Emitted High Energy Light Particle Data Base Development Using a Thermodynamic Coalescence Model

M PourArsalan, LW Townsend
The University of Tennessee
Knoxville, TN USA
ltownsen@utk.edu

ABSTRACT: In many applications, double-differential (energy and angle) secondary light particle production cross sections must be known for ion energies from tens of MeV/nucleon to tens of GeV/nucleon. Incorporating high energy light particle spectral and angular distribution cross section databases in the transport codes enable them to transport nearly any radiation field, in three dimensions, that humans and instruments might be exposed to in space, near accelerators or during charged particle radiotherapy. In this work a thermodynamics coalescence model is used to estimate the coalescence and emitting source radii for both symmetric and asymmetric heavy ion collision systems.

1- INTRODUCTION

The NUCFRG series of nuclear fragmentation codes [1-5] were developed at NASA Langley Research Center in the mid 1980’s in order to generate nuclear fragmentation cross section data bases for Galactic Cosmic Ray (GCR) transport codes. Such cross section databases are essential for space radiation protection studies for future long duration missions to Mars and beyond in order to identify and design adequate shielding to protect human crews and instruments from harmful space radiation. NUCFRG codes use an abrasion-ablation model of heavy ion fragmentation [6] to give reasonable estimates of isotopic production cross sections. Since secondary high-energy light particles penetrate deeper into the shielding over most of the forward hemisphere and may significantly contribute to radiation exposure, improvements to the light ion production cross section formalism in NUCFRG3 requires improved methods of estimating the coalescence radii used in the model. The work reported herein is the first step in improving these radii estimates.

The abrasion-ablation model (Figure 1) describes a two stage process that involves the collision between two relativistic heavy ions. In the first stage, the abrasion process, a relativistic projectile P, moving at some initial momentum, $p$, with respect to the stationary target T, collides with the target, and their overlapping volumes shear off. The sheared off volume has nucleon contributions from both projectile P and target T. It is called the participant region (C). In the second stage, the non-overlap piece of the projectile P, the projectile spectator, is in an excited state and continues in the direction of the pre-collision projectile. The excited projectile and target spectators decay by emitting gamma rays and/or disintegrate into lighter particles and nucleons. An overview of these models is presented in Ref. [7].

In the abrasion-ablation model of heavy ion fragmentation the participant region (region of overlapping nuclear volumes) is roughly spherical, extremely hot and compressed, expands violently outwardly and in the process cools off. It then becomes less dense and emits high
energy secondary light particles (deuterons, tritons, helions, and alpha particles) in the spherical regions where the relative momentum of the nucleons is less than the coalescence radius. High-energy light particles, which are emitted from participant regions, are emitted over most of the forward hemisphere. The expansion, cooling and high-energy secondary light particle emissions continue until the system reaches the freeze out radius where nucleons fly outward freely and coalescence ceases. Most of the light energetic particles are emitted as the hot and dense source region forms and starts expanding. Alpha particles may be emitted at the early stages of expansion because alphas have a high binding energy (28.3 MeV), while the deuterons with much lower binding energy (2.2 MeV) may be emitted in all stages of the expansion. Deuterons emitted in the early stage of the expansion, may coalesce with other nucleons to form heavier particles or they may break up into nucleons [9].

The energy, projectile and target dependent probability of the high energy secondary light particle emissions and the radius of the region emitting these secondary light particles can be related with a coalescence model [9-11]. The coalescence model is a pure phase space approach and makes no assumptions about the dynamics of the emitting source region. It involves a single free parameter namely the coalescence radius, $P_0$, which is the radius of the sphere in momentum space within which nucleons that are spatially close together coalesce to form high-energy secondary light particles. After the participant region reaches the freeze out radius, nucleons will not coalesce anymore and nucleons then freely fly outward.

The thermodynamic coalescence model [9-11] is based on the assumption that any two nucleons with relative momentum less than the coalescence radius, coalesce to form a deuteron, any three nucleons within a different coalescence radius in momentum space form a triton and so forth. In the thermodynamic model, the invariant phase space density of the formed light particles $d^3N_A/d^3p_A$ (number of nuclei per event per unit element of momentum space) and the phase space proton density $d^3N_p/d^3p$ (number of protons per event per unit element of momentum space), where $A$ is the emitted secondary light particle mass number, which can be related to the volume $V$ of a sphere with average radius $R$, where chemical and thermal

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**Figure 1** Schematic of abrasion-ablation model and the corresponding momentum distributions at different steps. The two-step model is shown as projectile $P$ colliding with target $T$ in the first step. Consequently, the system partitions into projectile prefragment $(A)$, target spectator $(B)$ and participants $(C)$. The pre-fragment then decays to the ground state by emitting secondary particles and gamma rays. The figure is adapted from Giacomelli et. al [8].
equilibrium of the emitting source region is maintained. The volume, $V$, is inversely related to
the coalescence radius $P_0$. Beginning in the early 1970’s, thermodynamic coalescence models
[9] were used to estimate the emitting source size. These emitting source radius estimates were
reasonable and much simpler to calculate than using other methods, such as the Hanbury, Brown
and Twist method (HBT method) [12-17].

A power law formula connects the secondary light particle emission cross section with the
proton cross section raised to the $A^{th}$ power where $A$ is the mass number of the secondary light
particle [9,11,18-20]. Volume, $V$, in the thermodynamic coalescence model reflects the largest
volume where chemical and thermal equilibrium is maintained and is different for different
projectile-target systems. The volume of the emitting light particle region is inversely related to
the cube of the coalescence radius. The source size of the nearly spherical region emitting the
high-energy secondary light ions can be estimated [21]. However, only a limited number of
experimentally measured multiplicities for the emitted secondary light particles for heavy ion
collision systems are available.

Rather than using the sparse experimental cross section database to extract $P_0$ we approach
the problem from the opposite direction. We use a coalescence model to estimate the coalescence
radius for a wide range of relativistic heavy ion collision systems. The coalescence radius
estimates in turn will be integrated into the coalescence model in the NUCFRG series of nuclear
fragmentation codes [1-4] to calculate spectral and angular cross sections for the emitted high
energy secondary light particles in the relativistic heavy ion collision systems for both symmetric
and asymmetric systems from tens of MeV/nucleon to tens of GeV/nucleon.

In the coalescence model, high-energy secondary light particles are mainly emitted from
the participant region. Therefore, we will estimate the average participant mass contribution from
the projectile and target [21-23]. Then we use the average participant mass to estimate the
emitted secondary light particle source radius [21]. Therefore, the main objective of our study is
to develop a methodology that can be used to calculate spectral and angular cross section
estimates of emitted high energy secondary light particles using an analytical thermodynamic
coalescence model [21]. Total light ion production cross sections can be estimated after the
present model of the coalescence radius is integrated into the NUCFRG code at NASA Langley
Research Center in the near future.

The outline of the paper is as follows: (1) overviews of the NUCFRG models and codes
are explained in section 2; (2) a historical overview of the coalescence model is discussed in
section 3; (3) then, we present the models used to estimate the coalescence radius using a
thermodynamic coalescence model and estimate the source radius in section 4; (4) in section 5,
our source radii estimates and coalescence radii are presented, discussed and compared with
results from other analyses; (5) finally, in section 6, a summary of this work is presented.

2- NUCFRG MODELS AND CODES

2.1 NUCFRG Models and Codes

An abrasion-ablation model [6] of heavy ion fragmentation is used in the NUCFRG codes
in order to estimate isotopic production cross sections in reasonable agreement with the
experimentally measured isotopic production cross section databases. The NUCFRG2 model [2,
3, 5] was an improved version of the classical geometric overlapping approach presented in the
abrasion-ablation model of Ref. [6]. The cross section predictions by Townsend and Cucinotta
[1] showed that using NUCFRG2 yielded general agreement within ~25% with published
There were also better agreements between predictions and measurements for elemental production cross-sections. Although, the NUCFRG2 version accounts for all fragment yields with mass number $A > 4$ with reasonable accuracy, it poorly predicted the nuclear yields for light ion fragments [4]. Thus, there is a need to incorporate better methods for predicting production cross section for mass numbers 2, 3 and 4 into the NUCFRG2 code. This work estimates production by coalescence of high-energy secondary light particles emitted from the participant region. Since the NUCFRG2 code is based on a semi-empirical formulation, the resulting predictions are in the form of total yields and production cross sections. The model does not yet include the calculations of spectral or angular distributions for the secondary fragments. For future long duration space applications using three dimensional transport models, the contributions of secondary high-energy heavy-ion particles and light ion particles at all angles are essential and a means of incorporating differential energy and angular production cross sections into the model is needed. Once the current coalescence model is incorporated into the newly-released NUCFRG3 code [5], an improved method for predicting secondary light particles emission from participant region by coalescing nucleons will be available in that code.

3- COALESCEENCE RADIUS OVERVIEW

Coalescence models have been used to predict secondary light particle production in heavy ion collision systems for nearly fifty years. The concept of secondary light particle production by coalescence in high energy heavy ion collisions was initially proposed to account for the emission of deuterons in reactions induced with protons at energies of 25-30 GeV [24, 25]. Butler and Pearson [24] related the deuteron density in the momentum space to the square of the proton density in the momentum space. Schwartzschild and Zupanic [25] extended it to secondary light particle emissions in nucleon-nucleus collisions. The concept was then extended to high-energy heavy ion collisions [18-19, 26-27]. Based on the theoretical formalism presented by those studies, Awes and others [26-30] have applied the coalescence model to the emission of high-energy secondary light particles in high-energy heavy ion collisions. Awes et. al [29, 30] introduced the coalescence model using a Poisson distribution to calculate the composition of the secondary light ions. Detailed derivations of a simple coalescence model are presented in [7, 21, 30]. All commonly used coalescence models can be grouped into four different types [31]. A brief description of each group with their assumptions is presented in [21].

4- COALESCEENCE RADIUS AND EMMITTING SOURCE RADIUS ESTIMATES USING A THERMODYNAMIC COALESCEENCE MODEL

4.1 Emitting Source Radius

The coalescence radius is inversely related to the emitting secondary particle source radius. Therefore we will first analytically estimate the source radius. The emitting source radius in this work is defined as the average radius corresponding to the largest participant volume where chemical and thermal equilibrium are maintained. The source radius can be estimated using the cube root of the average participant mass using (4.1.1). The coefficients $a$, $c$, $e$, and $g$ are independent of beam energy, but are slightly different for different group collision systems. They also vary slightly for different emitted secondary light particles. Collision systems are divided into seven groups, incremented by 30 mass units, according to the collision system average mass (csam), which is calculated using $csam = (A_P + A_T)/2$. Group 1 contains systems where $csam \leq 30$; group 2 contains $30 < csam \leq 60$, and so forth.
\[ R(\text{fm}) = a \left( A_{\text{Participant}} \right)^{1/3} + b \quad \text{for} \quad ^2\text{H} \]
\[ R(\text{fm}) = c \left( A_{\text{Participant}} \right)^{1/3} + d \quad \text{for} \quad ^3\text{H} \]
\[ R(\text{fm}) = e \left( A_{\text{Participant}} \right)^{1/3} + f \quad \text{for} \quad ^3\text{He} \]
\[ R(\text{fm}) = g \left( A_{\text{Participant}} \right)^{1/3} + h \quad \text{for} \quad ^4\text{He} \]

where \( a, c, e, \) and \( g \) are constants, but are slightly different for different collision system groups. \( A_{\text{Participant}} \) is the participant average mass number [21]. The constants are chosen such that the coalescence radius estimates are comparable to estimates from other analyses for the same system. Note that, the average participant mass is the same if the beam and the target are exchanged. Therefore the computed source radius will be the same if the projectile and target are switched.

4.2 Coalescence Radius Estimates Using the Thermodynamic Coalescence Model

We use a thermodynamic coalescence model to estimate emission source and coalescence radii. It is assumed that light energetic particles are formed in a bound state. In typical applications, it is also assumed that nucleons fill the chemical and thermal equilibrium volume, \( V \), uniformly and freeze out happens suddenly (coalescence ceases at freeze out). It is also assumed that neutron and proton spectra have similar distributions and differ by a factor of the system neutron to proton ratio. Since \( P_0 \) contains other implicit factors such as a spin alignment factor and phase factor [9]. Spin alignment is included in order to give the correct spin of the secondary light particle to be formed. For secondary light particles this factor is \((2s + 2)/2^A\) where \( A \) is light particle mass number and \( s \) is secondary light particle spin in the ground state. The second factor to be accounted for is the phase space factor, \( A^3 \), which comes from \( dN / dp \). Thus we have the differential multiplicity for a light ion composite,

\[
\left( P_0 \right)^{A-1} = A^3 \left( \frac{2s + 1}{2^A} \right) \left( \bar{P}_0 \right)^{A-1}
\]

(4.2.1)

The coalescence model then becomes

\[
\frac{d^3N_A(Z,n)}{dp^3} = \frac{1}{N!Z!} \left( \frac{N_p + N_T}{Z_p + Z_T} \right)^N A^3 \left( \frac{2s + 1}{2^A} \right) \left( \frac{4\pi \gamma}{3} \bar{P}_0 \right)^{A-1} \left( \frac{d^3N_p(1,0)}{dp^3} \right)^A
\]

(4.2.2)

Comparing equation (4.2.2) with the thermodynamic model from Mekjian [7] we find

\[
\left( \frac{4\pi \gamma}{3} \bar{P}_0 \right)^{A-1} = \left( \frac{\gamma h^3}{V} \right)^{A-1} e^{BE_A} Z!N! \]

(4.2.3)

Hence the power law for the thermodynamic coalescence model is

\[
\frac{d^3N_A}{dp^3} = A^3 \left( \frac{N_p + N_T}{Z_p + Z_T} \right)^N \frac{2s + 1}{2^A} \left( \frac{\gamma h^3}{V} \right)^{A-1} e^{BE_A} Z!N! \left( \frac{d^3N_p}{dp^3} \right)^A
\]

(4.2.4)

Therefore we can estimate the coalescence radius as [21]
where

\[ P_0 = \left( A \right)^{\frac{1}{(A+1)}} \left( \frac{2S_A + 1}{2A} \right)^{\frac{1}{(A+1)}} \left( e^{\frac{BE_A}{E_\gamma}} \right)^{\frac{1}{(A+1)}} \left( \frac{9Y}{2\pi^2} \right)^{\frac{1}{3}} \frac{h}{R} \]  \hspace{1cm} (4.2.5)

\[ \text{BE}_A = \text{binding energy of the light particle emitted MeV} \]
\[ \langle r^2 \rangle = \text{root mean square radius} = \left( \frac{3}{5} \right) R^2 \]
\[ S_A = \text{spin of the light particle emitted in ground state} \]
\[ N = \text{neutron number of the light particle emitted} \]
\[ Z = \text{proton number of the light particle emitted} \]
\[ A = \text{mass number of the light particle emitted} \]
\[ \theta_{\text{ave}} = \text{emitting source average temperature} \]
\[ p = \text{momentum of the proton} \]
\[ p_{A} = A \times p \]
\[ p_{A_{\text{p}}} = \text{momentum of the light energetic particle emitted} \]
\[ V = \text{largest volume of emitting source region where thermal and chemical equilibrium is maintained} \]
\[ R = \text{largest average radius of emitting source region where thermal and chemical equilibrium is maintained} \]

Hence, the coalescence radius can be estimated using eq. (4.2.5) with source radius, R, given by the parameterizations in (4.1.1).

5-REPRESENTATIVE SOURCE AND COALESCENCE RADIUS ESTIMATES

5.1 Source Radii Estimates

Parameterizations presented in (4.1.1) are used to estimate source radii for emitted hydrogen and helium isotopes for a wide range of symmetric and asymmetric heavy ion collision systems. The source radii do not depend on beam energy. The beam energy per nucleon investigated ranged from 100 MeV/nucleon to 4 GeV/nucleon for C+C and Ne+U heavy ion collision systems. Source radius estimates increase as system size (projectile and target mass numbers) increases. Source radii are larger for symmetric systems compare to asymmetric systems with the same collision system mass. The rise and fall of source radii for csam<150 are directly related to the symmetry of the collision system. The coefficients a, c, e, and g are slightly larger for heavier collision systems and they are also different for different emitted secondary light particles. The source radii of emitted secondary light particles are plotted as a function of collision system average mass (csam) in Figure 2. As expected, source radii are largest for \(^2\)H and smallest for alpha particles for any heavy ion collision system, since alpha particles have the highest binding energy and deuterons have the lowest binding energy. Source radii increase as system size increases, also as expected.

To further illustrate these results, estimated source radii from this work are compared with other analyses for \(^{12}\)C+\(^{12}\)C [20], and \(^{20}\)Ne + \(^{238}\)U [9] in Table 1. Note that the source radii agree to within ±10% for both symmetric system (\(^{12}\)C+\(^{12}\)C) and asymmetric system (\(^{20}\)Ne + \(^{238}\)U). Our estimated source radii for deuterons are always higher. Our analysis did not consider deuteron breakup.
Figure 2 Emission source radius estimates vs. collision system average mass.

Table 1 Comparisons of source radius estimates from this work with estimates from Lemaire [20] for the $^{12}$C+$^{12}$C system at 800 MeV/nucleon, and with estimates from Mekjian [9] for $^{20}$Ne+$^{238}$U at 400 MeV/nucleon.

| Ion  | Source Radii (fm) for $^{12}$C+$^{12}$C | Source Radii (fm) for $^{20}$Ne+$^{238}$U |
|------|----------------------------------------|------------------------------------------|
|      | This Work | Lemaire [20] | Difference | This Work | Mekjian [9] | Difference |
| $^2$H | 3.2       | 2.9          | +10%        | 7.2       | 6.8          | +6%         |
| $^3$H | 2.7       | 2.6          | +4%         | 5.6       | 5.9          | -5%         |
| $^4$He| 2.6       | 2.6          | 0%          | 5.4       | 5.9          | -8%         |
| $^4$He| 2.1       | Not Available|             | 4.4       | 4.9          | -10%        |

The source radii in our calculations are the largest average source radii where chemical and thermal equilibrium are maintained. Other analyses [20] use the source radius right after collision, as it starts expanding. Thus source radii in this work are often larger. Still other analyses [9] use the freeze out radius. Thus, the source radii in this work are sometimes smaller than those other analyses.

5.2 Coalescence Radius Results

The thermodynamic coalescence model equation (4.2.5) is used to estimate coalescence radii for emitted secondary light particles for a wide range of heavy ion collision systems from alpha+alpha to Pb+U for both symmetric and asymmetric systems. The coalescence radius increases less than 6% as beam energy increases from 100 Mev/nucleon to 4 GeV/nucleon for Ne+NaF and Ne+U heavy ion collision systems. Thus, the coalescence radius is nearly independent of beam energy. However, the coalescence radius decreases as system size (projectile and target mass number) increases since the coalescence radius is inversely related to the source radius. Coalescence radii are generally lowest for emitted deuterons and highest for emitted alpha particles. Coalescence radii are plotted versus collision system average mass (csam) in Figure 3.
Figure 3 Coalescence radius estimates vs. collision system average mass. The peaks occur for asymmetric systems.

In this work coalescence radius estimates are lower for a symmetric collision system compared to an asymmetric system with the same collision system average mass. Coalescence radius estimates are compared for three collision systems with average mass of 150.0 in Table 2. Note that, as expected, the more symmetric system (Sm+Sm) yields a smaller coalescence radius for the same average system mass than the asymmetric system (Mn+Am).

Table 2 Coalescence radius estimates for three different collision systems having the same system average mass number

| Collision System | csam | Coalescence Radius $^2$H (MeV/c) | Coalescence Radius $^3$H (MeV/c) | Coalescence Radius $^3$He (MeV/c) | Coalescence Radius $^4$He (MeV/c) |
|------------------|------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| $^{55}$Mn + $^{245}$Am | 150.0 | 123                             | 133                              | 129                              | 141                              |
| $^{128}$Sb + $^{178}$Hf | 150.0 | 114                             | 124                              | 121                              | 131                              |
| $^{150}$Sm + $^{150}$Sm | 150.0 | 113                             | 123                              | 120                              | 130                              |

Thermodynamic coalescence model estimates of coalescence radii for $^{12}$C+$^{12}$C and $^{20}$Ne+$^{207}$Pb are compared with other analyses [20] in Table 3. Additional comparisons with other analyses are made in Ref. [21]. The estimated coalescence radii from this work for $^{12}$C+$^{12}$C are within ±8% of estimates from Lemaire et al [20]. For $^{20}$Ne+$^{207}$Pb the estimates from this work are smaller but are within 17% of estimates from Lemaire et al [20].

Table 3 Comparisons of the thermodynamic coalescence model estimates from this work with estimates from Lemaire et al [20] for the $^{12}$C+$^{12}$C and $^{20}$Ne+$^{207}$Pb systems at a beam energy of 800 MeV/nucleon.

| Coalescence Radii $^{12}$C+$^{12}$C | Coalescence Radii $^{20}$Ne+$^{207}$Pb |
|-----------------------------------|--------------------------------------|
| Thermodynamic Model (MeV/c) | Lemaire[20] (MeV/c) | Difference | Thermodynamic Model (MeV/c) | Lemaire[20] (MeV/c) | Difference |
| $^2$H | 280 | 304 | -8% | 170 | 205 | -17% |
| $^3$H | 284 | 280 | +1% | 172 | 199 | -14% |
| $^3$He | 288 | 280 | +3% | 171 | 189 | -9% |
| $^4$He | 333 | Not Available | | 202 | Not Available | |

For collision systems with mass numbers larger than 150, coalescence radius estimates are almost always within 20% of other analyses (see Ref. [21]). Space limitations preclude
presenting them here. Light ion production cross section comparisons with experiment will be presented elsewhere after the model is incorporated into the NUCFRG3 code.

6- CONCLUSIONS

Average participant mass can be used to analytically estimate the source radius for a wide range of heavy ion collision systems and energies. The method yields reasonable estimates within ±10% of other methods. Source radii are independent of the beam energy, but increase as system average mass number increases. Source radii also depend on the symmetry of the system. Symmetric collision systems have larger source radii than an asymmetric collision system of the same total system mass number.

The thermodynamic coalescence model can be used to estimate coalescence radii analytically for both symmetric and asymmetric systems from tens of MeV per nucleon to tens of GeV per nucleon. It yielded estimates within ±17% of other methods. The modeled coalescence radii increase by only 6% for beam energies from 100 MeV per nucleon to 4 GeV per nucleon. The coalescence radii decrease as system mass number increases and are smaller for a symmetric collision system than an asymmetric one of equal mass number. Since coalescence radii estimates are very sensitive to the estimated source radii, other estimates of estimating the source radius, such as using the Hanbury, Brown and Twist method (HBT), may improve coalescence radii estimates and should be investigated.

7- REFERENCES

1. Townsend, L. and F. Cucinotta, Overview of Nuclear Fragmentation Models and Needs. Adv Space Res, 1996. 17(2): p. 59-68.
2. Wilson, J., L. Townsend, and F. Badavi, A Semiempirical Nuclear Fragmentation Model. Nuc Inst Meth Phys Res B, 1987. 18: p. 225-231.
3. Wilson, J., J. Shinn, L. Townsend, R. Tripathi, F. Badavi, and S. Chun, NUCFRG2: A Semiempirical Nuclear Fragmentation Model. Nuc Inst Meth Phys Res B, 1994. 94: p. 95-102.
4. Miller, T., Comprehensive Cross Section Database Development for Generalized Three Dimensional Radiation Transport Codes. PhD Dissertation, Nuclear Engineering Department, The University Of Tennessee, Knoxville, TN, 2004. p. 1-133.
5. Adamczyk, A., R. Norman, S. Sriprisan, L. Townsend, J. Norbury, S. Blattnig, and T. Slaba, NUCFRG3: Light Ion Improvements to the Nuclear Fragmentation Model. Nuclear Instruments and Method in Physics Research A, 2012. 678: p. 21-32.
6. Bowman, J., W.J. Swiatecki, and T. Tsang, Abrasion and ablation of Heavy Ions. University of California, 1973. Report No. LBL-2908.
7. Sriprisan, S., An Improved Knockout-Ablation-Coalescence Model for Prediction of Secondary Neutron and Light-Ion Production in Cosmic Ray Interactions. Nuclear Engineering Department, PhD Dissertation, The University of Tennessee, Knoxville, 2008. p. 1-111.
8. Giacomelli, M., L. Sihver, J. Skvarc, N. Yasuda, R. Llic, Projectile like Fragment Emission Angles in Fragmentation Reactions of Right Heavy Ions in the Energy Region < 200 MeV/nucleon: Modeling and Simulations. Phys. Rev. C, 2004. 69(6): p. 1-11.
9. Mekjian, A., Explosive Nucleosynthesis, Equilibrium Thermodynamics, and Relativistic Heavy-Ion Collisions. Phys. Rev. C, 1978. 17(3): p. 1051-1070.
10. Mekjian, A., *Thermodynamic Model for Composite-Particle Emission in Relativistic Heavy-Ion Collisions*. Phys. Rev. Letters, 1977, 38(12): p. 640-643.

11. Gupta, S. and A. Mekjian, *The Thermodynamic Model for Relativistic Heavy-Ion Collisions*. North-Holland Publishing Co, 1981: p. 133-183.

12. Hanbury Brown, R., R. Q. Twiss, and P. Mag, *Radio Astronomy*, Nature, 1954, 45(): p. 663-682.

13. Hanbury Brown, R. and R.Q. Twiss, *Correlation Between Photons in Two Coherent Beams of Light*. Nature, 1956, 177(4497): p. 27-29.

14. Frodermann, E. and U. Heinz, *Photon Hanbury-Brown-Twiss Interferometry for noncentral Heavy-Ion Collisions*. Phys. Rev. C, 2009, 80: p. 44903-1 to 16.

15. Bozek, P., M. Ploszajczak, and R. Botet, *Two and Many Particle Correlations in Nuclear and High Energy Physics*. Phys. Reports, 1995, 252: p. 101-176.

16. Lisa, M., S. Pratt, R. Soltz, and U. Wiedemann, *Femtoscopy in Relativistic Heavy Ion Collisions: Two Decades of progress*. Annu. Rev. Nucl. Part. Sci, 2005, 55: p. 357-402.

17. Wiedemann, U. and U. Heinz, *Particle Interferometry for Relativistic Heavy-Ion Collisions*. Phys. Reports, 1999, 319: p. 145-230.

18. Gutbrod, H., *Final-State Interaction in the Production of Hydrogen and Helium Isotopes by Relativistic Heavy Ions on Uranium*. Phys. Rev. Letters, 1976, 37(11): p. 667-670.

19. Gosset, J., H. Gutbrod, W. Meyer, A. Poskanzer, A. Sandoval, R. Stock, and G. Westfall, *Central Collision of Heavy Ions*. Phys. Rev. C, 1977, 16(2): p. 629-657.

20. Lemaire, M., *Composite Particle Emission in Relativistic Heavy Ion Collisions*. Phys. Rev., 1979, 85B(1): p. 38-42.

21. Pour Arsalan, M., *Secondary Light Particle Data Base Development Using a Thermodynamic Coalescence Model*, Nuclear Engineering Department, PhD Dissertation, The University of Tennessee, 2012. p. 1-78.

22. Hufner, J., *Approach to Equilibrium Based on Microscopic Models of Nuclear Collisions*. Proc of 4th High Energy Heavy-Ion Summer Study, Berkeley, LBL-7766, 1978: p. 135.

23. Nagamiya, S., *Production of Pions and Light Fragments At Large Angles in High Energy Heavy Ion Collisions*. Phys. Rev. C, 1981, 24(3): p. 971-1009.

24. Butler, S. and C. Pearson, *Deuterons from High Energy Proton Bombardment of Matter*. Phys. Rev., 1963, 129(2): p. 836-842.

25. Schwarzschild, A. and C. Zupancic, *Production of Triton, Deuteron, Nucleons, and Mesons by 30-Gev Protons on Al, Be, and Fe Targets*. Phys. Rev., 1963, 129(2): p. 854-862.

26. Datta, S., R. Cindro, R. Auble, J. Ball, and R. Robinson, *Coalescence Model Analysis of Alpha Particle and Deuteron Spectra from energetic H.I. Collisions*. Physics Letters B, 1987, 192(3,4): p. 302-306.

27. Datta, S., R. Caplar, N. Cindro, R. Auble, J. Ball, and R. Robinson, *A Refined Coalescence Model for Intermediate-Energy Heavy-Ion Collisions, Application to Deuteron Spectra*. J. Phys G: Nucl. Phys., 1988, 14: p. 937-948.

28. Machner, H., *Fast Particle Emission from Nuclear Reactions*. Physics Reports, 1985, 127(5): p. 309-377.

29. Awes, T., *Precompound Emission of Light Particles in the $^{16}O-^{238}U$ at 20 MeV/nucleon*. Phys. Rev. C, 1981, 24(1): p. 89-110.

30. Awes, T., *Light Particle Emission in $^{16}O$ Reactions at 140, 215 and 310 MeV*. Phys. Rev. C, 1982, 25(5): p. 2361-2390.

31. Llope, W., *The Fragment Coalescence Model*. Phys. Rev C., 1995, 52(4): p. 2004-2012.