First 3^- excited state of ^{56}Fe

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There is no reliable evidence for the existence of the 3.076 MeV (3^-) level adopted in the ENSDF evaluation for ^{56}Fe although it has been reported in a few experiments. Previous reports of the observation of this level appear to be based on an incorrect assignment in early (e, e') work. Recent neutron inelastic scattering measurements by Demidov *et al.* [Phys. At. Nucl. **67**, 1884, (2004)] show that the assigned γ-ray decay of this state does not occur at a level consistent with known properties of inelastic scattering. In the present work the ^{56}Fe$(n, n'\gamma)$ reaction was used to populate excited states in ^{56}Fe. Neutrons in the energy range from 1 to 250 MeV were provided by the pulsed neutron source of the Los Alamos Neutron Science Center's WNR facility. Deexciting γ rays were detected with the GEANIE spectrometer, a Compton suppressed array of 26 Ge detectors. The γ-γ data obtained with GEANIE were used to establish coincidence relations between transitions. All previously reported levels up to $E_x = 3.6$ MeV excitation energy were observed except for the 3.076 MeV (3^-) level. The 991- and 2229-keV transitions, previously reported to deexcite this level, were not observed in the γ-γ coincidence data obtained in the present experiment. The present work supports the assignment of the 4509.6 keV level as the first 3^- excited state in ^{56}Fe by observation of two previously known transitions deexciting this state.

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Introduction. The nucleus ^{56}Fe has only two proton holes outside the $Z = 28$ shell and only two neutrons outside the $N = 28$ shell. Study of ^{56}Fe is of interest to enrich our knowledge of nuclear structure in the vicinity of the magic number 28. In particular, the detailed experimental knowledge of states in this nucleus is important for shell-model calculations that are trying to shed light on the properties of pf-shell nuclei [1]. Also, the excitation energy of the lowest 3^- state in ^{56}Fe is important for comparison with results of angular-momentum and parity-projected level-densities calculations associated with nuclear pairing models [2].

Because of its importance, ^{56}Fe has been extensively studied over the years using numerous techniques [3], such as, heavy-ion fusion evaporation reactions, β decay, (t,p) reactions, inelastic particle scattering, etc. As a result, the level structure of ^{56}Fe at low excitation energies is well studied and understood with, perhaps, the exception of the 3^-_1 level. Our goal is to clarify the spectroscopy of the first 3^- level, denoted by 3^-_1.

Low-lying quadrupole and octupole vibrations dominate the excitation pattern of near spherical even-even nuclei. The first negative parity state in ^{56}Fe is expected to be a 3^- state that can be understood as the manifestation of the vibrational octupole degree of freedom. In the latest evaluation for ^{56}Fe [3] several 3^- states are included at low excitation energies, some with firm spin-parity assignments and for others only tentative: the lowest in excitation 3^- state is reported at 3076.2-keV excitation energy, although the spin-parity assignment is tentative; the next reported 3^- states, have both firm spin-parity assignment and lie at 4370- and 4509.6-keV excitation energies. We introduce here a brief history for each of these states: (i) The 3076.2-keV level is based on the original detection of a 3100-keV level with $L = 3$ in an (e,e') reaction performed at C.E.N. Saclay reported in Ref. [4] in 1962 and subsequent detection of a 3070-keV level with $L =(3)$ in (α,α') reactions, of a 3070(30)-keV level in a $(^3$He$,^7$Be$)$ reaction, and of a weakly populated 3076-keV level in a (p,γ) reaction [5] in 1992. Moreover, in the (p,γ) reaction, γ-ray branchings of this level to the lower 2^+_1 and 4^+_1 states were reported. The original $L = 3$ assignment in Ref. [4] was retracted in 1970 in a subsequent C.E.N. Saclay experiment [6]. Also a 2004 experimental work [7] using the ^{56}Fe$(n,n'\gamma)$ reaction and fast neutrons from a reactor, reported that the 3076.2-keV state does not exist at all, suggesting that the transitions assigned earlier in Ref. [5] to deexcite this state are likely to proceed between higher lying states. None of the above experiments has recorded γ-γ coincidence data in ^{56}Fe which are more definitive. (ii) The 3^- state at 4370-keV excitation energy has been observed only in (α,α') reactions, no transitions have been reported to deexcite this state, and it is included with a question mark in the evaluation of Ref. [3], since it could easily be the same as the 4509.64-keV 3^- state with a 140-keV error in energy calibration in the (α,α') experiment. (iii) the 4509.6-keV 3^- level, is the only level that so far has a firm assignment, confirmed in several experiments, together with several observed transitions deexciting this level.

γ-γ coincidence data have been recorded in ^{56}Fe in Ref. [8] before the present work, however that work used a fusion-evaporation reaction that (i) did not populate the 3^- state, and (ii) was oriented to resolve high-spin states. Hence, a γ-γ coincidence experiment should be performed in conjunction with a reaction that is likely to populate all the 3^- states reported previously. In the present work the ^{56}Fe$(n,n'\gamma)$ reaction with fast spallation neutrons (a highly unselective reaction, expected to populate all low-spin states) was used to study ^{56}Fe.

Experiment. The experiment was performed at the Los Alamos Neutron Science Center Weapons Neutron Research

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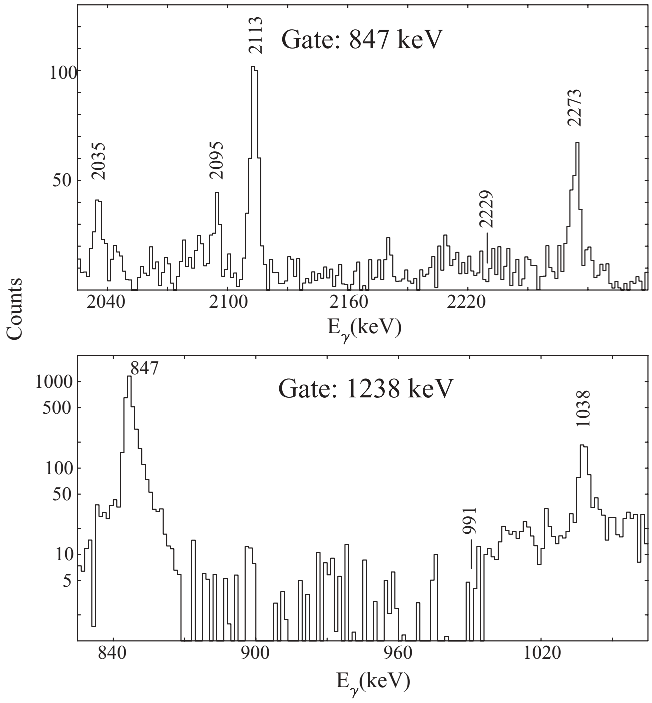

FIG. 1. Gated spectra on the previously known [3] 846.771 keV, $2_1^+ \rightarrow 0_1^+$ transition (upper spectrum) and 1238.282 keV, $4_1^+ \rightarrow 2_1^+$ transition (lower spectrum) of ^{56}Fe. The 991- and 2229-keV transitions from the (3^-), 3076.2-keV state are not observed in the 1238- and 847-keV gates, respectively.

(LANSCE/WNR) facility [9]. The γ-rays produced in the bombardment of a ^{56}Fe target by neutrons were measured with the GEANIE spectrometer [10].

The GEANIE spectrometer is located 20.34 m from the WNR spallation neutron source on the 60°-right flight path. The neutrons were produced in a ^{nat}W spallation target driven by an 800-MeV pulsed proton beam containing sub-nanosecond-wide pulses, spaced every 1.8 μs. The energy of the neutrons can be determined using the time-of-flight technique. In the present experiment GEANIE was comprised of 11 Compton-suppressed planar Ge detectors (low-energy photon spectrometers; LEPS), nine Compton-suppressed coaxial Ge detectors, and six unsuppressed coaxial Ge detectors. More information on the GEANIE array and flight path can be found in Refs. [11,12].

The ^{56}Fe target consisted of six square (5×5 cm^2) foils, each 0.5 mm thick. Only γ-γ and higher-multiplicity coincidence events were recorded in order to examine the coincidence relationships between the detected transitions. For that purpose, a symmetrized, two-dimensional matrix was constructed including all (regardless of incident neutron energies) the coincidence data obtained in the present experiment.

Experimental results and discussion. Figure 1 illustrates γ-ray coincidence spectra obtained with gates on the previously known 846.771 keV, $2_1^+ \rightarrow 0_1^+$, and 1238.282 keV, $4_1^+ \rightarrow 2_1^+$ transitions. These spectra represent the quality of the coincidence data.

The 991- and 2229-keV transitions from the (3^-), 3076.2-keV state are not present (within experimental observation limits) in the 1238- and 847-keV gates in Fig. 1, although expected from the level structure in Ref. [3]. An upper limit for these transitions is 0.2% and 0.4% (relative to the intensity of the strongest 847-keV transition in the spectra) for the 991- and 2229-keV transitions, respectively.

γ-ray deexcitations from all other previously known levels in ^{56}Fe [3] up to $E_x = 3.6$ MeV excitation energy were observed in the present experiment, through observation of at least one previously known transition from each level shown in the partial level scheme of ^{56}Fe in Fig. 2. Hence, within experimental observation limits, the present γ-γ coincidence experiment does not support the assignment of the 991- and 2229-keV transitions to deexcitation of the previously reported (3^-), 3076.2-keV state, and, hence, favors the conclusion of the recent work that the 3076.2-keV state does not exist [7]. Two transitions were observed from the previously known 4509.64-keV, 3^- state, and are shown in Fig. 2, supporting the

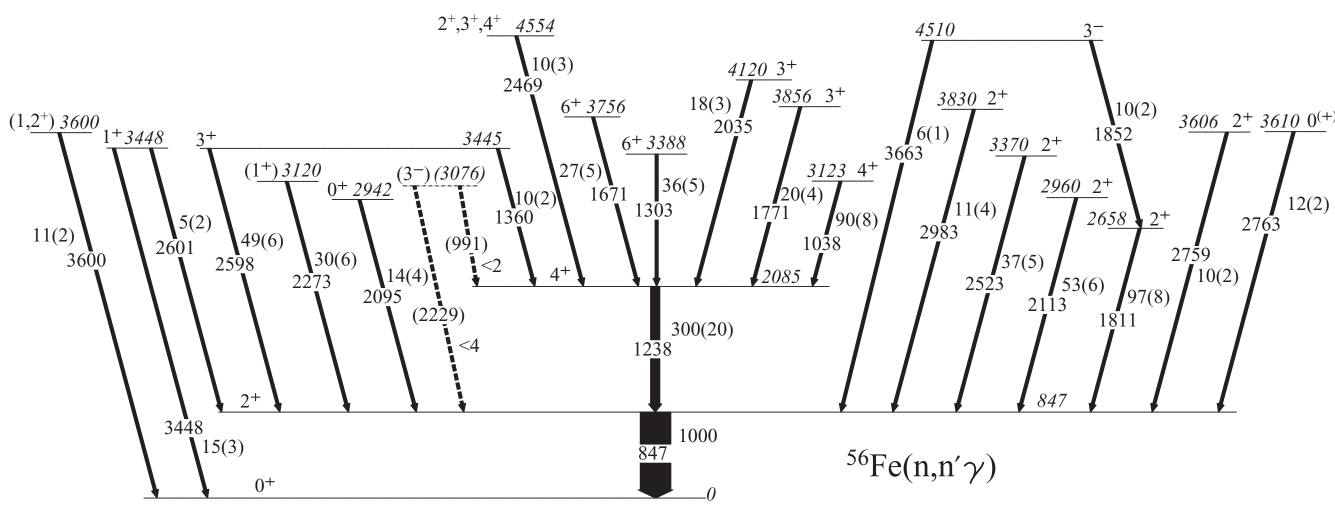

FIG. 2. Partial level scheme of ^{56}Fe as obtained in the present work. All γ-ray and level energies are given in keV. The observed intensities of each transition relative to that of the 847-keV, $2_1^+ \rightarrow 0_1^+$ transition (set arbitrarily to 1000) are also quoted. The 3076-keV level was not observed in the present work and is included in the level scheme only for comparison with the other levels.

existence of this state. No evidence for a 4370-keV level and no new levels were observed in the coincidence data of the present experiment. Finally, we note here that the 3076-keV and 4370-keV states are not observed in the spectra of a previous experiment that measured differential cross sections for neutron inelastic scattering [13], whereas the 4510-keV state was strongly populated in that experiment, and that recent theoretical calculations [14] predict the first 3^- state in ^{56}Fe at excitation energies well above 4 MeV. As for possible explanations on why the 3100-keV, $L = 3$ state was originally introduced in the experimental results of Ref. [4], we note here that such a state lies close (for the energy resolution of that experiment) to the (1^+), 3120-keV and 4^+, 3123-keV states (see Fig. 2), which were still unresolved in 1962, and their overlap can be easily misidentified as an $L = 3$ state. For all the reasons discussed in this section we propose that the 3076-keV level be removed from the database in the next ^{56}Fe evaluation.

Summary. In summary, γ-γ coincidence data in the $^{56}\mathrm{Fe}(n,n'\gamma)$ reaction was recorded with GEANIE in order to address the recently reported disagreement regarding the excitation energy of the 3_1^- state of ^{56}Fe. All previously known levels up to $E_x = 3.6$ MeV excitation energy were observed, by observation of at least one previously known transition from each level, except for the 3.076 MeV, (3^-) level. Moreover, no evidence for a 4370-keV, 3^- level was observed. The present experiment further supports the assignment of the 4509.6 keV level as the first 3^- state in ^{56}Fe.

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[1] M. Honma, T. Otsuka, B. A. Brown, and T. Mizusaki, Phys. Rev. C **69**, 034335 (2004), and references therein.
[2] K. Van Houcke, S. M. A. Rombouts, K. Heyde, and Y. Alhassid, Phys. Rev. C **79**, 024302 (2009), and references therein.
[3] J. Huo, Nucl. Data Sheets **86**, 315 (1999).
[4] J. Bellicard and P. Barreau, Nucl. Phys. **36**, 476 (1962).
[5] Z. Guo, C. Alderliesten, C. van der Leun, and P. M. Endt, Nucl. Phys. A **540**, 117 (1992).
[6] G. Bruge, J. C. Faivre, H. Faraggi, and A. Bussiere, Nucl. Phys. A **146**, 597 (1970).
[7] A. M. Demidov, L. I. Govor, V. A. Kurkin, and I. V. Mikhailov, Phys. At. Nucl. **67**, 1884 (2004).
[8] D. E. Appelbe *et al.*, Phys. Rev. C **62**, 064314 (2000).
[9] P. W. Lisowski, C. D. Bowman, G. J. Russell, and S. A. Wender, Nucl. Sci. Eng. **106**, 208 (1990).
[10] J. A. Becker and R. O. Nelson, Nuclear Physics News International **7**, 11 (1997).
[11] N. Fotiades, R. O. Nelson, M. Devlin, and J. A. Becker, Phys. Rev. C **76**, 014302 (2007).
[12] N. Fotiades *et al.*, Phys. Rev. C **69**, 024601 (2004).
[13] S. Mellema, R. W. Finlay, and F. S. Dietrich, Phys. Rev. C **33**, 481 (1986).
[14] E. Sh. Sukhovitskii, S. Chiba, J.-Y. Lee, Y.-O. Lee, J. Chang, T. Maruyama, and O. Iwamoto, J. Nucl. Sci. Technol. **39**(8), 816 (2002).