

Analysis of Nuclear Structure Properties and Stellar β -decay Rates of Even-Even 106-120Zr Isotopes (Postprint)

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Abstract

The nuclear ground state properties of even-even 106-120Zr nuclei have been investigated within the framework of the relativistic mean field (RMF) approach. The RMF model with density-dependent DDME2 and DDPC1 interactions is utilized for the calculation of potential energy curves, the nuclear ground-state deformation parameters (β_2), neutron separation energies (S_n and S_{2n}) and neutron skin thickness (r_{np}) of selected Zr isotopes. Later, the β -decay properties of Zr isotopes were studied using the proton-neutron quasi-particle random phase approximation (pn-QRPA) model. These include Gamow-Teller strength distributions, β -decay half-lives and stellar electron emission/positron capture rates. The β_2 values computed from the RMF model were employed in the pn-QRPA model as an input parameter for the calculations of β -decay properties for even-even 106-120Zr nuclei. The stellar rates were computed using the pn-QRPA framework with three different types of deformation parameters. Only at high temperature ($T_9 \geq 2$) and low density ($\rho \leq 10^7 \text{ g cm}^{-3}$) values, the sum of electron emission and positron capture rates has a sizeable contribution (with positive exponents) to the stellar rates.

Full Text

Preamble

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Searching Radio Signals from Two Magnetars and a High-magnetic Field Pulsar and the Serendipitous Discovery of a New Radio Pulsar PSR J1935+2200

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Abstract

Magnetars are slowly rotating, highly magnetized young neutron stars that can exhibit transient radio phenomena including radio pulses and fast radio bursts. We conducted radio observations of two magnetars, SGR J1935+2154 and 3XMM J185246.6+003317, and a high-magnetic-field pulsar, PSR J1846-0258, using the Five-hundred-meter Aperture Spherical radio Telescope (FAST). We performed both single-pulse and periodicity searches but detected no radio signals from these targets. However, from piggyback data recorded by other FAST telescope beams during our observations of SGR J1935+2154, we serendipitously discovered a new radio pulsar, PSR J1935+2200. Follow-up observations enabled us to obtain a timing solution based on these new data and archival FAST observations. PSR J1935+2200 is an isolated old pulsar with a spin period of 0.91 s, a spin-period derivative of $9.19 \times 10^{-15} \text{ s s}^{-1}$, and a characteristic age of 1.57 Myr. It is a weak pulsar with a flux density of 9.8 Jy at 1.25 GHz. The discovery of this new pulsar from 30-minute FAST observations implies that many more weak, older pulsars likely remain to be discovered in the Galactic disk.

Key words: stars: neutron -(stars:) pulsars: individual (PSR J1935+2200)

1. Introduction

Magnetars are slowly rotating young neutron stars with super-strong magnetic fields ($B > 10^{14} \text{ G}$) (Mereghetti et al. 2015; Kaspi & Beloborodov 2017), known for their diverse X-ray activities including short bursts, sustained outbursts, burst storms, and Giant Flares (Rea et al. 2010). The energy associated with

these activities can be interpreted as resulting from magnetic field decay (Duncan & Thompson 1992). To date, only six of nearly 30 known magnetars have shown detected radio emission: 1E 1547.0–5408, Swift J1818.0–1607, SGR 1745–2900, PSR J1622–4950, XTE J1810–197, and SGR 1935+2154 (Olausen & Kaspi 2014). Radio emission from magnetars is often temporally associated with X-ray outbursts (Camilo et al. 2006, 2007), and radio pulses from magnetars exhibit strong variability in flux density and profile shape compared to rotation-powered pulsars (Camilo et al. 2007; Kramer et al. 2007; Levin et al. 2010; Kirsten et al. 2021), possibly caused by untwisting of the dynamic magnetosphere. Additionally, averaged pulse profiles and single pulses often show high linear polarization (Lower et al. 2020), and the radio spectrum tends to be flat or inverted (Camilo et al. 2007).

SGR 1935+2154 was discovered in July 2014 by Swift/BAT through its X-ray short bursts (Stamatikos et al. 2014). Its position is associated with SNR G57.2+0.8 (Gaensler 2014), corresponding to a distance of 6.6–12.5 kpc (Sun et al. 2011; Zhong et al. 2020; Zhou et al. 2020; Kirsten et al. 2021). Subsequent observations by Chandra and XMM-Newton revealed its X-ray counterpart with a period of $P = 3.24$ s and a spin-down rate of $\dot{P} = 1.43 \times 10^{-11} \text{ s s}^{-1}$, implying a characteristic age of 3.6 kyr and a dipolar magnetic field of $B = 2.2 \times 10^{14}$ G (Israel et al. 2016). On 2020 April 28, the Canadian Hydrogen Intensity Mapping Experiment (CHIME) detected a millisecond-duration radio burst (FRB 20200428) associated with an X-ray burst from SGR 1935+2154 (CHIME/FRB Collaboration et al. 2020; Li et al. 2021), establishing the link between FRBs and magnetars. Follow-up observations have revealed ongoing radio activity from SGR 1935+2154 (Kirsten et al. 2021; Hu et al. 2024), and FAST also detected radio pulses from this source (Zhu et al. 2023). Many open questions remain about the connection between X-ray bursts, pulsar-like radio emissions, and FRBs, as well as their physical origins.

PSR J1846–0258 is a young, highly magnetic pulsar exhibiting magnetar-like X-ray bursts, making it an intermediate object between magnetars and radio pulsars (Gavriil et al. 2008). Located at the center of SNR Kes75 at a distance of 5.8 kpc (Leahy & Tian 2008), it has historically been radio-quiet. X-ray observations show a pulsation period of $P = 0.324$ s, a dipole magnetic field of $B = 4.9 \times 10^{13}$ G, and a characteristic age of 723 yr. Between May and June 2020, Swift/BAT and NICER detected another magnetar-like X-ray burst from this source (Krimm et al. 2020; Sathyaprakash et al. 2024), though follow-up radio observations detected no radio pulses (Majid et al. 2020), suggesting it is primarily a rotation-powered pulsar.

3XMM J185246.6+003317 (hereafter 3XMM J1852+0033) is a low magnetic field magnetar discovered by Zhou et al. (2014) using XMM-Newton data. Located near SNR Kes79 at a distance of 7.1 kpc (Rea et al. 2014), it exhibited intense X-ray activity between 2008 and 2009. 3XMM J1852+0033 has a spin period of $P = 11.56$ s and a spin-down rate of $\dot{P} = 1.4 \times 10^{-12} \text{ s s}^{-1}$, implying a characteristic age of $\tau > 1.3$ Myr and a dipolar magnetic field of $B < 4.1 \times$

10^{13} G (Rea et al. 2014). No further outbursts have been reported, and no radio signals have been detected to date.

FAST (Nan 2006; Nan et al. 2011) is currently the world's most sensitive radio telescope (Jiang et al. 2020) and serves as a powerful tool for searching for radio signals from magnetars and faint pulsars. Although the sky regions containing these magnetars have been searched extensively by many radio telescopes, FAST's exceptional sensitivity can still detect weak pulsars given sufficiently long tracking observations. Weak pulsars are crucial for understanding the lower end of the luminosity function and potentially important extreme objects in the universe and stellar evolution, particularly if they reside in binary systems. Previously, radio signals from SGR J1935+2154 have been successfully detected, prompting numerous follow-up observations (Good & Chime/Frb Collaboration 2020; Lin et al. 2020; Zhang et al. 2020; Bailes et al. 2021; Kirsten et al. 2021; Tang et al. 2021; Lu et al. 2024). Motivated by these results, we conducted radio observations of two magnetars and the high-magnetic-field pulsar PSR J1846-0258 using FAST, primarily to search for possible radio signals or establish strict upper limits on their flux densities. We describe our observations and data processing in Section 2, present the results in Section 3, and provide discussion and summary in Section 4.

2. FAST Observations and Data Reduction

We conducted observations of SGR J1935+2154, PSR J1846-0258, and 3XMM J1852+0033 using FAST (project PT2023_{0176}, PI: Lang Xie) in four sessions: (i) 2024 February 21 9:16:00-9:36:00 UTC for PSR J1846-0258; (ii) 2024 April 8 6:20:00-6:40:00 UTC for PSR J1846-0258; (iii) 2024 April 8 6:52:00-7:02:00 UTC for 3XMM J1852+0033; and (iv) 2024 April 8 7:14:00-7:44:00 UTC for SGR J1935+2154. All observations were performed in tracking mode with data from the L-band 19-beam receiver recorded in pulsar search format. The receiver covers a frequency range of 1.0-1.5 GHz with 2048 frequency channels. For each channel, data from four polarization channels (XX, YY, Re[X*Y], and Im[X*Y]) were recorded in FITS files with a sampling time of 49.152 s. At the beginning of each observation session, calibration signals with 1 K equivalent white noise and a 2 s period were injected into the feed for system calibration. All three sources were tracked using the FAST L-band central beam, while data from the other 18 beams were also recorded simultaneously.

We searched for radio pulses using the PRESTO module (Ransom 2011) and a single-pulse search module (Zhou et al. 2023), both of which have been employed in the Galactic Plane Pulsar Snapshot (GPPS) survey (Han et al. 2021, 2025). Data processing included the following steps: (1) Using rfind to detect radio frequency interference (RFI) and create a mask file to exclude contaminated data; (2) Dedicating data from all frequency channels using prepsubband based on estimated DM values; (3) Searching for periodic signals using accelsearch; and (4) Confirming candidates and folding data using prepfold.

Based on timing results from X-ray observations, we obtained initial positions and periods for the three sources. We used `rfind` to search for RFI and create masks, then performed standard dedispersion as done in the FAST GPPS survey (Han et al. 2021) with fine DM steps of 5-1350 pc cm⁻³. Subsequently, we conducted periodicity searches for the two magnetars and the high-magnetic-field pulsar using their derived spin periods. Additionally, we employed the single-pulse search module to search for radio pulses (Zhou et al. 2023). First, we dedispersed the data between 3 and 1000 pc cm⁻³ with a step size of 1 pc cm⁻³, then generated DM-time images using 4 s data segments. We searched for salient points in these DM-time images using YOLO target detection technology developed in the Darknet neural network framework (Bochkovskiy et al. 2020). Finally, we used artificial intelligence (AI) technology to rapidly identify individual pulses and performed period-finding on the collected pulses.

3. Results

3.1. Upper Limits of Flux Densities

No radio bursts from the three sources were detected by FAST, allowing us to establish upper limits on their flux densities during normal states. For the periodicity search, we derived an upper limit on flux density using the modified radiometer equation (Lorimer & Kramer 2004):

$$S_{\text{periodic, min}} = \frac{(S/N)_{\text{min}} T_{\text{sys}}}{G_0 \sqrt{BW \cdot n_p \cdot t_{\text{obs}}}} \sqrt{\frac{W_{\text{obs}}}{P - W_{\text{obs}}}}$$

where the system noise temperature $T_{\text{sys}} = 22$ K (Jiang et al. 2020), the effective telescope gain is $G_0 = 16.1$ K Jy⁻¹, the frequency bandwidth is $BW = 437.5$ MHz (after RFI removal), the number of polarization channels is $n_p = 2$, t_{obs} is the integration time, and the observed pulse width W_{obs} can be estimated by

$W_{\text{obs}} = \sqrt{W_{\text{intrinsic}}^2 + t_{\text{bin}}^2 + \tau_s^2 + \Delta t_{\text{chan}}^2}$, where $W_{\text{intrinsic}}$ is the intrinsic pulse width, t_{bin} is the sampling time, τ_s is the scattering timescale, and Δt_{chan} is the dispersion time within one frequency channel. Assuming a pulsar duty cycle of 0.03 and a minimum detection threshold of $S/N = 7$, our non-detections yield the flux density limits for periodicity searches listed in Table 1.

For single-pulse searches, the sensitivity limit is given by:

$$S_{\text{single, min}} = \frac{(S/N)_{\text{min}} T_{\text{sys}}}{G_0 \sqrt{BW \cdot n_p \cdot W_{\text{intrinsic}}}}$$

Assuming an intrinsic pulse width of 1 ms, we obtain the 7σ upper limits on flux densities for the two magnetars and the high-magnetic-field pulsar listed in Table 1.

3.2. Serendipitous Discovery

Pulse searches for the two magnetars and the high-magnetic-field pulsar yielded null results using both period folding and the single-pulse search module with a signal-to-noise ratio threshold of $S/N > 7$. However, a new radio pulsar was serendipitously discovered in the M07 beam during our observations of SGR J1935+2154.

This new radio pulsar, PSR J1935+2200, was discovered on 2024 April 8 using FAST during observations of SGR 1935+2154. The pulsar appeared prominently in the periodicity search of the M07 beam. Reprocessing of released archival FAST data at the same position confirmed the detection (see Table 2). Following the initial detection, we conducted two follow-up observations. Data were dedispersed using the optimal DM values and then folded. PSR J1935+2200 was detectable using the DSPSR software package (van Straten & Bailes 2011). We used PSRCHIVE to remove frequency channels affected by RFI (Hotan et al. 2004), integrated data from all frequency channels, and employed PAAS to create a noise-free standard profile template for determining times of arrival (TOAs).

Using all FAST data listed in Table 2 (both newly observed and previously archived), we obtained a phase-coherent timing solution for this pulsar (Table 3) and polarization profiles (Figure 1). The timing residuals are shown in Figure 2. PSR J1935+2200 has a period of 0.91 s and a period derivative of $9.19 \times 10^{-15} \text{ s s}^{-1}$, corresponding to a characteristic age of 1.57 Myr, a surface magnetic field strength of $2.93 \times 10^{12} \text{ G}$, and a spin-down luminosity of $1.83 \times 10^{32} \text{ erg s}^{-1}$. This indicates it is a moderately old pulsar. Based on currently limited timing data, we conclude that it is an isolated pulsar; otherwise, it would have to be in a binary system with an extremely long orbital period or an extremely low-mass companion, which we cannot measure from the available data.

With FAST's high time resolution, we determined the optimal DM value to be $293.68(2) \text{ pc cm}^{-3}$. The distance to this pulsar is estimated to be 8.8 kpc or 9.0 kpc according to the Galactic electron density distribution models NE2001 and YMW16, respectively (Cordes & Lazio 2002; Yao et al. 2017). Using our 4-polarization channel data and following the procedures of Wang et al. (2023), we obtained the polarization profile of PSR J1935+2200 shown in Figure 1. Polarization was calibrated using PAM in the PSRCHIVE software (Hotan et al. 2004). We measured a pulse-averaged flux density of $9.8(6) \text{ Jy}$ at a center frequency of 1250 MHz (Figure 3) and a spectral index $\gamma = -2.1(6)$ from flux densities in four subbands.

[Figure 1: see original paper]

[Figure 2: see original paper]

[Figure 3: see original paper]

4. Discussion and Conclusion

We searched for periodic radio signals and single pulses from two magnetars and one high-magnetic-field pulsar using FAST, detecting no radio pulses with dispersive features at signal-to-noise ratios $S/N > 7$. These observations provide upper limits on the flux densities for both single-pulse and periodicity searches for the three sources. Previously, Zhang et al. (2020) captured a radio event from SGR 1935+2154 on 2020 April 30 using FAST with a fluence of 51(2) mJy ms. Kirsten et al. (2021) detected two moderately bright radio bursts using the Westerbork telescope on 2020 May 24 with fluences of 112(22) Jy ms and 24(5) Jy ms, respectively. Lin et al. (2020) observed SGR 1935+2154 for 8 hr with FAST, obtaining an upper limit of 22 mJy ms, which is consistent with our result.

Radio bursts from magnetars are relatively rare transient phenomena. Two main hypotheses have been proposed for the mechanism of radio emission from magnetars. One is similar to the traditional pulsar radio emission model, suggesting that radio emission arises from outflows of highly relativistic particles from the polar cap region of the magnetosphere (Ruderman & Sutherland 1975; Arons & Scharlemann 1979; Cheng et al. 1986). The other proposes that radio emission originates from J-bundles in the closed magnetosphere, which maintain fluctuations in net charge through magnetic field line untwisting, providing conditions for particle acceleration and coherent radio radiation (Duncan & Thompson 1992; Beloborodov 2009; Wang et al. 2019). The non-detection of radio pulses from these two magnetars and the high-magnetic-field pulsar by FAST provides important constraints on the physical mechanisms by which magnetars produce radio bursts. Based on these two radio emission models, we suggest that multiple factors may combine to quench radio emission in most magnetars. First, the magnetar may be in an X-ray quiescent state and unable to fulfill the conditions necessary for J-bundle formation. Second, the magnetar may be unable to produce a large number of electron-positron pairs under certain circumstances. Some studies have shown that if the magnetic field strength exceeds the quantum critical field, the $\gamma\gamma$ QED processes would be strongly suppressed (Daugherty & Harding 1996; Hibschan & Arons 2001), largely leading to “radio-quiet” behavior. Finally, magnetar radio beams may be more collimated than high-energy jets, with most missing Earth.

We report the discovery of a new radio pulsar, PSR J1935+2200, and obtained its timing solution based on both newly conducted and archival FAST observations. We find that PSR J1935+2200 is an isolated old pulsar with a spin period of 0.91 s and a period derivative of $9.19 \times 10^{-15} \text{ s s}^{-1}$. Using FAST’s high temporal resolution, we determined an optimal DM value of 293.68(2) pc cm⁻³. The measured DM corresponds to distances of 8.8 kpc and 9.0 kpc for PSR J1935+2200 according to the NE2001 and YMW16 models, respectively. We searched archived images from Swift, Chandra, and XMM-Newton telescopes and found no X-ray or optical counterpart for this object. This pulsar was detected with only 30 minutes of FAST integration but was missed in previous

surveys due to beam offset, suggesting that many more old pulsars with weak radio emission await discovery in the Milky Way disk.

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