Source-Specific Neutron Detection Efficiencies of the TAMU Neutron Ball

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Abstract. In this paper, we report neutron detection efficiencies for the TAMU Neutron Ball located at the Cyclotron Institute at Texas A&M University. The results discussed are for symmetric reactions of ⁷⁰Zn, ⁶⁴Zn and ⁶⁴Ni at a beam energy of 35 MeV/nucleon. The overall neutron detection efficiency was found to be approximately 70%. We also briefly discuss the process of quasi-projectile (QP) reconstruction. The HIPSE-SIMON reaction simulation and de-excitation code is used in conjunction with a software filter which simulates the geometric and energetic acceptances of the Neutron Ball to provide QT (quasi-target) and QP-specific neutron detection efficiencies. These source-specific efficiencies can be used to estimate the number of free neutrons to associate with the QP during reconstruction of experimental data. With this information it is possible to study the decay processes of well-defined, exotic forms of nuclear matter.

1. Introduction
The NIMROD-ISiS (Neutron Ion Multidetector for Reaction Oriented Dynamics – Indiana Silicon Sphere) detector array [1], located at the Cyclotron Institute at Texas A&M University, has been a valuable tool in the study of the symmetry energy contribution to the nuclear equation of state [2-5]. Many experimental analyses of nucleus-nucleus collisions rely on precise reconstruction of the QP – the highly excited, forward-moving remnant of the projectile immediately after the collision [2]. By studying these QP’s, we can access the properties of exotic forms of nuclear matter at densities below nuclear saturation density. While the method for QP reconstruction can be found in literature [2,6,7], a detailed technique for associating detected free neutrons with the QP has not been previously published.

2. Overall Neutron Detection Efficiencies
The TAMU Neutron Ball is a ⁴π neutron detector modified from [8] and part of the NIMROD-ISiS array. The active volume is a liquid scintillator composed of ~0.3 wt% Gd doped 1,2,4-trimethylbenzene. The scintillation light is measured with photomultiplier tubes. A current schematic of the Neutron Ball is shown in figure 1.

![Figure 1](image-url)
Using the Neutron Ball, we can measure, event-by-event, the free neutron multiplicity resulting from a reaction. The efficiency of the scintillator and the efficiency of the Neutron Ball as a function of energy and angle from the target position are well established [9]. However, effective efficiencies for multifragmentation events and the sources produced in such events are advantageous in reconstructing the QP. The determination of these efficiencies, described in this paper, uses the HIPSE event generator [10] and the SIMON de-excitation code [11] for the symmetric reactions of $^{70}$Zn, $^{64}$Zn and $^{64}$Ni at a beam energy of 35 MeV/nucleon.

Only events with a reduced impact parameter between 5 and 9 were considered since the focus is on QP’s and QT’s which are produced in non-central collisions. The reduced impact parameter is defined as $b_{\text{red}} = \frac{10b}{r}$ where $b$ is the impact parameter of the collision and $r$ is the touching spheres radius. Once these events were selected, the neutron detection efficiencies were calculated by taking the ratio of neutrons that pass the filter and the number of neutrons produced. Table 1 gives the neutron detection efficiencies for events in the reduced impact parameter range which result in at least three fragments after de-excitation. Each event must also pass two software cuts – a sum $Z$ cut and a sphericity cut. The sum $Z$ cut is implemented to eliminate incompletely detected events and events that do not belong to the QP fragmentation mechanism. In order to pass the $Z$ cut, the sum of the $Z$’s of all fragments associated with the QP must be between 25 and 30. By imposing the sphericity cut we can limit ourselves to looking at events that result in a well-defined QP and that are thermally equilibrated [2]. A QP passes this sphericity cut if

$$Q = \frac{\sum p_{z,i}^2}{\sum p_{x,i}^2 + \sum p_{y,i}^2}$$ (2)

and $p_i$ is the momentum of a fragment that is associated with the QP.

Table 1. Neutron detection efficiencies of the TAMU Neutron Ball using HIPSE-SIMON simulations. Efficiencies are averaged over angle and energy and are given by reduced impact parameter from 5 to 9. Events have also been subjected to sum $Z$ and sphericity cuts. For systems and reduced impact parameters that have efficiencies listed as N/A, there are too few statistics to warrant an actual efficiency. All other efficiencies have statistical errors that are smaller or on the order of 1%.

| System       | $b_{\text{red}} = 5 - 6$ | $b_{\text{red}} = 6 - 7$ | $b_{\text{red}} = 7 - 8$ | $b_{\text{red}} = 8 - 9$ | Overall |
|--------------|--------------------------|--------------------------|--------------------------|--------------------------|---------|
| $^{70}$Zn + $^{70}$Zn | 69.0%                    | 69.4%                    | 69.5%                    | 69.4%                    | 69.1%   |
| $^{64}$Zn + $^{64}$Zn  | 68.7%                    | 68.7%                    | 68.9%                    | N/A                      | 68.7%   |
| $^{64}$Ni + $^{64}$Ni  | 68.7%                    | 69.1%                    | 69.0%                    | N/A                      | 68.8%   |

The reduced impact parameter allows us to compare the three different systems. The efficiency values are calculated using $\epsilon = \frac{N_{\text{det}}}{N_{\text{tot}}}$ where $N_{\text{det}}$ is the number of neutrons that pass the filter and $N_{\text{tot}}$ is the total number of neutrons produced in all events matching the reduced impact parameter bin. For the “Overall” efficiencies reported in table 1, all free neutrons from all events with reduced impact parameter 5-9 were considered. The neutron detection efficiencies are nearly independent of the system and reduced impact parameter within statistical uncertainty. The efficiencies reported in table 1 have been reproduced to within 2 % of the values shown using the CoMD (Constrained Molecular Dynamics) model.

It is important to know how the width of the measured neutron distribution is impacted by the finite efficiency of the Neutron Ball. In figure 2, the actual number of free neutrons produced in the event is shown as a function of the number of neutrons that pass the Neutron Ball filter for $^{70}$Zn + $^{70}$Zn events with reduced impact parameters between 5 and 9. For a given number of neutrons produced, the
distribution of neutrons detected is sharply peaked. For events which produce 5, 10 and 15 free neutrons the standard deviations in the number of neutrons detected are 1.02, 1.46 and 1.78 respectively.

![Figure 2. Plot showing the actual number of free neutrons in an event vs. the number that would be detected in the TAMU Neutron Ball. Results shown for HIPSE-SIMON simulation of $^{70}$Zn + $^{70}$Zn at 35 MeV/nucleon.](image)

3. Source-Specific Neutron Detection Efficiencies and QP Reconstruction

It is important to determine the make-up of the QP from the detected fragments so that the initial source can be determined. Experimentally, detected charged particles may be associated with the QP according to velocity cuts in which the velocity of each fragment in the beam direction ($v_z$) is compared to $v_z$ of the largest (projectile-like) fragment. The $v_z$ window of acceptance for fragments with $Z = 1$ is $(1\pm0.65)v_{z,PLF}$, for $Z = 2$ it is $(1\pm0.60)v_{z,PLF}$ and for $Z \geq 3$ the window is $(1\pm0.45)v_{z,PLF}$[2]. If the fragment passes the velocity cut it is associated with the QP during reconstruction. Each event also must pass the sum $Z$ cut and the sphericity cut described in the previous section. For the reconstruction of the QP in terms of its charge ($Z$) and the momentum vector, use of the charged particles alone is sufficient. For an accurate assessment of the composition ($N$ and $Z$) and the excitation energy, the free neutrons should be included. For any given $Z$, the QP has a range of masses. Figure 3 shows the mass distribution for QP’s with $Z=30$. The QP mass is calculated as the sum of the masses of the charged particles plus the mass of the free neutrons.

![Figure 3. HIPSE-SIMON simulation results for a $^{70}$Zn + $^{70}$Zn reaction at 35 MeV/nucleon beam energy. For QP’s with a fixed $Z$ ($Z = 30$ is shown in the figure), there is a distribution of masses. The QP’s in figure 3 are determined by a sum over charged particle fragments and free neutrons that we associate with the QP using velocity cuts.](image)

If the neutron velocity vectors are known, one could use a similar velocity cut on the neutrons in order to reconstruct the QP. Indeed, this can be implemented for the results of model calculations. The method of associating free neutrons with the QP using velocity cuts, though, cannot be used on experimental data since the Neutron Ball does not measure neutron energies. For this reason, a technique was developed to estimate the number of free neutrons that should be associated with the QP from the total number of detected free neutrons in an event[2]. This technique requires that we know source-specific neutron detection efficiencies. The HIPSE event generator is well suited for this purpose because of its ability to keep track of the sources of all emitted particles.
The total number of detected free neutrons can be written as [2]:

\[ n_{\text{det}} - n_{\text{background}} = n_{\text{QT}} \epsilon_{\text{QT}} + n_{\text{QP}} \epsilon_{\text{QP}} \]  
(2)

Where \( n_{\text{det}} \) is the detected number of free neutrons in the event, \( n_{\text{QT/QP}} \) are the numbers of free neutrons emitted by the QT, the QP. The \( \epsilon_{\text{QP/QT}} \) terms are the respective neutron detection efficiencies. The HIPSE code produces other sources in an event which most often correspond to neck clusters or evaporated fragments. The evaporated fragments can be ignored as sources of neutrons because of their small masses and their relatively low yield in multifragmentation events. For this analysis, we will not consider emission of neutrons from the neck region since the sphericity cut eliminates events with very elongated shapes. The \( n_{\text{background}} \) term is the background neutron multiplicity that is measured by the Neutron Ball. Experimentally, the background is determined using a 100 µs gate which opens immediately after the 100 µs event gate. For our analysis, however, we did not include a measurement of background neutrons. While consideration of these background neutrons would likely affect the event-by-event efficiencies, averaging over many events should effectively eliminate their significance.

We can approximate the ratio of neutrons emitted by the QT to the number emitted by the QP as the ratio of the number of neutrons in the target to the number of neutrons in the projectile, \( \frac{N_{\text{QT}}}{N_{\text{proj}}} \approx \frac{n_{\text{QT}}}{n_{\text{QP}}} \). Solving equation 2 for \( n_{\text{QP}} \) we get the following equation.

\[ n_{\text{QP}} = \frac{n_{\text{det}} - n_{\text{background}}}{\left( \frac{N_{\text{QT}}}{N_{\text{proj}}} \epsilon_{\text{QT}} + \epsilon_{\text{QP}} \right)} \]  
(3)

Using equation 3, we can estimate the number of free neutrons to add into the QP during reconstruction as long as we have QP/QT-specific detection efficiencies. For each fragment in an event, HIPSE designates the source from which it was emitted. To find source-specific efficiencies, the ratio of neutrons from each source type (QP or QT) that pass the filter in all events over the total number of neutrons that were emitted by that source type was taken. In table 2, the QP and QT specific neutron detection efficiencies are given.

| System     | HIPSE QP Neutron Eff. | Vcut QP Neutron Eff. | HIPSE QT Neutron Eff. |
|------------|------------------------|----------------------|------------------------|
| \(^{60}\text{Zn} + ^{60}\text{Zn}\) | 75.7%                  | 75.3%                | 62.7%                  |
| \(^{64}\text{Zn} + ^{64}\text{Zn}\) | 75.6%                  | 75.2%                | 62.2%                  |
| \(^{64}\text{Ni} + ^{64}\text{Ni}\) | 76.0%                  | 75.5%                | 62.4%                  |

Table 2 shows that the source-specific detection efficiencies are not dependent on the systems being analyzed. For the velocity cut QP neutron efficiency, neutrons were associated with the QP using a velocity cut similar to that used for the charged particles but corrected for the lack of Coulomb repulsion. The Coulomb boost in the QP frame was determined by taking the difference between the average energies of the protons and neutrons emitted by the QP:

\[ \langle E_{n}^{\text{QP}} \rangle = \langle E_{p}^{\text{QP}} \rangle - E_{c}. \]  
(4)
This extra Coulomb boost, $E_C$, was found to increase the emitted proton longitudinal velocity by 11% of the PLF’s longitudinal velocity on average. Therefore, the $v_z$ window for neutrons was set at $(1 \pm 0.49)v_{z, PLF}$. For the HIPSE QP and QT neutron efficiencies, neutrons were associated with the QP/QT based on their designation from HIPSE. As table 2 shows, the QP neutron detection efficiency is nearly identical for QP’s defined by HIPSE and QP’s defined by the velocity cut. The same velocity cut was implemented on neutrons produced using the CoMD model. Again, the values reported above were reproduced to within 2% using the CoMD code.

Equipped with the efficiencies reported in table 2, we can perform the QP reconstruction and take into account free neutrons. For each event generated by HIPSE, the total number of measured neutrons and the detection efficiencies were used to calculate the number of neutrons actually emitted by the QP using equation 3. For events in which we associate a specific number of free neutrons with the QP there is a distribution of actual free neutrons emitted by the QP. The results of the QP reconstruction are shown in table 3.

Table 3. Data shown for HIPSE-SIMON simulation of $^{70}$Zn + $^{70}$Zn at 35 MeV/nucleon. For events in which we add the specified number of neutrons to the QP, the average actual number of neutrons emitted by the QP is given along with the RMS width of that distribution.

| Neutrons Added to QP | Mean Actual Neutrons | $\sigma$ |
|----------------------|----------------------|---------|
| 0                    | 1.46                 | 1.1     |
| 1                    | 2.13                 | 1.21    |
| 2                    | 3.02                 | 1.64    |
| 3                    | 3.67                 | 1.68    |
| 4                    | 4.06                 | 1.75    |
| 5                    | 4.72                 | 1.88    |
| 6                    | 5.28                 | 1.97    |
| 7                    | 5.94                 | 2.04    |
| 8                    | 6.59                 | 2.14    |

As table 3 shows, we are able to predict the number of neutrons to associate with the QP to within 1 neutron of the actual number on average for events with between 3 and 6 neutrons added back into the QP. This corresponds to ~52% of the events analyzed. For events with between 0 and 8 neutrons added back into the QP we are able to get the actual number of QP neutrons to within 1.5 on average. This range corresponds to ~92% of the events analyzed. The width of the distribution of “actual neutrons” for each number of “associated neutrons” introduces uncertainty into the determination of the composition of the QP. In any analysis, the impact of this uncertainty on the results should be checked.

4. Conclusions

We have discussed, in detail, the procedure which we use to determine how many free neutrons to associate with a QP during reconstruction. HIPSE-SIMON was used to determine the overall and source-specific neutron detection efficiencies of the TAMU Neutron Ball. The method for neutron accounting in QP reconstruction presented in Reference [2] was found to be reasonably accurate and sufficiently precise as to allow for the study of well-defined QP sources. When applicable, the reported efficiencies evaluated using the HIPSE simulation code were reproduced to within 2% by CoMD. Future analysis of different simulation codes will help to determine if there may be more significant model dependencies.
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