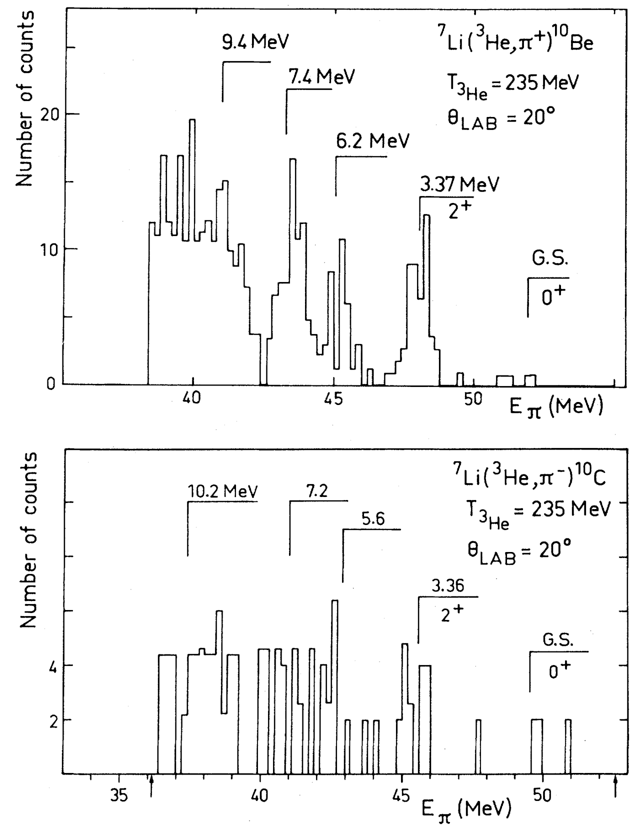

FIG. 1. Experimental spectra obtained at $\theta_{\mathrm{lab}}=20°$ and $T_{^3\mathrm{He}}=235$ MeV for $^7\mathrm{Li}(^3\mathrm{He},\pi^+)^{10}\mathrm{Be}$ and $^7\mathrm{Li}(^3\mathrm{He},\pi^-)^{10}\mathrm{C}$ reactions. An overall run time of about 30–40 hours was necessary to obtain these spectra. The normalization is the same for the two spectra.

ratio at 24° c.m. is

$$\sigma(^3\mathrm{He},\pi^-)/\sigma(^3\mathrm{He},\pi^+)=0.09\pm0.04 \ .$$

It is rougly twice the value of

$$\sigma(\mathrm{p},\pi^-)/\sigma(\mathrm{p},\pi^+)=0.055\pm0.015 \ ,$$

deduced from recent measurements[6,7] of $^7\mathrm{Li}(\mathrm{p},\pi^-)^8\mathrm{B}$ and $^7\mathrm{Li}(\mathrm{p},\pi^+)^8\mathrm{Li}$, for $\theta_{\mathrm{c.m.}}<60°$.

The comparison of the cross sections found for $(^3\mathrm{He},\pi^-)$ and $(^3\mathrm{He},\pi^+)$ reactions must imply strong constraints on the mechanism of these two types of reactions. Crude estimations of different possibilities are presented below.

In the first possibility, the π^- is produced by a two-step process where the incident ^{3}He undergoes first a proton charge exchange reaction on ^{7}Li followed by the $^7\mathrm{Be}(^3\mathrm{H},\pi^-)^{10}\mathrm{C}$ reaction. Assuming charge symmetry, this last reaction is identical to $^7\mathrm{Li}(^3\mathrm{He},\pi^+)^{10}\mathrm{Be}$ so that the π^- to π^+ ratio depends only on the initial scattering wave functions independent of the production mechanism. These wave functions have been estimated within the eikonal approximation using empirical optical potentials deduced from elastic and charge exchange of ^{3}He on light nuclei.[8] This leads at most to a ratio

$$\sigma(^3\mathrm{He},\pi^-)/\sigma(^3\mathrm{He},\pi^+)\sim0.005 \ ,$$

which is much smaller than the experimental ratio. Consequently the description of the $(^3\mathrm{He},\pi^-)$ reaction as a two-step process $(^3\mathrm{He},^3\mathrm{H})+(^3\mathrm{H},\pi^-)$ does not seem as plausible as was previously observed for (p,π^-) reactions.

The same kind of estimate for the two-step mechanism involving pion charge exchange in the final state $(^3\mathrm{He},\pi^0)+(\pi^0,\pi^-)$ yields also a small π^- to π^+ ratio of 10^{-4}. This comes from the fact that the isovector part of the π nucleon scattering amplitude is minimal close to our energy (37 MeV pion laboratory kinetic energy) so that any pion charge exchange graph is strongly suppressed.

Another possibility for explaining both the $(^3\mathrm{He},\pi^-)$ and $(^3\mathrm{He},\pi^+)$ reactions is presented in the graphs of Fig. 2. In this description we neglect all contributions coming from pion charge exchange and $\Delta T\neq0$ nuclear transitions at the emission vertex since they would involve tens of MeV excitation energy. It then follows that π^- production is due to target emission whereas π^+ production is due to projectile emission. A crude estimate of the ratio of the cross sections can be made within the impulse approximation, assuming the same coupling constants for $\pi-{}^3\mathrm{He}-{}^3\mathrm{H}$ and $\pi-{}^7\mathrm{Li}-{}^7\mathrm{Be}$ as well as the same nuclear structure. This gives

$$\frac{\sigma(^3\mathrm{He},\pi^-)}{\sigma(^3\mathrm{He},\pi^+)}=\left|\frac{2f_{\pi^-\mathrm{p}}(\pi-\theta)+f_{\pi^-n}(\pi-\theta)}{4f_{\pi^+n}(\theta)+3f_{\pi^+\mathrm{p}}(\theta)}\right|^2 \ ,$$

where $f_{\pi\mathrm{N}}(\theta)$ denotes the pion nucleon amplitude in defin-

TABLE I. Summary of the c.m. values of differential cross sections (pb/sr) extracted from the measurements at $T_{^3\mathrm{He}}=235$ MeV and $\theta_{\mathrm{lab}}=20°$. There is an overall normalization uncertainty of ±30% in addition to the statistical and background effect quoted in the table.

$^7\mathrm{Li}(^3\mathrm{He},\pi^+)^{10}\mathrm{Be}$		$^7\mathrm{Li}(^3\mathrm{He},\pi^-)^{10}\mathrm{C}$		$^{12}\mathrm{C}(^3\mathrm{He},\pi^+)^{15}\mathrm{N}$		$^{12}\mathrm{C}(^3\mathrm{He},\pi^-)^{15}\mathrm{F}$	
g.s.$_{(0^+)}$	≤ 62	g.s.$_{(0^+)}$	≤ 28	g.s.$_{(\frac{1}{2}^-)}$	102^{+50}_{-36}	g.s.$_{(\frac{1}{2}^-)}$	≤ 41
3.37 MeV (2^+)	497 ± 68	3.36 MeV (2^+)	43^{+18}_{-14}	6.32 MeV ($\frac{3}{2}^-$)	115^{+55}_{-36}		
6.2 MeV	363 ± 61						
7.4 MeV	785 ± 93						

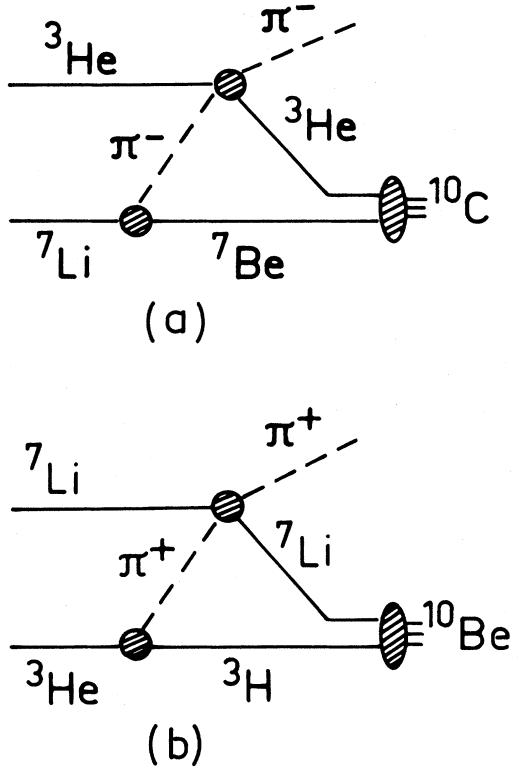

FIG. 2. Proposed mechanism for explaining the (a) (^{3}He, π^-) and (b) (^{3}He, π^+) exclusive reactions on ^{7}Li.

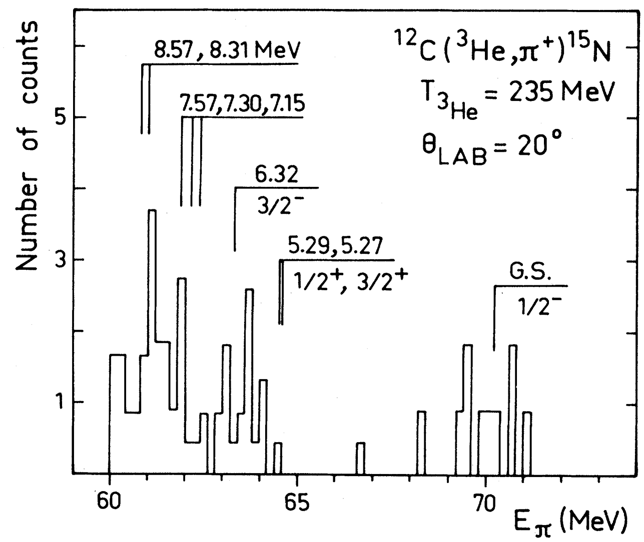

FIG. 3. Same as Fig. 1 but for ^{12}C(^{3}He, π^+)^{15}N reaction.

ite charge states. Assuming p_{33} dominance, this ratio equals $(\frac{5}{13})^2 = 0.15$ and is independent of the scattering angle. If the other partial waves are introduced we get

$$\frac{\sigma(^3\mathrm{He}, \pi^-)}{\sigma(^3\mathrm{He}, \pi^+)} = 0.09 \ ,$$

slowly varying with θ up to 60° and in excellent agreement with the experiment. This last interpretation is further supported by our (^{3}He, $\pi^\pm$) measurements on ^{12}C target. The ^{12}C(^{3}He, π^+)^{15}N differential cross sections were found comparable to those on ^{7}Li (see Fig. 3 and Table I). However, from our ^{12}C(^{3}He, π^-)^{15}F measurement, only an upper limit could be extracted for the excitation of the ground state of the exotic ^{15}F nuclei. The 41 pb/sr (c.m.) corresponds to two counts in the expected mass region. This low experimental value reinforces the hypothesis that $\Delta T \neq 0$ transitions at the pion emission vertex are strongly suppressed. This mechanism could be more rigorously tested by calculations of absolute cross sections. [See (p, π^+) conclusions.[9]] The experimental study of these two types of reactions complement the previous measurements on pion production with composite projectiles. The comparison of π^- and π^+ production in very similar cases should help to shed light on the reaction mechanism. On the other hand measurements of (α, π^-) reactions would also be of some value since they only go through the mechanism of Fig. 2(a).

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