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Subthreshold Pion Production

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I will begin with a very brief summary of some of the experimental and theoretical work with light projectiles, and this will serve as background for a discussion of some interesting results from our work at the Bevalac with heavy systems at beam energies near threshold.

Figure 1. Subthreshold Pion Experiments

Figure 1 summarizes the existing data on subthreshold pion production, according to projectile mass and energy per nucleon. (For a more extensive survey of the data, the reader is referred to two soon-to-be-published reports, Refs. 1 and 2. For additional discussions in these proceedings on the topic of subthreshold particle production, see the contributions of J. Carroll, U. Mosel and B. Schürmann.)

One of the things which makes subthreshold particle production in nucleus-nucleus collisions intriguing is that it requires the cooperation of more than two nucleons.† Probably the simplest example of this is the Fermi motion that nucleons in nuclei acquire as a consequence of being confined to a small volume in phase space. Subthreshold particle creation with the aid of Fermi momentum was predicted many years ago, and it is an interesting historical fact that the first pions created in the laboratory were subthreshold pions produced in 95 MeV/nucleon.

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†"Threshold" in this context refers to the threshold energy for particle creation in free nucleon-nucleon collisions. In nucleus-nucleus collisions, subthreshold means that the beam energy per nucleon is below threshold. For pions this energy is about 290 MeV/nucleon.
$^4\text{He} + ^{12}\text{C}$ collisions at the 184" cyclotron. This process is relatively well-understood, and one of the aims of subthreshold production experiments is to identify other collective effects. Some possible signatures of collective effects are:

- Production below the 'absolute' threshold.
- Production in excess of predictions of nucleon–nucleon models.
- A change in the characteristic behavior of the pion spectra as the threshold is crossed.

I'll briefly discuss the first two cases, and devote most of my attention to the third, which is where the Bevalac data come into play.

**Production below the absolute threshold.** While Fermi motion makes the concept of an energy threshold in nucleus-nucleus collisions ambiguous, Bertsch has calculated in the framework of the first collision model an absolute threshold value of 54 MeV, due to Pauli blocking of the final state phase space. Recent experiments at GANIL, and at MSU and ORNL have reported non-negligible cross sections for $\pi^0$ production below this limit. These range from about 1 nb for 25 MeV/nucleon $^{16}\text{O} + ^{27}\text{Al}$ to greater than 1 $\mu$b for 44 MeV/nucleon $^{40}\text{Ar} + ^{40}\text{Ca}$.

**Excess production.** At somewhat higher energies, where binary (i.e. nucleon-nucleon) production can take place, single collision models severely underpredict the inclusive cross sections, especially when the shell model is used to calculate the initial state nucleon momenta. Models which incorporate collective effects do better. The pion bremsstrahlung model of Vasak et al. gives a good account of the 44 MeV/nucleon $^{40}\text{Ar} + ^{40}\text{Ca}$ data and of the $\pi^0$ yield for 60–84 MeV/nucleon $^{12}\text{C}$ projectiles taken at the CERN SC, and two statistical models have been applied with some success over almost the entire range of subthreshold pion data. Bohrmann, Shyam and Knoll have extended the Fermi statistical model, while Aichelin and Bertsch and Prakash, Braun-Munzinger and Stachel, have made calculations based on the compound nucleus theory of Weisskopf.

**The 'trans-threshold' region.** (I define this to encompass beam energies between about 140 MeV/nucleon and threshold.) Near threshold one expects Fermi-boosted binary production to dominate, and the object is to go low enough in beam energy for other collective effects to become apparent above this incoherent background. Figure 2 shows the charged pion spectra at $\theta_{\text{c.m.}} \approx 90^\circ$ for three mass systems for a wide range of beam energies above and below threshold. All the spectra exhibit the well-known characteristics of inclusive pion measurements: exponential fall-off with pion energy, and slope parameters and yields monotonically decreasing with beam energy. Note that for the 246 MeV/nucleon La+La case, an intranuclear cascade simulation—essentially a folding together of nucleon-nucleon collisions—reproduces the slope and overestimates the yield.

Figure 3 shows slope parameters extracted from exponential fits to the invariant cross section, $E_\pi d^3\sigma/dp^3$, once again over a wide range in system mass and beam energy. There is little or no mass dependence. (This situation obtains also at beam energies down to 60 MeV/nucleon, after which the slope parameter becomes almost constant.) So, at least at first glance, nothing unusual is going on.

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1 Strictly speaking, the fits should be to the variant cross section, $d^3\sigma/dp^3$, but the difference is not significant in this case.
Figure 2. Inclusive cross section for charged pion production at $\theta_{c.m.} \simeq 90^\circ$ for
(a) $p + ^{64}\text{Cu} \rightarrow \pi^+ + X$ (Ref. 23) (b) $^{20}\text{Ne} + \text{NaF} \rightarrow \pi^- + X$ (Refs. 24 and 25)
(c) $^{139}\text{La} + ^{139}\text{La} \rightarrow \pi^- + X$ (Refs. 26 and 27)
Slope parameters for $A + A \rightarrow \pi^- + X (\theta_{cm}=90^\circ)$

- $^{12}\text{C} + ^{12}\text{C}$
- $^{20}\text{Ne} + \text{NaF}$
- $^{136}\text{La} + ^{139}\text{La}$

Figure 3. Slope parameter, $T_0$, for pion spectra at $\theta_{cm} = 90^\circ$, plotted as a function of beam energy for a variety of targets and projectiles, at beam energies between 85 and 3500 MeV in the lab. $T_0$ is the negative inverse slope extracted from fitting the invariant cross section by a function of the form $ae^{-T/T_0}$. Data are from Refs. 24–29.

**Mass dependence.** We next consider the mass dependence of the differential yield, $d\sigma/d\Omega$, for $\pi^-$ at $\theta_{cm} = 90^\circ$ (Figure 4). Note that the yield has been scaled by $(A_{tgt}A_{proj})^3$, a form which has been found to hold for almost all of the subthreshold pion data from light systems, and we can see from the figure that it holds for both light and heavy systems above about 400 MeV/nucleon. Below threshold, however, this scaling breaks down badly. Figure 5 shows how badly. Here we limit consideration to the data for $^{20}\text{Ne} + \text{NaF}$ and $^{139}\text{La} + ^{139}\text{La}$, which were taken in several different experiments on the same spectrometer, and which have a relative normalization close to unity. The horizontal lines denote several possible scalings, including some which are weighted by neutron number. (In a collision model negative pions come predominantly from neutron-neutron collisions.) What is more important than the nature of the scaling is the fact that it varies so strongly with beam energy, below threshold. With one, possibly significant, exception, this sort of behavior has not previously been observed in the subthreshold data. The exception is in the data at 44 and 48 MeV/nucleon where the scaled cross section for $\pi^0$ from 44 MeV/nucleon $^{40}\text{Ar} + ^{40}\text{Ca}$ is three times that for 48 MeV/nucleon $^{12}\text{C} + ^{12}\text{C}$.

At this point it's appropriate to note some of the other conclusions of our recent La+La experiment. From the associated charged particle multiplicities and the angular distributions we have constructed a picture of the typical subthreshold pion source as being at rest in the center of mass, and involving a large number of participants.26 This is certainly consistent with the possibility of collective effects, but as Dr. Schürmann has pointed out in his contribution, the transition from an $A^4$ to an $A^5$ or $A^2$ dependence could also be characteristic of an increased
incidence of multiple collisions, as might be expected in a central interaction of heavy nuclei.

**Charge dependence.** Another interesting feature of the La+La data is the charge dependence of the pion cross sections (Figure 6). This has been previously observed in light systems at forward angles. The observation of strong charge dependence at rapidities well-separated from the beam and target probably reflects the much greater charge of the La-La system. A number of models have been put forth to account for this phenomenon. For example, Gyulassy and Kauffmann and Bertsch have explained some of the data in terms of Coulomb distortion. Recently, Bonasera and Bertsch have combined Coulomb distortion with the compound nucleus model which has been successful in accounting for pion production at lower energies. The observed charge dependence may well turn out to be a convolution of effects acting at different stages of the pion production and emission process which, if it can be successfully unfolded, could give insight into the space-time structure of the interaction. To this end, it is probably best to study heavy, highly charged systems, where the charge dependence is strongest.

A complete understanding of the mass and charge dependence of subthreshold pion production will require additional data. Essentially, we want to fill in the gaps in Figure 1 by obtaining data for all three pion charge states for A > 40 at beam energies between 25 and 250 MeV/nucleon. In the near term, these experiments will continue to be done at the Bevalac. However, the low cross sections for subthreshold production make it desirable to have much higher beam intensities than presently available. Fortunately, we can look forward to these higher intensities at SIS-18 and (hopefully) at an upgraded Bevalac.

The data for pion production from La+La collisions at 138, 183 and 246 MeV/nucleon and from Ne+NaF collisions at 244 MeV/nucleon was taken at the Bevalac by an LBL/MSU/LSU/Clermont-Ferrand collaboration. A full list of collaborators is given in Ref. 26. In particular, I'd like to acknowledge contributions to the data analysis by G. Claesson and G. Landaud, and many helpful discussions with W. Benenson, G. Roche and L.S. Schroeder. I'd also like to thank the members of the INS/LBL group for their collaboration in setting up the detector system, and for allowing us to use some of their data prior to publication.

**References**

Figure 4.

Figure 5.
Figure 6. Charge dependence of subthreshold pion spectra from three systems:
(a) Ne+NaF at 0° (Ref. 33), (b) C+C at 0° (Ref. 34) and (c) La+La at θ_{c.m.} = 30° - 90° (Ref. 26).
Note the apparent inconsistency between (a) and the inset in (b). (Both plots are in the projectile frame.) This has not yet been resolved.