Pionic fusion of ^{4}He + ^{12}C

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Pionic fusion is the process by which two nuclei fuse and then deexcite by the exclusive emission of a pion. The resulting compound nucleus is left in or near its ground state [1]. The process requires that nearly all of the available kinetic and potential energy in the colliding system be concentrated into two degrees of freedom - the rest mass and kinetic energy of the emitted pion. Thus, the energy of the emitted pion is limited by the number of available final states of the fusion residue [2]. The combination of limited available energy and the extreme coherence required in the process ensures that the pionic fusion channel is greatly suppressed. Indeed, the measured pionic fusion cross sections range from hundreds of nanobarns for the lightest systems (He + He) to hundreds of picobarns as one moves to larger systems (A_{tot} = 6 - 24) [2-12].

An experiment was conducted at the Cyclotron Institute to measure the cross section of the pionic fusion reaction $^{4}\mathrm{He} + {}^{12}\mathrm{C} \rightarrow {}^{16}\mathrm{N} + \pi^{+}$ using the Momentum Achromat Recoil Spectrometer (MARS) [13] for detection of the ^{16}N fusion residue and the Partial Truncated Icosahedron (ParTI) phoswich array [14] for the detection of the charged pion. Over the past year, the analysis of the experimental data has nearly been completed. A detailed accounting of the various efficiencies associated with the experimental design and the measurement of the production of ^{16}N fragments detected at the MARS focal plane has been used to produce measured cross sections for the pionic fusion reaction. The Gemini statistical deexcitation code [15] has been used to estimate the ^{16}N background produced in reactions on ^{16}O, the likeliest source of contamination in the ^{12}C target. For those MARS events which were identified as ^{16}N fragments, there were no pions detected in the ParTI array.

Over the course of the pionic fusion experiment, data was collected while MARS was tuned at 6 different central Bρs - 0.5363 Tm, 0.554 Tm, 0.5829 Tm 0.6073 Tm, 0.6304 Tm and 0.6657 Tm. The lowest and highest of these Bρ windows are outside of the allowed energy distribution for ^{16}N residues resulting from the pionic fusion reaction of interest. Thus, any ^{16}N detected with these settings can only be attributable to background. In total, 2 counts of ^{16}N were detected - 1 in the allowable region in the 0.5829 Tm Bρ window and 1 in the background region at 0.6657 Tm. The 1 count in the 0.5829 Tm region corresponds to a cross section of 29.5 ± 29.7 pb and the 1 count in the background region corresponds to 28.9 ± 29.1 pb. The 0.5829 Tm Bρ window covers 42.9% of the total energy distribution of the pionic fusion ^{16}N residues. Scaling by this coverage, therefore, can produce an energy-integrated, gross cross section for pionic fusion of 68.8 ± 69.2 pb.

The level of background in the energy region of interest was estimated using the Gemini statistical deexcitation code. The most abundant contaminant in the ^{12}C target is ^{16}O from adsorbed water on the foil’s surface. Gemini was used to deexcite ^{20}Ne fusion residues from reactions on the ^{16}O contamination to predict the energy distribution of the ^{16}N residues created in this background reaction. Figure 1 shows this ^{16}N magnetic rigidity distribution in Tm with the shaded regions indicating the region of interest for pionic fusion (green) and the measured background region (red). Gemini predicts that the number of ^{16}N residues created in reactions on ^{16}O in the region of interest is 4x higher than the ^{16}N production in measured background region. Since it is not possible for pionic fusion to contribute to the cross section in the 0.6657 Tm background region, and given the reasonable assumption that reactions on ^{16}O are the likely source of the measured background, the expected background cross section in the region of interest would be 4 x 28.9 ± 29.1 pb, or 115.6 ± 116.4 pb.

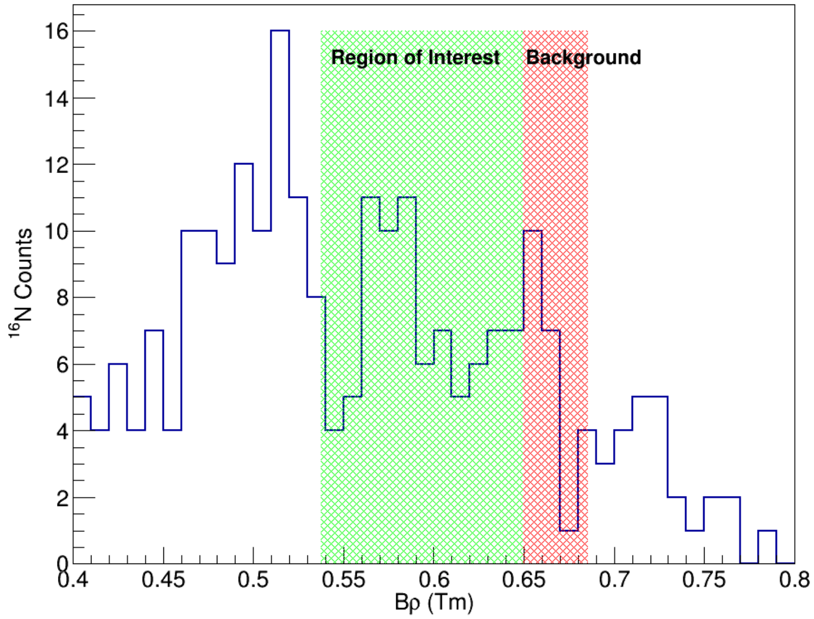

FIG. 1. The ^{16}N Bρ distribution predicted by Gemini deexcitations of ^{20}Ne compound nuclei corresponding to the complete fusion product of ^{4}He + ^{16}O background reactions. The green shaded region is the region of interest for ^{16}N residues of pionic fusion reactions and the red shaded region is the window corresponding to the background measurement around 0.6657 Tm.

The estimated background cross section in the region of interest is consistent with the measured gross cross section in the region of interest. After background subtraction, therefore, the measured pionic fusion cross section measured from the detection of ^{16}N fusion residues is consistent with zero. The upper limit of the cross section is determined by the sensitivity of the cross section measurement. In this case, it is the upper edge of the 1σ error bar on the background measurement - 232 pb. Fig. 2 shows this upper limit for the ^{4}He + ^{12}C → ^{16}N + π^+ pionic fusion reaction determined in this experiment compared to previous measurements of other pionic fusion reaction cross sections [4]. The horizontal axis is the total mass of the colliding system divided by 2 and the vertical axis is the cross section in nb. When compared with the other pionic fusion results, the measurement from this experiment implies a lower cross section than one would expect given the general trend as a function of colliding system mass. One might reasonably expect that the physics driving the pionic fusion mechanism are more sufficiently complex that a simple accounting for the size of the reacting system is not sufficient to predict cross sections. Such a situation could plausibly explain why this result is seemingly not consistent with the larger trend produced by previous measurements, none of which used alpha projectiles or the same energy above the pion production threshold (140 MeV center of mass energy). The state of the field of pionic fusion, however, is not such that the question can be answered confidently - highlighting the necessity for further data and theoretical work.

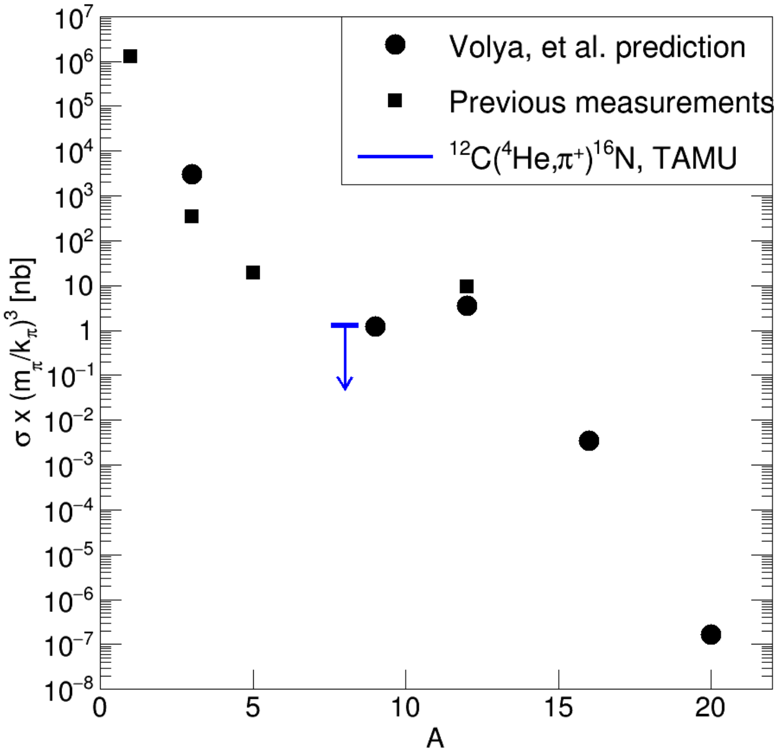

FIG. 2. A comparison of the upper limit for the pionic fusion cross section found in this experiment to previous measurements [4] and predictions [16]. The horizontal axis is the total system mass divided by 2 and the vertical axis is the cross section in nb scaled by the cube of the pion mass divided by the pion kinetic energy corresponding to the energy above the pion production threshold. The blue line is the location of the upper limit measured in this experiment.

The analysis of the ParTI array data from the pionic fusion experiment is still underway. However, it has been confirmed that there are no pion events that come in coincidence with either of the two ^{16}N events in MARS or with any of the other events which were identified as A = 16 particles. We are currently in the process of searching the ParTI array events which were collected without a coincident MARS residue of any kind for any charged pions. At the end of that search, a cross section will be reported based on the detection of charged pions. Because detection of charged pions using the ParTI array is a less sensitive method than detection of the residues using MARS, we expect to report an upper limit on a cross section using this data as well, but with less precision than order 100's pb.

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