MEASUREMENT OF \((p,\pi)\) AND \((^3\text{He},\pi)\) REACTIONS BY RECOIL DETECTION

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Measurements of exclusive \((p,\pi)\) and \((^3\text{He},\pi)\) reactions by recoil detection using the large solid angle QQSP spectrometer at 0° at the Indiana University cyclotron, in conjunction with a heavy-ion focal-plane detector consisting of two parallel-plate avalanche counters and a proportional counter, were done in the past several years. The method has been described in a previous paper.\(^1\)

The analysis of the pionic fusion reaction \(^{12}\text{C}(^3\text{He},\pi^+)\)\(^{15}\text{N}\) at 170.2 MeV and 236.3 MeV bombarding energy has been finished. At \(T(^3\text{He}) = 170.2\) MeV the angle-integrated cross section for the population of both the \(^{15}\text{N}_{\text{g.s.}}\) and a broad group of unresolved \(^{15}\text{N}\) excited states between \(E_x = 6\) MeV and 10 MeV is less than 0.03 nb. At \(T(^3\text{He}) = 236.3\) MeV the total cross section summed over both groups is \((0.8 \pm 0.2)\) nb. The angular distribution of the pions corresponding to this whole range of states is fairly isotropic with perhaps some peaking in the forward direction. The cross section \(\sigma(T_\pi)\) peaks at a pion c.m. energy \(T_\pi\) of several tens of MeV. Up to now enough data are available only for the \(^3\text{He}(^3\text{He},\pi^+)\)\(^6\text{Li}_{\text{g.s.}}\) reaction, which can give a limited insight into the dependence of the pionic fusion process cross section on the energy above threshold.

Figures 1a and b show scatter plots of \(^{15}\text{N}\) recoils as a function of their emission angle, \(\theta\), and relative momentum, \(p/p_o\), for 236.3 MeV and 170.2 MeV bombarding energy, respectively. The plots were made with sorting conditions requiring \(A/Q = 2.143\) and \(Z = 7\). These data were taken in 9 – 10 hour runs with an average beam current of about 100 particle nanoamps. The elliptical curves are the predicted boundaries of the kinematic loci for the \(^{15}\text{N}\) fusion products from the \(^{12}\text{C}(^3\text{He},\pi^+)\)\(^{15}\text{N}\) reaction in the excitation energy range \(E_x = 0 – 10\) MeV. For \(T(^3\text{He}) = 170.2\) MeV (Fig. 1b) the ellipses become small and the inner boundary of the locus shrinks to a point in the center of the outer ellipse. The spectrograph was set so that the beam entered at an angle \(\beta = 84.65\) mr relative to the optical axis; consequently, the lower part of the kinematic loci is truncated by the entrance collimator. The \(Z\) identification does not completely separate the \(^{12}\text{C}\) from the \(^{15}\text{N}\) events of interest causing some background counts in the \(p/p_o - \theta\) plane. There are events in Fig. 1a distributed along the whole kinematic locus with perhaps some more on the low momentum side suggesting a fairly isotropic angular distribution, with perhaps some peaking in the forward direction. For \(T(^3\text{He}) = 170.2\) MeV only two events are detected within the kinematically allowed region. From these, upper limits of the cross sections can be determined.
Figure 1. Two-dimensional plots of $^{15}$N recoil events from the $^{12}$C($^3$He,$\pi^+$)$^{15}$N reaction in the $\theta$ vs $p/p_o$ plane. $\theta$ is the emission angle at the target, $p$ is the momentum of the reaction product, and $\alpha$ is the angle of the particle relative to the spectrometer (QQSP) focal plane normal. The reference rigidity of the QQSP, expressed by the reference momentum $p_o$ of a particle with charge $Q$, is $p_o/Q$. (a) Bombarding energy $T(^3\text{He}) = 236.3$ MeV, $p_o/Q = 0.571$ Tm. The dashed lines delineate the region where $^{15}$N recoils with excitation energies in the range $E_x = 0 - 10$ MeV are expected. (b) $T(^3\text{He}) = 170.2$ MeV, $p_o/Q = 0.482$ Tm. The dashed line marks the outer boundary of the region for the $^{15}$N recoils with $E_x = 0 - 10$ MeV. The inner boundary has shrunk to a dot in the center of the outer boundary ellipse.
In Fig. 2 all reported differential cross sections \(\frac{d\sigma}{d\Omega}\) are drawn as function of the pion c.m. energy \(T_\pi\) for the \(^3\text{He}\left(^3\text{He},\pi^+\right)^6\text{Li}_{g.s.}\) (full dots) and the \(^{12}\text{C}\left(^3\text{He},\pi^+\right)^{15}\text{N}\) reactions (open dots). The full circles denote \(\frac{d\sigma}{d\Omega}\) measurements of the \(^3\text{He}\left(^3\text{He},\pi^+\right)^6\text{Li}_{g.s.}\) reaction from Orsay\(^2\)), the full squares and full triangles were obtained from \(\frac{d\sigma}{d\Omega}\) data of the time reserved \(^6\text{Li}\left(\pi^+,^3\text{He}\right)^3\text{He}\) reaction from LAMPF\(^3\) and TRIUMF\(^4\), respectively. The open triangles denote \(\frac{d\sigma}{d\Omega}\) values of the \(^{12}\text{C}\left(^3\text{He},\pi^+\right)^{15}\text{N}\) reaction where \(\frac{d\sigma}{d\Omega}\) was obtained from the measured angle-integrated cross section \(\sigma\) by \(\frac{d\sigma}{d\Omega} = \sigma/4\pi\) assuming isotropy. The results at \(T_\pi \approx 5\) MeV and 60 MeV are from the present data, the value at 15 MeV was measured previously at IUCF\(^5\). The open circle denotes a \(\frac{d\sigma}{d\Omega}\) measurement of the \(^{12}\text{C}\left(^3\text{He},\pi^+\right)^{15}\text{N}_{g.s.}\) reaction from Orsay\(^6\).

As the recoil detection with the present setup has a limited energy resolution, the angle-integrated cross section is summed over the ground state and a wide range of bound excited states. The three cross sections obtained for the \(^{12}\text{C}\left(^3\text{He},\pi^+\right)^{15}\text{N}\) reaction follow a curve which is similar in energy dependence to that reported for the \(^3\text{He}\left(^3\text{He},\pi^+\right)^6\text{Li}_{g.s.}\) reaction. However, the cross section for the pionic fusion reaction with the \(^{12}\text{C}\) target is more than two orders of magnitude smaller than that with the \(^3\text{He}\) target. For both reactions the cross section rises rapidly above threshold and peaks at a pion c.m. energy of several tens of MeV.

The data analysis of the \(^{12}\text{C}\left(p,\pi^+\right)^{13}\text{C}\) and the \(^{12}\text{C}\left(p,\pi^0\right)^{13}\text{N}_{g.s.}\) reactions has been extended to include the forward angle range of the differential cross section in the c.m. system. At a bombarding energy of 166.05 MeV the \(^{12}\text{C}\) and \(^{13}\text{N}\) ions have a minimum energy of 10.6 and 10.4 MeV, respectively, corresponding to a pion angle of 0°. Since the velocity at which the ions pass through the proportional counter is small, they can no longer be distinguished by their energy loss in the proportional counter. Instead, they can be separated by their energy loss in the first two detector foils which leads to a difference in the time-of-flight (TOF) between the first and second parallel plate avalanche counter (PPAC1 and PPAC2) for \(^{12}\text{C}\) and \(^{13}\text{N}\) recoil ions.

The measured TOF between PPAC1 and PPAC2 \((t_2)\) and the calculated TOF for \(^{12}\text{C}\) \((t_c)\) and \(^{13}\text{N}\) recoils \((t_n)\) – depending on angle and momentum – are used to calculate the quantity \(Z = 6+(t_2-t_c)/(t_n-t_c)\), which is independent of angle and momentum, and by means of which \(^{12}\text{C}\) and \(^{13}\text{N}\) recoils can be separated. Fig. 3 shows such a Z spectrum for ions with a mass to charge ratio of \(A/Q = 13/5\). The two windows for selecting \(^{12}\text{C}^5^+\) and \(^{13}\text{N}^5^+\) ions are drawn.

Fig. 4a shows the distribution of \(^{13}\text{C}^5^+\) recoil events in the momentum-angle plane, Fig. 4b correspondingly for the \(^{13}\text{N}^5^+\) ions. Since at the bombarding energy of 166.05 MeV the reactions to the ground states are only 16.3 and 18.7 MeV above threshold, respectively, the compete half ellipses can be observed. Since the \(\pi^0\) mass is smaller than the \(\pi^+\) mass, the ellipse for the \(^{13}\text{N}^5^+\) ions is larger than the ellipse for the \(^{12}\text{C}^5^+\) ions. The C and N ions have been selected by means of the TOF method using the windows shown in Fig. 3, respectively. For the high momentum branches of the two ellipses the TOF difference becomes small, and C and N can no longer be separated. The \(Z = 7\) peak (Fig. 3) merges into the \(Z = 6\) peak leaving no events in the right branch of the N.
Figure 2. Differential cross section \( \frac{d\sigma}{d\Omega_{\text{cm}}} \) of pionic fusion reactions vs center-of-mass pion energy \( (T_{\pi^{+}})_{\text{cm}} \). The points denote measurements, the curves theoretical calculations. The pion emission angle \( (\theta_{\pi^{+}})_{\text{cm}} \) of the \( d\sigma/d\Omega_{\text{cm}} \) value is marked in degrees. Data points without angles denote \( d\sigma/d\Omega_{\text{cm}} \) values which were obtained from the measured angle-integrated cross section \( \sigma \). For \( ^{3}\text{He}(^{3}\text{He},\pi^{+})^{6}\text{Li}_{g.s.} \): the full circles, squares and triangles, correspond to Refs. 2, 3 and 4. KDH means Kilingenbeck, Dillig, Huber; GW Germond and Wilkin. For \( ^{12}\text{C}(^{3}\text{He},\pi^{+})^{15}\text{N} \): open triangles at \( (T_{\pi^{+}})_{\text{cm}} \approx 5 \text{ MeV} \) and 60 MeV are the present data: the open triangle at 15 MeV is from Ref. 5; the open circle is from Ref. 6; KTK means Kajino, Toki, and Kubo.
ellipse. However, in the high momentum region the ion velocity is large enough that the Z separation can be achieved by a ΔE measurement in the proportional counter.

The differential cross section for the \((p, π^+)\) reaction using TOF separation in the forward direction and ΔE selection in the backward direction is plotted in Fig. 5. The data from the 5\(^+\) and 6\(^+\) charge state of \(^{13}\)C are in good agreement. They can be compared with the sum of data from Green\(^7\) and Soga\(^8\) for the population of the ground state and the first three exited states of \(^{13}\)C at 169 MeV, which were obtained by pion detection. The recoil data are in good agreement with these data.

Using isospin-invariance the expected cross section for the \(^{12}\)C\((p, π^+)\)^\(^{13}\)N\(_{g.s.}\) reaction is half of the cross section for the \(^{12}\)C\((p, π^+)\)^\(^{13}\)C\(_{g.s.}\) reaction. In Fig. 6, \(dσ/dΩ\) values obtained from the \(^{12}\)C\((p, π^+)\)^\(^{13}\)N\(_{g.s.}\) recoil experiment and \((1/2)(dσ/dΩ)\) values from the \(^{12}\)C\((p, π^+)\)^\(^{13}\)C\(_{g.s.}\) pion experiment\(^7\) are compared. At small angles the measured \((p, π^+)\) cross section is about a factor two larger than that expected from the \((p, π^+)\) data. The deviation, which may be due in part to direct electromagnetic effects, remains to be explained.

Figure 3. Z spectrum for ions with \(A/Q = 13/5\).
Figure 4. Two-dimensional plots of recoil events from $^{12}\text{C}(p,\pi)$ reactions at 166.05 MeV bombarding energy in the $\theta$ vs $p/p_0$ plane; $p_0/Q = 0.329$ Tm. The drawn lines mark windows around the kinematic loci and the acceptance of the QQSP-detector system, respectively. (a) $^{12}\text{C}(p,\pi^+)^{13}\text{C}$ reaction. (b) $^{12}\text{C}(p,\pi^0)^{13}\text{N}_{g.s.}$ reaction.
Figure 5. Differential cross section, $d\sigma/d\Omega_{cm}$, vs. pion emission angle, $\theta_{cm}$, for the $^{12}$C($p,\pi^+)^{13}$C reaction. The x's, squares and rhombs are data from the present experiment. The crosses are results$^{7-8}$ which were obtained by $\pi^+$ detection where the cross sections for forming the four bound states of $^{13}$C have been added.

Figure 6. $d\sigma/d\Omega_{cm}$ vs $\theta_{cm}$. The rhombs are data from the present $^{12}\text{C}(p,\pi^0)^{13}\text{N}_{g.s.}$ experiment. The crosses are results by Green\textsuperscript{7} for the $^{12}\text{C}(p,\pi^+)^{13}\text{C}_{g.s.}$ reaction, which were obtained by $\pi^+$ detection, where $d\sigma/d\Omega_{cm}$ has been divided by two.