Effect of isospin-dependent cross-section on fragment production in the collision of charge asymmetric nuclei

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Abstract. To understand the role of isospin effects on fragmentation due to the collisions of charge asymmetric nuclei, we have performed a complete systematical study using isospin-dependent quantum molecular dynamics model. Here simulations have been carried out for $^{124}X_n + ^{124}X_n$, where n varies from 47 to 59 and for $^{40}Y_m + ^{40}Y_m$, where m varies from 14 to 23. Our study shows that isospin-dependent cross-section shows its influence on fragmentation in the collision of neutron-rich nuclei.

Keywords. Heavy-ion collisions; multifragmentation; symmetry energy.

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1. Introduction

Heavy-ion collisions have been extensively studied over the last decades. The behaviour of nuclear matter under the extreme conditions of temperature, density, angular momentum etc., is a very important aspect of heavy-ion physics. Multifragmentation is one of the extensively studied fields at intermediate energies. One of the major ingredient in heavy-ion collisions is the symmetry energy, whose form and strength are two of the hot topics these days [1]. This quantity vanishes at a certain incident energy. Finite nuclei studies predict values for the symmetry energy at a saturation of the order of 30–35 MeV. In heavy-ion collisions, highly compressed matter can be formed for short time-scales. Thus, the study of such a dynamical process can provide useful information on the high-density dependence of symmetry energy. Even at low incident energies which belong to even smaller baryonic densities, the isospin dependence of the mean-field potential was shown to yield the same result obtained with potentials that have no isospin dependences. These results are in similar lines and they also indicate that even binary phenomena like fission will also be insensitive towards isospin dependence of the dynamics [2]. Recently, theoretical studies on the high-density symmetry energy have been started by investigating

heavy-ion collisions of asymmetric systems [3,4]. Comparisons of collisions of neutron-rich to that of neutron-deficient systems provide a means of probing the asymmetry term experimentally [5–7]. The experimental analysis of the isospin effects on fragment production has yielded several interesting observations: Dempsey *et al* [8], in their investigation of ^{124,136}Xe + ^{112,124}Sn at 55 MeV/nucleon, found that multiplicity of intermediate mass fragments (IMFs) increases with the neutron excess of the system. A more comprehensive study carried out by Buyukcizmeci *et al* [9] showed that symmetry energy of the hot fragments produced in the statistical freeze-out is very important for isotope distributions, but its influence is not very large on the mean fragment mass distributions. Effect of symmetry energy on isotope distributions can survive after secondary de-excitation. Moreover, Schmidt *et al* [10] in their investigation on the analysis of light charged particles production and isospin dependence of ^{124}Sn + ^{64}Ni, ^{124}Sn + ^{58}Ni, ^{124}Sn + ^{27}Al at 35 MeV/nucleon and 25 MeV/nucleon collisions found that isospin effects were demonstrated in the observables, such as the angular distribution of light particles emitted in central collisions at 35 MeV/nucleon and LCP emission. On the other hand, Tsang *et al* [11], in their investigation of ^{112}Sn + ^{124}Sn, ^{124}Sn + ^{112}Sn systems at an incident energy of $E = 50$ MeV/nucleon, showed the effects of isospin diffusion by investigating heavy-ion collisions with comparable diffusion and collision time-scales. They showed that the isospin diffusion reflects driving forces arising from the asymmetry term of the EOS. With the passage of time, isospin degree of freedom in terms of symmetry energy and nucleon–nucleon cross-section is found to affect the balance energy or energy of vanishing flow and related phenomenon in heavy-ion collisions [12]. Liu *et al* [13] studied the effect of Coulomb interaction and symmetry potential on the isospin fragmentation ratio $(N/Z)_{\text{gas}}/(N/Z)_{\text{liq}}$ and nuclear stopping R. They showed that Coulomb interaction induces important isospin effects on both $(N/Z)_{\text{gas}}/(N/Z)_{\text{liq}}$ and R. However, the isospin effects of symmetry potential and Coulomb interaction on $(N/Z)_{\text{gas}}/(N/Z)_{\text{liq}}$ and R are different.

Our present study will shed light on the effect of isospin on multiplicity of fragments produced in the collision of charge asymmetric colliding nuclei. We study the microscopic effect of isospin-dependent nucleon–nucleon cross-section on charge asymmetric nuclear matter. In this paper our aim is two-fold, one is to look for the effect of density-dependent symmetry energy on fragmentation and second is to look for the influence of isospin-dependent (σ_{iso}) and isospin-independent cross-sections (σ_{noiso}) on fragmentation due to the collision of charge asymmetric nuclei.

This study was carried out within the framework of isospin-dependent quantum molecular dynamics model that is explained in §2. The results are presented in §3 and the summary is presented in §4.

2. Isospin-dependent quantum molecular dynamics (IQMD) model

Theoretically, many models have been developed to study the heavy-ion collisions at intermediate energies. One of them is the quantum molecular dynamical (QMD) model [14,15], which incorporates N-body correlations as well as nuclear EOS along with important quantum features like Pauli blocking and particle production.

In order to explain experimental results in a much better way and to describe the isospin effect appropriately, the original version of the QMD model was improved which is known as isospin-dependent quantum molecular dynamics (IQMD) model.

The isospin-dependent quantum molecular dynamics (IQMD) [16] model treats different charge states of nucleons, deltas and pions explicitly, as inherited from the VUU model. The IQMD model has been used successfully for the analysis of a large number of observables from low to relativistic energies. The isospin degree of freedom enters into the calculations via both cross-sections and mean field.

In this model, baryons are represented by Gaussian-shaped density distributions

$$f_i(\vec{r}, \vec{p}, t) = \frac{1}{\pi^2 \hbar^2} e^{-(\vec{r}-\vec{r}_i(t))^2 (1/2L)} e^{-(\vec{p}-\vec{p}_i(t))^2 (2L/\hbar^2)}. \tag{1}$$

Nucleons are initialized in a sphere of radius $R = 1.12 A^{1/3}$ fm, in accordance with the liquid drop model. Each nucleon occupies a volume of h^3, so that the phase space is uniformly filled. The initial momenta are randomly chosen between 0 and Fermi momentum (p_F). The nucleons of the target and the projectile interact via two- and three-body Skyrme forces and Yukawa potential. The isospin degree of freedom is treated explicitly by employing a symmetry potential and explicit Coulomb forces between protons of the colliding target and the projectile. This helps in achieving correct distribution of protons and neutrons within the nucleus.

The hadrons propagate using Hamilton equations of motion:

$$\frac{dr_i}{dt} = \frac{d\langle H \rangle}{dp_i}; \qquad \frac{dp_i}{dt} = -\frac{d\langle H \rangle}{dr_i}, \tag{2}$$

with

$$\begin{aligned}
\langle H \rangle &= \langle T \rangle + \langle V \rangle \\
&= \sum_i \frac{p_i^2}{2m_i} + \sum_i \sum_{j>i} \int f_i(\vec{r}, \vec{p}, t) V^{ij}(\vec{r}', \vec{r}) \\
&\quad \times f_j(\vec{r}', \vec{p}', t) d\vec{r} \, d\vec{r}' \, d\vec{p} \, d\vec{p}'.
\end{aligned} \tag{3}$$

The baryon–baryon potential V^{ij}, in eq. (3), reads as

$$\begin{aligned}
V^{ij}(\vec{r}' - \vec{r}) &= V_{\text{Skyrme}}^{ij} + V_{\text{Yukawa}}^{ij} + V_{\text{Coul}}^{ij} + V_{\text{sym}}^{ij} \\
&= \left[t_1 \delta(\vec{r}' - \vec{r}) + t_2 \delta(\vec{r}' - \vec{r}) \rho^{\gamma-1} \left(\frac{\vec{r}' + \vec{r}}{2} \right) \right] \\
&\quad + t_3 \frac{\exp(|\vec{r}' - \vec{r}|/\mu)}{(|\vec{r}' - \vec{r}|/\mu)} + \frac{Z_i Z_j e^2}{|\vec{r}' - \vec{r}|} \\
&\quad + t_6 \frac{1}{\varrho_0} T_3^i T_3^j \delta(\vec{r}_i' - \vec{r}_j).
\end{aligned} \tag{4}$$

Here Z_i and Z_j denote the charges of the ith and jth baryons, and T_3^i, T_3^j are their respective T_3 components (i.e. $1/2$ for protons and $-1/2$ for neutrons). Meson potential consists of Coulomb interaction only. The parameters μ and $t_1, ..., t_6$ are adjusted to the real part of the nucleonic optical potential. For the density dependence of the nucleon optical potential, standard Skyrme-type parametrization is employed. The choice of the

equation of state (or compressibility) is still controversial. Many studies advocate softer matter, whereas, much more believe the matter to be harder in nature. We shall use the soft (S) equation of state that has the compressibility of 200 MeV.

The binary nucleon–nucleon collisions are included by employing the collision term of the well-known VUU–BUU equation. The binary collisions are done stochastically, in a similar way as are done in all transport models. During the propagation, two nucleons are supposed to suffer a binary collision if the distance between their centroids

$$|r_i - r_j| \leq \sqrt{\frac{\sigma_{\text{tot}}}{\pi}}, \qquad \sigma_{\text{tot}} = \sigma(\sqrt{s}, \text{type}), \tag{5}$$

where 'type' denotes the ingoing collision partners (N–N, N–Δ, N–π,..). In addition, Pauli blocking (of the final state) of baryons is taken into account by checking the phase-space densities in the final states. The final phase-space fractions P_1 and P_2 which are already occupied by other nucleons are determined for each of the scattering baryon. The collision is then blocked with probability

$$P_{\text{block}} = 1 - (1 - P_1)(1 - P_2). \tag{6}$$

The delta decays are checked in an analogous fashion with respect to the phase space of the resulting nucleons.

3. Results and discussion

To check the influence of density-dependent symmetry energy on fragmentation, we have simulated $^{124}\text{Sn}_{50} + ^{124}\text{Sn}_{50}$ and $^{107}\text{Sn}_{50} + ^{124}\text{Sn}_{50}$ reactions using isospin-dependent quantum molecular dynamics (IQMD) model at an incident energy of 600 MeV/nucleon for complete colliding geometry. The phase space generated using IQMD model has been analysed using the minimum spanning tree (MST) algorithm [16] and the minimum spanning tree with momentum cut [17] (MSTP). The results obtained are discussed as follows:

Figure 1 shows multiplicity of free nucleons (FNs), light mass fragments (LMFs) and intermediate mass fragments (IMFs) as a function of scaled impact parameters for $^{124}\text{Sn}_{50} + ^{124}\text{Sn}_{50}$ and $^{107}\text{Sn}_{50} + ^{124}\text{Sn}_{50}$. Our findings are as follows:

(1) The effect of symmetry energy is negligible for FNs, because FNs are produced from the violent collision zone where the effect of symmetry energy is negligible. In fact, the symmetry energy affects the production of LMFs more than that of the free nucleons [18]. Moreover, as we move from central to peripheral collisions, the free nucleons and LMFs decrease because the participation zone decreases which leads to lower number of free nucleons and LMFs. But for IMFs, the curve shows a 'rise and fall' because for central collision the overlapping of participant and spectator zone is maximum and we get very small number of IMFs. For semiperipheral collisions, the participant and spectator zones decrease and the production of IMFs increases and for peripheral collisions a very small portion of the target and the projectile overlap and so again only a few IMFs are observed and most of the fragments go out as heavy mass fragments (HMFs).
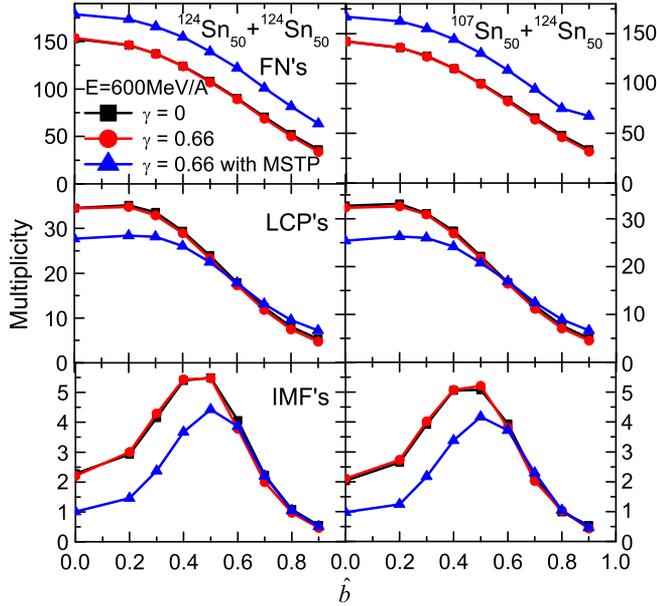
Figure 1. Multiplicity of free nucleons, LMFs and IMFs as a function of scaled impact parameter.

(2) Number of free nucleons, LMFs and IMFs produced in $^{107}Sn_{50}+^{124}Sn_{50}$ are smaller compared to $^{124}Sn_{50} + ^{124}Sn_{50}$ because for the neutron-rich system, heavy residue with low excitation energy will predominantly emit neutrons, a channel that is suppressed in the case of neutron-poor nuclei. The equation

$$E(\rho) = E(\rho_0) \left(\frac{\rho}{\rho_0}\right)^\gamma \tag{7}$$

gives us the theoretical conjecture of how symmetry energy varies against density. γ tells us the stiffness of the symmetry energy [19]. In figure 1, we display the scaled impact parameter dependence of the free nucleons, LMFs and IMFs for $\gamma = 0$ and 0.66. Both the curves clearly indicate the density dependence of symmetry energy.

(3) A small difference is observed in both curves in the case of LMFs at a scaled impact parameter range from 0.0 to 0.4 because the density during the fragmentation is smaller than the normal nuclear matter density. Hence the role of density-dependent symmetry energy is negligible. In fact fragmentation is a low-density phenomenon and the symmetry energy is directly proportional to the scaled density. Since the density is low, the effect of density-dependent symmetry energy on the production of LMFs is negligible even though they are produced from the participant zone. But its effect is more pronounced in other parameters like, nuclear stopping (R and Q_{ZZ}), directed flow (v_1) and elliptical flow (v_2).

(4) When we apply momentum cut in addition to space cut, the free nucleons increase because at low impact parameters participant zone increases and a large number of free nucleons produced. On the other hand, the number of LMFs and IMFs decreases with MSTP cut.

Although we have tried simulation for two different parametrizations of density-dependent symmetry energy, its influence is very small, because the density at which fragmentation takes place is lower than the normal nuclear matter density. Hence the influence of symmetry energy on fragmentation is very small, which is in agreement with the observation of ref. [20].

Now to check the role of different cross-sections on fragmentation for charge asymmetric colliding nuclei, we have chosen two sets of reactions, one where the mass of the colliding nuclei is 40 units, but charge varies from 14 to 23. For the first set the chosen reactions are $^{40}X_m + {}^{40}X_m$, where $^{40}X_m = ({}^{40}V_{23}, {}^{40}Sc_{21}, {}^{40}Ca_{20}, {}^{40}Ar_{18}, {}^{40}Cl_{17}, {}^{40}S_{16},$ $^{40}P_{15}$ and $^{40}Si_{14}$) respectively. For the second set we have chosen the reactions for which the mass of the colliding nuclei is 124 units, but charge varies from 47 to 59. The chosen reactions are $^{124}Y_n + {}^{124}Y_n$, where $^{124}Y_n = ({}^{124}Ag_{47}, {}^{124}Cd_{48}, {}^{124}In_{49}, {}^{124}Sn_{50}, {}^{124}I_{53},$ $^{124}Cs_{55}, {}^{124}Ba_{56}$ and $^{124}Pr_{59}$) respectively. All the simulations are carried out for $\hat{b} = 0.3$ at 100 MeV/nucleon for symmetry energy corresponding to $\gamma = 0.66$. Here we take three different nucleon–nucleon cross-sections, because at low energy cross-sections have very large influence on fragment production. Moreover, they have a small effect on fragment production for central collision, whereas fragment production is strongly influenced at semicentral ($\hat{b} = 0.3$ in this case) collisions [21]. In figure 2, we have displayed the multiplicity of free nucleons (FNs) and light mass fragments (LMFs) as a function of charge asymmetry (N/Z). One can clearly see the effect of different cross-sections on the production of FNs and LMFs. It has been observed that

(1) If we fix $\sigma_{nn} = \sigma_{pp} = \sigma_{np} = 55$ mb, then maximum production of FNs and LMFs takes place. Isospin effect can be clearly seen when we use isospin-dependent cross-section σ_{iso} ($\sigma_{np} = 3\sigma_{nn} = 3\sigma_{pp}$) and isospin-independent cross-section σ_{noiso} ($\sigma_{nn} = \sigma_{pp} = \sigma_{np}$).

σ_{noiso} will reduce the cross-section and thus the number of collisions leading to less production of FNs and LMFs but σ_{iso} will enhance the number of collisions and hence the production of FNs and LMFs. Moreover, one can see the nearly constant difference in the production with σ_{iso} and σ_{noiso}.

(2) Minimum production takes place when $N/Z = 1$, i.e. symmetric charge collisions. The nuclei offer very interesting isospin situation where, the symmetry potential, Coulomb interaction and isospin-dependent nucleon–nucleon collisions are simultaneously present. The Coulomb interaction is an important asymmetry term which can bring an important isospin effect into the observable quantities in the intermediate energy heavy-ion collision.

(3) The symmetry energy affects the production of LMFs more than that of the free nucleons. The $(N - Z)^2$ plays a crucial role [18]. It has been studied that the isospin effects play more important role in the case of LMFs rather than free nucleons.

From figure 2, it is clear that minimum fragment production is achieved at $N = Z$ in the case of FNs because they are produced in collision dynamics. But for LMFs the fragment
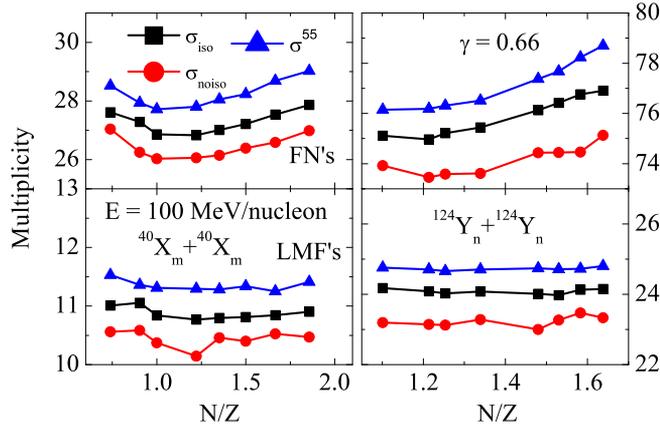
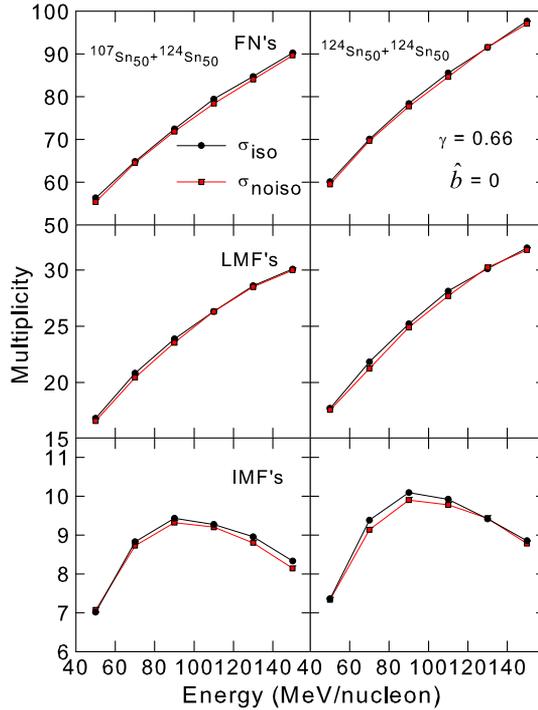**Figure 2.** Multiplicity of free nucleons and LMFs with N/Z. The left panels represent the set of reactions $^{40}X_m + {}^{40}X_m$, where $m = 14, 15, 16, 17, 18, 20, 21$ and 23 and the right panels represent the set of reactions $^{124}Y_n + {}^{124}Y_n$ where $n = 47, 48, 49, 50, 53, 55, 56$ and 59.

production is nearly constant. Moreover, it is clear from figure 2, that multiplicity of FNs and LMFs shows the same trend for the two sets of reactions (one with mass = 40 units and other with mass = 124 units). However, for FNs the slope of the curve is steeper for the set of reactions with mass = 40 units than for the set of reactions with mass = 124 units. This is due to the N/Z effect because the set of reactions with mass = 40 units are neutron-deficient reactions but the set of reactions with mass = 124 units are neutron-rich reactions.

Figure 3 shows the variation of multiplicity of free nucleons, LMFs and IMFs, with energy for central collision, for $^{124}Sn_{50} + {}^{124}Sn_{50}$ and $^{107}Sn_{50} + {}^{124}Sn_{50}$ for two different nucleon–nucleon cross-sections. It has been observed that multiplicity of free nucleons and LMFs increases with increase in energy. On the other hand, one can see a 'rise and fall' in the multiplicity of IMFs. This behaviour is similar to the behaviour shown by Aladin group [22]. Moreover, the number of free nucleons and LMFs produced are very large compared to IMFs because for central collisions, interactions are violent, and so a large number of free nucleons and LMFs are produced. It is clear from the figure that the slope of the curve is steeper for $^{124}Sn_{50} + {}^{124}Sn_{50}$ than for $^{107}Sn_{50} + {}^{124}Sn_{50}$ and this theoretical observation is in agreement with the experimental observation of Sfienti *et al* [22]. This rise is due to the fact that in neutron-rich system, heavy residues with low excitation energy will predominantly emit neutrons, a channel that is suppressed for neutron-poor nuclei. Here one can see the difference in the production of FNs, LMFs and IMFs due to different cross-sections. Since the proton number in both the cases is the same but neutron number is different, we expect some difference in the production.

In figure 4, we have shown IMFs as a function of Z_{bound}. The quantity Z_{bound} is defined as the sum of all atomic charges Z_i of all fragments with $Z_i > 2$. Here we observe that at semiperipheral collisions, the multiplicity of IMFs shows a peak because most of the spectator source does not take part in collision and a large number of IMFs are observed. In central collision the collisions are violent and so a few IMFs are observed.

Figure 3. Multiplicity of free nucleons, LMFs and IMFs with energy at fixed scaled impact parameter for $^{124}Sn_{50} + ^{124}Sn_{50}$ and $^{107}Sn_{50} + ^{124}Sn_{50}$.

For peripheral collisions also, a very small portion of the target and the projectile overlap and so again a few number of IMFs are observed. Most of the fragments goes out in heavy mass fragments (HMFs). In this way we get a clear 'rise and fall' in multifragmentation emission. But the influence of σ_{iso} and σ_{noiso} is negligible here because IMFs are produed from the spectator zone. It is observed that IMFs show an agreement with the data at low
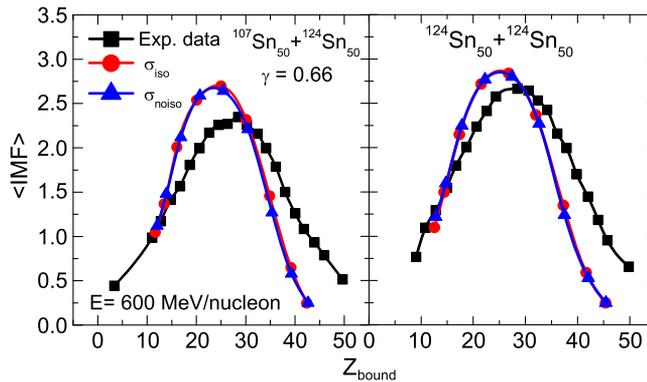
Figure 4. Multiplicity of IMFs as a function of Z_{bound}.

impact parameters but fails at intermediate impact parameters because MST [16] does not deal with time-scale of fragmentation and also in experiments, cuts on threshold energy and angles are applied. These cuts are very complicated in nature and we do not have access for these. Because of this reason a direct comparison cannot be made for higher Z_{bound} values.

4. Summary

By using isospin-dependent quantum molecular dynamics model we have studied the role of isospin effects on fragmentation due to the collisions of charge asymmetric nuclei. Here calculations were carried out for $^{124}X_n + ^{124}X_n$, where n varies from 47 to 59 and for $^{40}Y_m + ^{40}Y_m$, where m varies from 14 to 23. It has been observed that isospin-dependent cross-section shows its influence on fragmentation in the collision of neutron-rich nuclei and there is a constant difference in the production of FNs and LMFs with σ_{iso} and σ_{noiso} for charge asymmetric nuclei.

Acknowledgement

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