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INTRODUCTION

Why has so much effort been expended in the measurement and interpretation of the phenomena of photon and γ-ray yields in heavy ion collisions? Several motivations may be given:

1. These data may give information on the early reaction time scale during the most violent part of the reaction.

2. They may provide a probe of the nuclear equation of state (EOS).

3. Their interpretation via reaction models may suggest interesting new mechanisms for these reactions, and in any case provide a better understanding of mass and energy transport.

Of these (3) may be the strongest motivation, in that much more straightforward measurements of emitted nucleons probably will give better answers to (1) and (2) than the more convoluted interpretation of the production of secondary reaction products such as photons and mesons.

The next question is how these experiments have been interpreted. Many different approaches have been taken. These include a set applying equilibrium phase space arguments to a space or subspace; among these the thermal, statistical, and fireball models.[1-5] Approaches have also been suggested in which collective nucleus-nucleus,[6-8] or nucleon-cluster[5] interactions have been treated with the pions or photons produced in the deceleration following these collective interactions.

Perhaps the largest total effort has been based on the more familiar microscopic description that the emissions result from nucleon-nucleon collisions during the evolution of the nucleus-nucleus interaction; these models have been treated most frequently as a sum of incoherent processes,[9-19] with the range of validity of this simplification having been investigated recently by Heuer et al.[20] This straightforward physics has or may be treated in a wide range of nuclear transport calculations each with its own simplifying approximations. In the next section we describe different formulations for treating the nucleon-nucleon transport physics. These will all be semi-classical treatments; however considerable work has been done considering the relationship between quantal and semi-classical formulations.[21-23] In the following section we discuss additional input specific to calculation of pion and photon yields, and present comparisons between calculated and experimental results, mostly for high energy photons. Conclusions and suggestions for future work are presented in the last section.

DIFFERENT FORMULATIONS FOR HI REACTION/TRANSPORT CALCULATIONS

Event by Event Calculations.

Intranuclear cascade (INC). Follow the trajectories of nucleons in 3-dimensions, versus the time increment after the nuclei begin to interpenetrate.[24] Treat all nucleons in the overlap region until all have left the region. Assume the nucleons are bound within a central nuclear potential well. When there is a NN collision, use probability of N-N-$\gamma(\pi)$ vs NN elastic collisions to estimate the $\gamma(\pi)$ production cross sections and spectra.[25] Extreme approximations are made regarding the effect on nuclear densities following nucleon rearrangement so that it is difficult to follow the time dependent nuclear density evolution in this approach. Cluster formation may be predicted.[15] Because it is an event by event calculation, a very large number of events may have to be followed in order to generate adequate statistics for rare events. Nucleons move in straight line trajectories except for surface refraction and reflection processes. Only excited nucleons are followed in the cascades.

Quantum molecular dynamics model. The nucleons are bound in a potential which is explicitly calculated from the nucleon-nucleon force based on the total number of target/ projectile nucleons. The reaction is followed in 3-dimensions readjusting (x, y, z, p_x, p_y, p_z) of each nucleon in small time steps. During each time step the long range interaction of each nucleon with every other nucleon is followed; the nuclear density also changes, and the nucleon-nucleon interaction changes according to density and EOS. The nucleons move in curved trajectories due to the long range N-N force. When nucleons come within a fixed distance $\sigma_{NN}(E)$ of one another, a 'hard' collision takes place (as in the INC). Then pions or photons may be produced with a probability based on elementary N-N-$\gamma(\pi)$ cross sections.[20] The fate of each nucleon is followed as in the INC, so many events must be followed to generate satisfactory statistics for rare events.[26-28] As in INC, cluster formation may be estimated; unlike INC, the EOS influences the reaction dynamics in a quite natural way. The photon emission process has been followed in the QCD approach with phase relationships maintained in order to test the range of validity of the more common incoherent amplitude summation.[20] Nucleon momenta are given a Gaussian width during the selection process following a collision in order to mimic quantal effects of the Heisenberg principle.

Nucleon exchange transport model. Vandenbosch and Randrup have used the one body dissipation model of Randrup to treat nucleon and photon emission in HI collisions.[17] In this approach one nucleon at a time is allowed to transfer between the two nuclei as they approach and begin to overlap along some trajectory. The momentum of the nucleon is selected in Monte-Carlo fashion from a distribution based on the Fermi distribution with energy transfer based on the one body dissipation formula.[29] Once selected the fate of the nucleon is followed much as in the INC model, until it is emitted or undergoes a two body elastic or inelastic (NNγ) interaction. Then another nucleon is allowed to transfer, etc. The momentum of the two interacting heavy ions is decremented following the transfer of each nucleon.

Continuous (Semi-Continuous) Nucleon Distributions

The Boltzmann-Uehling-Uhlenbeck model. This approach[13,14,16,21,31-33] is in some ways similar to the QMD treatment except that the nucleons are bound in a mean field determined by local density and the EOS rather than one generated explicitly via the long range N-N interaction, and the nucleons are each divided into an arbitrary number of 'test particles' (typically

50-100) which have a spread in position and momenta about the mean nucleon value to approximate requirements of the Heisenberg principle. It is, as in QMD and INC, necessary to run a sufficiently large number of events to generate satisfactory statistics for calculated results. The evolution is, as in QMD, followed in small time steps with nucleon trajectories readjusted in each time step with a density dependent central potential. Thus the EOS is included in this calculation. The INC, QMD and BUU approaches each follow (x, y, z, p_x, p_y, p_z) of the nucleons (or test particles), and so predict angular distributions. In each case a coalescence criterion may be applied for treating cluster emission.[34] All approaches include some estimate of the influence of the Pauli exclusion factor.

Boltzmann master equation (BME). The BME approach[35-37] simplifies the transport calculation in several ways with respect to the other models described; this leads to much greater computational speed and flexibility, while retaining many of the main elements of physics. Its success depends on the assumption that the spatial evolution is of secondary importance to the energy relaxation history. This approach uses a continuous nucleon (probability) distribution which avoids the costly event mode method of computation; entire distributions may be followed as probability flux on a time dependent basis. One price paid for this simplification is that clusters cannot be followed in a coalescence approach, whereas other physical ideas may easily be tested. Angular distributions have not generally been calculated within this model, although there is no reason this cannot be done.[38]

The main simplifications of the model are (1) following evolution of the excited nucleons in an energy space only, with collision and emission rates calculated from energy and isospin dependent nucleon-nucleon and nucleon-nucleus phase space, and (2) the assumption that the result of coupling the entrance channel projectile energy with the Fermi energy may be given by few-quasiparticle distribution functions based on the assumption that every energy conserving partition occurs with equal a-priori probability.[36] This result is consistent with earlier precompound model analyses of α and ^{3}He induced reactions.[39] It has an advantage over the other models described in that the exciton distribution function used allows a probability distribution which goes smoothly to the full energy available, consistent with experimental results, whereas some of the other semi-classical approaches use a classical sharp-cutoff of this distribution due to the coupling of Fermi and beam momenta. The QMD and BUU approaches offer some relief from this classical approximation in use of some nucleon momentum width about the mean value. The BME has also been used by Scobel with a Fermi sphere coupling distribution rather than using the exciton distribution function.[40] The detailed formulation of the BME model has been presented elsewhere.[35-37,9-11]

MODEL APPLICATION TO EXPERIMENTAL RESULTS

Test of Nucleon Energy Distributions

Before using transport codes to calculate secondary processes such as N-N-π or N-N-γ, we need to know that the correct energy distributions for nucleons prior to N-N collisions are going into the calculation. This may be checked by comparisons with (HI, xn) spectra, which result when nucleons are emitted after the nucleus-nucleus interaction, and before a N-N interaction (higher emission energy regime) or after one or more N-N collisions (medium emission energy regime). Confirmation of the validity of the initial distributions is shown in Figs. 1-3, where the BME may be seen to give excellent agreement with a very broad range of experimental results, using a single standard parameter set.[41-45]

There are several additional points to note in Figs. 1 and 2. The insert to Fig. 2 shows that the high energy neutrons are emitted in less than 10^{-22} sec; if N-N collisions occur before emission, the emission energies are decreased and lifetimes increase. Thus these spectra represent

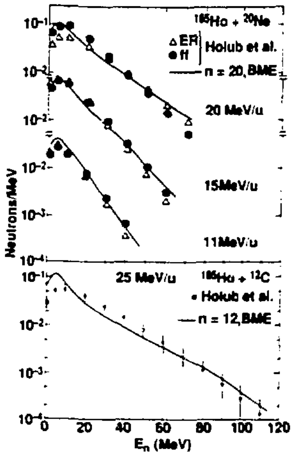

Figure 1

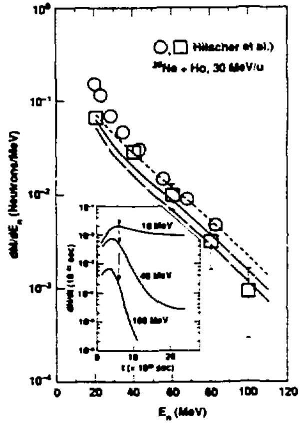

Figure 2

Fig. 1 Calculated and experimentally deduced spectra for the ^{165}Ho(^{20}Ne,n) and the ^{165}Ho(^{12}C,n) systems. Experimental points from (41) and (42) result from an integration of a moving source fit to experimental yields for the fast component only. Experimental yields for ^{20}Ne projectiles were gated on evaporation residues (ER) as represented by open triangles, and on fission fragments (FF) shown by closed circles. Results for ^{12}C were gated on ER. Calculated results are shown for the BME with $n = A_p$ in the exciton distribution function, where we assume total excitation is shared by n excitons with equal a-priori probability.

Fig. 2 Experimental and calculated neutron energy spectra from 30 MeV per nucleon ^{20}Ne on Ho. The squares represent the preequilibrium yields deduced by Hilscher (43) by fitting an assumed isotropically emitting moving source to the high energy data. The circles represent the total differential data of Hilscher et al., integrated directly. The solid line is the BME result; the short and long dashed lines correspond to increasing and decreasing the nucleon mean free path by 50%. The insert shows the calculated time dependence of the emission of 10, 40 and 100 MeV neutrons. The arrows represent the time at which fusion is assumed complete in the calculation.

the nucleus-nucleus stopping process through the time/energy dependence of the emitted nucleon spectra. The second point is the observation that the nucleon spectra go smoothly to energies which exceed the semiclassical limit of Fermi plus beam momentum coupling.

Subbarrier Pion Emission

Experimental N-N-π cross sections may be used in the nucleon transport codes described to estimate the pion yields in heavy ion reactions. This

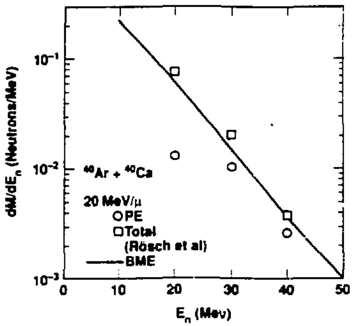

Fig. 3 Calculated and experimental $^{40}Ca(^{40}Ar,n)$ spectra for 20 MeV/u incident energy, gated on evaporation residues. Data are from Rösch (44). The solid line is the result of the BME calculation assuming 40 excitons.

was done successfully with the BME[9]; results are summarized in Table II of Ref. 9. Other transport calculations have similarly found good agreement with measured pion yields.[12,14,19] For pions, there is an ambiguity due to the reabsorption prior to escape from the nuclei. Within this uncertainty the several nucleon transport calculations give good agreement with data, confirming that one possible interpretation of the pion emission is as being due to N-N collisions with nucleons boosted in energy by coupling of beam and Fermi momenta.[46]

Photons do not have the strong reabsorption expected for pions, and so many experimental groups chose to study photon emission. In the following subsection we consider the requirements to enter this capability into the transport codes.

High Energy γ Emission in Heavy Ion Collisions

For the nucleon transport codes described in the previous section, photon production spectra may be calculated if the differential (or double differential) neutron-proton-bremsstrahlung cross sections are known. The evaluation of this basic input to the calculation has an interesting history, and somewhat divides the results obtained thus far. We note that neutron-neutron or proton-proton quadrupole bremsstrahlung are expected to be one to two orders of magnitude smaller than n-p electric dipole bremsstrahlung, and are therefore generally ignored.[47,48]

A semi-classical description of the p-n-γ differential cross section is given in several approximations in the textbook of Jackson; one form is[49]

$$\frac{d^2N}{dE_\gamma d\Omega_\gamma} = \frac{1}{E_\gamma}\frac{\alpha^2}{(2\pi)^2}\sum_{k=1}^{2}\left|\frac{\hat{\epsilon}_k \cdot \beta_i}{1-\hat{q}\cdot\beta_i} - \frac{\hat{\epsilon}_k \cdot \beta_f}{1-\hat{q}\cdot\beta_f}\right|^2 \times P_{fac}(1+X) \quad . \qquad (1)$$

Here, $\alpha = \frac{1}{137}$ is the fine structure constant; $\hat{q}$, $\hat{\epsilon}_1$, and $\hat{\epsilon}_2$ are the unit vectors denoting the γ-ray direction of propagation and two directions of polarization, and $\beta_{i,f}$ denote the initial and final velocities of the proton. $P_{fac} = (\gamma_f\beta_f)/(\gamma_i\beta_i)$ is a quantal correction for the reduced final-state phase space in nucleon-nucleon vs. nucleon-heavy nucleus scattering, where $\gamma_{i,f}$ represents the relativistic contraction factor.[50,51] The (1 + X) factor represents the uncertainty due to neglecting meson exchange effects in the radiation formula.[47,48] A relativistic quantal calculation including meson exchange effects was given in early works by Brown[47] and by Brown and Franklin,[48] but the results were not cast in a form easily used to replace Eq. (1). These authors concluded that neglect of meson exchange in Eq. (1) resulted in an underestimate of the differential cross section by roughly a factor of two. Neuheuser and Koonin[52] integrated the equations of Brown and Franklin[48] non-relativistically to calculate the differential γ-ray spectra, and gave a prescription for scaling the semiclassical result of Eq. (1) to approximate the quantal result. We will refer to their results shortly. Other authors have also recently reconsidered the problem with inclusion of meson exchange.[53-54]

The only set of reasonably extensive experimental data with which to make comparisons were, until recently, the nucleus (p, γ) measurements due to Edgington and Rose using 140 MeV protons.[55] Deuterium was one of the targets used, which except for the internal momentum of the neutron in deuterium, gives the p-n-bremsstrahlung spectrum. Therefore most groups doing the heavy ion-γ-ray transport calculation began by comparing their results with the data of (52); e.g. in Fig. 4 we show results of Remington et al.,[10] using Eq. (1), and Eq. (1) multiplied by two and corrected for the internal momentum of the deuteron. The results of Neuheuser and Koonin (N-K) are also shown.[52] Based on these comparisons Eq. (1) multiplied by two was used by Remington et al.[10]; the N-K results[52] were also used in many of their calculations. In Fig. 5 we show a similar result from Ref. 12 using a semiclassical radiation formula.[49]

More recently nucleus (p, γ) measurements have been made by Kwato Njock et al., for 72 and 168 MeV protons on several targets.[56,57] When these are scaled and compared with the results of Edgington and Rose,[55] they suggest that for photon energies in excess of 50 MeV, the results of (55) are low by a factor of 3-4 versus the newer data (Fig. 6). This in turn suggests that the results of N-K (see Fig. 4) may be more realistic than the scaled results of Eq. (1) which have been used frequently in transport code analyses. In Fig. 4, we show the $^{12}C(p,\gamma)$ measurement of (57) for 168 MeV protons, scaled in magnitude by 140/168, but not scaled in energy, versus the N-K and semi-classically calculated spectra at 140 MeV. That the N-K results are in better agreement with the 168 MeV experiment is obvious. The calculations of Nakayama, with inclusion of meson exchange effects, should also be in better agreement with the newer p-nucleus measurements,[53-54] based on improved results in applications to nucleus-nucleus gamma ray yields.

In Figs. 4 and 7, we show comparisons between calculated and experimental high energy γ ray data from several sources,[58,60] calculated with the BME and with the BUU model in Fig. 5. The data of Stevenson et. al.[58,60] have been replotted with a recent detector efficiency recalibration.[60] Using the newer data of Stevenson et. al., it may be seen in Figs. 4, 5 and 7 that the semi-classical radiation expression underestimates the experimental γ-ray spectra, and this underestimation becomes worse as the incident heavy ion energy increases. The N-K quantal calculation for p-n-γ, on the contrary, may be seen in Figs. 4 and 7, to give a satisfactory agreement for all energies for which it has been tried, as well as being in better agreement with the newer experimental p-nucleus measurements of Kwato-Njock et al.

These results, as well as similar results by other groups using formulations briefly summarized in Section II, confirms that incoherent N-N-bremsstrahlung processes provide one viable explanation of the high energy

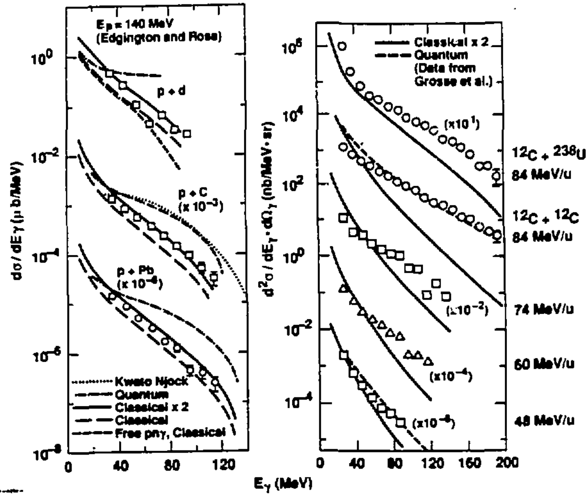

Fig. 4 (Left): Comparisons of calculations with high energy γ-ray data of Edgington and Rose (55) for a 140 MeV proton beam. At the top, the p+d data are used as a standard with which to "normalize" the pnγ bremsstrahlung equation. The short-dashed line corresponds to a semi-classical bremsstrahlung formula for free neutron-proton scattering. The long-dashed line is the same, only with the momentum distribution of the target neutron in deuterium taken into account. The solid line corresponds to the deuteron calculation multiplied by two to crudely account for the effect of meson exchange. The dotdashed line corresponds to folding the quantum bremsstrahlung result of Neuheuser and Koonin (52) into the deuteron calculation. The lower two spectra show γ-ray data for $p+^{12}C$ and p+Pb. The curves represent calculations with the master equation using tho semiclassical bremsstrahlung cross sections (dashed lines), the semi-classical cross sections multiplied by two for meson exchange (solid lines), and the quantum bremsstrahlung cross sections (dot-dashed lines). For C+p, the dotted curve is the experimental result of Kwato Njock et al. (57) for 168 MeV protons, scaled in magnitude by 140/168, but not scaled for energy.
(Right): γ-ray data (61) for $^{12}C + ^{238}U$ at 84 MeV/nucleon (top, $^{12}C + ^{12}C$ at 84, 74, 60 and 48 MeV/nucleon. The solid lines represent the master equation calculation for a sharp-cutoff initial exciton distribution, while the dot-dashed line is for a continuous exciton distribution. The dashed lines represent master equation calculations using the quantum bremsstrahlung cross sections.

γ-rays observed in HI reactions. The success of the BME in reproducing these data suggests that nuclear compressibility properties are not yet an issue. Data at higher energies may yet provide results for which the EOS is an essential ingredient in interpretation. This should be checked by model calculations. Meanwhile, Heuer et al.,[20] are confirming the regime in which the problem may be modeled as a semiclassical sum of incoherent N-N-γ processes via the QMD approach.

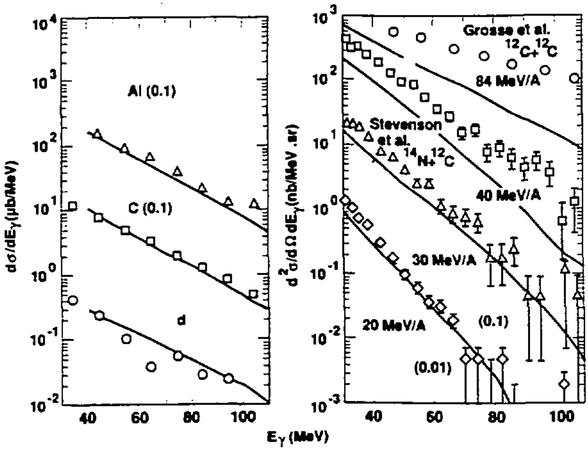

Fig. 5 (Left) Comparison of p, nucleus bremsstrahlung spectra calculated using the semi-classical formula as reported in (13) (solid lines) compared with the data of Edgington and Rose (55). Right hand side shows spectra from the $^{14}N + ^{12}C$ (58,60) and $^{12}C + ^{12}C$ reactions (59) compared with BUU calculations using the same semi-classical radiation formula (13).

CONCLUSIONS

Several transport codes have been described which interpret pion or photon production as an incoherent result of nucleon-nucleon scattering, with nucleons having a distribution of energies resulting from Fermi plus beam momentum coupling. All of these provide a description of the time dependence of the nucleus-nucleus interaction resulting from nucleon-nucleon scattering in a potential due to the nuclear matter. All give a generally satisfactory reproduction of experimental pion and photon yields and spectra. Analyses have been performed for the production of mesons other than pions, but these results are not discussed in this work.[61,62]

Some of the codes discussed are limited by the semi-classical Fermi plus beam velocity coupling limit. This point should be addressed and understood for those particular phenomena which are sensitive to the approximation (e.g., pion production near the thermodynamic threshold). A problem for all nucleon transport codes when used to calculate photon production is a lack of a sufficient body of data (e.g., d(p, γ)) to test and if necessary modify theoretical models which provide the basic n-p-γ input to the transport codes. Recent results of Kwato Njock et al.,[56,57] suggest that values frequently used are significantly in error. Better model calculations await a more comprehensive determination of the basic p(n, γ) differential cross sections over a sufficient range of incident nucleon energies. These data will be essential if γ-rays are to be used as a tool for answering questions of significance regarding the EOS based on results of heavy ion collisions. The general overall agreement of different calculations with and without the EOS included suggests that in the incident energy regime up to 84 MeV/A the EOS does not have a great influence on results.[63,64] Once the basic p(n,γ) process is understood in a reasonably quantitative fashion, transport calculations may be performed to see if

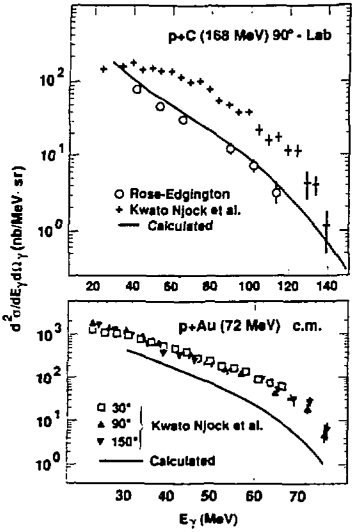

Figure 6

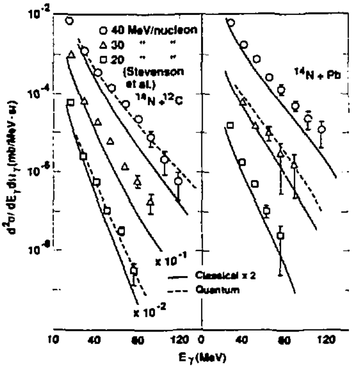

Figure 7

Fig. 6 The solid curves are results of a semi-classical radiation formula from (49) compared (upper) with 168 MeV p + ^{12}C gamma ray spectra from (57). The results of Rose and Edgington scaled from 140 MeV by multiplication of ordinate and abscissa by 168/140 are shown for comparison. In the lower section data for p + Au with 72 MeV protons from (56) are shown versus predictions of the same semi-classical radiation formula. All results are taken from (56, 57).

Fig. 7 The γ-ray data of Stevenson (58,60) are shown for $^{14}N+^{12}C$ (left side) and for ^{14}N+Pb (right side) at 20, 30 and 40 MeV/nucleon. The solid lines correspond to the BME calculation using the semi-classical bremsstrahlung cross sections with X=1 in Eq. 1 while the dashed lines correspond to quantum bremsstrahlung cross sections of Ref. (52). The results of Stevenson et al. have been plotted to include the recent detector calibration results (60).

the γ-ray yields in nucleus-nucleus collisions should be (and at what level) sensitive to the EOS. Making extensive experimental measurements of nucleus-nucleus results when there are nearly no nucleon-nucleon results on which to base an interpretation brings to mind the idiomatic expression "don't put the cart before the horse."

Since completion of this work a very comprehensive review paper on the same topic by Nifenecker and Pinston has been received; the author wishes to call this outstanding review to the attention of interested parties.[65]

During the course of this work the author has greatly benefited from discussions with W. Greiner, R. Heuer, H. Stöcker, G. F. Bertsch and H. Nifenecker.

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