β-decay study of ^{54,55}Ni produced by an element-selective laser ion source

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β-decay studies of the neutron-deficient ^{54,55}Ni isotopes have been performed at the Leuven isotope separator on-line facility (LISOL) at Louvain-la-Neuve. The nuclei of interest are produced using an element-selective laser ion source coupled to the on-line mass separator. The half-life of ^{55}Ni ($T_{1/2}=$ 204$\pm$3 ms) was remeasured precisely and the β^+ decay of ^{54}Ni was observed for the first time. The β^+-decay Gamow-Teller strength [B(GT)] associated with the ($J^\pi=1^+$) level at 937.2 keV in the daughter nucleus ^{54}Co was deduced. The β^+ GT strength of 1.09$\pm$0.25 obtained from the measured half life of ^{54}Ni ($T_{1/2}=106\pm12$ ms) and branching ratio ($I_\beta=22.4\pm4.4$%) towards this level is in agreement with the GT strength obtained from (p,n) reaction studies on ^{54}Fe [B(GT$-$)$=1.172\pm0.078$]. [S0556-2813(99)03405-6]

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I. INTRODUCTION

In the mid 1980s (p,n) or (n,p) charge-exchange reactions proved to be a powerful tool to investigate the total Gamow-Teller (GT) strength in nuclei as they are not limited by a Q-value window as is β decay. In such studies the $\Delta L=0$ forward-angle cross section should be proportional to the β^- or β^+-decay Gamow-Teller strength, B(GT$-$) or B(GT$+$) [1]. However, there are still some difficulties to deduce the absolute values of the GT strength, since a distorted-wave impulse-approximation analysis is involved. Fortunately β decay is very well suited to determine absolute values of the GT strength. Charge-exchange reactions and β decay are complementary tools to study the GT strength since the GT strength associated with one particular level determined from β decay can be used to normalize the total GT strength determined from charge-exchange reactions. In the sd shell a systematic theoretical and experimental study of the GT strength has been carried out in order to study the quenching of the GT strength, i.e., the overestimation of the theoretical GT strength with respect to the experimentally determined GT strength [2,3]. For $\beta^\pm$ decay the GT strength is defined as in Ref. [2]:

$$\mathrm{B(GT)}=(g_A/g_V)^2\langle\sigma\tau\rangle^2 \text{ with } \langle\sigma\tau\rangle=\frac{\left\langle f\left\|\sum_k \sigma^k t^k_\pm\right\| i\right\rangle}{\sqrt{2J_i+1}}, \tag{1}$$

where $t_\pm=(1/2)(\tau_x\pm i\tau_y)$ and J_i is the spin of the initial state of the nucleus. The sum is over the nucleons in the decaying nucleus. The constants g_A and g_V are the axial-vector and vector coupling constant for free-neutron decay, respectively. The quenching of the GT strength can be due to either a renormalization of g_A in the nucleus or a renormalization of the $\sigma\tau$ operator. As a result of the systematic study in the sd shell a value for the quenching factor q, defined as the square root of the ratio of the experimental GT strength to the theoretical GT strength, of 0.77 is obtained [3]. In the fp shell there is still a lack of experimental data. Furthermore GT properties of medium mass nuclei are important for precollapse evolution of supernova [4]. If the core of a massive star exceeds the Chandrasekhar limit, electrons will penetrate into the nuclei leading to increased electron capture; the strength will be significantly influenced by Gamow-Teller transitions [5]. Due to a lack of theoretical and experimental data, in stellar evolution simulations one always assumes that the GT strength is concentrated in one single resonance. However, experimentally one sees that the GT strength is often fragmented over many states and that the total strength is quenched compared to theory.

The experimental and theoretical information on the so-called $f_{7/2}$ nucleus ^{54}Fe ($Z=26$, $N=28$) [6–16] is very rich and moreover this nucleus is of astrophysical interest [5,17,18]. The 0^+ ground states of the $f_{7/2}$ nuclei ^{54}Fe-^{54}Co-^{54}Ni form a $T=1$ isospin multiplet. Anderson *et al.* measured the B(GT$-$) in the ^{54}Fe$(p,n)^{54}$Co reaction at 135 MeV [9]. The B(GT$-$) is highly fragmented: they identified GT strength in more than 30 excited states. A level at 937.2 keV in ^{54}Co represents one of the main contributions

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to the total GT strength. To study the renormalization of the axial-vector coupling constant g_A in a nucleus or the renormalization of the $\sigma\tau$ operator, a comparison with theory is necessary. There are two ways to compare experimental GT strength with theory. First of all, the experimental value for the total B(GT−) observed in discrete peaks combined with the B(GT+) strength determined from (n,p) reaction studies [7,8] can be compared with the model-independent $3(N\text{-}Z)$ Ikeda sum rule which assumes that the nucleons are the elementary building blocks of the nucleus [19]. This results in a lower limit of 48% of the Ikeda sum rule [9]. If a multipole decomposition of possible GT strength above the ''quasifree scattering background'' is performed this number becomes 73% [9]. Secondly, comparison with shell-model calculations is possible. Large-scale shell-model calculation have been performed by Caurier *et al.* [16]: the B(GT−) distribution for ^{54}Fe is well described by $0\hbar\omega$ calculations if the $\sigma\tau$ operator is quenched by the standard factor 0.77 [16]. The overestimation of the GT strength by shell-model predictions is generally ascribed to two effects omitted in conventional shell-model calculations, namely higher-order configurations neglected in a limited model space and subnucleonic degrees of freedom in the form of Δ-isobar excitations. Although both mechanisms shift the GT strength to higher excitation energies, higher-order configuration mixing is believed to be the more important quenching mechanism [20]. Recently full fp shell-model Monte Carlo calculations became possible [13–15]. They resulted in a strong sensitivity of the GT strength on the effective interaction and, therefore, the conclusion cannot be drawn that complete fp basis calculations recover the quenching totally until improved interactions are available.

In the (p,n) reaction experiment on ^{54}Fe target by Anderson *et al.* the amount of GT strength associated with the $\Delta L=0$ GT strength is obtained relative to the Fermi strength assumed to be concentrated in the 0^+ ground state. Therefore β-decay studies are needed as a complementary tool to investigate the absolute GT-strength distribution in ^{54}Co. Under the assumption of isospin symmetry, the GT strength to specific levels determined from β^+ decay of ^{54}Ni and that of ^{54}Fe$(p,n)^{54}$Co should be identical since ^{54}Ni and ^{54}Fe form a mirror pair (see Fig. 1). The β^+ decay of ^{54}Ni ($T=1$, $T_z=-1$) has so far not been studied. The β^+ decay of ^{54}Ni will be governed by superallowed 0^+ to 0^+ Fermi decay to the ground state of ^{54}Co, its $T=1,T_z=0$ isospin multiplet member. The β decay of the latter is one of the nine well-known cases (^{10}C, ^{14}O, ^{26}Al^m, ^{34}Cl, ^{38}K^m, ^{42}Sc, ^{46}V, ^{50}Mn, and ^{54}Co) where all β-decay parameters (Q value, $T_{1/2}$ and branching ratios) are known with great precision [21,22].

Several levels in ^{54}Co are known through in-beam γ-ray spectroscopy and charge-exhange reactions on ^{54}Fe [23]. Although the mass of ^{54}Ni has been measured via the ^{58}Ni$(\alpha,{}^{8}$He$)$ reaction [24] (mass excess -39.21 ± 0.05 MeV), no further information on this isotope, only two neutrons away from the double-magic ^{56}Ni nucleus, is available. The estimated half-life of ^{54}Ni is 140 ms [23,24], assuming only the superallowed Fermi decay from the 0^+ ground state of ^{54}Ni towards its isobaric analog state, the 0^+ ground state of ^{54}Co. From the B(GT−) values deduced by Anderson *et al.*, the corresponding β-branching ratios and the half-life of ^{54}Ni can be calculated. The branching ratio towards the first 1^+ state in ^{54}Co at 937.2 keV should be 24% and the half-life 105 ms. Also the influence of the experimental error of the Q_{EC} value on the half-life of ^{54}Ni can be calculated. A deviation from the Q_{EC} value of $+/-50$ keV yields a half-life of 101 and 108 ms, respectively.

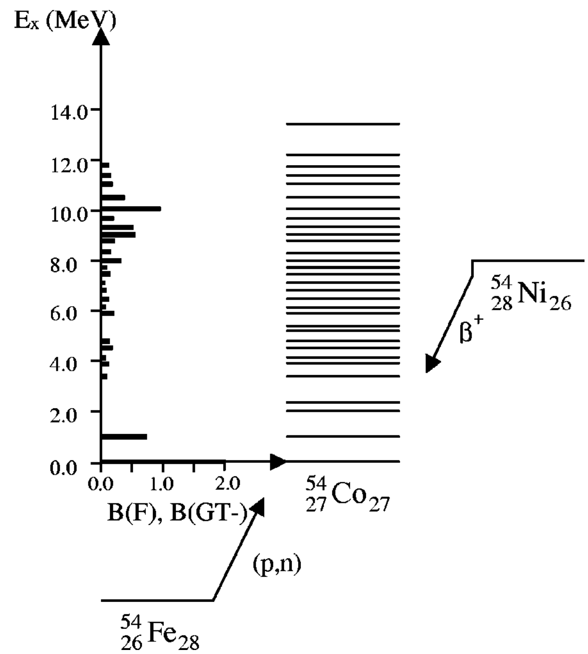

FIG. 1. The GT strength to specific levels determined from the ^{54}Fe$(p,n)^{54}$Co reaction and from the β^+ decay of ^{54}Ni should be identical since ^{54}Ni and ^{54}Co form a mirror pair. The left graph shows the B(GT−) relative to the Fermi strength [B(F)] assumed to be concentrated in the 0^+ isobaric analog state obtained from the ^{54}Fe$(p,n)^{54}$Co reaction by Anderson *et al.* [9].

Nuclei near double-magic nuclei often exhibit simple and interesting features. The β^+ decay of the mirror nucleus ^{55}Ni, one nucleon removed from the double-magic nucleus ^{56}Ni, to ^{55}Co is studied by Hornshøj *et al.* ($T_{1/2}=189\pm5$ ms) [25], by Äystö *et al.* [26] ($T_{1/2}=208\pm5$ ms), by Hama *et al.* ($T_{1/2}=212\pm4$ ms) [27] and by our group [28] ($T_{1/2}=155\pm10$ ms). The half-life obtained by Hornshøj *et al.* and by our group differ significantly from the other published half-lives. The β^+ decay of ^{55}Ni is governed by fast mixed Fermi and GT transition to the ground state of ^{55}Co. Hagberg *et al.* observed three new β^+-decay branches from ^{55}Ni to ^{55}Co [29] representing 0.5% of the decay strength. The fast ground-state branch accounts for 99% of the decay strength. Measurement of the log *ft* value will result in the GT strength since the Fermi strength can be calculated easily.

II. EXPERIMENTAL DETAILS

Because of its chemical properties, short-lived nickel isotopes like ^{54}Ni, are difficult to produce at on-line isotope separators using conventional high-temperature target ion source techniques since the delay time is too long compared with the half-life of the nuclei of interest [30]. Furthermore, the ^{54}Ni β decay will be dominated by the ground state to ground-state transition and the spectra will be overwhelmed with the decay of its ^{54}Co^g ($T_{1/2}=193.23$ ms) and

$^{54}Co^{m}$ ($T_{1/2}$=1.48 m) isobars. For example HIVAP cross section calculations [31] predict for the $^{54}Fe(^{3}He,xnyp)$ reaction a production of ^{54}Co which is at least two orders of magnitude larger than of ^{54}Ni. In the experiments described in the framework of this paper a fast, universal, efficient and element-selective laser ion source has been used. The ionization process is based on the resonant photoionization (efficient and element-selective) of reaction products in a buffer gas (fast). Such a target-ion source has been developed and applied at the LISOL facility at Louvain-la-Neuve [28,32].

The isotopes of interest, namely $^{54,55}Ni$ were produced in the fusion-evaporation reaction $^{54}Fe(^{3}He,xnyp)$ at energies of 45 and 27 MeV, respectively. The target with a thickness of 3 mg/cm^2 was enriched in ^{54}Fe up to 96.66%. The reaction products were thermalized and neutralized in 500 mbar helium gas and subsequently photoionized near the exit hole of the ion source. The laser light is supplied by two synchronized, 400 Hz, 60 W XeCl excimer and two pulsed dye lasers with frequency-doubling option. For the photoionization a two-step resonant-ionization scheme described in Refs. [28,32] was used. After ionization, the nuclei were accelerated, mass separated, and implanted on a movable tape in order to suppress long-living daughter activities. The implantation spot was surrounded by a detection setup consisting of a ΔE-E telescope for the detection of β^{+} particles. For ^{55}Ni, a 300 mm^2 and 500 μm thick PIPS detector was used as a ΔE detector, in the case of ^{54}Ni a NE104 plastic scintillator of 1 mm thickness, and in both cases, the E detector was a 5 cm$\times$5 cm NE102A plastic scintillator. A large high-purity germanium detector with 75% efficiency for the 1332.5 keV line of ^{60}Co relative to the efficiency of a 3 inch $\times$ 3 inch NaI(Tl) detector at a distance of 25 cm from the source was installed for the detection of γ singles as well as β-coincident γ rays. For ^{54}Ni also an alternative setup, consisting of two NE104 plastic ΔE detectors each followed by a high-purity germanium detector (70% and 75% relative efficiency), was used. Standard γ-calibration sources were used for energy calibration of the germanium detectors. Efficiency calibrations of β and germanium detectors were performed with intensity calibrated β and γ sources. To take into account the influence of summing effects in the germanium detector(s) on the photopeak efficiency, GEANT [33,34] simulations have been performed for $^{54}Co^{m}$. To avoid electron recombination of the laser-ionized species and to reduce the background, the cyclotron beam and the mass-separated beam were pulsed in antiphase. The time structure was typically of the order of 30 ms on and 30 ms off, the time necessary to evacuate the reaction products from the gas cell. Superimposed on this time structure an implantation-decay mode was used to allow for half-life measurements. For ^{55}Ni and ^{54}Ni the implantation/decay periods were 1 s/2 s and 0.5 s/1 s, respectively. To suppress long-living daughter activities the tape was moved every minute. All coincidence events were recorded together with the time relative to the start of the implantation period using a time to digit converter. For ^{55}Ni the two time cycles were not synchronized while for ^{54}Ni they were synchronized. This implies that for ^{54}Ni one has to take into account the specific time structure of the cyclotron and mass-separated beam while fitting the data.

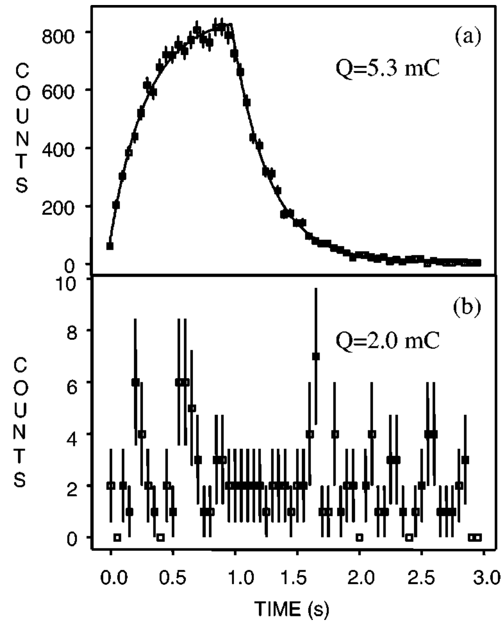

FIG. 2. Implantation/decay spectrum of ^{55}Ni with lasers ON (a) and OFF (b). The implantation/decay cycle was 1 s/2 s. The accumulated charge of the $^{3}He^{++}$ beam on the target (Q) is indicated. The solid line reperesents the fit to the data.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. The decay of ^{55}Ni

On ^{55}Ni, conflicting half lives have been reported by others and by our group [28]. In the experiment by Hornshøj *et al.* [25] β^{+} spectra were recorded after irradiation of the ^{54}Fe target together with time information. This experiment was performed in-beam. In order to decrease the contamination level, a β^{+}-energy selection was used. In the experiments by Äystö *et al.* [26] and by Hama *et al.* [27] an IGISOL (ion guide isotope separator on-line) system was used to separate ions according to A/q leaving isobaric contaminants like ^{55}Co in the mass-separated beam. The half-life measurement was repeated with a considerably improved setup consisting of an element-selective ion source coupled to the Leuven isotope separator on-line. In this way a contamination-free ^{55}Ni beam could be produced. The production rate of ^{55}Ni was 1208 at/μC resulting in an ion source efficiency of 3.7% with the lasers ON. In Fig. 2 the implantation-decay TDC spectrum for ^{55}Ni is shown with the lasers ON (a) and OFF (b). To be sure that the activity was originating only from ^{55}Ni decay, data were taken in laser ON and laser OFF mode. Clearly, Figs. 2(a) and 2(b) show that the high selectivity with the laser system results in very pure and almost background-free spectra. The selectivity, defined as the ratio of background subtracted counts while the lasers were ON relative to the lasers OFF was 421. The fitted half-life, 204$\pm$3 ms, is in agreement with Ref. [26] ($T_{1/2}$=208$\pm$5 ms) but disagrees with our previously published value of 155$\pm$10 ms [28]. Possible reasons for the disagreement can be found in the low production rate in our previous experiment (54 at/μC), the simplified detection setup (only a ΔE Si detector was used in singles) and cyclotron-beam induced background during the previous experiment [28]. The fitted half-life was used to determine

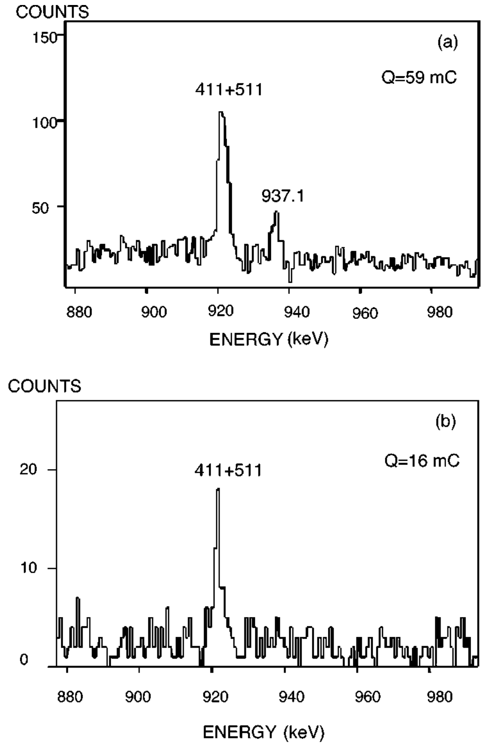

FIG. 3. Part of the β-gated γ spectrum of ^{54}Ni with lasers ON (a) and OFF (b). The peak at 922 keV is due to the summing of a 411 keV γ with 511 keV annihilation radiation originating from ^{54}Co^{m}. The accumulated charge of the ^{3}He^{++} beam on the target (Q) is indicated.

B(GT). A B(GT) of 0.466 ± 0.027 was obtained which can be compared to 0.803 from a shell-model calculation using a modified Kuo-Brown interaction and permitting up to two particle excitations from the $f_{7/2}$ orbital to the higher lying $p_{3/2}$, $f_{5/2}$ or $p_{1/2}$ orbitals in the fp shell [35]. A comparison results in a quenching factor q of 0.76.

B. The decay of ^{54}Ni

In the case of the ^{54}Ni experiment, the selectivity only reached a value of 12, leaving a high contamination of ^{54}Co in the β spectrum: a long-living component (^{54}Co^{m}, 1.48 min) and a short-living component (^{54}Co^{g}, 193.23 ms) [23]. The best production rate that has been achieved for ^{54}Ni was 13 at/μC; this beam was contaminated by 99 at/μC of ^{54}Co^{g} and 159 at/μC of ^{54}Co^{m}. Figure 3 shows part of the γ spectrum gated by the opposite β detector at mass $A = 54$ with lasers ON (a) and OFF (b). The γ line at 937.1 ± 0.5 keV is only present in the laser ON spectrum and therefore only can originate from the ^{54}Ni decay. From the time behavior of the 937.1 keV γ ray in the decay part of the cycle (shown in Fig. 4), a half life of 103 ± 22 ms was deduced. No other resonant γ rays were detected and the decay scheme of ^{54}Ni is thus, as expected, limited to a β branch to a level at 937.1 keV in competition with ground-state feeding (see Fig. 5). A second independent method to obtain half-life information from a different part of the data is fitting the time behavior of the β events or β-γ events with $E_{\gamma} \leqslant 511$ keV. As the ^{54}Ni beam is contaminated with, in the ^{54}Fe(^{3}He,$xnyp$) reaction, directly produced 193.23 ms ^{54}Co^{g} and 1.48 min ^{54}Co^{m} (see Fig. 5 for their decay schemes) which survive the neutralization in the He buffer gas, events due to the decay of these nuclei are present. It is possible to construct a "contaminant-free" ^{54}Ni spectrum by combining a Ni-resonant spectrum with a Co-resonant spectrum, both taken with the same experimental conditions. By tuning the lasers to a resonance ionization scheme for Co it is possible to obtain pure ^{54}Co^{m,g} data events. Due to pressure and power broadening of the laser line width the isomer and the ground state of ^{54}Co are not resolved and both are ionized with the same efficiency. The ^{54}Co^{m,g} data set is then combined with the Ni resonant data set and through the normalization with the ^{54}Co$^{m}\gamma$ lines a pure ^{54}Ni data set can be obtained. But as ^{54}Ni feeds the 193.23 ms ^{54}Co^{g} the total time behavior will be an admixture of the decay of the parent ^{54}Ni and the growing-in-decay of the daughter ^{54}Co^{g}. The half-life of ^{54}Ni obtained from fitting the time behavior of the "contaminant-free" ^{54}Ni data set was 108 ± 15 ms (see Fig. 6). A final value of the half-life of ^{54}Ni is 106 ± 12 ms taking the weighted average of the two independent results. In order to determine the GT strength it is important to know the branching ratio towards the level at 937.2 keV in ^{54}Co. Experimentally this branching ratio can be obtained by comparing the total amount of ^{54}Ni, determined from the intensity of the 511-keV annihilation radiation after correction for the contribution of ^{54}Co, and the emitted 937.1-keV γ rays. Therefore the efficiency

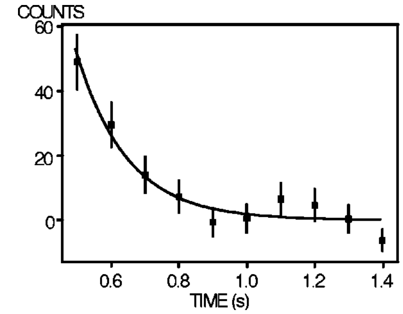

FIG. 4. Decay spectrum of the 937.1 keV γ line. The solid line represents a single-exponential fit to the data.

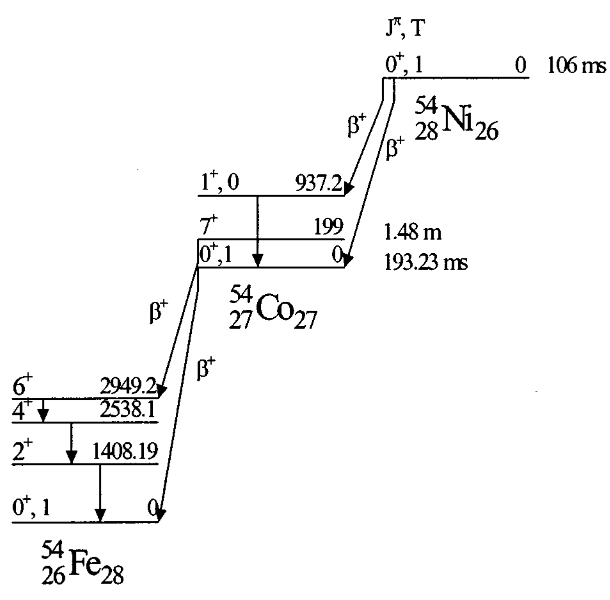

FIG. 5. Decay scheme of ^{54}Ni and ^{54}Co^{m,g}.

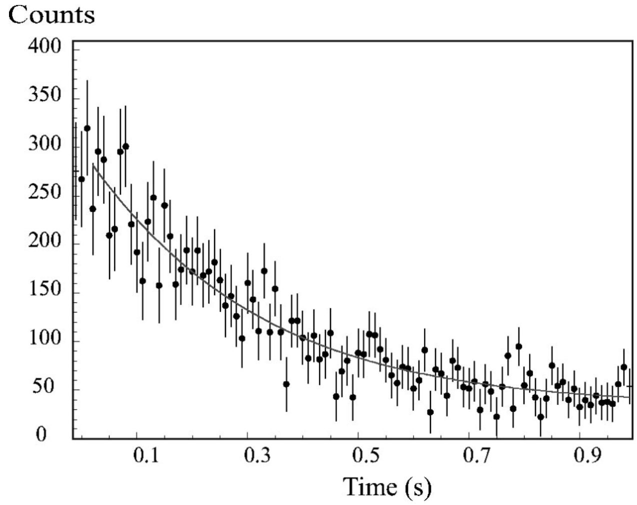

FIG. 6. A ''contaminant-free'' decay spectrum of ^{54}Ni constructed from β and β-γ events with $E_\gamma \leqslant 511$ keV. The β -937.1 keV events are excluded from this data set. The solid line represents a fit to the data that includes the decay of ^{54}Ni followed by the decay of ^{54}Co^g.

of the 511 keV annihilation radiation and the 937.1 keV γ ray is needed. In order to understand the influence of summing effects on the γ efficiency and the influence of the spatial distribution of the 511 keV annihilation source, extensive Monte Carlo simulations using the code GEANT [33] have been performed to determine the efficiencies. The simulations have been verified experimentally using the decay of ^{54}Co^m and are in good agreement with the experiment. Summing in the germanium detector with a β particle, a 511, 1130 or 1408 keV γ ray reduces the 411 keV photopeak efficiency by 43% in the present setup consisting of two plastic ΔE detectors each followed by a germanium detector compared to the single-line photopeak efficiency. The branching ratio towards the 1^+ state at 937.1 keV is 22.4 $\pm$4.4%. The branching ratio and half-life determined in this work, and the Q_{EC} value reported in Ref. [24] were used to calculate the GT strength towards the 1^+ state at 937.2 keV. This results in a GT strength of 1.09 ± 0.25 to be compared with B(GT$-$)$=1.172\pm0.078$ from (p,n) reaction studies [9]. For this comparison, the B(GT$-$) value from Ref. [9] was multiplied with $(g_A/g_V)^2=(1.262)^2$ [36,37] since a different definition of the GT strength was used. The GT strength determined from the β^+ decay of ^{54}Ni and the B(GT$-$) determined from (p,n) reaction studies on ^{54}Fe are in good agreement and thus, the normalization of the GT strength with respect to the Fermi strength, assumed to be concentrated in the ground state to ground state transition, used by Anderson *et al.* is justified.

IV. CONCLUSION

In conclusion, we remeasured the half-life of ^{55}Ni and studied the β^+ decay of ^{54}Ni for the first time. From the half-life of ^{55}Ni ($T_{1/2}=204\pm3$ ms) the B(GT) was deduced (0.466 ± 0.027) leading to a quenching factor q of 0.76. For ^{54}Ni Gamow-Teller feeding to the 1^+ state at 937.2 keV, decaying directly to the ground state was observed. The corresponding β-branching ratio (22.4 ± 4.4 %) was deduced and the half-life of ^{54}Ni ($T_{1/2}=106\pm12$ ms) was measured. The obtained β^+ GT strength from the measured branching ratio and half-life (1.09 ± 0.25), is in agreement with the (p,n) B(GT$-$) from Ref. [9] (1.172 ± 0.078) justifying the normalization used by Anderson *et al.* With the laser ion source we can extend this study to other nuclei where element selectivity is indispensable. An investigation of other $f_{7/2}$ nuclei like ^{42}Ti, ^{46}Cr, and ^{50}Fe, produced in light-ion induced reactions, is planned. The first step, finding an efficient laser ionization scheme, has been accomplished for titanium. A further extension towards the heavier $N=Z$ nuclei will be accomplished after the development of the laser ion source for heavy-ion fusion-evaporation reactions.

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[1] T. N. Taddeucci, C. A. Goulding, T. A. Carey, R. C. Byrd, C. D. Goodmann, C. Gaarde, J. Larsen, D. Horen, J. Rapaport, and E. Sugarbaker, Nucl. Phys. **A469**, 125 (1987).
[2] B. A. Brown and B. H. Wildenthal, At. Data Nucl. Data Tables **33**, 348 (1985).
[3] B. A. Brown and B. H. Wildenthal, Annu. Rev. Nucl. Part. Sci. **38**, 29 (1988).
[4] H. A. Bethe, Rev. Mod. Phys. **64**, 491 (1992).
[5] M. B. Aufderheide, I. Fushiki, S. E. Woosley, and D. H. Hartmann, Astrophys. J. **91**, 389 (1994).
[6] J. Rapaport, T. Taddeucci, T. P. Welch, C. Gaarde, J. Larsen, D. J. Horen, E. Sugarbaker, P. Koncz, C. C. Foster, C. D. Goodman, C. A. Goulding, and T. Masterson, Nucl. Phys. **A410**, 371 (1983).
[7] M. C. Vetterli, O. Häusser, W. P. Alford, D. Frekers, R. Helmer, R. Henderson, K. Hicks, K. P. Jackson, R. P. Jeppesen, C. A. Miller, M. A. Moinester, K. Raywood, and S. Yen, Phys. Rev. Lett. **59**, 439 (1987).
[8] M. C. Vetterli, O. Häusser, R. Abegg, W. P. Alford, A. Celler, D. Frekers, R. Helmer, R. Henderson, K. H. Hicks, K. P. Jackson, R. P. Jeppesen, C. A. Miller, K. Raywood, and S. Yen, Phys. Rev. C **40**, 559 (1989).
[9] B. D. Anderson, C. Lebo, A. R. Baldwin, T. Chittrakarn, R. Madey, J. W. Watson, and C. C. Foster, Phys. Rev. C **41**, 1474 (1990).
[10] N. Auerbach, G. F. Bertsch, B. A. Brown, and L. Zhao, Nucl. Phys. **A556**, 190 (1993).
[11] T. Rönnqvist, H. Condé, N. Olssen, E. Ramström, R. Zorro, J.

Blomgren, A. Häkansson, A. Ringbom, G. Tibell, O. Jonsson, L. Nilsson, P.-U. Renberg, S. Y. van der Werf, W. Unkelbach, and F. P. Brady, Nucl. Phys. **A563**, 225 (1993).

[12] M. B. Aufderheide, S. D. Bloom, D. A. Resler, and G. J. Mathews, Phys. Rev. C **48**, 1677 (1993).

[13] Y. Alhassid, D. J. Dean, S. E. Koonin, G. Lang, and W. E. Ormand, Phys. Rev. Lett. **72**, 613 (1994).

[14] D. J. Dean, P. B. Radha, K. Langanke, Y. Alhassid, S. E. Koonin, and W. E. Ormand, Phys. Rev. Lett. **72**, 4066 (1994).

[15] K. Langanke, D. J. Dean, P. B. Radha, Y. Alhassid, and S. E. Koonin, Phys. Rev. C **52**, 718 (1995).

[16] E. Caurier, G. Martínez-Pinedo, A. Poves, and A. P. Zuker, Phys. Rev. C **52**, R1736 (1995).

[17] G. M. Fuller, W. A. Fowler, and M. J. Newman, Astrophys. J. **252**, 715 (1982).

[18] S. D. Bloom and G. M. Fuller, Nucl. Phys. **A440**, 511 (1985).

[19] K. Ikeda, S. Fujii, and J. I. Fujita, Phys. Lett. **3**, 271 (1963).

[20] F. Osterfeld *et al.*, Rev. Mod. Phys. **64**, 491 (1992).

[21] J. C. Hardy, I. S. Towner, V. T. Koslowski, E. Hagberg, and H. Schmeing, Nucl. Phys. **A509**, 429 (1990).

[22] G. Savard, A. Galindo-Uribarri, E. Hagberg, J. C. Hardy, V. T. Koslowski, D. C. Radford, and I. S. Towner, Phys. Rev. Lett. **74**, 1521 (1995).

[23] H. Junde, S. Huibin, Z. Weizhong, and Z. Qing, Nucl. Data Sheets **68**, 887 (1993).

[24] R. E. Tribble, J. D. Cossairt, D. P. May, and R. A. Kenefick, Phys. Rev. C **16**, 917 (1977).

[25] P. Hornshøj, L. Højsholt-Poulsen, and N. Rud, Nucl. Phys. **A288**, 429 (1977).

[26] J. Äystö, J. Ärje, V. Koponen, P. Taskinen, H. Hyvnen, A. Hautojärvi, and K. Vierinen, Phys. Lett. **138B**, 369 (1984).

[27] H. Hama, M. Yoshii, K. Taguchi, T. Ishimatsu, T. Shinozuka, and M. Fujioka, in *Nuclei Far from Stability*, Ontario, Canada, edited by I. S. Towner, AIP Conf. Proc. No. 164 (AIP, New York, 1987), p. 650.

[28] L. Vermeeren, N. Bijnens, M. Huyse, Yu. Kudryavtsev, P. Van Duppen, J. Wauters, Z. N. Qamhieh, P. Thoen, E. Vandeweert, and R. E. Silverans, Phys. Rev. Lett. **73**, 1935 (1994).

[29] E. Hagberg, V. T. Koslowski, G. Savard, J. C. Hardy, and I. S. Towner, Conference Proceedings Exotic Nuclei and Atomic Masses, Arles, France, edited by M. de Saint Simon and O. Sorlin, 1995, p. 563.

[30] A. Jokinen, A-H. Evensen, E. Kugler, J. Lettry, H. Ravn, P. Van Duppen, N. Erdmann, Y. Jading, S. Köhler, K-L. Kratz, N. Trautman, A. Wöhr, V. N. Fedoseyev, V. I. Mishin, V. Tikhonov, and the ISOLDE Collaboration, Nucl. Instrum. Methods Phys. Res. B **126**, 95 (1997).

[31] W. Reisdorf, Z. Phys. A **300**, 227 (1981).

[32] Yu. Kudryavtsev, J. Andrzejewski, N. Bijnens, S. Franchoo, J. Gentens, M. Huyse, A. Piechaczek, J. Szerypo, I. Reusen, P. Van Duppen, P. Van den Bergh, L. Vermeeren, J. Wauters, and A. Wöhr, Nucl. Instrum. Methods Phys. Res. B **114**, 350 (1996).

[33] Http://wwwinfo.cern.ch/pl/geant.

[34] L. Weissman, J. Van Roosbroeck, K. Krouglov, A. Andreyev, B. Bruyneel, S. Franchoo, M. Huyse, Y. Kudryavtsev, W. F. Mueller, R. Raabe, I. Reusen, P. Van Duppen, L. Vermeeren, Nucl. Instrum. Methods Phys. Res. A (in press).

[35] H. Miyatake, K. Ogawa, T. Shinozuka, and F. Fujioka, Nucl. Phys. **A470**, 328 (1987).

[36] E. Klempt, P. Bobb, L. Hornig, J. Last, S. J. Freedman, D. Dubbers, and O. Schärpf, Z. Phys. C **37**, 179 (1988).

[37] S. J. Freedman, Comments Nucl. Part. Phys. **19**, 209 (1990).