Freeze-out configuration properties in the $^{197}$Au + $^{197}$Au reaction at 23 AMeV

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Data from the experiment on the $^{197}$Au + $^{197}$Au reaction at 23 AMeV are analyzed with an aim to find signatures of exotic nuclear configurations such as toroid-shaped objects. The experimental data are compared with predictions of the ETNA code dedicated to look for such configurations and with the QMD model. A novel criterion of selecting events possibly resulting from the formation of exotic freeze-out configurations, "the efficiency factor", is tested. Comparison between experimental data and model predictions may indicate for the formation of flat/toroidal nuclear systems.

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I. INTRODUCTION

The search for exotic nuclear configurations was inspired by J.A.Wheeler [1]. His idea was investigated by many authors who studied the stability of exotic nuclear shapes (see e.g. [2-4]). Theoretical investigations have shown that very exotic extra superheavy nuclei can be reached only if non-compact shapes are taken into account. Calculations for bubble structures showed that such nuclei can be stable for $Z > 240$ and $N > 500$ (see e.g. [5-7]). Recently it was found that for nuclei with $Z > 140$ the global energy minimum corresponds to toroidal shapes [8, 9]. In contrast to bubble nuclei, the synthesis of toroidal nuclei is experimentally available in collisions between stable isotopes.

To address this issue simulations were performed for Au + Au collisions in a wide range of incident energies using the BUU code [10, 11]. These calculations indicate that the threshold energy for the formation of toroidal nuclear shapes is located around 23 AMeV.

Also Improved Quantum Molecular Dynamics Model calculations performed for U + U collisions have shown a possible formation of toroidal freeze-out configurations above a specific collision energy for this heavy system [12]. Such toroidal-shape complex can be also created in macroscale in binary droplet collisions above some threshold velocity [13].

A number of observables were suggested as the signatures of noncompact freeze-out configurations. These were:

- Larger number of intermediate mass fragments should be observed than would be expected for the decay of a compact object;
- Enhanced similarity in the charge and size of the fragments should also be observed;
- Suppressed sphericity in the emission of fragments should be visible.

The simulations of decay process of different break up configurations using the ETNA code were performed to study the ability of the CHIMERA detector for recognition of non-compact configurations. Analysis of different observables have shown that a quantity named “the efficiency factor” of events with 5 heavy fragments can be used as a criterion of selecting events possibly resulting from formation of toroidal configurations [10, 17].

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II. EXPERIMENT AND DATA CALIBRATION PROCEDE

The experiment for the $^{197}$Au + $^{197}$Au reaction at 23 AMeV was performed at INFN-LNS Superconducting Cyclotron of Catania. During the experiment two gold targets were used: 164 and 396 $\mu$g/cm$^2$. The thinner target was used in calibration measurements and the thicker one in the production runs. Reaction products were detected with the CHIMERA multidetector [14, 15] that is used in the production runs. Reaction products were detected in telescope placed at $\theta = 5.2^\circ$ for Au + Au reaction at 23 AMeV.

In this work we report results of our analysis focused on the question of exotic configurations involving the breakup of the $^{197}$Au + $^{197}$Au system into 5 or more fragments. The experimental data are compared with model predictions. Conclusions regarding the shape of the freeze-out configuration are drawn.

This paper is organized as follows. In Sec. 2 we present the experiment and data calibration procedures. General characteristics of experimental data are shown in Sec. 3. The dedicated observables are discussed in Sec. 4. The conclusions are presented in Sec. 5.

FIG. 1: $\Delta E - E$ spectrum (upper panel) and the corresponding $Z$ spectrum (bottom panel) for fragments detected in telescope placed at $\theta = 5.2^\circ$ for Au + Au reaction at 23 AMeV.
The $t_0$ offset that must be determined for each detector individually. Moreover, $t_0$ depends on mass, charge and kinetic energy of the detected fragment. The $t_0$ values for well identified light fragments and Au-like nuclei fragments located at the left-hand-side edge of the $\Delta E-TOF$ distribution (see Fig. 2) are presented by color symbols in Fig. 2. For relatively light fragments a well tested parametrization of $t_0$ for CHIMERA detectors was proposed [21]. To calibrate $t_0$ for medium and heavy fragments in $^{197}$Au + $^{197}$Au experiments a new calibration method based on a functional dependence of $t_0$ on mass, charge and pulse-height-defect dependent kinetic energy was developed (see e.g. [28]) and applied in analysis of the ternary breakup experiment [21].

In the present analysis we use another method of the parametrization of $t_0$ offset:

$$t_0 = \begin{cases} t_{0, \text{sat}} & t_{0, \text{sat}} < \Delta t \\ t_{0, \text{sat}} - \Delta t & t_{0, \text{sat}} > \Delta t \end{cases}$$

$$\Delta t = B - A(1 - \exp(\gamma \cdot m)) \cdot \left(\frac{E}{E_{PT}}\right)^{(\alpha - \delta \cdot m)} \cdot \exp[-\left(\frac{E + (\beta + \mu \cdot m)E_{PT}}{E_{PT}}\right)^\gamma],$$

where $t_{0, \text{sat}}$ is determined for particles punching through the silicon detector. The $E_{PT}$ is the highest energy deposited by particles with mass $m$.

III. THE GENERAL CHARACTERISTICS OF EXPERIMENTAL DATA

In Fig. 3 two dimensional distribution mass versus parallel velocity of identified fragments is shown. Location of quasielastic Au peak is visible at mass around 200 and velocities close to the beam velocity ($v_p = 6.67 \text{cm/ns}$).
Peak corresponding to Au recoil fragments can be found at velocities close to zero. Here one can observe an underestimation of mass value for these fragments due to the imperfection of used $t_0$ parametrizations (see Eq. 2). At velocities between these two limits fragments originating from fission of the Au-like nuclei are located. One can also identify a separated region located at low masses and velocity close to center of mass velocity. This region correspond to the intermediate velocity source.

For the registered events we have constructed the plot presenting the dependence between the total charge of identified fragments, $Z_{tot}$, versus total parallel momentum of those fragments normalized to the beam momentum, $p_{\parallel, tot}/p_{proj}$ (see Fig. 1).

One can distinguish different regions on this plot. In the region of low values of total collected charge and low parallel momentum one observes the ridge corresponding to the badly detected events. In the region of total parallel momentum close to 1 and total collected charge close to the charge of projectile one observes the maximum corresponding to deep inelastic collisions where the target like fragment remains undetected. Region where the total detected charge is close to total charge of the system and the total parallel linear momentum is close to linear momentum of the projectile can be called as region of well reconstructed events. In our present analysis this region is selected imposing the conditions: $120 < Z_{tot} < 180$ and $0.8 < p_{\parallel, tot}/p_{proj} < 1.1$. The number of events fulfilling these conditions is equal $5.9 \times 10^6$.

For this class of well reconstructed events in the Au + Au reaction the multiplicity distribution of fragments with charge $Z_{frag} \geq 3$ and $Z_{frag} \geq 10$ are presented in Fig. 7. One can notice here that the number of events with five or more fragments corresponding to above charge thresholds is equal about 116 000 and 6 000, respectively.

IV. DATA ANALYSIS

Based on results of Ref. [18], [19] and [20], in analysis of ternary and quaternary events one expects the ob-
configurations are considered: (i) ball geometry with vol-
out configurations \[16\]. In this model three freeze out
clear system assuming compact and noncompact freeze
cions. The ETNA model can simulate the decay of nu-
for events with five and more fragmets we have compared
results of analysis of this particular class of reactions can
servation of binary deep-inelastic collisions followed by
breakup of one or both primary reaction products. Re-
results of analysis of this particular class of reactions can
be found in \[21\].

For the class of events with five fragments one can con-
ider at least two mechanisms responsible for the presence
of the fifth heavy fragment: (i) creation of the fragment
in the interaction region (intermediate velocity source)
for peripheral collisions or (ii) the multifragmentation of
the composite nuclear system formed in central collisions.

In order to investigate the reaction scenario responsible
for events with five and more fragments we have compared
experimental data with ETNA and QMD model predic-
tions. The ETNA model can simulate the decay of nu-
clear system assuming compact and noncompact freeze
out configurations \[16\]. In this model three freeze out
configurations are considered: (i) ball geometry with vol-
ume 3 and 8 times greater than normal nuclear volume
\(V_0\) (fragments uniformly distributed inside the sphere);
(ii) fragments distributed on the surface of the sphere
mentioned above (bubble configuration); (iii) fragments
distributed on the ring with diameter 12 fm and 15 fm
(toroidal configuration). In this model we consider events
corresponding to central collisions only (0-3 fm impact
parameter range).

In order to simulate the contribution from noncen-
tral collisions the QMD model \[29\] calculations were per-
fomed in the full impact parameter range 0 - 12 fm. In
our analysis the QMD code developed by Lukasik et al.
\[30\] was used. This code takes into account: (i) protons
and neutrons (in standard QMD each nucleon has an
effective \(Z/A\) charge); (ii) momentum dependent Pauli
potential (Skyrme + Coulomb + Symmetry + Surface
+ Pauli) is used instead of the Yukawa potential; (iii)
initial nuclei in their real ground states with minimum
energy (thanks to the Pauli potential) are prepared,(iv)
strict angular momentum conservation in collisions is ap-
plied; (v) to simulate the Pauli blocking: in Lukasik code
the overlap of 6-dimensional Gaussians is used, unlike in
standard QMD where overlap of appropriate spheres in
configuration and momentum space is included.

A. The shape sensitive observables

In our analysis several observables sensitive to the
freeze-out break-up configuration are investigated. As
a first, we consider the shape of events in the momentum
space \[31\]. The diagonalization of the momentum tensor
gives three eigenvalues \(\lambda_1\) and three eigenvectors \(\mathbf{c}_i\). The
sphericity and coplanarity variables are defined as:

\[
s = 1.5(1 - \lambda_1), \quad c = \frac{\sqrt{3}}{2}(\lambda_2 - \lambda_3),
\]

where \(\lambda_1 > \lambda_2 > \lambda_3\) are normalized to their sum.

In the coplanarity vs sphericity plane all events are lo-
cated inside a triangle defined by points (0,0), \(\left(\frac{1}{2}, \frac{\sqrt{3}}{2}\right)\),
and \((1,0)\). In Fig. 8 the \((s,c)\) distribution for experi-
mental data is compared to the ETNA model predic-
tions for Ball 8\(V_0\), Toroid 15 fm freezeout decay configura-
tions and with QMD predictions. In the case of ball geom-
etry the maximum of the corresponding distribution is
located in the centre of the triangle. For toroidal con-
figuration the distribution is located closer to the line
\((0,0), \left(\frac{3}{7}, \frac{3\sqrt{3}}{7}\right)\). One can see that the experimental distri-
bution looks very similar to QMD distribution which is
dominated by noncentral collisions contribution.

In order to reduce noncentral contribution we have in-
vestedig for the QMD model predictions the depend-
ence between flow angle, \(\theta_{\text{flow}}\), and impact parameter
(see Fig. 9 (panel a)), where \(\theta_{\text{flow}}\) is the angle between beam axis and the eigenvector \(\mathbf{c}_1\) for the largest
eigenvalue \(\lambda_1\). One can see on this plot that most noncentral
events are located at small \(\theta_{\text{flow}}\) angles. The similar
dependence is observed for experimental data between
\(\theta_{\text{flow}}\) and total transverse momentum, \(p_{\text{trans}}\), used as
impact parameter estimator (see Fig. 9 (panel c)). We
decide to reduce contribution of noncentral events both

![Fig. 7: (color online) Multiplicity distributions of fragments with \(Z_{\text{frag}} \geq 3\) (red histogram) and \(Z_{\text{frag}} \geq 10\) (blue histogram), respectively.](image1)

![Fig. 8: (color online) The coplanarity vs sphericity distributions for Ball 8\(V_0\), Toroid 15 fm, QMD and experimental data.](image2)
for experimental data and model predictions by using the condition $\theta_{\text{flow}} > 20^\circ$.

The $\delta$, and $\Delta^2$ observables as most sensitive to the shape of freeze out configurations were selected. The $\delta$ variable is related to sphericity and coplanarity variables. The $\delta$ variable measures the distance between a given point of the $(s,c)$ distribution and the line defined by points $(0,0), (\frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2})$. In the Fig. 10 (left panels) the $\delta$ distributions are presented for experimental data, ETNA model predictions for considered freeze-out geometries and QMD predictions. One can see here that the $\delta$ distribution for experimental data is similar to that corresponding QMD predictions. The biggest difference can be observed with the distribution for Ball 8V0 configuration.

The $\Delta^2$ variable used in our analysis gives a measure of the event flatness in the velocity space. For each event we are establishing the plane in the velocity space. The parameters of this plane are selected in the way that the sum of squares of distances between the plane and the endpoints $(v_{x,i}, v_{y,i}, v_{z,i})$ of velocity vectors reach the minimum value. This last quantity is called the $\Delta^2$ parameter and is defined as:

$$\Delta^2 = \min \sum_{i=1}^{N_{fr}} (d_i^2(A, B, C, D)),$$

where:

$$d_i = \frac{|A \cdot v_{x,i} + B \cdot v_{y,i} + C \cdot v_{z,i} + D|}{\sqrt{A^2 + B^2 + C^2}},$$

and parameters A, B, C, and D are the plane parameters. The plane parameters and the velocities of fragments are in the velocity of light units.

The $\Delta^2$ distributions are shown in Fig. 11 (right panels) for data and model predictions. One can see here that for $\Delta^2$ variable the biggest difference between experimental distribution and model predictions is observed for the Ball 8V0, Bubble 8V0 freeze-out geometries and QMD predictions. In contrast to that, the experimental data seem to be more consistent with the simulations assuming toroidal freeze-out configurations.

In relation with $\Delta^2$ parameter one can define an angle, $\theta_{\text{plane}}$, between the beam direction and vector normal to the plane defined by parameters A, B, C, and D. For events corresponding to noncentral collisions, where most of reaction products are located in the reaction plane, $\theta_{\text{plane}}$ should be close to 90°. This behavior is illustrated in Fig. 9 (panel b) for QMD model predictions, where most of noncentral events are located in the reaction plane. The similar dependence is observed for experimental data between $\theta_{\text{flow}}$ and total transverse momentum, $p_{\text{trans}}$, used as impact parameter estimator (see panel d).

The dependence between $\theta_{\text{plane}}$ and $\theta_{\text{flow}}$ for Ball 8V0, Toroid 15 fm, QMD and experimental data is presented in Fig. 11. One observe here that for experimental data most of events is located in the region selected by conditions $\theta_{\text{flow}} < 20^\circ$ and $\theta_{\text{plane}} > 75^\circ$. The same behavior is observed in the case of QMD calculations. These observations indicate that such events correspond to noncentral collisions. For the Ball 8V0 configuration one observes the correlation between $\theta_{\text{flow}}$ and $\theta_{\text{plane}}$ angles. For toroidal configuration the correlation between these angles is even stronger. Most of these events is located in the region defined by conditions $\theta_{\text{flow}} > 20^\circ$ and $\theta_{\text{plane}} < 75^\circ$.

Following the method proposed in Ref. 10 we select
events corresponding to a toroidal shape by the set of conditions:

$$\Delta^2 < 0.001 \, \sigma^2 \text{ and } \delta < 0.05.$$  (7)

As an efficiency measure of the above conditions we take ratio of number of events fulfilling the selection conditions to the number of events with five and more heavy fragments. Hereafter, this ratio is called the efficiency factor (EF).

The results of this procedure are presented in the Fig. 11 for different regions of $\theta_{\text{flow}}$ and $\theta_{\text{plane}}$ angles. As one can see the EF is very low for spherical freeze-out configurations with respect to the corresponding values for toroidal configurations.

For QMD calculations the value of the efficiency factor is strongly dependent on the $\theta_{\text{plane}}$ range. The condition $\theta_{\text{plane}} < 75^\circ$ reduces the number of flat noncentral events mostly located in the reaction plane. For events selected additionally by the condition $\theta_{\text{flow}} < 20^\circ$ the EF drops to zero.

For experimental data the value of the efficiency factor is about 50% for events located in the reaction plane ($\theta_{\text{plane}} > 75^\circ$) and is reduced by factor of 2 for events perpendicular to the reaction plane. These values are weakly dependent on the $\theta_{\text{flow}}$ angle range.

One observes that the values of the EF for experimental data are much larger than the correspondind predictions for QMD model. The biggest difference is observed for events located outside the reaction plane ($\theta_{\text{plane}} < 75^\circ$) at small $\theta_{\text{flow}}$ angles.

In order to investigate a possible formation of toroidal configurations in our analysis we selected the region where according to ETNA predictions the toroidal configuration is most pronounced in the $\theta_{\text{flow}}$ and $\theta_{\text{plane}}$ plane ($\theta_{\text{plane}} < 75^\circ$ and $\theta_{\text{flow}} > 20^\circ$). In Table I the efficiency factor values are given for experimental data and model predictions. The efficiency factor values are shown for four threshold values of the fragment charge.

From Table I we notice that the EF values for experimental data are very close to the model predictions for toroidal configurations. This observation may be one of arguments in favor of the formation of toroidal flat freeze-out configuration created in the Au + Au collisions at 23 AMeV.

$$\text{FIG. 11: (color online) The dependence between } \theta_{\text{plane}} \text{ and } \theta_{\text{flow}} \text{ for Ball 8V$_5$ (panel a), Toroid 15 fm (panel b), QMD (panel c) and experimental data (panel d).}$$

$$\text{FIG. 12: (color online) The EF values for different windows of } \theta_{\text{plane}} \text{ and } \theta_{\text{flow}}. \text{ The presented results were sorted using the condition } Z_{\text{frag}} \geq 10.$$
FIG. 13: (color online) The distributions of standard deviation of the fragment mass for non-flat events (red lines) and flat events (green lines) for experimental data (solid lines) and QMD model predictions (dashed lines).

All the distributions presented here are constructed using the condition $Z_{frag} \geq 10$.

B. Other observables

In order to get additional evidence to support the hypothesis that toroidal objects are created the behaviour of other observables was investigated. We consider here for each event separately: (i) standard deviation of fragment mass ($\sigma_A$), (ii) relative velocities of fragments pairs ($v_{ij}$), (iii) mean velocities of fragments as a function of their mass.

First we construct these observables for events selected by conditions $\theta_{flow} > 20^\circ$ and $\theta_{plane} < 75^\circ$, where observation of toroidal freeze-out configurations is expected. The distributions of these observables are generated for flat events selected by condition (7) (thick green histograms) and non-flat events (thin red histograms) selected by condition:

$$\Delta^2 > 0.001 \ c^2 \ \text{and} \ \delta > 0.05. \ \ \ \ (8)$$

Comparison of the $\sigma_A$ distributions (Fig. 13) for flat and non-flat events indicates that in the case of flat events this distribution is slightly shifted to larger values. This observation is in contrast with the expectation that for the flat events the enhanced similarity in the size of fragments should be visible. The corresponding distributions for QMD calculations are similar (dashed lines). Their centroids are shifted to smaller values with respect to experimental data.

In Fig. 14 one observes that the distribution of relative velocities $v_{ij}$ of fragments pairs for non-flat events (red lines) and flat events (green lines) for experimental data (points with error bars) and QMD model predictions (dashed lines) show a similar dependence. The corresponding distributions for Toroid 15 fm and Ball 8$V_0$ ETNA model predictions show a similar dependence. This observation may indicate that the behaviour of these $v_{ij}$ distributions is insensitive to the shape of the freeze-out configuration.

In Fig. 15 the distributions of mean velocities of fragments as a function of their mass for a flat and non-flat events are presented. On can observe that for flat events velocities of fragments decrease weaker with mass comparing to the same dependence for non-flat events. Comparison with same dependences presented for Pb + Ag and Pb + Au systems at 29 AMeV indicates that toroidal configurations may be created for some subclass of flat events.
Properties of flat events in the region where observation of toroidal freeze-out configurations is expected ($\theta_{\text{flow}} > 20^\circ$ and $\theta_{\text{plane}} < 75^\circ$) can be also compared with properties of flat events corresponding to other regions of $\theta_{\text{flow}}$ and $\theta_{\text{plane}}$ angles. Here the considered regions are the same as presented in Fig. 12. The distributions for $\sigma_A$ of fragments, and $v_{ij}$ of fragments pairs are presented in Fig. 16 using the condition $Z_{\text{frag}} \geq 10$. The mean values of these distributions are listed in Table II. We can notice here that the corresponding mean values of the distribution of $\sigma_A$ are similar for all $\theta_{\text{flow}}$ and $\theta_{\text{plane}}$ windows for a given threshold value of the fragment charge $Z_{\text{frag}}$. Such observation shows us that information carried by $\sigma_A$ can not be used as an indication of toroidal objects formation. For $v_{ij}$ distributions one observes that the mean values for class of events located outside the reaction plane are smaller in comparison to the case of events located in the reaction plane. The smallest mean values are seen for the region where observation of toroidal freeze-out configurations are expected. This observation may be used as an indication that for events located outside the reaction plane freeze-out configuration is more extended in comparison with that for events located inside reaction plane.

Results obtained for the considered observables suggest that the formation of toroidal configurations can be related to a fraction of flat events tilted with respect to the reaction plane ($\theta_{\text{plane}} < 75^\circ$). The probability for these events is much greater than the prediction of the QMD model. The nature of these events should be investigated.

Assuming that the total number of detected events corresponds to 80% of total reaction cross section, the cross section related to creation of flat tilted events located in the region where observation of toroidal freeze-out configurations is expected can be estimated to be equal 17$\mu$b.

### TABLE II: The mean values of mass standard deviation of the fragments, and of relative velocities $v_{ij}$ of fragments pairs for flat events located in different windows of $\theta_{\text{flow}}$ and $\theta_{\text{plane}}$ angles.

| Observable | Threshold | $\theta_{\text{flow}} > 20^\circ$ | $\theta_{\text{flow}} > 20^\circ$ | $\theta_{\text{flow}} < 20^\circ$ | $\theta_{\text{flow}} < 20^\circ$ | $\theta_{\text{plane}} > 75^\circ$ | $\theta_{\text{plane}} > 75^\circ$ | $\theta_{\text{plane}} < 75^\circ$ | $\theta_{\text{plane}} < 75^\circ$ |
|------------|-----------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| $\sigma_A$ (a.m.u.) | $Z_{\text{frag}} \geq 3$ | 72.09 ±0.47 | 71.09 ±0.35 | 76.43±0.52 | 73.33±0.13 | 47.01±1.88 | 47.15±1.33 | 46.41±2.68 | 45.06±0.58 |
| | $Z_{\text{frag}} \geq 10$ | 38.31±2.98 | 38.53±1.24 | 35.24±5.11 | 35.58±0.98 | 31.01±0.68 | 31.10±2.60 | 25.15±5.15 | 27.17±1.59 |
| | $Z_{\text{frag}} \geq 15$ | 17.51±5.07 | 18.95±5.86 | 20.94±4.82 | 18.50±2.23 | 3.01±0.01 | 3.17±0.01 | 3.27±0.02 | 3.36±0.01 |
| | $Z_{\text{frag}} \geq 20$ | 3.13±0.05 | 3.30±0.03 | 3.30±0.08 | 3.51±0.02 | 3.16±0.08 | 3.27±0.05 | 3.27±0.15 | 3.49±0.04 |
| | $Z_{\text{frag}} \geq 25$ | 3.14±0.24 | 3.25±0.11 | 3.24±0.52 | 3.50±0.06 | 2.98±0.31 | 3.28±0.33 | 3.26±0.81 | 3.46±0.13 |

We presented an analysis of events produced in Au + Au collisions at 23 AMeV. Basic information about data calibration procedure were summarized. The bulk properties of the experimental data were shown. The experimental data were compared with ETNA and QMD model predictions. Proximity of efficiency factor values for experimental data and toroidal freeze-out configurations may be used as an indication of the formation of an exotic freeze-out configuration. The juxtaposition of the standard deviation of fragment mass values for events located outside and inside the reaction plane are not suggestive of a toroidal freeze-out configuration. Comparison of distributions of relative velocities for event with different orientation in respect to reaction plane gives evidence that the freeze-out configuration is more extended for events located outside reaction plane. The behavior of mean velocities of fragments as a function of their mass for flat and non-flat events gives an indication that toroidal configuration may be created for some subclass of flat events.

The probability of apperence of these flat events is much greater than the prediction of the QMD model. The nature of flat events tilted with respect to the reaction plane should be investigated.

### VI. ACKNOWLEDGMENTS

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