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Brief Reports

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Pionic fusion near threshold using the ^{208}Pb(^{3}He,π^-)^{211}At reaction

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The coherent production of pions in the ^{208}Pb(^{3}He, π^-)^{211}At reaction was measured radiochemically using activation techniques near the physical pion threshold at energies of 158–270 MeV. Above threshold, the total cross sections were measured in the 1–10 nb range. A theoretical fit of the summed total cross section into all particle bound states was made using the two-nucleon model of Dillig with appropriate two-body scaling of the momentum transfer.

Several recent experimental[1–6] and theoretical[7–11] studies of pion production with complex projectiles below the threshold in free nucleon-nucleon collisions have attracted wide interest. Wall *et al.*[1] measured the ^{208}Pb(^{3}He,π^0) inclusive cross section at 200 MeV to be 6.0×10^{-2} nb/sr MeV, yielding a total cross section of about 2 nb for 6 MeV pions. Bertsch[7] calculated the (^{3}He,π) reaction cross section at 70 MeV/nucleon in an independent model which gave results of zero if collective Fermi motion were neglected and about 1 nb if the internal momenta of the ^{3}He nucleons are included. The interest in these subthreshold studies center on the coherent or collective nature of the π production mechanism. The reasons are (1) the total free energy of the entrance channel is converted into a pion and, (2) the target and projectile must undergo a fusion process to a bound state (doubly coherent or ultracold fusion). Huber[8,9] has termed this process *pionic fusion.* The present paper reports results on the production of ^{211}At through the ^{208}Pb(^{3}He,π^-) reaction near the physical π threshold. The results were compared with two-nucleon model (TNM) calculations of Dillig[12] which were appropriately scaled using quasi-two-body scaling (QTBS)[13,14] of the momentum transfer and included collective Fermi motion of ^{3}He.

The ^{208}Pb(^{3}He,π^-)^{211}At reaction was studied using 130–270 MeV ^{3}He beams accelerated in the Indiana University Cyclotron Facility (IUCF) separated-sector isochronous cyclotron. The enriched ^{208}Pb (99.14%) targets of 10–200 mg/cm^2 were bombarded with 10–200 nA beams for periods of 2–8 h. ^{211}At (7.2 h) α decays were measured using Si surface barrier detectors whose efficiencies were 7–15 %. The ^{211}At activity was radiochemically separated from the bulk target using the radiochemical procedure described in Ref. 15. The radiochemical yields were typically 35%. In Table I are listed the results of this study. The relative error in these measurements were $\pm$15–30 %, whereas the absolute uncertainty of 25–55 % reflects the uncertainties in quadrature of the statistics ($\pm$15–30 %), chemical efficiency ($\pm$15%), detector efficiency ($\pm$15%), integrated beam current ($\pm$4%), and target thickness ($\pm$7%). The below threshold measurements at 130 MeV did not produce a detectable amount of astatine at the 0.1–0.5 nb detection limit. The results in Table I are tabulated using both α-decay branches of ^{211}At (7.2 h), the 5.867 MeV (41.9%), and 7.450 MeV (57.6%) transitions. To be sure, the exclusive ^{208}Pb(^{3}He,π^-)^{211}At reaction is well suited for the study of pionic fusion processes using activation techniques since the reaction product is easily detected and background levels due to secondary particles or elemental impurities are minimal.

Interest in pionic fusion reactions are due to two important points as noted by Huber and Klingenbeck[9]: (1) the kinetic energy of the entrance channel is completely converted into the pion field requiring a coherent interaction of all nucleons involved, and (2) the target and projectile fuse in the entrance channel to form a well defined final state that is a specific state bound in the residual nucleus (ultracold fusion). Therefore the energy and momentum of the system is defined by two-body kinematics in which the single degree of freedom (the pion field) must couple to the relative motion of the two nuclei, the two nucleon subsystem which produces the pion, and the propagation of the pion in the nucleus. This model has been formulated by Huber and Dillig[16] and applied[8] to the ^{3}He(^{3}He,π^+)^{6}Li reaction studied by Willis *et al.*[6]

The pionic fusion process is given[8] by a general expression that depends explicitly on the t matrix of the final (f) and initial (i) states,

$$T_{fi}=\langle \mathbf{k}_\pi, A_{12}\,|\,H_{\rm int}\,|\,A_1A_2\mathbf{k}\rangle \;, \tag{1}$$

TABLE I. Pionic fusion production cross sections for the ^{208}Pb(^{3}He,π^-)^{211}At reaction.

Beam energy (MeV)	^{211}At cross section (nb)[a]		
	$E_\alpha=5.87$ MeV	$E_\alpha=7.45$ MeV	Averaged
130	<0.5	<0.5	<0.5
158	10.1 ± 3.3	10.2 ± 2.9	10.1 ± 3.3
198	4.3 ± 0.8	4.0 ± 0.7	4.2 ± 0.8
200	7.3 ± 1.6	6.0 ± 1.2	6.6 ± 1.6
230	3.0 ± 1.0	2.5 ± 0.8	2.8 ± 1.0
270	0.9 ± 0.5	1.2 ± 0.6	1.1 ± 0.6

[a] ^{211}At cross sections measured using both α-decay branches: 5.867 MeV (41.9%) and 7.450 MeV (57.6%).

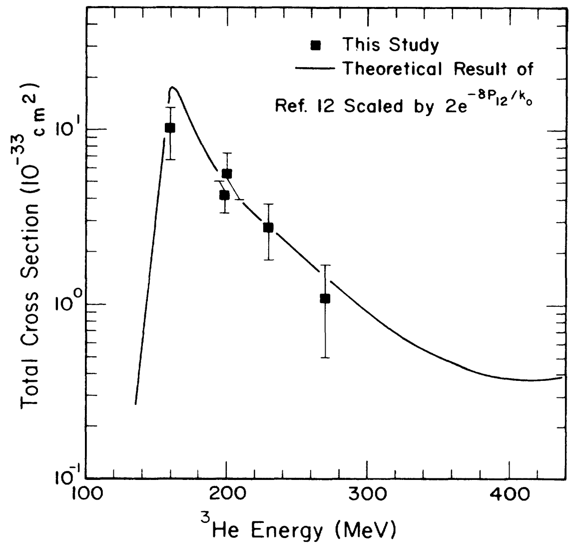

FIG. 1. Comparison of the measured pionic fusion cross sections for the reaction ^{208}Pb(^{3}He,π^-)^{211}At and TNM calculation by Dillig (Ref. 12), for the ^{209}Bi(p,π^0)^{210}Po reaction, appropriately scaled by the difference in momentum transfer to the bound final states. See text for description of the scaling procedure.

where H_{int} is constructed on the basis of an elementary NN$\rightarrow$NNπ vertex. The nuclear transition amplitude, T_{fi}, depends on the mechanism assumed to govern the π production. Dillig[12] calculated the summed total cross section into all particle bound states for the doubly coherent reaction ^{209}Bi(p,π^0)^{210}Po using the TNM for π production near threshold. A good theoretical fit was made to the data using a density of states factor, a two nucleon t matrix, and by taking into account the initial state (proton) and final state (pion) distortions using optical potentials. Uniquely the coherence of the two reactions, ^{209}Bi(p,π^0)^{210}Po and ^{208}Pb(^{3}He,π^-)^{211}At, permit scaling of the total cross section if one neglects small differences due to Coulomb effects, distortion, recoil effects, and density of states factors. QTBS, first defined by Amado and Woloshyn[13] and formulated by Frankel,[14] scales the π production cross section by the minimum internal momentum necessary to produce a pion of given momentum. The π production has an exponential falloff of the form $G(k_{\min})=\exp(-k_{\min}/k_0)$ with $k_0\sim70$ MeV/c. To be sure, the exponential falloff has been observed by the author in doubly coherent (p,π^-) reactions to high-spin 2p1h states at IUCF with $k_0\sim70$ MeV/c. Scaling from (p,π^0) to the (^{3}He,π^-) reaction channel is given by the difference in momentum transfer to the bound final states in the form $G(\delta k_{\min})=\exp(-\delta k_{\min}/k_0)$ with

$$\delta k_{\min}=|\,\delta P_1+\delta P_f+\delta P_\pi\,|=|\,\delta P_{12}\,| \ , \qquad (2)$$

where P_1, P_f, P_π, and P_{12} are the projectile, internal Fermi momenta, pion momentum, and final state momentum transfer. An additional factor of 2 relates the two isospin channels,

$$\sigma(^3\text{He},\pi^-)=2\sigma(\text{p},\pi^0)G(\delta k_{\min}) \ , \qquad (3)$$

so that the total scaling is approximately given by

$$\sigma(^3\text{He},\pi^-)\approx2\sigma(\text{p},\pi^0)\exp(-\delta P_{12}/k_0) \ . \qquad (4)$$

Figure 1 shows a comparison of the data obtained in this study for the (^{3}He,π^-) reaction and the scaling applied to the TNM calculation of Dillig[12] for the (p,π^0) reaction. The agreement between the calculated and experimental results is quite good considering the large uncertainties in the data ($\pm50\%$) and the appropriate nature of the scaling which neglects small differences in proton and ^{3}He Coulomb, recoil, and distortion effects. The fact that good agreement is obtained by scaling the momentum transfer in the range of 500–1300 MeV/c lends support to the notion put forth in Refs. 13 and 14 that π production measurements are a direct determination of the shape of the high momentum component distribution in nuclear matter. Furthermore, the good agreement could only be obtained by including the collective Fermi momentum (a factor of about 4) which supports previous views[7–11] that subthreshold π production in nucleus-nucleus collisions are collective cooperative phenomena.

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