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THE POTENTIAL OF HEAVY ION BEAMS TO PROVIDE SECONDARY MUON/NEUTRINO BEAM

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Abstract

This paper focuses on the exploration into the potential of heavy ion beams to produce charged pions/muons within different energy ranges which is widely needed for fundamental and applied research. The investigation is performed for the different kinds of beams involving ^{1}H, ^{4}He, ^{12}C, ^{16}O, ^{40}Ar and ^{136}Xe with medium energy within the range of 0.5~2.5 AGeV and high energy of 10 AGeV. Three kinds of typical target configurations, thin graphite plate, long tungsten rod and medium thickness nickel block are adopted. For comparison, graphite and nickel are also used for the long rod geometry. Basically, most of the conventional charged pion/muon beams production cases including surface muon, low energy decay muon, medium energy pion/muon for neutrino beam and highly forward energetic muon are involved and the feasibility of heavy ion beam for these cases is analyzed.

INTRODUCTION

Usually, the charged muon beam is produced using proton beam as well as accelerator-based neutrino beam. To be specific, the low energy decay muon as well as surface muon beam lines at TRIUMF, PSI and RCNP are based on proton beam with hundreds of MeV energy while that of MLF at J-PARC share 3 GeV proton beam with neutron source. This kind of conventional muon beam lines usually adopt a thin graphite target consuming a small proportion of the proton beam. In addition, the pion capture solenoid is set beside the target. The MuSIC at RCNP is an exception. By placing the target in the pion capture solenoid and using a thicker target to use full proton beam, the muon production efficiency can be 1000 times higher [1].

The medium-energy muon beams for various accelerator-based neutrino oscillation experiments are usually provided by energetic proton beam. The pion capture solenoid is necessary. Thus, a target long rod target would be used to achieve a high production and collection efficiency. In general, the energy of desired muon is in the range of 100~500 MeV/c. For example, the Neutrino Factory (NF) was designed to collects the 40~180 MeV pions/muons while the MOMENT would select that in the range of 150~450 MeV/c. This kind of facilities usually use the forward charged pions/muons. Based on this beam-target and capture solenoid configurations, a considerable number of backward muons can also be provided. In fact, the Mu-e conversion experiments like Mu2e and COMET as well as the MuSIC mentioned above adopt this kind of design.

Another typical case is the 3.09 GeV/c beam for g-2 and EDM experiments. This kind of muon beam line at FNAL is driven by 8 GeV proton beam. An inconel target is set to be with a 7.5-cm effective beam-target thickness and the high energy charged pions are collected by a Li lens with a 1 cm radius. Except this quasi-mono-energy beam, the energetic and highly forward muon beam can also be applied to tomographic Imaging.

Along with the development of heavy-ion accelerator technology, more high-intensity heavy ion accelerator facilities have been proposed over the world. Among these facilities, HIAF, FAIR, FRIB and Spiral2 are under construction. The most typical two, HIAF and FAIR can provide relativistic heavy ion beams with an unprecedented intensity. In addition, the upgrade plan has been proposed for HIAF to increase the beam energy to more than 10 AGeV by using superconducting boost ring.

The high-intensity and relativistic heavy ion can not only expand nuclear and related researches into presently unreachable region, but also have the potential to provide high-intensity muon/neutrino beams. Here the production of the low energy charged pions (below 200 MeV/c) as well as the surface muon is investigated for various heavy ions with energy varies from 500 AMeV to 2.5 AGeV with a 1-cm thick graphite target. With 10 AGeV beam energy and a long rod target, the characteristics of charged pions within the range of 100 ~ 500 MeV/c as well as that below 200 MeV/c is explored for different beams and different materials. At last, the production of 2~4 GeV/c muon beam from 7.5-cm thickness nickel target is investigated.

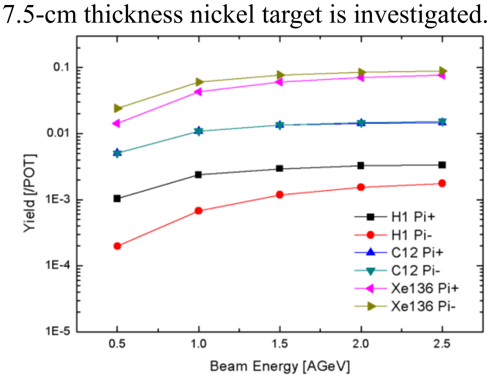

Figure 1: The yields of Pi+ and Pi- below 200 MeV/c for ^{1}H, ^{12}C and ^{136}Xe with energy varies from 0.5 to 2.5 AGeV with a 1-cm thick graphite target.

CONVENTIONAL SIDE-COLLECTED CASE

In this section, the production of conventional low energy muon beam with a thin target is investigated. The graphite target is 1 cm in thickness. Figure 1 shows the

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yields of Pi+ and Pi- below 200 MeV/c per beam particle on target (POT). The yields of both Pi+ and Pi- from ^{12}C, ^{136}Xe are apparently higher than that from proton. It is interesting that the ratios of the Pi- to Pi+ for ^{1}H, ^{12}C and ^{136}Xe are quite different. For ^{1}H, the yield of the Pi+ is several times of that of Pi- and the ratio decreases for a higher beam energy. For ^{12}C, the yields are very close while Pi- is more than Pi+ for ^{136}Xe.

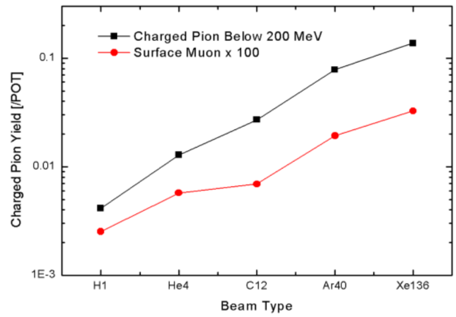

Figure 2: The yields of the charged pions below 200 MeV/c and surface muons for different beams with 1.5 GeV energy.

To see the increasing tendency of the yields of the charged pions below 200 MeV/c as well as the surface muons along with the nucleon number of the beam particle, the 1.5 AGeV beam energy and five typical particles from ^{1}H to ^{136}Xe are chosen. As shown in Fig. 2, the production rate increases from ~0.004 to ~0.14 for charged pions, which means a > 30 times of increase. The surface muon yiled increases with a slightly smaller slope.

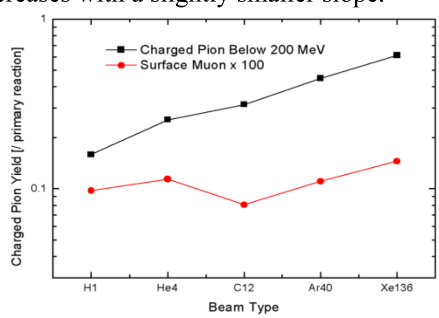

Figure 3: Same as Fig. 2 except that the yield is divided by primary reaction number instead of POT.

What is worth noting is that the tens of times of increase from ^{1}H to ^{136}Xe mainly comes from the much higher reaction rate for ^{136}Xe. For ^{1}H, the reaction rate is 2.5% while that of ^{136}Xe is 22.5%. Figure 3 gives the actual yield rate dividing the yield by the number of primary reactions. For the charged pions, the value for ^{136}Xe is just ~4 times of that for ^{1}H. For the surface muon, the actual yield for different beam are quite close and that for ^{12}C is even less than ^{1}H. In a word, the actual production efficiency for heavy ion beams within this energy range is much lower than that for ^{1}H taking into consideration the total beam energy.

PRODUCTION SOLENOID CASE

Figure 4 and Fig. 5 shows the production efficiency of charged pions within 100 ~ 500 MeV/c range and below 200 MeV/c respectively. The beam energy is 10 AGeV and the target geometry is D2xL60 cm for graphite, D1xL40 cm for nickel and D1xL20 cm for tungsten. Here the production efficiency is defined as the yield divided by 10*A. It is can be seen that the production efficiency for a heavier ion is lower and the decrease is more significant for the material with a higher density. Generally, the value of ^{136}Xe is more than around 60% of that of ^{1}H, at least, which means that the ^{136}Xe ion can provide around 80 times more pions than ^{1}H.

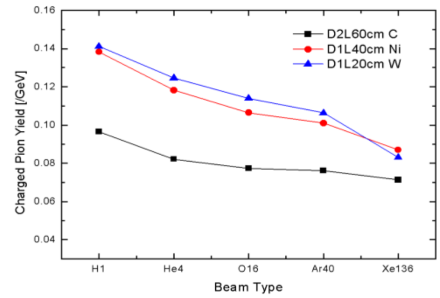

Figure 4: The production efficiency of forward charged pions within the range of 100 ~ 500 MeV/c.

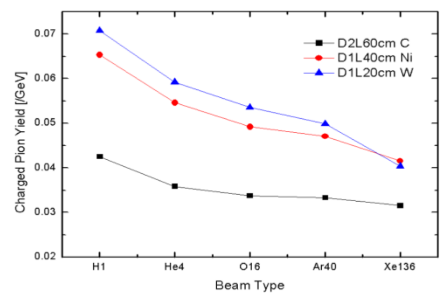

Figure 5: The production efficiency of charged pions below 200 MeV/c.

As mentioned in the previous section, the ratios of Pi- to Pi+ for different ions are quite different. For 10AGeV energy and for different materials, there are still some new features have not been exhibited in Fig. 1. As shown in Fig. 6 and Fig. 7, the ratios for the four heavy ions are quite close. Both ratios for tungsten target are significantly larger than 1 while that for nickel and graphite targets are very close to 1 except for the ^{1}H ion. It is interesting that within 0 ~ 200 MeV/c range Pi- is less than Pi+ for nickel target for all ions.

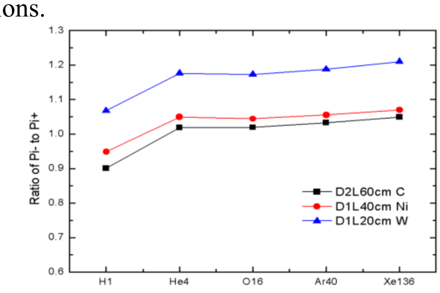

Figure 6: The ratio of Pi- to Pi+ for 100 ~ 500 MeV/c pions.

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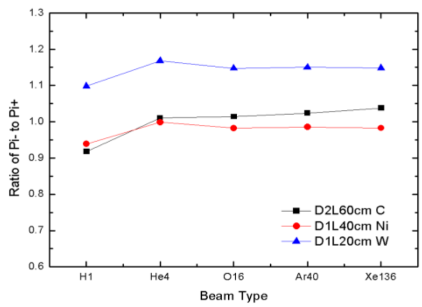

Figure 7: The ratio of Pi- to Pi+ for pions below 200 MeV/c.

HIGHLY FORWARD AND ENERGETIC CASE

Figure 8 shows the production efficiency of 2 ~ 4 MeV/c Pi+ and Pi- within 20º. The nickel target is 7.5 cm in thickness and the beam energy is also 10 AGeV. For Pi-, all of the heavy ions have higher efficiency than ^{1}H and ^{40}Ar is even more than 2 times higher. For Pi+, the difference between all ions is less 20%.

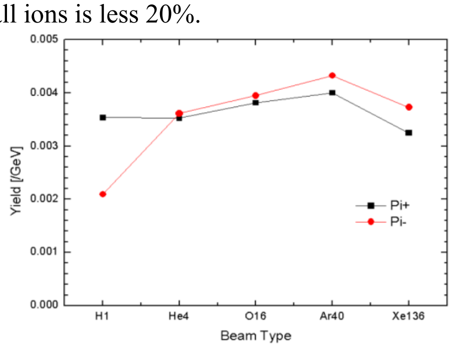

Figure 8: The production efficiency of Pi+ and Pi- within the 2 ~ 4 GeV/c range.

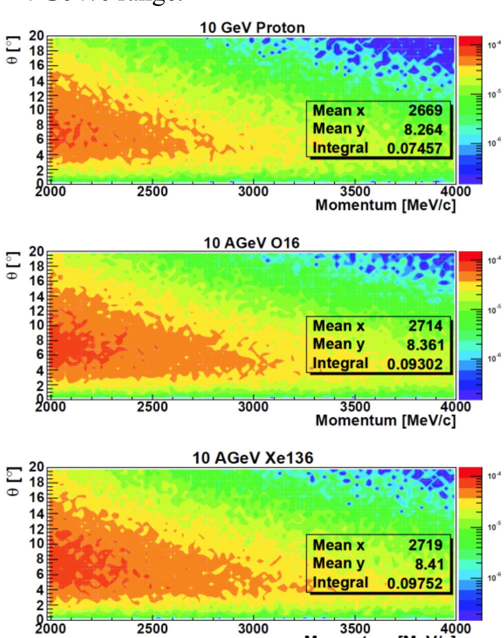

Figure 9: The momentum-angle distribution for the scaled yields of Pi+ for ^{1}H, ^{16}O and ^{136}Xe.

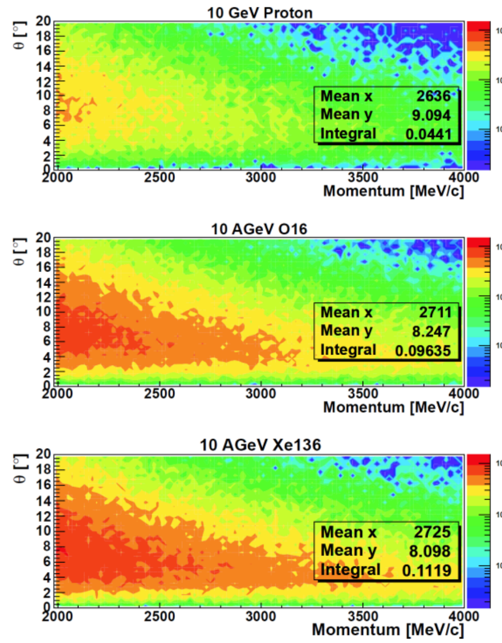

Figure 10: Same as Fig. 9 except for Pi-.

Figure 9 and Fig. 10 gives the momentum-angle distribution the for 2 ~ 4 GeV/c Pi+ and Pi- within 20º respectively. The values are scaled by the total yield for each case. The integral is the proportion of the pions in the range of 2 ~ 4 GeV/c within 20º to the total yield. It is shown that the proportions for ^{16}O and ^{136}Xe are significantly larger than that for ^{1}H. The value of Pi- for ^{136}Xe is around 2.5 times of that for ^{1}H.

CONCLUSION

For heavy ion beams, especially for the high mass number ones, with a thin graphite target, which is the typical configuration in the conventional low energy muon beam facilities, the muon production efficiency is much lower than that for proton beam. As for the production solenoid case with a long-rod target, the heavy ion with 10 AGeV energy can provide much more muon/neutrino than proton with a slightly lower efficiency. Of particular interest is the production of the highly forward muons with high energy. The heavy ion has the advantage even from the viewpoint of production efficiency.

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