ISOSPIN EFFECTS ON PION PRODUCTION BY HEAVY IONS

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Cross section ratios π^-/π^+ for pions produced in heavy ion reactions are calculated in the statistical model, using measured absorption cross section ratios, and a simple model for the level density ratio We find overall agreement for data in the energy range 80–400 MeV/nucleon for systems ranging from $^{12}C + ^{12}C$ to $^{139}La + ^{139}La$.

In recent years much experimental data on subthreshold pion production has become available [1-3]. Many different theoretical models have been proposed to explain the data [8-15]. These models have a different underlying physical assumption such as first chance N–N collision [12,13], thermal evaporation [5-7], cluster formation [11], bremsstrahlung [10] and so on. Even though the proposed mechanisms are different, they all seem to explain most (if not all) of the available data. Often these models contain parameters or "ad hoc" assumptions that makes difficult to judge their validity. The purpose of this note is to extract from experimental data some quantity that could be directly compared with the basic assumption of the various models. In particular, we will compare the ratio of the π^- to π^+ double differential cross section to the calculated ratio from the evaporation model.

In the Weisskopf model [12] the probability of evaporation of a pion of mass m and kinetic energy e is given by

$$W_{if} = \frac{\rho(U)}{\rho(E)} \frac{(2s+1)m}{\pi^2} \sigma_{fi}^{abs} e , \tag{1}$$

where $\rho(U)$ is the level density of the evaporation residue, $\rho(E)$ is the same quantity for the compound nucleus, σ_{fi}^{abs} is the cross section for π absorption from the compound nucleus, s is the intrinsic spin. If we consider the evaporation of a π^+ or a π^- from a compound nucleus, the ratio of the pion productions for a given pion kinetic energy is

$$R_{-/+} = \frac{\rho^-(U)/\rho(E)}{\rho^+(U)/\rho(E)} \frac{\sigma_{\pi^-}^{abs}}{\sigma_{\pi^+}^{abs}} = \frac{\rho^-(U)}{\rho^+(U)} \frac{\sigma_{\pi^-}^{abs}}{\sigma_{\pi^+}^{abs}} , \tag{2}$$

$\rho(E)$ is the level density of the initial compound system, which is the same whether the decay is by π^+ or π^-. The difference in the final level density is due to the difference in the chemical potentials of neutrons and protons.

We can express the ratio of the final level densities as [4]

$$\frac{\rho^-(U)}{\rho^+(U)} = \exp[-2(\mu_p - \mu_n)/T] , \tag{3}$$

where $\mu_p - \mu_n$ is the difference in chemical potentials between protons and neutrons, and T is the temperature of the compound system. There are several effects contributing to the difference in chemical potential, namely the Coulomb potential, the nuclear symmetry potential and the Fermi energy [13,14]. For stable nuclei in isolation these contributions nearly cancel, so we need only consider changes due to the heavy-ion collision. The most important is the different Coulomb field, which now is that of the combined system. We estimate the change for identical projectile and target as

$$\Delta(\mu_p - \mu_n)_{Coul} = \frac{1.44Z}{r_0 A^{1/3}}(2^{2/3} - 1),$$

$$r_0 \approx 1.25 \text{ fm} , \tag{4}$$

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where Z and A are the charge and mass number of the projectile or target. This is just the difference in Coulomb energy of the separated nuclei, and the combined system at normal density.

The nuclear symmetry potential and Fermi energies can change if the density of the emitting system is different from ordinary nuclear matter density. Probably the pions are emitted early in the collision when the density would be higher than normal. This would increase the Fermi energy difference, which goes in the opposite direction to the Coulomb energy. However, we do not feel we can make any quantitative estimate of compressional effects, so we will use eq. (4) in our comparison,

$$\mu_p - \mu_n \approx \Delta(\mu_p - \mu_n)_{Coul} .$$

The final expression for $R_{-/+}$ is

$$R_{-/+} = \frac{\sigma_{\pi^-}^{abs}}{\sigma_{\pi^+}^{abs}} \exp[-2(\mu_p - \mu_n)/T] . \quad (5)$$

The temperature is determined from the average experimental slope, some of the used values are given in table 1 [1-3].

Notice that $R_{-/+}$ increase with increasing energy for a fixed ratio of the absorption cross sections, i.e. fixed pion kinetic energy.

The absorption cross sections are taken from refs. [15-17]. However, since the existing data regards only a few systems we will adopt the following parametrization. For a fixed pion kinetic energy, the relationship between the mass number and the absorption cross section is given by

$$\sigma_\pi^{abs} = KA^b . \quad (6)$$

K and b are parameters fitted to the data, A is the mass number of the compound nucleus. The values of the parameters are listed in table 2.

Set I is calculated from the data of ref. [15], while set II is obtained from refs. [16,17]. The parameter b lies between 2/3 and 1, which are the extremes characterizing strong surface absorption and weak volume absorption.

In fig. 1, we plot the experimental ratio for the reaction ^{138}La+ ^{138}La at $E_{lab}=246$ MeV/nucleon [3] (□) together with the model predictions. The average estimated temperature is in this case $T\approx 29$ MeV. The calculation using set I in table 2 gives a good agreement with the trend of the data, slightly underpredicting the ratio. Note, that using set II we obtain a slightly smaller result at higher energies than set I.

The interesting predictions of eq. (5) is that for lower beam energies the ratio should be smaller and eventually, at low enough beam energy, more π^+ are created than π^-. In table 1 we compare the result of our calculation with different data. The ^{138}La+ ^{138}La experiment at 138 MeV/nucleon gives a ratio that is smaller than in the previous case, fig. 1. Again the theory underpredicts the ratio. The theory of ^{12}C+ ^{12}C case at 85 MeV/nucleon predicts more π^+ production than π^-. In this case the experimental ratio is somewhat less than theory. For the reaction Ne+NaF the experimental ratio is greater than 2 at $E_{lab}/A=400$ MeV, while it is definitely smaller than 1 at $E_{lab}/A=100$ MeV ($T_\pi^{CM}\approx 30$ MeV). However, since in the last case the data are taken at 0°, it is quite difficult to extract the value of the slope, therefore we cannot determine an empirical temperature. Data on ^{138}La+ ^{138}La at $E_{lab}\approx 40$ MeV/nucleon would be a definitive check of this model.

In conclusion, we have shown that a simple estimate based on the statistical model, using measured

Table 1
Ratio π^-/π^+ extracted from the data of refs. [1-3] compared with the calculation assuming evaporation from the compound nucleus π-absorption cross sections are calculated using eq (11)

T_π^{CM}	$R_{-/+}^{exp}$	System	$\rho^-(U)/\rho^+(U)$	$R_{-/+}^{theory}$	T
55	1 2±0.6	La(138 MeV/A)	0.48	0.9	20
70	1 2±0.6	La(138 MeV/A)	0.48	0.8	20
125	0.7±0.5	La(138 MeV/A)	0.48	0.6	20
37	0.8±0.1	C(85 MeV/A)	0 78	1 3	14
50	0.7±0 1	C(85 MeV/A)	0.78	1.1	14
70	0.6±0 1	C(85 MeV/A)	0.78	0 9	14

Table 2
Parameters fit to the data of ref [15], set I, and refs. [16,17], set II. The symbols + and − refer to the charge of the pions.

	T_π	b^+	K^+	b^-	K^-
set I	37	0.799	12.11	1.000	10.80
	52	0.697	24.50	0 833	22.12
	68	0 621	36.35	0.805	23 90
	83	0.629	37.76	0 780	25.64
	100	0 646	35 06	0.751	28 52
	125	0.671	32 26	0.731	29 43
	151	0.674	32.09	0 759	24.20
	187	0.695	28.10	0.793	17.46
	233	0 692	24.24	0.735	21 56
	280	0.694	22.40	0 765	16.12
set II	50	1.162	3 77	1.099	14 33
	125	0.731	28.34	0.713	34.14
	165	0.746	29 42	0.634	41.63

absorption cross section ratio, and a simple model for the level density ratio, reproduces the general trends of the data. The slight disagreement, if significant, might indicate the importance of omitted terms in the chemical potential or of direct mechanisms for pion production.

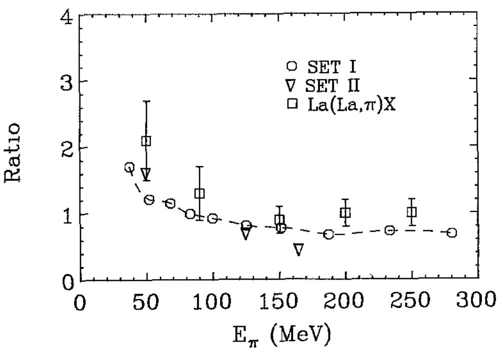

Fig. 1. π^-/π^+ ratio for the reaction La+La at 246 MeV/ A [3] (□) compared with results of our calculations using set I (○) [15] and set II (▽) [16,17].

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