β decay of ^{26}Ne

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A pure neutron-rich ^{26}Ne beam was obtained at the ISOLDE facility using isobaric selectivity. This was achieved by a combination of a plasma ion source with a cooled transfer line and subsequent mass separation. The high quality of the beam and good statistics allowed us to obtain new experimental information on the ^{26}Ne β-decay properties and resolve a contradiction between earlier experimental data and prediction of shell-model calculations.

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I. INTRODUCTION

Recently, large-scale shell-model calculations have successfully been implemented in the *fp* shell for nuclei approaching the mass region $A \approx 70$ [1]. Calculations for lighter nuclei in the *sd* shell were developed much earlier and proved to be successful and reliable [2]. One can certainly have considerable confidence in the theoretical predictions for the nuclei at $A < 30$ that are not far from the stability line. It is therefore very interesting to examine the cases where experimental data, available in the literature, are in contradiction with the results of calculations. One such case is the β decay of the ^{26}Ne. The decay scheme reported in the literature [3,4] is compared with the calculated decay in the left and central plates of Fig. 1 (see the discussion section for details on the theoretical calculations). One can observe from the figure that there is a significant difference between the calculated and the experimental spectra. The ground and first excited levels of ^{26}Na (3^+ and 1^+, respectively) are in reasonable agreement within $\approx$100 keV, which is within a typical range for predictive power of the theoretical calculations. However, the 1_2^+ level in the experimental spectrum has 233 keV excitation energy, while the 1_2^+ level in the calculated spectrum lies as high as 1531 keV. Such a surprisingly large discrepancy indicates either a serious problem in the theory or an incorrect interpretation of the experimental results.

Therefore, it is interesting to reexamine the ^{26}Ne β decay in order to verify or disprove the possible contradiction. In this Brief Report, we present the results of an experiment performed at the ISOLDE facility, CERN.

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II. EXPERIMENT AND RESULTS

A detailed description of the experimental setup and its calibrations can be found in our previous publication [7]. Here only brief information is provided. Neutron-rich ^{26}Ne nuclei were produced in extremely asymmetric fission reactions, induced by 1.4 GeV proton pulses (3×10^{13} protons per pulse) bombarding a standard ISOLDE uranium carbide graphite target. The target was connected to a standard FEBIAD MK-7 plasma ion source. A water cooled line between the target and the ion source served for condensation of all effused elements, except gaseous products. Thus, a high-purity noble gas ^{26}Ne ion beam could be obtained after extraction from the ion source and mass separation. The leakage of nongaseous isobars through the cooled line was negligible.

The ^{26}Ne ions were implanted into an aluminized tape. The implantation point was placed close to Kapton windows, and was surrounded by four thin plastic beta detectors with a total detection efficiency of $\approx$35(4)%. Two germanium detectors of 75% and 65% relative efficiency were placed next to the implantation point for detection of γ radiation. The detection times of the γ rays and β particles were recorded by a precise time-stamping module. The efficiencies of the β and γ detectors were calibrated using sources that were collected on-line. The beam gate period was 20 ms. Before the beam gate opened, there was a 50 ms delay period after each pulse. The time duration between successive proton pulses was 3.6 s. The high yield of ^{26}Ne obtained at ISOLDE ($\approx 10^5$ atoms per μC of proton beam [8]) determines a rather narrow beam gate and long delay. Even for a relatively short beam gate, the dead time effects in the DAQ were considerable and a separate measurement was done for determination of the ^{26}Ne half life (see below). The tape was not moved during this measurement.

The β-gated γ spectrum collected for the separator mass setting $M=26$ and for 1250 proton pulses on the target is shown in Fig. 2. Due to the purity of the obtained ^{26}Ne source, all transitions in the β-gated spectrum belong to the

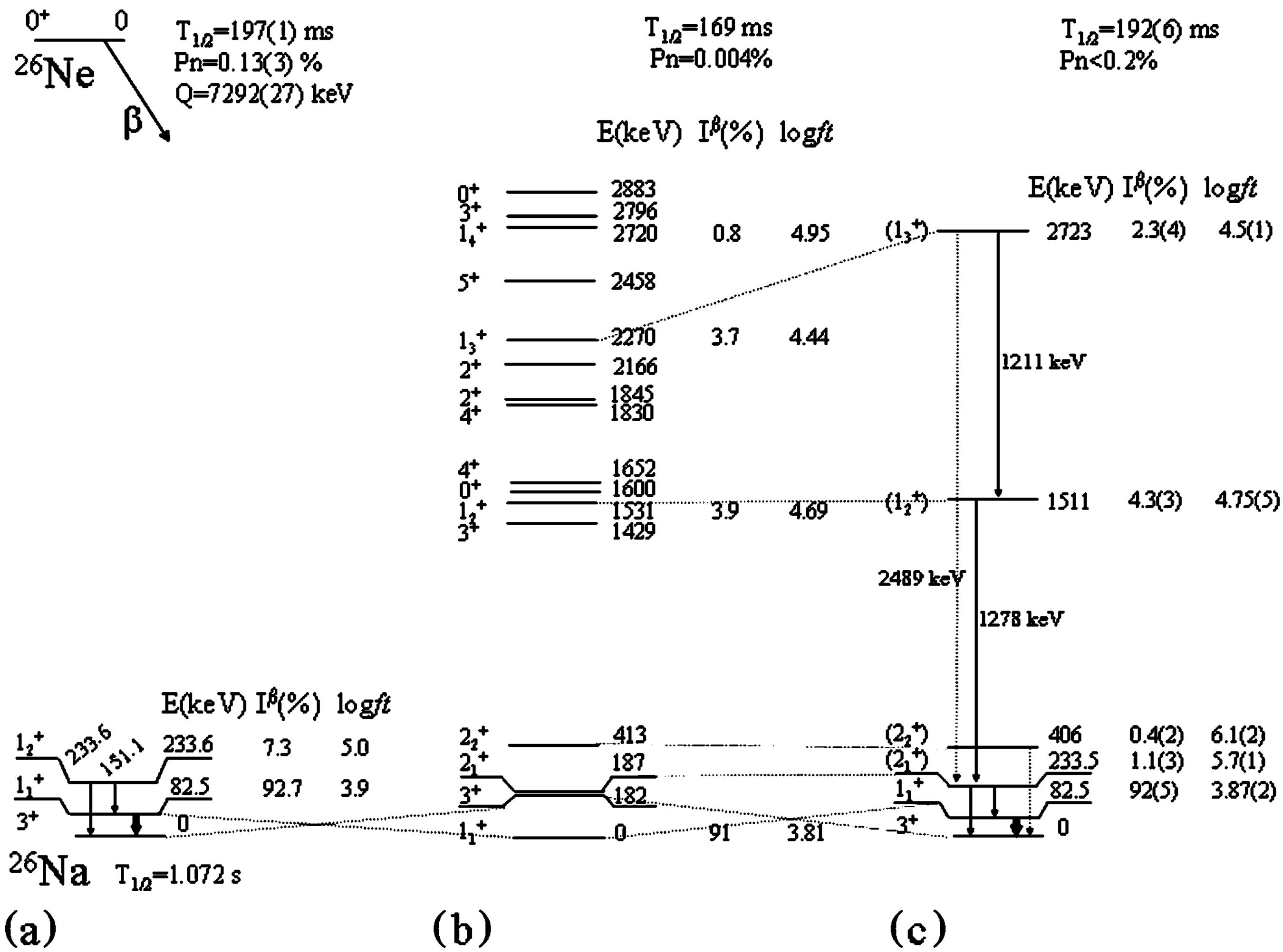

FIG. 1. (a) ^{26}Ne decay scheme from the literature [3,4]. The Q_β value is taken from [5]. (b) Result of shell-model calculations [2], the branching ratios, and log ft calculated only for the allowed decays. (c) A tentative ^{26}Ne decay scheme suggested in this work.

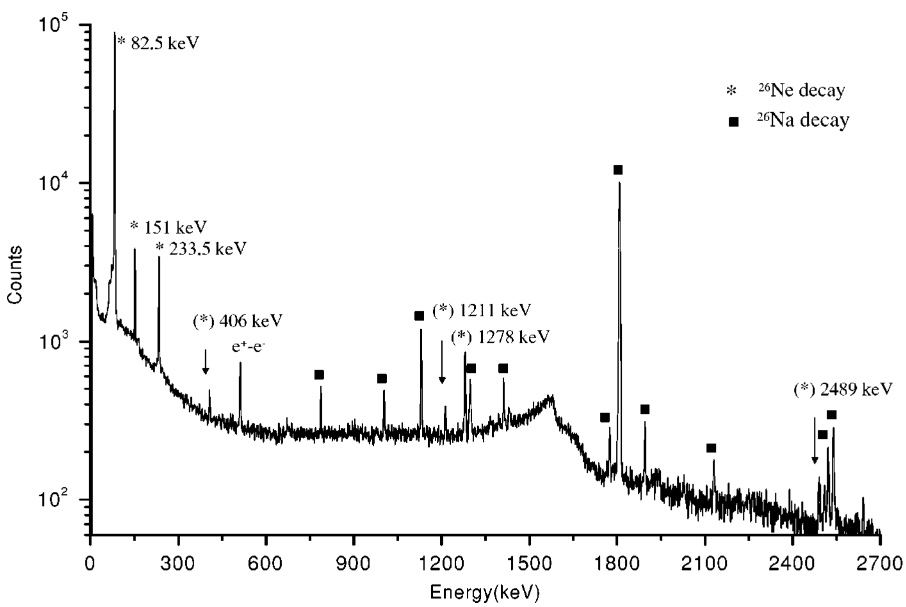

FIG. 2. β-gated γ spectrum collected for the $M=26$ separator mass value is shown. The γ rays belonging to the ^{26}Ne and ^{26}Na decays are indicated by squares and asterisks correspondingly. The asterisks symbols are taken in parentheses for the newly observed transitions.

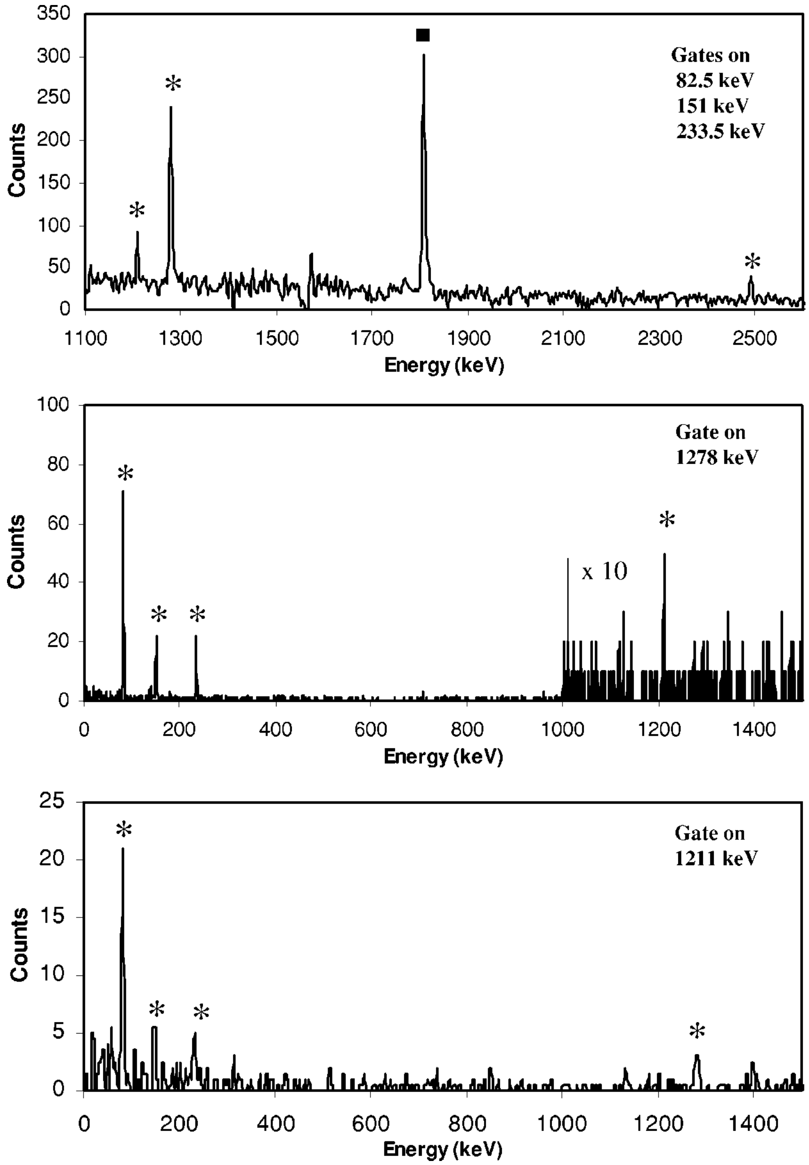

FIG. 3. The coincidences spectra obtained by applying (a) gates on the 82.5, 151, and 232.5 keV transitions, (b) a gate on 1278 keV, and (c) a gate on 1211 keV. The background is subtracted. Not completely subtracted, the strongest 1808 keV transition is observed in the top spectrum.

^{26}Ne or ^{26}Na β decays. The γ-ray transitions of the well-studied ^{26}Na decay [3] are indicated in the spectrum by square symbols, including the first and second escape peaks of the strong 1808 keV γ ray (1297 and 786 keV). All other peaks in the spectrum are candidates for γ-ray transitions belonging to the ^{26}Ne decay (asterisks symbols). Several unknown γ lines, at 406, 1211, 1279 and 2489 keV, are observed in addition to the reported 82.5, 150, and 232.5 keV transitions from the ^{26}Ne decay [4]. Gating of the trigger by these γ-ray transitions shows that all the transitions of interest originate from a decay with a half-life shorter than 300 ms. Some of the coincidence γ spectra, obtained by applying gates on the transitions of interest, are shown in Figs. 3(a)–3(c). The spectrum obtained by applying gates on the known 82.5, 150, and 232.5 keV transitions indicates that the 1211, 1279, and 2489 keV transitions belong to the same decay cascade [Fig. 3(a)]. The gates on the 1278 and 1211 keV transitions indicate a correlation between these γ rays [Figs. 3(b) and 3(c)]. The relative intensities of the transitions of interest corrected for the detector efficiencies are shown in Table I. The DAQ time window was relatively short (26 μs) compared to the half-life of the 82.5 keV level [9(2) μs [4]]. The relative intensity of this line was corrected by 14% to compensate for the fraction of undetected intensity. The error bars on the relative intensity values in Table I correspond to the statistical errors, the uncertainty in determination of the detectors efficiencies, and the uncertainty of

TABLE I. The relative intensities of the ^{26}Ne γ rays.

Nucleus	E (keV)	Rel. int.	Coincidences
^{26}Ne	82.5	100	151, 233.5, 1278, 1211, 2489
	151	3.3(7)	82.5, 1278, 1211, 2489
	232.5	4.9(10)	1278, 1211, 2489
	406	0.4(2)	not observed
	1211	1.3(4)	82.5, 151, 233.5, 1278
	1278	5.9(10)	82.5, 151, 233.5, 1211
	2489	1.1(3)	82.5, 151, 233.5

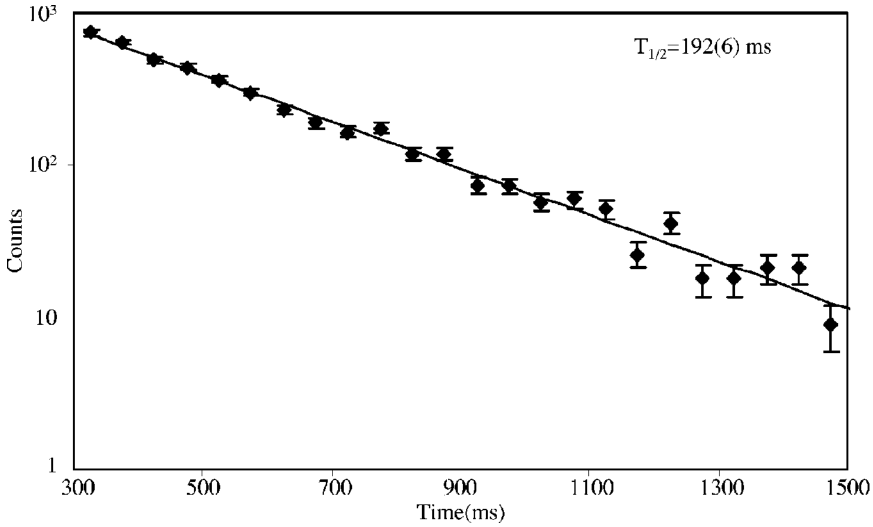

FIG. 4. The decay time profile gated by the 82.5 keV is shown. The background was subtracted.

the correction to the 82.5 keV line intensity. The latter is associated with the experimental error on the half-life of the 82.5 keV level.

No γ-ray transitions from the ^{25}Na decay were visible in the data, indicating a small ^{26}Na neutron emission probability. The obtained upper limit for the P_n value of ^{26}Ne is 0.2%. This value is in agreement with the results of an earlier experimental study with a β-neutron detector setup [9].

The measurement shown in Fig. 2 yields good statistics but suffers from dead time effects. A special measurement with a shorter beam gate of 3 ms, with a 100 ms delay after every proton pulse, was done for the careful determination of the ^{26}Ne half-life. The tape was moved after every pulse to reduce the background from the daughter activity. The decay time profile gated by the 82.5 keV γ ray is shown in Fig. 4. The half-life obtained from the fit is 192(6) ms. This value is also in agreement with Ref. [9]. The fit started at 300 ms after a proton pulse. Such a delay with respect to the beam gate allows one to avoid the systematic error associated with prompt diffusion of noble gas atoms from the implantation host [10,11].

III. DISCUSSION

A tentative decay scheme of ^{26}Ne is presented in the right plate of Fig. 1. The positions of the first two excited levels and the corresponding 82.5, 151, and 233.5 keV transitions in ^{26}Na are known from [4]. The 1278 keV and 1211 keV transitions are placed according to the observed coincidence relations. Placement of the weak 2489 keV transition was done according to its coincidence relations as well as its energy value. The weak 406 keV transition does not exhibit any coincidence relations and was tentatively assumed to decay to the ground state from the 406 keV energy level. The latter level probably corresponds to the 0.420(15) MeV level that was observed in the earlier reaction study [6,12].

The branching ratios for beta decay to the observed levels and the corresponding log *ft* values are also indicated in the right plate of Fig. 1. The low branching ratios to the 233.5 and 406 keV levels point to the forbidden character of these decays.

Shell-model calculations for ^{26}Ne and ^{26}Na were performed in the full *sd* shell using the USD effective interaction [2] in a fashion similar to the work reported in [13]. A quenching factor of 0.77 for the GT matrix elements was used in this calculation. Only allowed decays to 1^+ levels were calculated. The shell-model results for the excitation energies in ^{26}Na, the corresponding log *ft* values, and the branching ratios for the lowest four 1^+ states are given in the central plate of Fig. 1. The calculated half-life of ^{26}Ne amounts to 169 ms and is in reasonable agreement with the experimental one of 197(1) ms [9] or 192(6) ms in this work.

Comparison for the energies of the 233.5 keV and 406 keV levels with the results of the theoretical calculations together with the values of the experimental branching ratios suggests 2^+ spin-parity assignments for these levels. These assignments are in agreement with the results of Ref. [6].

The relatively strong feeding to the 1511 keV and 2723 keV levels allows one to assume that the decays to these levels are allowed. Thus, the spin parity of these levels can be assigned as 1^+. The energy position of the second 1_2^+ level (1511 keV) is in extraordinary agreement with the theoretical prediction (1531 keV). There is also good agreement between theory and experiment for the log *ft* values and branching ratios. By examining Fig. 1, it is now possible to understand that the contradiction between the calculations and the earlier experimental study arose from incomplete experimental information rather than from the fault of the theory. The sum of the branching ratios to 233.5, 1511, and 2723 keV amounts to 7.7(10)%. This feeding is similar to the 7.3% feeding to the 233.5 keV level reported in [4]. The relatively strong feeding deduced in [4] led to the 1_2^+ assignment for the 233.5 keV level in that report. The observation of the new 1511 and 2723 keV levels, which take a major part of this feeding, modifies the assignment for the 233.5 keV level and lifts the “contradiction” between experiment and theory.

The USD calculations predict four 1^+ states below 2.8 MeV, however only three 1^+ are observed experimentally. This indicates that either the fourth USD state is weakly populated or it lies at much higher energy. The energy of the experimental 1_3^+ level, 2723 keV, is rather high compared to the calculated 1_3^+ state (2270 keV), but it is remarkably close to the excitation energy of the calculated 1_4^+ state (2720 keV). The shell-model log ft and branching ratios for the calculated 1_3^+ state are in slightly better agreement with the corresponding experimental values for the 1_3^+ state at 2723 keV. Furthermore, the experimental ratio of the intensities of the γ-ray transitions decaying from the 1_3^+, 2723 keV, level to the 1_2^+ and 2_1^+ levels is 1.2(1). The corresponding ratios calculated for the 1_3^+ and 1_4^+ theoretical levels are 0.6 and 0.1, respectively. This again favors the 1_3^+ assignment for the 2723 keV level. However, the final answer to this question can be obtained only after observation of the fourth 1^+ state predicted by the theory.

To investigate further the reliability of the theoretical predictions, we have performed similar calculations utilizing two other effective interactions, namely CW [14] and HBUSD [15]. The result of the calculations yield a similar decay pattern to that in Fig. 1(b), although variation in the level energies up to 200 keV was observed for the different models. All three calculations support the suggestion regarding the 1_3^+ assignment for the 2723 keV level.

The results of the presented work have been confirmed in the recent study of excited levels of the ^{26}Na nucleus performed by utilizing the ^{14}C(^{14}C,d) reaction [16].

In conclusion, a pure ^{26}Ne beam was produced at the ISOLDE facility. The high-quality of the beam and the good statistics allowed one to obtain new experimental information on the ^{26}Ne β-decay properties and resolve the contradiction between the earlier experimental data and the prediction of shell-model calculations.

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[1] E. Caurier, F. Nowacki, and A. Poves, Eur. Phys. J. A **15**, 145 (2002).
[2] B.A. Brown and B.H. Wildenthal, Annu. Rev. Nucl. Part. Sci. **38**, 29 (1988).
[3] R. Firestone, *Tables of Isotope* (John Wiley and Sons, New York, 1996).
[4] J.P. Dufour *et al.*, in Proceedings of the 5th International Conference on Nuclei Far from Stability, Rosseau Lake, Canada, D1 (1987).
[5] G. Audi, A.H. Wapstra, and C. Thibault, Nucl. Phys. **A727**, 337 (2003).
[6] K.I. Pearce *et al.*, Phys. Rev. C **35**, 1617 (1987).
[7] L. Weissman *et al.*, Phys. Rev. C **70**, 024304 (2004).
[8] U.C. Bergmann *et al.*, Nucl. Instrum. Methods Phys. Res. B **204**, 220 (2003).
[9] O. Tengblad *et al.*, Z. Phys. A **342**, 303 (1992).
[10] U.C. Bergman *et al.*, Nucl. Phys. **A714**, 21 (2003).
[11] L. Weissman *et al.*, Phys. Rev. C **67**, 054314 (2003).
[12] P.M. Endt, Nucl. Phys. **A521**, 1 (1990).
[13] B. H. Wildenthal, M. S. Curtin, and B. A. Brown, Phys. Rev. C **28**, 1343 (1983).
[14] W. Chung, Ph. D. thesis, Michigan State Univ., 1976; B.H. Wildenthal and W. Chung, in *Mesons in Nuclei*, edited by M. Rho and D. Wilkinson (North-Holland, Amsterdam, 1979), Vol. II, p. 722.
[15] B.A. Brown, W.A. Richter, R.E. Julies, and B.H. Wildenthal, Ann. Phys. (N.Y.) **182**, 191 (1988).
[16] I. Calderin *et al.* (unpublished).