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The Manhattan Project and the Development of Nuclear Astrophysics

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Abstract. This paper will provide a historical analysis of the impact of the US Manhattan Project from 1942 to 1945 and the subsequent nuclear test program 1945-1970 towards the development of the field of Nuclear Astrophysics and the interpretation of nuclear reaction processes in stars and explosive stellar environments.

1 Introduction

Nuclear Astrophysics is concerned with the question about the origin of the elements in our universe. It is a question born out the spectroscopy of solar and stellar light and coupled to the question about the energy source of stars. While the idea of chemical energy and the gradual release of gravitational energy was dismissed during the 19^{th} century, the idea of energy release by radioactive decay was replaced by the the suggestion of Arthur Eddington, that the energy release through nuclear reactions might be a possible alternative“... *what is possible in the Cavendish Laboratory may not be too difficult in the Sun.”* [1]. This statement reflects the hour of birth of the field, which before the war was pioneered by Hans Bethe, George Gamow, Edward Teller, and Carl Friedrich von Weizsäcker. The war, in particular the developments of the Manhattan Project and the nuclear test program, changed the direction of the field, with a new generation of pioneers entering the field, such as Fred Hoyle and William Fowler, whose ideas and contributions still shape the field today. This paper will provide a summary of these three development stages during the 20^{th} century

2 Nuclear Astrophysics before 1942

The suggestion of Arthur Eddington that nuclear reactions between light isotopes might act as stellar energy source was a paradigm shift in the interpretation of stars. Spectroscopy had shown that stars consists primarily pf hydrogen with some spurious amounts of heavier elements. The natural assumption was therefore that light proton induced reactions drive the energy generation of the sun. Based on the 1928 paper by George Gamow [2], postulating the reaction probability as determined by the tunneling probability of charged particles through the deflecting Coulomb barrier, Gamow and Houtermans derived the lifetime of heavy alpha emitters [3]. Based on this, Atkinson and Houtermans were the first to formulate a model for calculating the lifetimes of elements due to proton induced interactions [4]. It was a

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seminal, unfortunately today largely forgotten paper, which not only offered the first quantum physics based reaction mechanism for radiative capture at stellar environment conditions but also considered for the first time quantum effects such as electron screening in fusion processes. The paper also demonstrated that the heavy elements could not be produced by proton induced reactions; since neutrons were not known at the time, the authors speculated on Compton effect and electron induced processes as potential source for the production of heavy elements. While this relied on energy release due to nuclear reactions, it could only be quantified a few years later when based on suggestion of George Gamow for a droplet model of alpha particles - without the knowledge of neutrons - [5]. Carl Friedrich von Weizsäcker proposed the droplet model including neutrons for all observed nuclei [6] as a first reliable approach to calculate nuclear masses, mass difference and binding energies. This paper allowed to quantify the energy production due to nuclear reaction processes. George Gamow, who at that time had settled in the United States at George Washington University, developed with Edward Teller, a former coworker of Heisenberg and refugee from Germany, for the first time a reliable reaction rate formalism based on the Maxwell Boltzmann distribution of interacting particles using the mass formula to calculate the energy production in stars [7].

The discovery of neutrons by Chadwick caused a major change in scientific thinking on the origins of the elements in the universe. Weizsäcker published in 1937 his first paper on the nucleosynthesis of heavy elements [8] in which he proposed neutrons as the source for the production elements beyond iron. He suggested that neutrons are being produced in stars by the d+d fusion reaction which he expected to be fueled by a catalytic reaction cycle involving ^{5}Li, ^{5}He, and ^{8}Be assuming those to be particle stable [9]. This assumption, based on the mass formula was dismissed by experiment, but Weizsäcker's work was the first paper which clearly identified neutron induced processes as the source for elements beyon iron, more so, based on observations it suggested that there should be more than just one neutron based reaction mechanism, a first glimpse at the s-process and the r-process, as sources of heavy elements. Nevertheless, demotivated about the possibility of neutron sources by the response by Hans Bethe and George Gamow about the experimental evidence for ^{5}He and ^{8}Be he dismissed the idea and proposed in a subsequent paper [10] another catalytic carbon based reaction cycle for solar energy production. Weizsäcker learned from Gamow that Hans Bethe worked on a quantitative solution for the CNO cycle at the same time [11]. Hans Bethe not only derived reaction rates for the CNO cycle but also for light hydrogen fusion processes, which provided the foundation of the pp-chains.

The discovery of neutrons as possible driver for nuclear reactions also led to the improvement of nuclear reaction theory with Eugene Wigner proposing the R-matrix model for resonances [12, 13], Victor Weisskopf complemented this approach by suggesting a statistical approach for multiple resonance systems [14], the predecessor of the so-called Hauser-Feshbach model, based primarily on the improvements suggested by Herman Feshbach after the war.[15] These models were also used for the description of charged particle reactions complementing the previous adaptions of simple potential models; in these cases the reaction cross section was also influenced by the transition probability through the Coulomb barrier.

The discovery and interpretation of fission in 1938 had a fundamental impact on the direction of nuclear physics, Weizsäcker was intrigued and focused his interest on this new phenomenon and its possible applicability. The first theoretical calculation of the fission probability was presented by Niels Bohr and Archibald Wheeler in 1939, using the statistical model approach by simulating the fission process as a sequence of vibrational states, eventually splitting the nucleus [16].

George Gamow, as the main intellectual driver of nuclear astrophysics at the time became less focused on the quantum physics of stars but sought to explain the overall impact of nuclear processes and newly discovered phenomena such as neutrinos on the fate of stars.

His papers suggested a first theory of novae [17] and the evolution of red giant stars [18], in which he, however, misinterpreted the Hertzsprung Russell diagram as a dynamic trajectory signature for stellar evolution assuming hydrogen as the only available nuclear fuel in stars [19, 20]. More interesting are his papers interpreting the role of neutrinos in stellar nucleosynthesis in which he suggests for the first time a kind of neutrino driven wind model for supernovae [21]. During this period Edward Teller focused more on nuclear interaction and scattering processes in different media associated with energy transport and energy loss in different media. The decision of the US government to provide funding for the Manhattan Project did however change the direction of the field from the physics of stars to the physics of the bomb, a change as regrettable as it seems, triggered multiple new ideas and concepts.

3 Nuclear Astrophysics between 1942 and 1950

The initiation of the Manhattan Project in 1942 as a highly classified effort to develop a nuclear bomb, based on the instantaneous release of fission energy, was a major shift in the purpose and sociology of the science community. Open curiosity driven research with limited public funding was replaced by a secretive goal oriented research effort with enormous resources. However, not everybody was invited to participate, most notably George Gamow was excluded since held the rank of a colonel of the Soviet Army at the time of his immigration to the United States. While this was the nominal rank for a teacher at an army school, it nevertheless caused considerable concern with the United States security officers [22]. Gamow as well as Einstein, who had suggested the development of the bomb in his famous letter to President Roosevelt were not part of the Manhattan Project. Nevertheless, the Manhattan project was stimulated by the developments and ideas of the nuclear physics community at the time, the theoretical reaction models were utilized for calculating fission yields and experimental facilities at universities were used to test the various predictions.

All in all, the physics of fission was clear, the challenge was more the generation of a sufficient amount of fuel material such as ^{235}U by separating it from the much more abundant ^{238}U using diffusion or electromagnetic separation techniques at the newly founded Oak Ridge National Laboratory. The alternative fuel was ^{239}Pu which was produced by "breeding" through neutron exposure at the pile I pilot reactor in Chicago, the X-10 test reactor in Oak Ridge and subsequently on an industrial level at the nine reactors at the Hanford facilities. Generating the fuel was the concern of experimental physicists such as Ernest Lawrence and Enrico Fermi, while theorists evaluated the potential and the risk. The best known case for the latter was formulated by Edward Teller on the basis of his knowledge of fusion reactions and fusion probabilities at the time he was recruited into the program at a classified meeting in Berkeley. Teller expressed his concern about the possibility of fusion of nitrogen nuclei within the fireball of the bomb, causing a chain reaction igniting the atmosphere in a nuclear fusion fireball. Hans Bethe as head of the Los Alamos T-division dismissed this idea out of hand [23], but Oppenheimer became concerned and traveled by train from Berkeley to Chicago [24] to inform himself through discussions with Arthur Compton, head of the Chicago Metallurgical Project and that time the world expert on electron and photon radiation physics [25] about the different radiative cooling mechanisms through electron, X-ray, and γ ray emission which would keep the fireball at a cooler level and prevent such an event.

Arthur Compton in discussion with the Notre Dame theorist Arthur Haas, a Jewish refugee from Austria had developed new ideas to test the electron matter interaction at the open air electron accelerator built in 1938 at the University of Notre Dame [26]. This discussion was the basis for the development of an experimental program in electron and photon induced excitation and photo-disintegration processes at the accelerator. After 1942 this program was intensified at the newly installed 8 MV particle accelerator, which operated secretly for the following years to explore radiation induced processes on behalf of the Manhattan Project [27]. These experiments, which were performed by Bernie Waldman as well as Harry Agnew as graduate student of Enrico Fermi, provided a basis for deriving the energy loss effects due to electron and photon radiation from the hot fireball of the Trinity bomb. While the specific results of the experiments were classified at the time, some details can be extracted from the experimental results published at a later time. It confirmed the energy loss estimated by Compton, which were later displayed in the Los Alamos report by Konopinski, Teller, and Marvin in 1946 [28].

The remaining question was the reaction rate of the ^{14}N+^{14}N fusion reaction as a function of temperature. This was seen as the most likely reaction because of the high content of nitrogen in the atmosphere, another possibility the physicists considered was the fusion of ^{14}N with hydrogen from dissociated water vapor. For calculating the reaction rate, Teller used the model he and Gamow had developed for calculating reaction rates in stellar burning some years earlier. The cross sections for these reactions he estimated from the size of the ^{14}N nuclei corrected for the tunnel probability of the nuclei through the Coulomb barrier. It was a crude estimate, but most likely provided a reliable upper limit. The comparison between the likelihood for ignition by temperature increase and cooling curve by radiation emission generated a safety factor which however decreased towards higher temperature and density conditions. Teller recognized that and expressed his concern with respect to the anticipated development of more powerful bombs generating much higher temperatures and the planning of deep underwater tests which would have much higher density conditions. He concluded: *The disquieting feature is that the "safety factor", i.e. the ratio of losses to gains of energy, decreases rapidly with the initial temperature, and descends to a value of only about 1.6 just beyond a 10-MeV temperature. It is impossible to reach such temperatures unless fission bombs or thermonuclear bombs are used which greatly exceeds the bombs now under consideration* [28]. Indeed it was a concern, which was kept a secret. During the deep underwater test program *Operation Crossroad* on the Pacific islands the military leaders strongly denied the dangers of triggering a chain reaction in the ocean - presumably due to hydrogen induced capture reactions on oxygen as most abundant components. The commander of the test program Admiral William H. P. Blundy stated in a public speech in an attempt to pacify the critics: *he bomb will not start a chain-reaction in the water converting it all to gas and letting all the ships on all the oceans drop down to the bottom. It will not blow out the bottom of the sea and let all the water run down the hole. It will not destroy gravity. I am not an atomic playboy, as one of my critics labeled me, exploding these bombs to satisfy my personal whim* [29]. At the end he was right, despite the density of water is about a thousand times higher than air, the oceans did not ignite - from the nuclear physics point of view because the proton capture on ^{16}O has a low Q-value and an extremely low cross section.

4 Nuclear Astrophysics after 1950

However more dangers loomed on the horizon with the development of thermonuclear weapons based on the fusion of deuterium and tritium isotopes. The power released by these bombs is about two to three orders of magnitude larger compared to fission bombs. This required the direct measurement of fusion reactions to test and verify the early calculation. The Atomic Energy Commission as predecessor of the department of energy approved the construction of a new high intensity cyclotron for the study of fusion reactions, which came into operation in 1952 [30]. A young researcher, Alex Zucker, was put in charge of the cyclotron and developed a first successful program in heavy ion reaction studies. He not only confirmed that the estimates of Teller on the fusion rate of ^{14}N+^{14}N were correct, but he studied many other fusion reactions for the first time [31]. This program was continued at Berkeley with the construction of the 88" cyclotron to study nuclear structure effects detailing the cross section curves by resonance features which were interpreted as molecular configurations between alpha clusters in the nuclei. These features are today of critical importance for the understanding of carbon- and oxygen burning during late stellar evolution of massive stars and the ignition of type Ia supernovae and superbursts, as still not quite well understood explosive phenomena [32]. The Oak Ridge Cyclotron was mothballed for many decades until it was refurbished in the late 1990s to be used as driver machine for the HRIBF radioactive beam program [33]. It was this sequence of events that turned the fear about igniting the atmosphere into a successful research program towards the understanding of stars.

The results of the nuclear test program with thermonuclear bombs and later with targeted underground explosions. The analysis of the bomb debris of IVY MIKE, the first full-scale test of a thermonuclear device showed the very neutron rich plutonium 244, produced by neutron capture on the fuel material plutonium 239, but also gave first evidence of superheavy elements Fermium and Einsteinium in the depositions on corals and on the window of an observer plane, which was too close to the mushroom cloud. The deposits were shipped to Berkeley were they were chemically analyzed to confirm the discovery of new elements, produced in the enormous neutron flux generated by the hydrogen bomb [34]. This discovery stimulated Glenn Seaborg, who had received in 1951 the Nobel-prize for chemistry for his identification or ^{239}Pu, to search for even heavier elements, the trans-actinides. As president of the Atomic Energy Commission (AEC) from 1961 to 1971 he had enormous influence and managed to steer several of the weapon tests in the direction of his scientific desires. During this period nine underground tests were performed, codenamed Anacostia (5.2 kilotons, 1962), Kennebec (<5 kilotons, 1963), Par (38 kilotons, 1964), Barbel (<20 kilotons, 1964), Tweed (<20 kilotons, 1965), Cyclamen (13 kilotons, 1966), Kankakee (20-200 kilotons, 1966), Vulcan (25 kilotons, 1966), and the biggest one Hutch (200 kilotons, 1969). In particular the Hutch test was extremely successful in extracting transactinide isotopes from Curium to Einsteinium [35].

The discovery of these very heavy isotopes and the realization that they had been produced by a sequence of neutron capture reactions on the plutonium fuel of the bomb, revitalized the old idea of Carl-Friedrich von Weizsäcker of a sequence of neutron capture reactions generating the heavy elements. It was a young physicist William A. Fowler, a former student of Oppenheimer at Caltech. During the war he associated with the Manhattan Project effort in California. He was stationed at the Naval Weapons Center at China Lake in California for rocket development but had also participated at a number of other weapons related activities such as the development of a ^{210}Po^{9}Be neutron source for the warheads. This was based on his earlier research work as graduate student with Charles Lauritsen at Caltech.[36] After the war he had returned to the university and built an experimental program in nuclear astrophysics measuring key reaction of the pp-chains and the CNO cycles to confirm earlier theoretical predictions by Hans Bethe [37].

But the collaboration with the British scientist Fred Hoyle changed and broadened the direction of Fowler's research. The measurement of the second excited 0^+ state in ^{12}C by Ward Whaling and his group at Caltech [38] confirmed Fred Hoyle's idea of the triple-alpha process, a three particle interaction mechanism that, by bridging the mass A=5 and A=8 gap allowed stellar helium burning [39]. This paper by Hoyle predicted also a number of possible alpha induced neutron sources such as ^{13}C(α, n) and ^{22}Ne(α, n) in helium burning environments. This was the idea Weizsäcker had been missing, the possibility of helium burning, which opened the opportunity for neutron sources triggered by α capture reactions.

Fowler recognized in the observation of ^{99}Tc in stellar spectra an indication of a slow neutron capture process driven by such neutron sources, on the other hand in the shape of the lightcurve of supernovae type Ia he saw the decay of ^{254}Cf reflected, a product of a rapid neutron capture process in stellar explosion such as it occurred in nuclear explosions [40]. This was the origin of the idea of two neutron driven nucleosynthesis processes, the slow ($s-$) neutron capture and the rapid ($r-$)neutron capture process, which were thought to be responsible for the origin of all the heavy elements in the universe [41]. The site of these processes remained unknown, for decades different environments in stellar helium burning were discussed, but challenged by the need of the appropriate neutron source while it was assumed that the r-process would take place in a single site, the type-II core collapse supernovae [42].

Today, a whole range of nucleosynthesis environments are discussed for both $s-$ and $r-$process. For the $s-$process, two environments have been identified, the weak $s-$process in the core of red giant stars and the main $s-$process in the helium burning shell of AGB stars [43, 44], the latter is possibly enhanced by the so-called intermediate or $i-$process in deep convective shells of early AGB star generations [45]. Also the $r-$process abundances seem to have been originated through a mixture of different sites, such as neutron driven nucleosynthesis in merging neutron stars for the very heavy nuclei - possibly in the early phase of the universe [46], complemented by a weak $r-$process driven by neutrino driven winds in supernovae [47], possibly complemented by the $n-$process, triggered by the supernova shockfront, traversing the helium burning shell of the pre-supernova star[48], as well as plus an $i-$process contribution initiated in accreting early white dwarf environments [49]. The field is active and well, trying to identify these different sites through experiment, observation, and modeling, an intellectual challenge, born out the physics first studied in the framework of the Manhattan Project and the nuclear test program.

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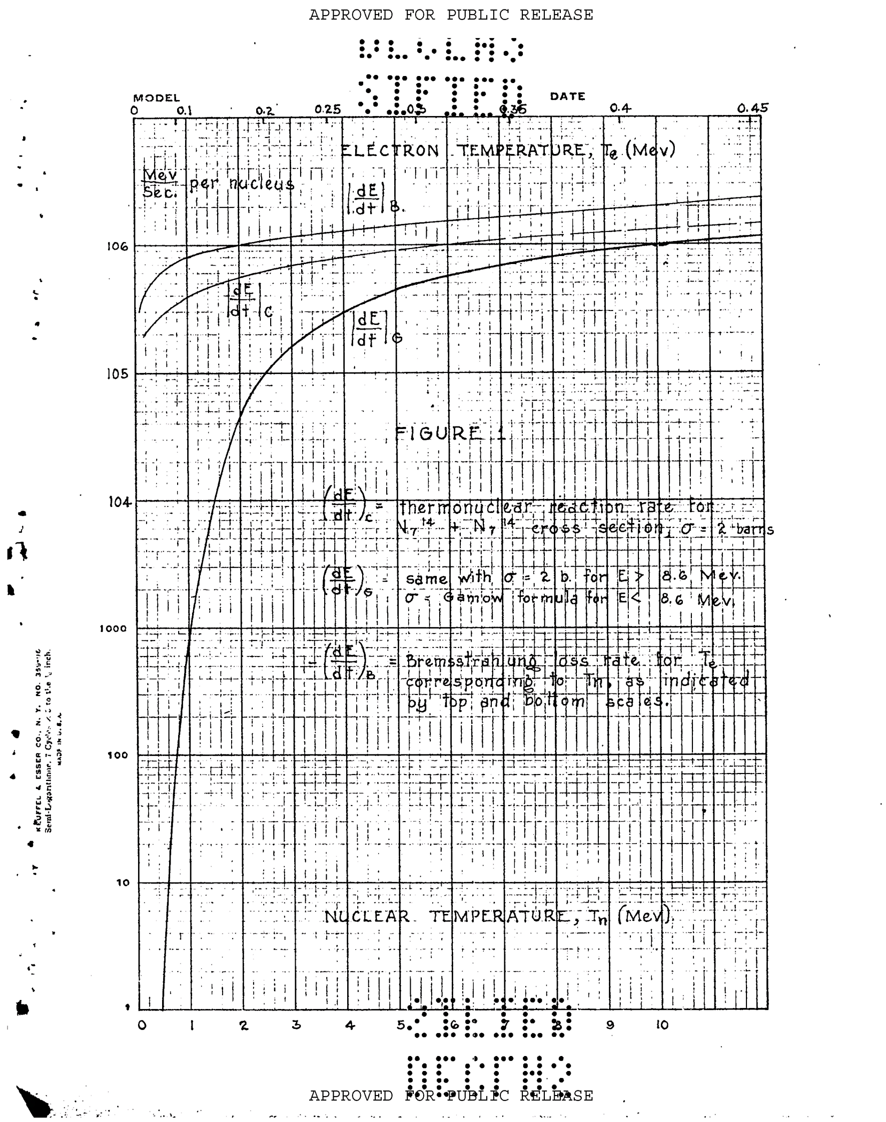

Figure 1. The rate of energy production as a function of temperature (in MeV), from the originally classified 1946 Los Alamos report Ignition of the Atmosphere with Nuclear Bombs [28]. Three curves characterize the energy-transport conditions for different temperatures in the nuclear fireball. The $\frac{dE}{dt}_C$ curve shows the reaction rate for the fusion of two nitrogen-14 nuclei when a constant cross section is assumed. The $\frac{dE}{dt}_G$ curve shows the ^{14}N + ^{14}N fusion reaction rate when the cross section is assumed to rapidly decrease at low energies, as predicted by George Gamow. And the $\frac{dE}{dt}_B$ curve shows the radiative energy loss through x-ray emission, as predicted by Arthur Compton.

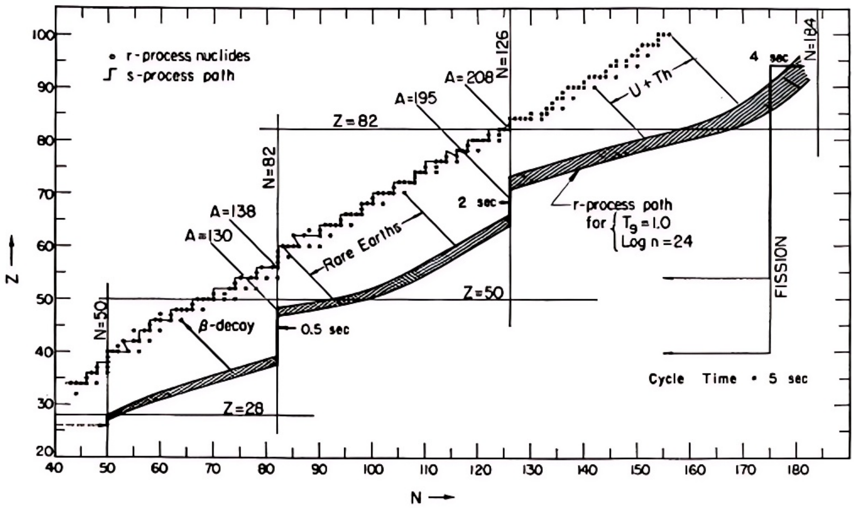

Figure 2. The reaction trajectory for the slow and the rapid neutron capture process as envisioned by Willi Fowler and Fred Hoyle at Caltech as a consequence of stellar observations and the nuclear test program.