Creation Research Society Quarterly 2021 57:185–199

Supernova Light Curves and Accelerated Decay

Eugene Chaffin*

Abstract

Neutrinos and antineutrinos are emitted in great quantity in supernova explosions. In a previous paper they were linked to a hypothetical acceleron field and the variations in this acceleron field as the blast reached earth were investigated as a cause for accelerated nuclear decays. In this paper, the nuclear decays, which are thought to be primarily decays of Nickel-56 and Cobalt-56, which power the light curves of supernovae are investigated. The half-lives and other properties of Nickel-56 and Cobalt-56 have been measured in the laboratory, and the theory of the ground state and other levels of these nuclei are investigated to see if they are sensitive to changes in the acceleron field. One cannot induce stars to explode, but supernovae are often observed in distant galaxies and their study may be used to infer what the possible behaviors are. Nuclear theory is examined to see what the characteristics of Ni-56 and Co-56 might be, including whether the ground states of these nuclei have a pairing gap in their energy states. The calculations indicate that Ni-56 has no pairing gap and the neutrons in Co-56 have no pairing gap. There is a weak pairing gap for protons in Co-56. The implications of this for whether accelerated decay would result for these nuclei, and hence whether accelerated decay would be compatible with the observed light curves if the acceleron mechanism is adopted.

Introduction

In order to match the evident amount of decay that has occurred in Earth rocks, and fit the Biblical timescale, the RATE project emphasized an accelerated decay episode, beginning early in the year of the Genesis Flood, and tapering off somewhere between a minimum of about ten years and a maximum somewhat less than a thousand years after the Flood (Vardiman, Snelling, and Chaffin, 2005).

In this article, we will consider some isotopes such as Nickel-56 and Iron-56 which are of astrophysical interest (Rehm, 1998; Thielemann, Hashimoto and Nomoto, 1990). They are thought to be involved in nuclear reactions in the interiors of stars which go supernova. Also, they are the most important contributors to the light output during early

---

* Eugene Chaffin, retired physics professor currently serving as vice president of the CRS

Accepted for publication February 9, 2021

stages of various types of supernovae, the "light curves" (Pinto and Woosley, 1988).

Fardon, Nelson, and Weiner (2004) proposed that the neutrino mass could vary with the strength of a hypothetical "acceleron field." Chaffin (2017) considered whether this theory, or an adaptation of it, could enable the passage of the neutrino burst by Earth to give a consistent picture for an accelerated decay episode. In a paper submitted to the *Quarterly*, some issues raised by this scenario are considered (Chaffin, 2020). In this article, we concentrate on a few nuclei, including Nickel-56 and Cobalt-56, which are observed via the light curves of supernovae.

The consideration of the contributions to supernova light curves by nuclear decays necessarily leads away from pure astronomy into the field of nuclear physics. Nuclear physics calculations, while greatly aided by modern computing abilities, do not give exact numerical results. However, some answers are found which we do not think would be changed by the exact numbers. The reasons for the numerical uncertainties include our inability to give equations for the forces of attraction between the nuclear particles which are valid in all cases, but also due to our inability to solve some problems to exact mathematical precision. We are often forced, in nuclear physics, to become familiar with approximation techniques such as perturbation expansions, Hartree-Fock-Bogoliubov methods, mean field methods, and effective field theory (Rowe, 1970; Krane, 1987). Hence, the reader may be led into some interesting areas of study.

Supernova Light Curves and Radioactive Decay

According to current, state of the art, simulations and models, the light output from a supernova remnant is thought to be largely due to the energy from the radioactive decay of ^{56}Ni (half-life $t_{1/2} = 6.075 \pm 0.010$ days, Cruz et al., 1992) and its daughter ^{56}Co (half-life $t_{1/2} = 77.08 \pm 0.08$ days, Lesko et al., 1989, Yang et al., 2018, p. 2). This expectation has been supported by the observation (Pinto and Woosley, 1988) of the approximate 77.1-day exponential decay of the light output from supernova 1987A, and other observations including those of SN 2014J in M82 by Yang et al. (2018).

Yang et al. (2018, p. 2) wrote: "The decay chain of $^{56}\text{Ni} \rightarrow {}^{56}\text{Co} \rightarrow {}^{56}\text{Fe}$ provides the main source of energy deposition into the ejecta of Type I SNe (Arnett, 1982)." Assuming this is factual, one seems well advised to consider the extent to which the half-lives of ^{56}Ni and ^{56}Co are affected by accelerated decay.

The Nickel-56 nuclear ground state has a spin and parity of 0^+, decaying nearly 100% of the time by electron capture with a 6-day half-life, producing an excited state of Cobalt-56, usually the 1^+ state with 1.72 MeV excitation (Nudat 2.8 online interactive chart). This is not a forbidden transition. The Cobalt-56 ground state is 4^+, usually decaying under laboratory conditions by electron capture to various excited states of Iron-56 with either 4^+ or 3^+ spin and parity. However, there is evidence (McLaughlin and Wijers, 2002; Nadyozhin, 1994) that some fraction of the time, around 19%, Cobalt-56 undergoes beta-plus decay instead of electron capture. In that case, positrons are emitted. None of the prevalent Co-56 decays are forbidden decays, although the half-life is 77 days. It should be pointed out that in the hot environment of a star, the atoms may be completely ionized, and then, there being no electrons to capture, the electron capture gives place to beta-plus decay.

Sur et al. (1990) established a lower limit of 2.9×10^4 yr for the half-life of fully ionized ^{56}Ni nuclei in cosmic rays. Denoting neutron number as N and proton number as Z, the N = Z = 28, doubly closed shell, nuclide ^{56}Ni is the most abundantly produced isotope in many supernova case scenarios (Fisker, 1999, p. 8; Clayton et al., 1992, p. 155; Thielemann et al., 1990, p. 222; Jones et al., 2019, Table 4, p. 13). Neutral ^{56}Ni decays to ^{56}Co via an allowed electron capture transition. Fully ionized ^{56}Ni must undergo beta-plus decay with the much longer half-life of at least 2.9×10^4 years as the prevalent decay. A similar expectation exists for ^{56}Co. Neutral ^{56}Ni decays to the 1720-keV energy level in ^{56}Co with a ~100% branch and a half-life of 6.0 days. A half-life value of 6.076 ± 0.010 days was reported by Cruz et al. (1992).

Yang et al. (2018) observed that the luminosity of the supernova SN 2014J in M82 appeared to follow, from days 200 to about 800 after the explosion, the exponential decay with an approximate 77-day half-life, matching the ^{56}Co half-life. This would imply that the ^{56}Co nuclei had attracted surrounding electrons to become a neutral atom or a least a partially ionized ion which could undergo electron capture decay. It would also imply that any episode of accelerated decay of ^{56}Co had largely passed. Otherwise, the graph decline would not correspond to the 77-day half-life. After 800 days one finds a flattening of the curve, apparently from the decline of Co-56 abundance as it decayed and consequent rise in importance of additional energy input from other radioisotopes, presumably ^{57}Co, ^{44}Ti and others (Suntzeff, 1992).

In the laboratory, *neutral* ^{56}Ni decays by electron capture (Fisker et al., 1999). The ^{56}Ni that we find is synthesized in nuclear reactions in extremely hot environments as a fully-ionized nucleus. Fully ionized ^{56}Ni nuclei in a low-density environment cannot decay by the laboratory mode of electron capture, there being then no electrons to capture, but instead can only undergo beta-plus decay with its attendant much longer half-life. However, the ^{56}Ni-rich material in most astrophysical situations rapidly expands and cools, and thus ^{56}Ni does not remain fully ionized for long. Hence, we find a ready explanation for the observed exponential decay of many supernova light curves from 200 to 800 days after the explosion.

Using given data for luminosity versus time it is possible to find the half-life by analyzing the graph for the linear portion between about 150 days and 500 days (Figure 1). The graph of the log to base ten of luminosity versus time in days should be linear if the decline is truly due to radioactive decay. From the data shown in the visual magnitude versus Julian day graph of Gehrz (1988, Gehrz's Figure 1) I find a trendline slope yielding a half-life of 68.5 days. Gehrz himself states that his data yields 72.5 days, which is very close to the laboratory value of 77 days for the half-life of ^{56}Co. From the graphs of Woosley and Phillips (1988) and Woosley and Weaver (1989), I find values of 75.2 days and 66.9 days, respectively. Of course, these authors were studying SN1987A, which was a Type II supernova.

Catchpoole et al., (1988) presented SN1987A data of bolometric luminosity versus time after 100 days. For the linear part of the curve from 160 days to 260 days, for four different methods of integrating the flux distribution, the corresponding half-lives are 76.5 days, 73.0 days, 75.6 days, and 71.9 days. These four values are all less than the Cobalt-56 laboratory value of 77.2 days.

Yang et al. (2018, their Figure 3), gave some data for SN2014J, which occurred in the galaxy numbered M82 in the Messier numbers list. M82 is a relatively nearby galaxy (12 million light-years), only slightly further away than Andromeda (2.5 million light-years). The SN2014J supernova was a Type Ia, and data presented include Hubble Space Telescope data labelled the F475W band and the F775W band. From these data, fitted with a trendline, I find 54.7 days and 59.0 days, respectively, for the corresponding half-life.

Hence, the data indicate that the half-life of Co-56 in these explosive environments is not orders of magnitude different from the current laboratory value of 77 days, but it is not necessarily exactly the same, averaging around 10% smaller than the 77 days. Is this what we would expect? We will come back to this question after a brief digression about nuclear forces.

Nuclear Force?

In order to overcome the electrical repulsion between protons and hold both neutrons and protons together in a nucleus, a nuclear force is required. Feynman (1985, p. 131) wrote: "There was also the problem of what holds neutrons and protons together inside the nucleus. It was realized right away that it could not be the exchange of photons, because the forces holding the nucleus together were much stronger—the energy required to break up a nucleus is much greater than that required to knock an electron away from an atom…"

Consider a process in which an electron goes between two points, as in Figure 2. In part (a.) on the left, it simply proceeds without interaction. In the middle part (b.), a virtual photon is emitted and absorbed and the electron still ends up at the same final point. In part (c.) on the right the electron emits one virtual photon, and then before reabsorbing it, it emits another. These are drawn following Feynman (1985), the Figure 77 in his book, *QED*.

Feynman points out in his book *QED* that the mass of virtual electrons

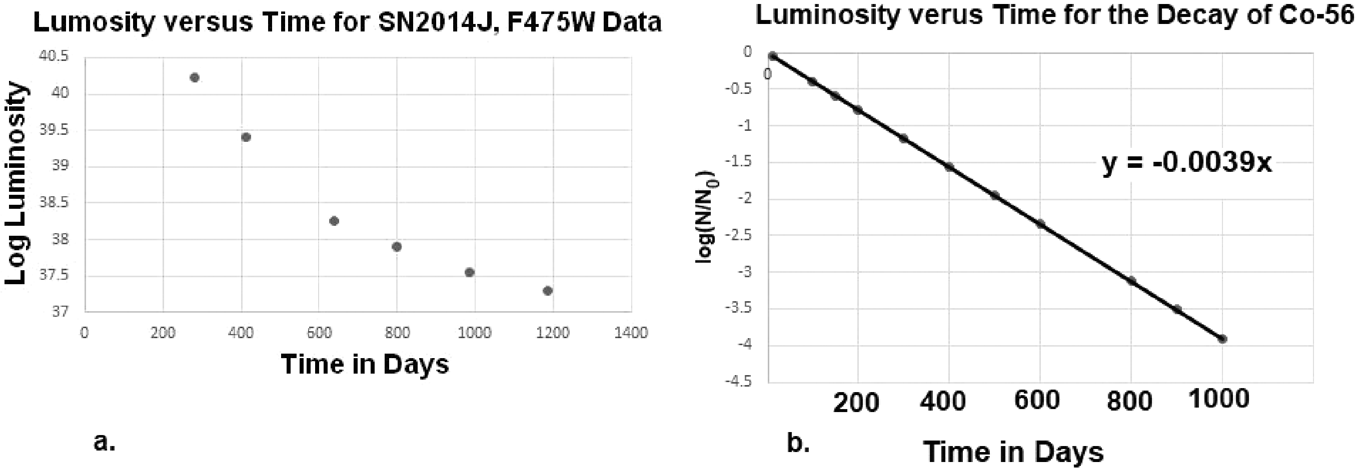

Figure 1. a. Log of Luminosity versus time for SN2014J for the dates 200 to 1200 days. Data from Yang et al., 2018), b. A graph for the decay of Co-56 plotted with a logarithmic scale for N/N_0, the fraction that has not decayed, versus time. The SN2014J data are only linear within a certain time interval, because other decays than Co-56 power it at other times.

is not the same as that of real electrons. This goes for W particles or any particle with rest mass as well. These intermediate particles, whose lines do not extend outside of the diagram, called virtual particles, are not constrained to have the same mass as a real particle, whose lines extend to infinity, and thus whose mass can be measured in the laboratory. If we note this fact, then there is a sense in which energy is not conserved if we insist on imagining the virtual particles to have the same mass as the real ones, which Feynman denies. However, energy must be conserved in the final states. On page 126 Feynman wrote: "Since the mass and charge of an electron are affected by these and all other alternatives, the experimentally measured mass, m, and the experimentally measured charge, e, of the electron are different from the numbers we use in our calculations, n and j." On page 128, Feynman adds: "So it appears that the only things that depend on the small distance between coupling points are the values for n and j, theoretical numbers that are not directly observable anyway;… " Thus the virtual particles do not have the same mass as real particles, which makes one wonder whether the mental pictures we associate with the mathematics are adequate.

Prior to Feynman's work, Hideki Yukawa (1935) introduced the conceptual framework for a systematic approach to the nucleon-nucleon interaction. His then postulated "U field" later became the pion field. This provided the basic mechanism of charge exchange between proton and neutron. From the form of the potential, $e^{-\mu r}/r$, and from the estimated range of the nuclear force, the mass of the U particle was predicted to be about 200 times that of the electron (Feynman, 1985, p. 132, 143). This is about the mass of the pions, which come with positive, negative and zero charge. The π^0 (pi nought) has a mass about 264 times the electron mass (135 MeV/c^2 = 264 x 0.511 MeV/c^2) while the charged pions ($\pi^\pm$) are slightly heavier.

This U particle was initially identified with the muon discovered in 1937, but which it turns out has nothing to do with nuclear forces. The "real" U particle was the π meson which was discovered a decade later (Occhialini et al., 1947) in cosmic rays and then produced for the first time (Lattes et al., 1947) at the Berkeley, California cyclotron.

Subsequent to Yukawa's original work, the 1950's saw an impressive effort to investigate whether the meson-exchange theory could match the facts. The evidence was investigated via a large number of papers in the Japanese journal *Progress of Theoretical Physics*, with some spill over into *Physical Review* and other journals. Taketani et al. (1951), considering the graph of potential versus distance between nucleons (Figure 3) into various pieces. At large distance, exchange of a single pion was thought to prevail, whereas at shorter distances two-pion exchange became important. It is found that a theory of nuclear forces involving the exchange of pions, ω (omega) mesons, ρ (rho) mesons, etc. represents the nuclear force very well (McCarthy, 1968, p. 52). The quark-gluon theory is hardly needed.

The quark was not proposed until Gell-Mann (1964), who wrote (1964, p. 215):

> A search for stable quarks of charge -1/3 or +2/3 and/or stable di-quarks of charge -2/3 or 1/3 or +4/3 at the highest energy accelerators would help to reassure us of the non-existence of real quarks.

Today the theory of the strong nuclear force at shorter distances involves quarks and gluons, which were unknown in the 1950's. Hence it is interesting that, in the 1950's the Japanese theoretical physicists (Konuma et al., 1958; Taketani et al., 1951) were reluctant to say that the Yukawa theory was working at short distances. At larger distances, one-pion exchange was thought and still is thought to prevail (Brown and Rho, 1983; Dean and Hjorth-Jensen, 2003,

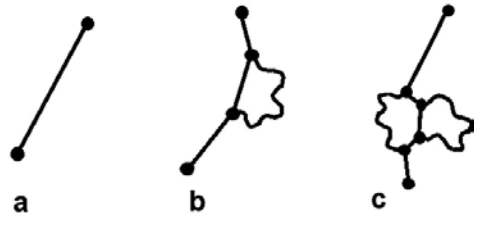

Figure 2. Three Feynman diagrams showing an electron going between two points with increasing complexity caused by photon emission. See the text.

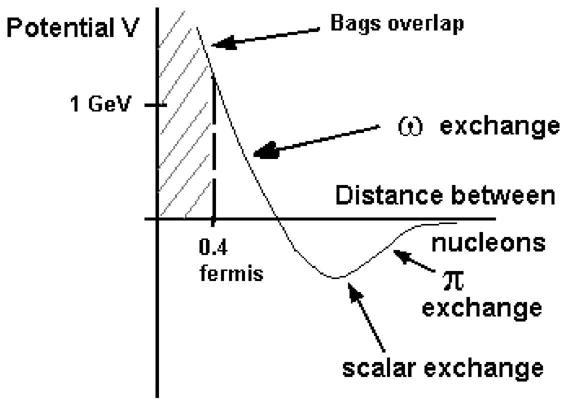

Figure 3. A graph of potential felt by a nucleon versus distance from a second nucleon, after Brown and Rho (1983).

p. 6) since the quarks are confined to a "bag" and should not matter at those distances. The quarks and gluons are thought to occupy a "core" of about 0.5 femtometers radius, while a meson cloud of pions and other mesons still prevails at larger distances (Brown and Rho, 1983, p. 51). The ρ (*rho*) meson, which consists of two pions, is thought to be a contributor, as is the ω (*omega*) meson.

According to the Pauli exclusion principle, two identical particles may occupy the same state only if they have opposite spins. However, the neutron and proton are not "identical." The nuclear force for neutron and proton approaching each other from opposite positions is stronger when the spins are parallel (Otsuka et al., 2005). The deuteron is the bound state of one neutron and one proton, ^{2}H. Evidently, there is only one bound state of the deuteron, and that is in the case where the spins of the neutron and proton are parallel, yielding +1 for the total spin quantum number (McCarthy, 1968, p. 51).

Nuclei and Superconductivity

Bardeen, Cooper, and Schrieffer (1957) (hereafter referred to as BCS) proposed that a very weak attractive force between pairs of electrons with opposite momentum was responsible for superconducting currents observed in many materials at low temperature. This at first appears counterintuitive since electrons are negatively charged, and two like charges should repel each other. However, the BCS theory is not concerned with two electrons moving in a vacuum, but in a crystalline solid where the medium includes a regular arrangement of positive ions. We picture the solid as a three-dimensional arrangement of positive ions called the *lattice*, surrounded by a gas of free electrons. The idea is that one electron attracts the positive ions near to it, causing a distortion of the crystal lattice, which may be transmitted through the solid in the form of quantized elastic waves, called *phonons*.

As the electron moves through the lattice, the positive ions nearby are displaced, forming a thin tube of displacement which follows the electron as it moves through the lattice. A second electron may be attracted to the tube of concentrated positive charge, but the attraction is only large if an electron moves along the direction of the tube opposite to the direction of the first electron. Otherwise the encounter is too short and the attractive interaction is too weak. Also, this mechanism is only effective at low temperature, where other lattice motions do not interfere. The two electrons, together with their tubes of displaced ions trailing along behind them, form a quantum state called a *Cooper pair* (Cooper, 1956) or also a *quasiparticle*. The electrons in a crystal obey the Pauli exclusion principle, which states that no two electrons can occupy the same state unless they have opposite spins. Having the opposite spin also makes the state different, so taking spin into account enables the statement to be changed to the requirement that no two electrons can occupy the same state. Particles which obey the Pauli exclusion principle have half-integral spin and are called *fermions*. The other category of particles includes particles of integral spin, called *bosons*, and these particles do not obey the Pauli exclusion principle and can have more than one particle per quantum state. In a solid, there is an amount energy called the Fermi energy, named after Enrico Fermi, which at absolute zero would divide occupied electron energy states from unoccupied energies. At a finite temperature, the Fermi energy still divides occupied levels from unoccupied levels, but the boundary is not so sharp, the occupation numbers changing from one to zero only over a finite interval or spread of energy. This means that Cooper pairs can only be formed by electrons near to the Fermi energy, because the energy from the weak attractions of one electron for another can only be effective if the electrons can change their quantum states to unoccupied levels. Cooper (1956) showed that two fermions of opposite spin attract each other to form a bound state, and that this Cooper pair has zero spin and behaves like a boson.

The adoption of BCS theory into nuclear physics followed the tentative plans offered by Bohr, Mottelson, and Pines (1958) and the more detailed form given by Belyaev (1959). Bohr et al. explained the energy gap observed in the spectra of even-even nuclei in terms of the BCS ideas, and then Belyaev used the mathematics of field theory, and approximations that followed from it that made possible simple calculations of the effects of pairing in nuclei in terms of independent quasi-particles.

In nuclei pairs of neutrons and also pairs of protons couple to a total spin of 0, giving a little extra binding energy. This has been noticed in several lines of research. Experimentally we find that nuclei with an even number of protons and also an even number of neutrons have a total angular momentum of zero in their ground states. The nuclear force just naturally leads to this. It is thought to be due to the short-range portion of the interaction between nucleons. The ground states of the majority of nuclei are very well described in terms of "superfluid condensates," in which pairs of protons or pairs of neutrons form.

Since they do not have to obey the Pauli exclusion principle, a neutron and a proton of parallel spin will be attracted to each other and pair up when in states of opposite orbital angular momentum. Also, two protons of antiparallel spin can pair up, or two neutrons of antiparallel spin can pair up. The pairing forms what are called "quasiparticles" and the formation of large numbers of these pairs of particles into quasiparticles is a "condensation" which lowers the overall energy of the nucleus, forming a "pairing gap," a lowering of the overall nuclear energy (Bohr, Mottleson, and Pines, 1958).

Is Nickel-56 a Special Nucleus?

Nuclei with doubly-closed shells are only a small fraction of the nuclei which have been charted. In theory, Nickel-56 has proton number and neutron number Z = N = 28, which would be doubly closed because of the filling of the $f_{7/2}$ orbital with the required eight particles, both for neutrons and protons, which filling brings the total number of particles to 28 counting the 20 particles in subshells of lower energy. Of course, then 28+28 is 56. However, if the ground state of this nucleus were deformed, the orbital energies could be modified and could destroy this property. This has been documented to occur for nuclei far from stability (Datta et al., 2018; Diriken et al., 2014). Evaluations of experimentally measured rates of excitation and subsequent gamma emission of a nucleus to the excited 2^+ state by electron collision have been used to infer the amount of deformation for the 2^+ state to ground state transition. This spheroidal deformation is measured by the "quadrupole deformation parameter β_2" (Pritychenko et al., 2016). The quadrupole deformation parameter for the ^{56}Ni transition determined in this way ranges from 0.144 according to Yanagisawa et al., (1998, quoted in Pritychenko et al., 2016, p. 43), to 0.173 according to values tabulated by Raman et al., 2001, p. 38, Table I). The 0.173 value originated with Kraus et al. (1994, p. 1775), who inferred the value from experimentally measured transition rates between the ground state and the first 2^+ excited state, using phenomenological equations (Raman et al., 2001, p. 14). This value is found from a transition rate between two states, more precisely the reduced electromagnetic transition rate B(E2: $0^+ \rightarrow 2^+$), and does not give the deformation of the 0^+ ground state of ^{56}N (Elliott, 1958, p. 576; Burcham, 1963, p. 690; Blatt and Weisskopf, 1979, p. 30; Bethe and Morrison, 1947, p. 175). On the other hand, very powerful computer calculations by Möller et al. (2016, p. 87) gave zero for the deformation parameter for the ground state. Also, we shall see below that even-even nuclei in their ground states invariably have zero spin and zero quadrupole moment. This does not necessarily mean zero deformation, as Burcham (1963, p. 690) pointed out:

> Quantum mechanical states with I = 0 and I = 1/2 have spherically symmetrical charge distributions and electric (E) moments are not observed for such states. This does not mean that a nucleus in such a state is necessarily a spherical object, since the spherical symmetry may arise because of the averaging over spin directions.

The nucleus in such a quantum state would have a deformation and react accordingly if it could be observed at rest, but its motion causes an averaging to zero effect. An example where the ground state has zero spin and zero quadrupole moment but still is deformed is ^{42}Si, which according to Möller et al., (2016, p. 53) is an oblate spheroid in the ground state.

Atomic nuclei, with their discrete energy levels, sometimes follow the "rigid rotor model" (Segre, 1965, p. 254; Burcham, 1963, p. 85). In such a case, for even neutron and proton number, the various energy levels form "bands" with spin I = 0, 2, 4, 6, etc. and have energies which increase in proportion to I(I+1). In some nuclei, such as ^{20}Ne and ^{22}Ne, the transition quadrupole moments found from the reduced electromagnetic transition rates B(E2: $0^+ \rightarrow 2^+$), B(E2: $2^+ \rightarrow 4^+$), and B(E2: $4^+ \rightarrow 6^+$) remain constant consistent with a rigid rotor model of the nucleus (Schwalm et al., 1972, p. 482 and their Table 5). Other nuclei, such as ^{24}Ne, exhibit a spherical state or a small oblate deformation for I = 0^+ and 2^+, while a prolate deformation is found at I = 4^+ (Bottoni et al., 2012, p. 5–6 and their Figure 7). Although no experimentally measured B(E2: $2^+ \rightarrow 4^+$), and B(E2: 4+ → 6+) values have been reported for Nickel-56, the trends indicate that it follows a more complicated behavior than the rigid rotor model.

Experimentally, one can use various indicators to provide evidence that closed shells, also called "magic numbers," do in fact exist. Taniuchi et al. (2019) discussed the size of the energy gap between the ground state, which invariably has a spin and parity of 0^+ in these even Z, even N cases and the first 2^+ excited state (see Figure 4).

Another line of evidence depends on values of the separation energies of the last pair of neutrons, as discussed by Thibault et al. (1975). An unexpected increase in this separation energy for Na-31 and Na-32 indicated nonexistence of a shell closure for these sodium isotopes. Rodriguez-Guzman et al. (2002) used these separation energies to show evidence for nonexistence of the N= 28 shell closure for the very neutron-rich nuclides Mg-40 (Z = 12, N= 28), Si-42 (Z = 14, N = 28, and S-44 (Z= 16, N = 28). However, Ni-56 is nearer the line of stability and is not neutron rich (Z = N = 28). The separation energies provide evidence for a shell closure in Nickel-56.

Pairing Phase Changes and Relevant Half-Lives

In modern physics, the nucleus, which consists of a finite number of neutrons and protons bound together by the strong nuclear force, is successfully treated using quantum theory, whereas exact equations for the nuclear interaction are not known. Various effective interactions, labelled GXPF1, the Kuo-Brown KB3, the Argonne V18 interaction, the Nijmegen interaction, the Gogny force, etc. have been found to give acceptable computational results (Lisetskiy et al., 2003; Langanke et al., 1995; Machleidt and Slaus 2001; Dechargé and Gogny, 1980). Although the nucleus consists only of a finite number of particles, the concept of a *phase transition* is useful for describing structure changes in the atomic nucleus (Chaffin, 2008, p. 180). The phase can consist of a state dominated by pairing forces in which the particles “condense out” into pairs of quasiparticles, referred to as a “superfluid.” Alternatively, there are “shape transitions” in which the nucleus selects oblate, spherical, or prolate shapes (Figure 5). Some nuclei are said to be “soft,” meaning that they may easily change to triaxial asymmetric shapes.

In the description of current nuclear physics models and theories, the term “residual interaction” refers to the leftover interaction after an average potential is assumed. “Pairing” is the part of this residual interaction of the pairs of particles in the correctly corresponding orbits are selected. When this interaction is strong enough, there can be a “condensation” of the particles into pairs which yields a “pairing gap” Δ, which is a reduction in energy of the nucleus resulting from the pairing. Typically, the pairing gap Δ is of the order of 1 MeV, which is smaller than the shell gap, which is several MeV depending on the particular gap to which we refer (see Figure 7). When the pairing interaction is not strong enough, then $\Delta = 0$ and the overall nuclear energy is not reduced. This does not mean that the pairing interaction vanishes, only that it is not strong enough to cause the condensation. This $\Delta = 0$ situation may occur in the ground state of some nuclei, whereas in other nuclei, at some excitation energy, there occurs a phase transition [second order] to a “heated” nucleus where the pairing effects may be neglected (Volya, Zelevinsky, and Brown, 2002).

In Chapter 7 of RATE, volume 2 (Chaffin, 2005a), quantum mechanical calculations were presented for an alpha particle in a nucleus. In quantum mechanics, the wavefunction is a quantity whose square gives the probability density for finding the particle, the alpha particle in this case. The calculations showed that, if the strength of the strong nuclear force were to change, the number of nodes in the effective wave function could change suddenly. This results in a jump in the decay constant (which is 0.693 divided by the half-life, and also the fraction of the nuclei decaying per unit time). Here we are concerned with changes in the weak nuclear force caused by an acceleron field pulse associated with a supernova burst. It is not the strong nuclear force that is affected, but nevertheless the weak force affects the nuclear particles.

In Chaffin (2017), it was considered that, during the nearby supernova event, the mass of U-238 nuclei could change, resulting in beta-minus decay becoming the predominate decay mode rather than alpha decay. This consequently results in a drastic change in nuclear half-life. The mass change of the U-238 nucleus was linked to the weak force rather than the strong nuclear force. However, the weak force also affects the dynamics of the nuclear particles. The weak force changes are hypothesized to be caused by the changes in the acceleron field.

In Chaffin (2008), the dependence of nuclear pairing phases on the strength of the nuclear force were discussed. For some nuclei it was shown that a slight change in nuclear force strength could cause a discontinuous change in half-life. For other nuclei, such as C-14, this was not the case. For C-14, the half-life is not as drastically altered. C-14 is exceptional in that there may be no pairing,

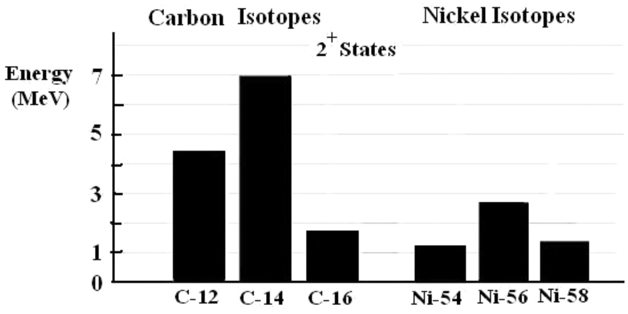

Figure 4. Energy gap between the 0^+ ground state and the first 2^+ excited state in even N-even Z carbon and nickel nuclei. Carbon-14, with neutron number N = 8 has a closed shell, whereas Carbon-12 and Carbon-16 do not. The smaller energy gap shown provides evidence that Carbon-14 does in fact have a closed neutron shell (Negret et al., 2006). Nickel-56 has doubly closed shells N=Z=28, and the bar height is higher for it than for its even N-even Z neighbors Nickel-54 and Nickel-58. This is experimental evidence for a closed shell (Taniuchi et al., 2019, their Figure 1].

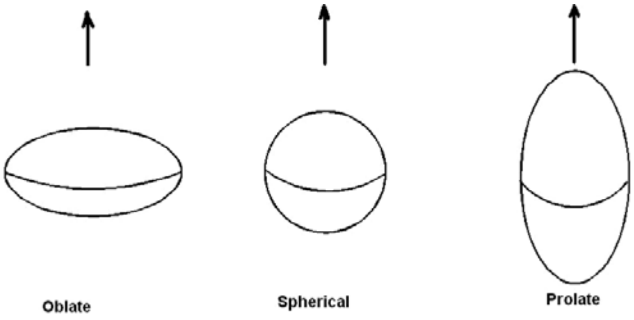

Figure 5. Oblate, spherical, and prolate ellipsoidal shapes. These are axially symmetric possibilities that a nucleus may assume depending on its energy level.

hence when the nuclear force strength changes, no phase change of the nucleus occurs. This implies that that half-life may change slightly, but not drastically.

Nickel-56 is important in the supernova explosion, since this nuclide is the most abundantly produced isotope in many supernova case scenarios (Yang et al. (2018, p. 2). As discussed above, Ni-56 is a *doubly closed-shell* nucleus with both neutron and proton numbers equal to 28. Empirically (and theoretically) one expects closed shells for nucleon numbers 8, 20, 28, 50, 82, 126, etc., and Ni-56 happens to have Z = N = 28. Figure 6 shows a graph, the result of computer calculations as in Chaffin (2008), of pairing gap versus pairing strength for Ni-56, assuming a spherical shape.

The actual pairing strength is thought to be 0.343 MeV, hence the pairing gap should be zero and there would be no "pairing condensate" or the Nickel-56 ground state would not exist in the pairing phase.

This zero-pairing gap for ^{56}Ni agrees with the results shown in Figures 5 and 6 of Li et al. (2015). Their graph shows the pairing gap curves on both sides (N < 28 and N > 28) dropping off precipitously to zero for N = 28. Terasaki and Engel (2006) presented a similar graph (their Figure 9), but the theoretical part used the Skyrme interaction. It also gave a zero-pairing gap for Nickel-56.

As explained in Chaffin (2008), Nilsson, et al. (1969, p. 17), found that the overall mass number A-dependence of the pairing strength G was found to be proportional to A^{-1}. Nilsson et al. gave the equation for G times A:

$$GA = g_0 \pm g_1(N\text{-}Z)/A,$$

with g_0 = 19.2 MeV and g_1 = 7.4 MeV. For the ± sign, the plus sign is for protons, the minus sign for neutrons. However, when more involved theoretical studies have been done, better, more precise calculations than this empirical approximation may be possible.

Ni-56, with proton number Z = 28 and neutron number N = 28, has an expected pairing strength of 0.343 MeV for both protons and neutrons, which according to my results is too small, and there is no expected pairing gap for this doubly-closed-shell nucleus. This would imply that, like Carbon-14, the half-life of Ni-56 is not sensitive to changes in either the weak or strong nuclear forces, since changes in these forces could not cause a phase transition since none is available. The single particle energy levels that should be used in these computer calculations are not precisely given, hence estimating the uncertainty in the critical pairing strength, given above as 0.41 MeV for a spherical nucleus, could be done by varying these single particle energies. For example, Gade et al. (2005, p. 4) and Sagawa et al. (2013, their Figure 1) gave some different sets of single particle energies for Nickel-56 which could be adopted for the calculation of these uncertainty intervals. For neutrons we find that the critical pairing strength G_p is between 0.36 and 0.42 MeV, while for protons in Nickel-56 it is between 0.36 and 0.41 MeV. Thus, the actual value of 0.343 MeV is well outside this range, indicating that small variations will not cause a phase change.

Gambacurta and Lacroix (2014) presented a graph, their Figure 2, showing that the pairing gap should be zero for Nickel-56. There calculations showed that their "Skyrme energy density functional" is minimized for a spherical shape with zero pairing gap, thus confirming my results.

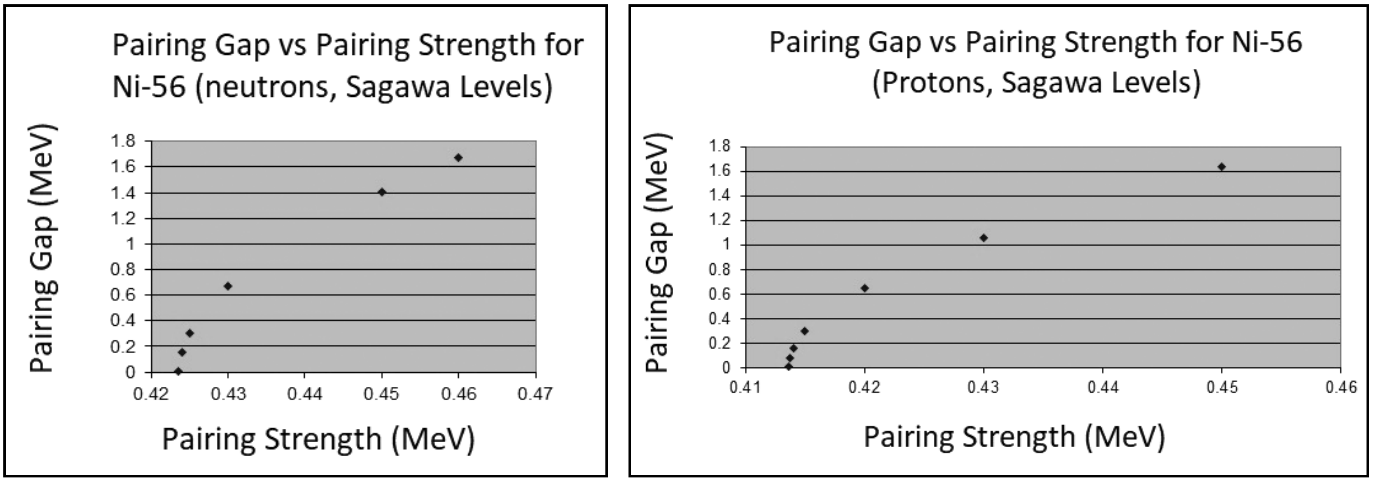

Figure 6. Pairing gap versus pairing strength for the doubly-closed shell nucleus Nickel-56, Z=N=28, neutron results on the left, protons on the right. For pairing strengths below 0.41 MeV, which includes the actual value, the pairing gap vanishes. The single-particle levels were adjusted using data given in Sagawa, Tanimura, and Hagino (2013).

However, the situation for Ni-56 is clouded by the fact that, it exhibits "shape-coexistence." In other words, according to this concept, a nucleus in some excited states has a deformation even though the ground state is a spherically symmetric shape (Chiba and Kimura, 2014, 2015). Blatt and Weisskopf (1979, p. 26) gave an interesting proof that an even Z, even N nucleus will have zero angular momentum and must have a zero-quadrupole moment in their ground state. This is borne out in experimental tables (Stone, 2005). The "electric quadrupole moment" which Blatt and Weisskopf defined more precisely than we will here, measures the amount of spheroidal deformation of the nucleus. A prolate (cigar-shaped) spheroid has a positive quadrupole moment, whereas an oblate (pancake-shaped, see Figure 5) spheroid has a negative quadrupole moment. Chiba and Kimura found that the Nickel-56 nucleus is "soft" against oblate deformations, and that the potential energy surface also had minima for prolate deformations. Rudolph et al. (1999) found bands of energy levels correspond to inferred deformations. Thus, although the ground-state is spherical and has zero angular momentum, Ni-56 is easily excited to energy levels with nonzero angular momentum and nonzero quadrupole moment. This idea is supported by the results of some earlier theoretical calculations of Otsuka et al. (1998) which indicated that the ground state of Ni-56 was not a pure doubly-closed-shell configuration but contained an appreciable mixture of something else. Honma et al. (2004, p. 24) characterized it as a 68% doubly-closed nucleus with a mixture of one particle excited across the shell gap, leaving one hole in the "core." They did not speculate on whether this meant there was a deformation, although their Figure 18 shows a value of about 20 e•fm^2 for the quadrupole moment of the first excited 2^+ level. However, as we discussed above, experimental data involving 2^+ excited states and two-neutron separation energies speaks in favor of the existence of the doubly-closed shell. Also, the calculations of Chiba and Kimura (2014, p. 6) led to a transition probability from the first excited 2^+ state to the ground state, the so-called B(E2) value, larger than the experimental value. They therefore concluded that "the actual deformation of ^{56}Ni is smaller than the present result." Rudolph (1999, p. 3764), Heyde and Wood (2011, p. 1496) and Horoi et al. (2006, p. 1) divide the levels of ^{56}Ni into a "spherical" ground state band and two "superdeformed," prolate bands. No experimental evidence for an oblate band has been found. Also, the shell gap shown in Möller, Nix, and Kratz (1997, p. 172) for either neutrons or protons at N or Z = 28, is slightly larger for the spherical shape than for the oblate deformation ($\mathrm{eps}_2 = -0.40$). One could also reiterate the findings, from theoretical calculations, of Möller et al. (2016, p. 87), mentioned above, which gave zero for the deformation parameter for the ground state of ^{56}Ni. Therefore, the factuality of a doubly-closed shell, spherical or at least nearly spherical configuration for Ni-56 is not appreciably modified.

Another complication for Ni-56 concerns possible pairing between neutrons and protons, called *np*-pairing. In most nuclei, only proton-proton pairing (*pp*-pairing) or neutron-neutron (*nn*-pairing) is of any importance. However, for nuclei with N = Z the states of the neutrons and protons are very similar and *np*-pairing can be important. The *np* Cooper pairs are not deuterons (^{2}H nuclei), but involve an attractive interaction in which the particles of the pair remain further apart (Isaule, et al., 2016). In neutron star interiors both these *np* states are thought to occur, but at nuclear densities the deuteron state is not favored (Rubtsova et al., 2017). Cederwall et al. (2011) wrote:

> For all known nuclei, including those residing along the N = Z line up to around mass 80, a detailed analysis of their properties such as binding energies [9] and the spectroscopy of the excited states [10] strongly suggests that normal isovector (T = 1) pairing is dominant at low excitation energies.

Here, the term "isovector pairing" refers to a type of *np*-pairing in which the neutrons and protons couple in a certain way, as opposed to the other type called isoscalar pairing. Frauendorf and Macchiavelli (2014) wrote: "The *np* pairs can couple to angular momentum zero and isospin T = 1 (isovector), or, since they are no longer restricted by the Pauli exclusion principle, they can couple to T = 0 (isoscalar) and J = 1." We need not concern ourselves with the details here, but the interested reader can refer to the Cederwall et al. (2011) paper and references therein. The relevant theory states that *np*-pairing could exist for N = Z nuclei such as Ni-56. However, for the ground state of Ni-56, indications are that the pairing of this type does not materialize.

Martinez-Pinedo, Langanke, and Vogel (1999), in a numerical study of iron isotopes (proton number Z = 26), found that the strength of *np*-pairing decreased as the neutron number N increased away from the N = Z = 26 nucleus ^{52}Fe. For the closed shell nucleus N = 28 (^{54}Fe), where the $f_{7/2}$ subshell is full with 8 neutrons and the entire N = 28 shell is full, they found that the strength of the $f_{7/2}$ isovector and isoscalar pairing was substantially less (Martinez-Pinedo et al., 1999, their Figure 7). As other subshells, associated with higher neutron single particle energies (see Figure 7) across the shell gap, begin to fill, the overall *np*-pairing strength increases again.

Discussing nuclei with N ~ Z nuclei near the A = 56 mass number of Nickel-56, Poves and Martinez-Pinedo (1998, p. 207) wrote: "Finally we discard the presence of isoscalar pairing condensates everywhere in the region, as well as the existence of isovector pairing condensates at N = Z." In heavier nuclei, with proton numbers from 55 to 70, such *np*-pairing condensates have been found (Gezerlis, et al., 2011), but not near proton number Z = 28. Also, for short-lived nuclei with either very large or very small numbers of neutrons, relative to the proton number, *np*-pairing has not been ruled out. Nevertheless, in the doubly closed N = Z = 28 nucleus ^{56}Ni, there is no *np*-pairing gap or it is zero since the strength of *np*-pairing is not enough for this nucleus. Thus, a small change in nuclear attraction will not change the nuclear phase and will not drastically affect the half-life of this nucleus.

Nickel-56 decays to Co-56. For the case of Co-56, proton number Z = 27 and neutron number N = 29, and with the 77-day half-life and with a slight deformation, I have done computer calculations similar to those reported in Chaffin (2008), for both neutrons and protons, investigating the existence of pairing correlations. According to computer calculations, based on a liquid drop model corrected by single-particle microscopic methods, Möller et al. (1995, p. 235), found that Co-56 has a slight quadrupole deformation, measured by a parameter $eps_2 = 0.083$. More refined work (Möller et al., 2016, p. 85) gave $eps_2 = 0.07$. Taking the quadrupole deformation as factual leads to modified single particle levels (Möller, Nix and Kratz, 1997, p. 172). A prolate ellipsoidal shape occurs (Peng and Chen, 2018, p. 4). This deformation was taken in to account using the single particle level graphs presented in Möller, Nix and Kratz (1997), which show the shift in the levels as a result of the quadrupole deformation parameter. My results are shown in Figure 8.

Due to uncertainties in the single particle energy levels, there are corresponding uncertainties in the possible pairing gaps. For Co-56, G_p the limit point for neutrons is about 0.405 MeV, below which the pairing gap is zero. The limit point for protons is around G_p = 0.26 MeV. The actual pairing strength is G_p = = 0.338 MeV for neutrons and G_p = 0.347 MeV for protons. Thus, there should be no pairing gap for neutrons. For protons there would be a pairing gap of around 0.8 MeV. Co-56 is an odd-odd nucleus in that both the proton and neutron numbers 27 and 29 are odd numbers. For particle number N = 29, there

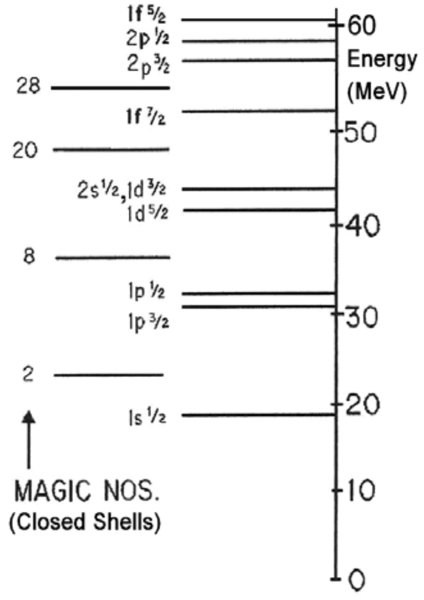

Figure 7. Nuclear single particle levels in the shell model plotted using their energies and showing the shell gaps. Nickel-56 would have a filled shell corresponding to the N = 28 shell gap.

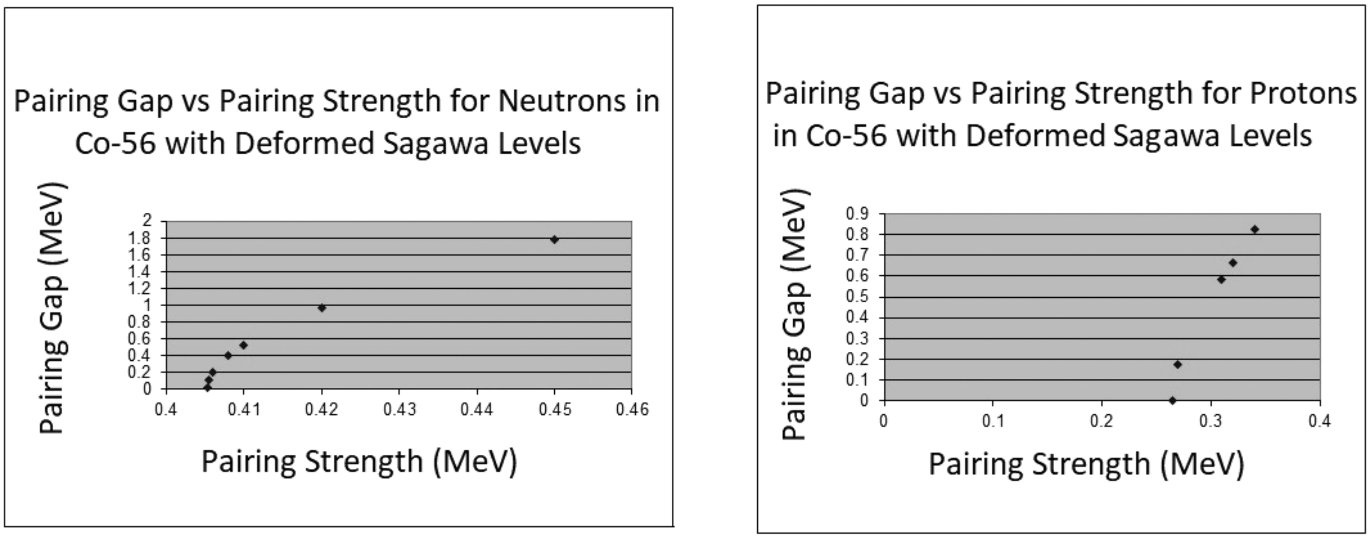

Figure 8. The two graphs show the pairing gap as a function of the pairing strength, in Co-56, Z = 27, N= 29, showing neutrons for the left pane and protons for the right pane. The single-particle levels were adjusted using data given in Sagawa, Tanimura, and Hagino (2013).

is one neutron outside the closed shell at N = 28, which odd neutron is more likely to be at larger distance than the others, hence has less of a pairing probability. On the other hand, the subtraction of one proton from the closed shell at Z= 28 does not decrease the likelihood of proton pairing as much as for the neutrons. Hence, we find the limit point for protons (0.26±.02 MeV) is smaller than for neutrons (0.405±.02 MeV). This is an example of what is called "blocking" (Rowe, 1970, p. 194). Rowe wrote: "If one particular single-particle state μ is singled out and occupied by a physical particle, that state is no longer available for the pair correlations of the other particles. In other words, the single-particle state μ is blocked." Compared to Ni-56, there is more of a likelihood that the pairing phase for protons persists as the weak nuclear force changes (a change we think is due to the acceleron field). Thus, the sensitivity of Co-56 to changes in nuclear forces should be somewhat more than Ni-56, but not as pronounced as for some other nuclei.

The pairing gap may be plotted against neutron number as shown in Figure 9. The pairing gap is seen to drop precipitously to zero as the neutron number nears the N = 28 closed shell.

Langanke et al. (1995) performed a type of improved calculation for nuclei that are of interest for supernova studies such as those of interest here. The Langanke et al. (1995) figure [Fig. 6 in the original article, Fig. 12 when essentially the same figure was reproduced in Dean and Hjorth-Jensen (2003)] shows that pairing strength in even-even nuclei is smallest in the closed shell nucleus. Langanke et al. studied the BCS-like pairing content of the ground states of even-even nuclei ^{52,54,56,58,60}Fe [Z=26], ^{56,58,60,62,64}Ni [Z=28], and ^{60,62,64}Zn [Z=30] by measuring the expectation values for the pairing fields, which was their expression $<\Delta^\dagger\Delta>$, for proton-proton and neutron-neutron pairing. Nuclei such as cobalt have Z=27, an odd number, and thus cannot be even-even, regardless of neutron number. However, these calculations show that the pairing correlations get smaller as you approach a closed shell.

The size of the pairing gap is determined by the density of single particle states close to the "Fermi surface," or the position (energy) separating occupied from unoccupied levels. We find that the total energy is lowered when there is an unusually high-level density, since the higher the level density, the larger the number of levels into which pairs can be scattered. At a closed shell, the level density is small and consequently pairing gets weaker.

Dean and Hjorth-Jensen (2003, p.2) stated: "Second, there is a critical value of the pairing-force strength for which no non-trivial solution exists." This was viewed as a negative aspect of the BCS approximation which could be "corrected" by the Lipkin-Nogami "trick." This "trick" involves an extra term in the constraint equation from which the working approximations are derived (Nogami, 1964, 1965). However, phase transitions are still expected, although this does not necessarily imply vanishing of all correlations, such as neutron-proton correlations (Clark and Macchiavelli, 2008). A nucleus, after all, has a finite number of particles, not the very large numbers usually encountered in the thermodynamics of phase transitions. Clark and Macchiavelli found evidence that the doubly-closed-shell nucleus, Pb-208, is very close to the critical-point of the pairing phase transition. Although the sharpness of a pairing to no-pairing phase transition remains an uncertainty, nevertheless the occurrence of such transitions can be considered as an important event.

Conclusion: Expectation for Changed Half-Life

As the strength of the nuclear force changes, a half-life may either increase or decrease Chaffin (2005a, Figure 3, p. 530). The half-life is not a steadily changing (monatonic) function of one parameter. However, when the nucleus undergoes a phase change, a dramatic alteration in half-life is to be expected rather than a miniscule alteration. Hence, these studies point to very little change in the doubly-closed shell Nickel-56 half-life. For Cobalt-56, the neutrons are not condensed into the pairs called quasiparticles, hence a slight change in nuclear parameters

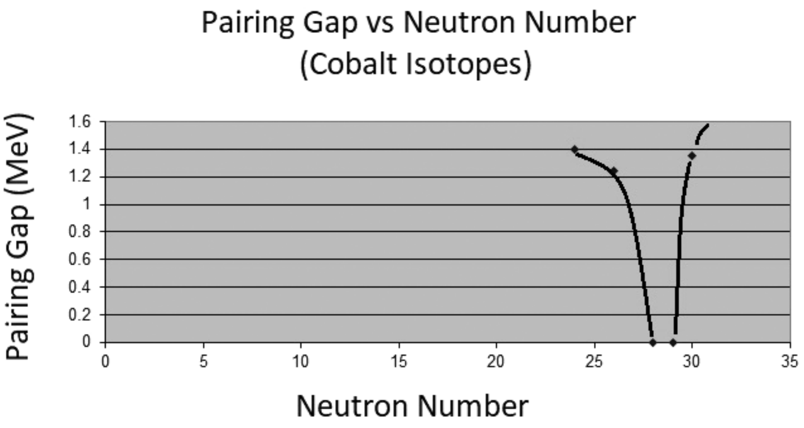

Figure 9. The calculated pairing gap is plotted versus neutron number, showing how the gap drops to zero as the number of neutrons approaches the N = 28 closed-shell value.

would probably not produce dramatic phase change and/or associated half-life change. According to the present study, for the Co-56 protons a slight change caused by the acceleron field or any other factor affecting the nucleus is more likely to alter the half-life, and this is a subject for future studies.

References

CRSQ: Creation Research Society Quarterly

Arnett, W.D. 1982. Type I supernovae. I. Analytic solutions for the early part of the light curve. *Astrophysical Journal* 253: 785–797.

Bardeen, J., L.N. Cooper, and J.R. Schrieffer. 1957. Theory of superconductivity. *Physical Review* 108: 1175–1204.

Belyaev, S.T. 1959. Effect of pairing correlations on nuclear properties. *Matematisk-Fysiske Meddelelser Udgivet Af Det Kongelige Danske Videnskabernes Selskab* 31(11): 1–55.

Bethe, Hans A. and Philip Morrison. 1947. *Elementary Nuclear Theory*. John Wiley and Sons. New York.

Blatt, John M. and Victor F. Weisskopf. 1979. *Theoretical Nuclear Physics*. Dover Publications. New York. Originally published 1952.

Bohr, A., B.R. Mottleson, and D. Pines. 1958. Possible analogy between the excitation spectra of nuclei and those of the superconducting metallic state. *Physical Review* 110: 936–938.

Bottoni, S., G. Benzoni, S. Leoni, D. Montanari, A. Bracco, F. Azaiez, S. Franchoo, I. Stefan, N. Blasi, F. Camera, F.C.L. Crespi, A. Corsi, B. Million, R. Nicolini, E. Vigezzi, O. Wieland, F. Zocca, L. Corradi, G. DeAngelis, E. Fioretto, B. Guiot, N. Marginean, D. R. Napoli, R. Orlandi, E. Sahin, A.M. Stefanini, J.J. Valiente-Dobon, S. Aydin, D. Bazzacco, E. Farnea, S. Lenzi, S. Lunardi, P. Mason, D. Mengoni, G. Montagnoli, F. Recchia, C. Ur, F. Scarlassara, A. Gadea, A. Maj, J. Wrzesinski, K. Zuber, Zs. Dombradi, S. Szilner, A. Saltarelli, G. Pollarolo. 2012. Reaction dynamics and nuclear structure of moderately neutron-rich Ne isotopes by heavy-ion reactions. *Physical Review* C 85(6): 064621 [7 pages].

Brown, Gerald E. and Mannque Rho. 1983 The structure of the nucleon. *Physics Today* 36(2): 24–32.

Burcham, W.E. 1963. *Nuclear Physics An Introduction*. McGraw-Hill. New York.

Catchpoole, R.M. et al. 1988. Spectroscopic and photometric observations of SN1987A - III. Days 135 to 260. *Monthly Notices of the Royal Astronomical Society* 231: 75–89.

Cederwall et al. 2011. Evidence for a spin-aligned neutron-proton paired phase from the level structure of ^{92}Pd. *Nature* 469: 68–71.

Chaffin, E.F. 2001. A model for the variation of the Fermi constant with time. *CRSQ* 38: 127–138.

Chaffin, Eugene F. 2005a. Accelerated decay: theoretical considerations. In Vardiman, L., A.A. Snelling, and E.F. Chaffin (editors), *Radioisotopes and the Age of the Earth, Volume 2, Results*. Institute for Creation Research and Creation Research Society, Dallas, TX and Chino Valley, AZ., pages 525–585.

Chaffin, E.F. 2005b. Accelerated decay: Theoretical models. In Ivey, Robert L. (editor) *Proceedings of the Fifth International Conference on Creationism*. Creation Science Fellowship. Pittsburgh, PA, pages 3–15.

Chaffin, E.F. 2008. Studies of the dependence of nuclear half-lives on changes in the strength of the nuclear force. In Snelling, Andrew A. (editor) *Proceedings of the Sixth International Conference on Creationism*. Creation Science Fellowship. Pittsburgh, PA and Institute for Creation Research, Dallas, TX., pages 179–192.

Chaffin, E.F. 2017. Variable neutrino mass, supernovae, and accelerated decay. *CRSQ* 53: 180–190.

Chaffin, E.F. 2019. A discontinuous change in half-life seems to characterize many findings regarding accelerated decay. *CRSQ* 55: 248–251.

Chaffin, E.F. 2020. Supernova driven accelerated decay confronts the evidence. *CRSQ* 57: 98–112.

Chiba, Y. and M. Kimura. 2014. Collectivity and instability of the N=Z=28 shell gap and strongly deformed bands with $g_{9/2}$ configuration in ^{56}Ni. *Physical Review* C 89(5) 054313 [9 pages].

Chiba, Y. and M. Kimura. 2015. Collectivity and instability of the N = Z= 28 shell gap in ^{56}Ni. In *Proceedings of the Conference on Advances in Radioactive Isotope Science (ARIS2014)*. *Journal of Physics Conference Series Proceedings* 6: 030047 [4 pages].

Clark, R. M. and Macchiavelli, A. O. 2008. Exact and collective treatments of the pairing phase transition. *Physical Review* C77(5): 057301 [4 pages]

Clayton, D.D., M.D. Leising, L.-S. The, W.N. Johnson, and J.D. Kurfess. 1992. The ^{57}Co abundance in SN1987A. *Astrophysical Journal* 399: L141–L144.

Cooper, L. N. (1956). Bound electron pairs in a degenerate Fermi gas. *Physical Review* 104: 1189–1190.

Cruz, M.T.F. da, Y. Chan, R.-M. Larimer, K.T. Lesko, E.B. Norman, R.G. Stokstad, F.E. Wietfeldt, I. Zlimen. 1992. Half-life of Ni-56. 1992. *Physical Review* C46: 1132–1135.

Datta, U. A. Rahaman, S. Chakraborty, B.K. Agrawal, T. Aumann, K. Boretzky, C. Caesar, H. Emling, H. Geissel, C. Langer, T. Le Bleis, Y. Leifels, J. Marganiec, G. Münzenberg, C. Nociforo, R. Plag, V. Panin, R. Reifarth, M.V. Ricciardi, D.Rossi, C. Scheidenberger, H.Simon, S.Typel, V. Volkov, F. Wamers, J.S. Winfield, H. Weick, B. Jonson, H.Johansson, T.Nilsson, A. Wagner, G.De.Angelis, and B.V.Carlson. 2018. Weakly Bound Neutron-Rich Nuclei and Cosmic Phenomena. Available at arXiv.org: 1810.08996 [nucl-ex].

Dean, D. J., M. Hjorth-Jensen. 2003. Pairing in nuclear systems: from neutron stars to finite nuclei. *Reviews of Modern Physics* 75: 607–656. arXiv.org nucl-th/0210033.

Dechargé, J. and D. Gogny. 1980. Hartree-Fock-Bogolyubov calculations with the D1 effective interaction on spherical nuclei. *Physical Review* C 21: 1568–1593.

Diriken, J., N. Patronis, A.N. Andreyev, S. Antalic, V. Bildstein, A. Blazhev, I.G. Darby, H.De Witte, J. Eberth, J. Elseviers, V.N. Fedossev, F. Flavigny, Ch. Fransen, G. Georgiev, R. Gernhausen, H. Hess, M. Huyse, J. Jolie, Th. Kroll, R. Krücken, R. Lutter, B.A. Marsh, T. Mertzimekis, D. Muecher, F. Nowacki, R. Orlandi, A. Pakou, R. Raabe, G. Randisi, R. Reiter, T. Roger, M. Seidlitz, M. Seliverov, K. Sieja, C. Sotty, H. Tornvist, J. Van De Walle, P. Van Duppen, D. Voulor, N. Warr, F. Wenander, and K. Wimmer. 2014. Study of the deformation-driving $\nu d_{5/2}$ orbital in ${}^{67}_{28}\mathrm{Ni}_{39}$ using one-neutron transfer reactions. 2014. *Physics Letters* B 736: 533–538. Erratum *Physics Letters* B 743: 543–543.

Elliott, J.P. 1958. Collective motion in the nuclear shell model II. The introduction of intrinsic wave-functions, *Proceedings of the Royal Society*, *Series* A, *Mathematical and Physical Sciences* 245: 562–581.

Fardon, R., A.E. Nelson, and N. Weiner. 2004. Dark energy from mass varying neutrinos. *Journal of Cosmology and Astroparticle Physics* 10 (005): 75–100. arXiv.org: astro-ph/0309800.

Feynman, Richard P. 1985. *QED: The strange theory of light and matter*. Princeton University Press: Princeton, NJ.

Fisker, Jacob Lund. 1999. Large Scale Shell Model Calculations of The Forbidden β^+ Decays of ^{56}Ni and The Thermonuclear Reaction Rates of The rp-Process on Nuclei in The Intermediate Mass Range. MS Thesis, Institute of Physics and Astronomy, University of Aarhus Denmark.

Fisker, J. L., G. Martinez-Pinedo, K. Langanke. 1999. Halflife of Ni-56 in cosmic rays. *European Physical Journal* A5: 229–231.

Frauendorf, S. and A.O. Macchiavelli. 2014. Overview of neutron-proton pairing. *Progress in Particle and Nuclear Physics* 78: 24–90. arXiv.org 1405.1652 [89 pages].

Gade, Alexandra, A. Becerril, C,M, Campbell, J.M. Cook, D.J. Dean, D.-C. Dinca, T. Glasmacher, G.W. Hitt, M.E. Howard, W.F. Mueller, H. Olliver, J.R. Terry, and M.E. Yoneda. 2005. Quadrupole deformations of the self-conjugate nucleus ^{72}Kr. *Physical Review Letters* 95: 022502 [4 pages].

Gambacurta, D. and D. Lacroix. 2014. Deformation effects on the coexistence between neutron-proton and particle like pairing in N = Z medium mass nuclei. *Physical Review* C 91(1): 014308 [14 pages] arXiv.org: 1411.1891.

Gehrz, Robert D. 1988. Supernova 1987A. Casting light on the ejecta. *Nature* 333: 705–706.

Gell-Mann, M. 1964. A schematic model of baryons and mesons. *Physics Letters* 8: 214–215.

Gezerlis, Alexandros, G.F. Bertsch, and Y.L. Luo. 2011. Mixed-Spin Pairing Condensates in Heavy Nuclei. *Physical Review Letters* 106: 252502 [4 pages].

Heyde, K. and J.L. Wood. 2011. Shape coexistence in atomic nuclei. *Reviews of Modern Physics* 83: 1467–1521.

Honma, M. T. Otsuka, B. A. Brown, and T. Mizusaki. 2004. New effective interaction for pf-shell nuclei and its implications for the stability of the N=Z=28 closed core. *Physical Review* C 69 034335 [34 pages].

Horoi, M., B.A. Brown, T. Otsuka, M. Honma, and T. Mizusaki. 2006. Shell model analysis of the ^{56}Ni spectrum in the full *pf* model space. *Physical Review* C73(6): 061305R [4 pages].

Isaule, F., H.F. Arelano, and A. Rios. 2016. Di-neutrons in neutron matter within a Brueckner-Hartree-Fock approach. *Physical Review* C 94: 034004 [26 pages] arXiv.org 1602.05234.

Jones, S., F.K. Röpke, C. Fryer, A.J. Ruiter, I.J. Seitenzahl, L.R. Nittler, S.K. Ohlmann, R. Reifarth, M. Pignatari, and K. Belczynski. 2019. Remnants and ejecta of thermonuclear electron-capture supernovae. Constraining oxygen-neon deflagrations in high-density white dwarfs. *Astronomy and Astrophysics* 622: A74 [22 pages].

Konuma, M., H. Miyazawa, and S. Otsuki. 1958. Two-pion-exchange nuclear potential. *Progress of Theoretical Physics* (Kyoto) 19: 17–30.

Krane, K. S. 1987. *Introductory nuclear physics*. New York: John Wiley.

Kraus, G. P. Egelhof, C. Fischer, H. Geissel, A. Himmler, F. Nickel, G. Miinzenberg, W. Schwab, A. Weiss, J. Friese, A. Gillitzer, H. J. Korner, M. Peter, W. F. Henning, J.P. Schiffer, J.V. Kratz, L. Chulkov, M. Golovkov, A. Ogloblin and B.A. Brown. 1994. Proton Inelastic Scattering on ^{56}Ni in Inverse Kinematics. *Physical Review Letters* 73(13): 1773–1776.

Langanke, K., D. Dean, P. Radha, Y. Alhassid, and S. Koonin. 1995. Shell-model Monte Carlo studies of fp-shell nuclei. *Physical Review* C 52: 718–725.

Lattes, C.M.G., H. Muirhead, G.P.S. Occhialini and C. F. Powell. 1947. Processes involving charged mesons. *Nature* 159: 694–697.

Lesko, K.T., E. B. Norman, B. Sur, and R.-M. Larimer. 1989. Half Life of ^{56}Co. *Physical Review* C40: 445–448.

Li, Jia Jie, Jérôme Margueron, Wen Hui Long, and Nguyen Van Giai. 2015. Pairing phase transition: A finite-temperature relativistic Hartree-Fock-Bogoliubov study. *Physical Review* C 92: 014302, arXiv 1506.04507 [13 pages].

Lisetskiy, A.F., N. Pietralla, M. Honma, A. Schmidt, I. Schneider, A. Gade, P. von Brentano, T. Otsuka, T. Mizusaki, and B.A. Brown. 2003. Experimental evidence for ^{56}Ni—core breaking from the low-spin structure of the N=Z nucleus ${}^{58}_{29}\mathrm{Cu}_{29}$. *Physical Review* C 68: 034316 [10 pages] arXiv.org: nucl-ex/0306032

Machleidt, R. and I. Slaus. 2001. The nucleon-nucleon interaction. *Journal of Physics G: Nuclear and Particle Physics*, 27(5): R69-R108.

Martinez-Pinedo, G., K. Langanke, and P. Vogel. 1999. Competition of isoscalar and isovector proton neutron pairing in nuclei. *Nuclear Physics* A 651: 379–393. arXiv.org: nucl-th/9811060.

McCarthy, I.E. 1968. *Introduction to Nuclear Theory*. John Wiley & Sons: New York.

McLaughlin, G.C. and R.A.M.J. Wijers. 2002. Delayed nickel decay in gamma-ray bursts. *Astrophysical Journal* 580: 1017–1023.

Möller, P., J. R. Nix, W. D. Myers, and W. J. Swiatecki. 1995. Nuclear ground-state masses and deformations. *Atomic Data and Nuclear Data Tables* 59, 185–381.

Möller, P., J. R. Nix, and K.-L. Kratz. 1997. Nuclear properties for astrophysical and atomic beam applications. *Atomic Data and Nuclear Data Tables* 66: 131–343.

Möller, P. A.J. Sierk, T. Ichikawa, H. Sagawa. 2016. Nuclear ground state masses and deformations: FRDM(2012). *Atomic Data and Nuclear Data Tables* 109–110: 1–204. arXiv.org 1508.06294.

Nadyozhin, D.K. 1994. The properties of Ni → Co → Fe decay. *Astrophysical Journal Supplement Series*, 92: 527–531

Negret, A. et al. 2006. Gamow-Teller strengths in the A= 14 multiplet: A challenge to the shell model. *Physical Review Letters* 97: 062502 [4 pages].

Nilsson, S.G., C.F. Tsang, A. Sobiczewski, Z. Szymanski, S. Wycech, C. Gustafson, I-L. Lamm, P. Möller, and B. Nilsson. 1969. On the nuclear structure and stability of heavy and superheavy elements. *Nuclear Physics* A 131: 1–60.

Nogami, Y., 1964, Improved superconductivity approximation for the pairing interaction in nuclei. *Physical Review* 134B, 313–321.

Nogami, Y. 1965. On the superconductivity theory of the nuclear pairing interaction. *Physics Letters* B15(4): 335–337.

NuDat 2.8 (accessed 2020)

Occhialini, G.P.S. and C.F. Powell. 1947. Nuclear disintegrations produced by slow charged particles of small mass. *Nature* 159: 186–190.

Otsuka, T., M. Honma, and T. Mizusaki, 1998. Structure of the N = Z = 28 closed shell studied by Monte Carlo shell model calculation. *Physical Review Letters* 81: 1588–1591.

Otsuka, T., T. Suzuki, R. Fujimoto, H. Grawe, and Y. Akaishi. 2005. Evolution of nuclear shells due to the tensor force. *Physical Review Letters* 95, 232502 [4 pages].

Peng, J. and Q. B. Chen. 2018. Exploring nuclear multiple chirality in the A ≈ 60 mass region within covariant density functional theory. *Physical Review* C 98 024320 [13 pages]. arXiv.org 1808.03776.

Pinto, P.A. and S. E. Woosley. 1988. The theory of gamma-ray emergence in supernova 1987A. *Nature* 333: 534–537.

Poves, A. and G. Martinez-Pinedo. 1998. Pairing and the structure of the *pf*-shell N ~ Z nuclei. *Physics Letters* B 430: 203–208. arXiv.org nucl-th/9802047

Pritychenko, B., M. Birch, B. Singh, M. Horoi. 2016. Table of transition probabilities from the first 2^+ states in even-even nuclei. *Atomic Data Nuclear Data Tables* 107: 1–175. arXiv.org: 1312.5975.

Raman, S., C. W. Nestor Jr., P. Tikkanen. 2001. Transition probability from the ground to the first-excited 2^+ State of even–even Nuclides. *Atomic Data and Nuclear Data Tables* 78: 1–128.

Rehm, K.E., F. Borasi, C.L. Jiang, D. Ackermanm, I. Ahmad, B.A. Brown et al. 1998. Study of the ^{56}Ni(d,p)^{57}Ni reaction and the astrophysical ^{56}Ni(p,g)^{57}Cu Reaction Rate. *Physical Review Letters* 80: 676–679.

Rodriguez-Guzman, R., J. L. Egido, and L. M. Robledo. 2002. Quadrupole collectivity in N ≈ 28 nuclei with the angular momentum projected generator coordinate method. *Physical Review* C 65: 024304 [14 pages].

Rowe, D.J. 1970. *Nuclear collective motion: models and theory*. Methuen, London.

Rubtsova, O. A., V.I. Kukulin, V.N. Pomerantsev, and H. Müther. 2017. In-medium bound states and pairing gap. *Physical Review* C 96: 034327 [10 pages] arXiv.org 1706.05299.

Rudolph, D., C. Baktash, M. J. Brinkman, E. Caurier, D.J. Dean, M. Devlin, J. Dobaczewski, P.-H. Heenen, H.-Q. Jin, D. R. LaFosse, W. Nazarewicz, F. Nowacki, A. Poves, L. L. Riedinger, D. G. Sarantites, W. Satula, and C.-H. Yu. 1999. Rotational Bands in the Doubly Magic Nucleus ^{56}Ni. *Physical Review Letters* 82: 3763–3766.

Sagawa, H., Y. Tanimura, and K. Hagino. 2013. A competition between T = 1 and T = 0 pairing in pf-shell nuclei with N = Z *Physical Review* C87: 034310 [4 pages] arXiv.org 1212.5992.

Schwalm, D., A. Bamberger, P. G. Bizzeti, B. Povh, G. A. P. Engelbertink, J. W. Olness and E. K. Warburton. 1972. Reorientation measurements using the Doppler shift method: static quadrupole moments of ^{20}Ne, ^{22}Ne, ^{24}Mg, ^{26}Mg, and ^{28}Si. *Nuclear Physics* A192: 449–495.

Stone, N.J. 2005. Table of nuclear magnetic dipole and electric quadrupole Moments *Atomic Data and Nuclear Data Tables* 90: 75–176.

Suntzeff, N.B. 1992. The energy sources powering the late-time bolometric evolution of SN1987A. *Astrophysical Journal* 384: L33–L36.

Sur, Bhaskar, Eric B. Norman, K. T. Lesko, Edgardo Browne, and Ruth-Mary Larimer. 1990. Reinvestigation of ^{56}Ni decay. *Physical Review* C 42(2): 573–580.

Taketani, Mituo, Seitaro Nakamura and Muneo Sasaki. 1951. On the Method of the Theory of Nuclear Forces. *Progress of Theoretical Physics* 6(4): 581–586.

Taniuchi, R., C. Santamaria, P. Doornenbal, A. Obertelli, K. Yoneda et al. 2019. ^{78}Ni revealed as a doubly magic stronghold against nuclear deformation. *Nature* 569(7754): 53–58. arXiv.org: 1912.05978 [nucl-ex].

Terasaki, J. and J. Engel. 2006. Self-consistent description of multipole strength: Systematic calculations. *Physical Review* C74(4) 044301 [19 pages].

Thibault, Catherine, R. Klapisch, C. Rigaud, A.M. Poskanzer, R. Prieels, L. Lessard, and W. Reisdorf. 1975. Direct measurement of the masses of ^{11}Li and $^{26-32}$Na with an on-line mass spectrometer. *Physical Review* C12: 644–657.

Thielemann, F.-K., M. Hashimoto and K. Nomoto. 1990. Explosive nucleosynthesis in SN1987A. II. Composition, radioactivities, and the neutron star mass. *Astrophysical Journal* 349: 222–240.

Vardiman, L., A.A. Snelling, and E.F. Chaffin, (editors) 2005. *Radioisotopes and the Age of the Earth*, *Volume 2*, *Results*. Institute for Creation Research and

Creation Research Society, Dallas, TX and Chino Valley, AZ.

Volya, Alexander, Vladimir Zelevinsky, and B. Alex Brown. 2002. Coherent and chaotic properties of nuclear pairing. *Physical Review* 65: 054312 [11 pages].

Woosley, Stan E. and M.M. Phillips. 1988. Supernova 1987A! *Science* 240 (4853): 750–759.

Woosley, Stan and Tom Weaver. 1989. The great supernova of 1987. *Scientific American* 261(2): 32–40.

Yanagisawa, Y., T. Motobayashi, S. Shimoura, Y. Ando, H. Fujiwara, I. Hisanaga, H. Iwasaki, Y. Iwata, H. Murakami, T. Minemura, T. Nakamura, T. Nishio, M. Notani, H. Sakurai, S. Takeuchi, T. Teranishi, Y. X. Watanabe, and M. Ishihara. 1998. Coulomb excitation of ^{56}Ni. In B. Sherrill, D. Morrissey, and C. Davids, editors, *Proceedings of the Conference on Exotic Nuclei and Atomic Masses 98 (ENAM 98)*, Bellaire, Michigan, June 23–27, *American Institute of Physics Conference Proceedings* 455, p. 610–613.

Yang, Yi, Lifan Wang, Dietrich Baade, Peter.J.Brown, Aleksandar Cikota, Misty Cracraft, Peter A. Höflich, Justyn R. Maund, Ferdinando Patat, William B. Sparks, and Jason Spyromilio. 2018. Late-time Flattening of Type Ia Supernova Light Curves: Constraints from SN2014J in M82. *Astrophysical Journal* 852: 89–98.

Yukawa, Hideki. 1935. On the interaction of elementary particles. I. *Proceedings of the Physico-Mathematical Society of Japan*. 17 (1935), 48–57.