$N = 40$ Neutron Subshell Closure in the ^{68}Ni Nucleus

R. Broda, B. Fornal, W. Królas, and T. Pawłat
H. Niewodniczański Institute of Nuclear Physics, PL-31-342 Kraków, Poland

D. Bazzacco, S. Lunardi, C. Rossi-Alvarez, and R. Menegazzo
Dipartimento di Fisica dell'Universitá di Padova and INFN, I-35131 Padova, Italy

G. de Angelis, P. Bednarczyk, J. Rico, and D. De Acuña
INFN Laboratori Nazionali di Legnaro, I-35020 Legnaro, Italy

P. J. Daly, R. H. Mayer, and M. Sferrazza
Chemistry Department, Purdue University, West Lafayette, Indiana 47907

H. Grawe, K. H. Maier, and R. Schubart
Hahn–Meitner–Institut Berlin, D-14109 Berlin, Germany
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The ^{68}Ni nucleus has been identified among the products of deep-inelastic reactions of ^{64}Ni projectiles bombarding ^{130}Te and ^{208}Pb targets. Three new states, including the high-lying 2^+ (2033 keV) and the 0.86 ms 5^- isomer, indicate a substantial subshell closure at neutron number $N = 40$. The level structure and the observed very slow $E3$ transition speed are discussed within the shell model.

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In spherical nuclei the $1g_{9/2}$ orbital is distinctly separated in energy from all other single-particle levels. This gives rise to the well established magicity of the neutron and proton numbers $N,Z = 50$ and points towards a somewhat less pronounced closure at $N,Z = 40$. For protons the $Z = 40$ subshell closure is clearly demonstrated by the well known level structure of the ^{90}Zr nucleus [1], for which the lowest excitation is the 1.76 MeV 0^+ state, the first 2^+ state appears at 2.19 MeV, and the lowest lying particle-hole ($p_{1/2}^{-1}g_{9/2}$) excitation produces the long-lived 5^- isomeric state. The study of similar features in magic nuclei with the neutron number $N = 40$ must cope with formidable experimental problems, since the nuclei in question lie very far from the stability line and are not easily available for spectroscopic investigation.

Out of two possibilities which can be considered within reach, the extremely neutron deficient $N = Z = 40$ ^{80}Zr nucleus was found to be strongly deformed and did not show any trace of the shell closure signature [2]. The only other candidate with the $N = 40$ neutron number and closed proton shell is the ^{68}Ni nucleus. It lies much closer to the stability line, but it is located on the neutron-rich side, and it cannot therefore be produced by fusion-evaporation reactions. In a previous mass separator study which determined the ground-state β-decay half-life of 19 s [3], the ^{68}Ni was produced in multinucleon transfer reactions. In other experimental attempts the two-proton transfer reaction ^{70}Zn(^{14}C,^{16}O) was used and provided the ^{68}Ni mass-excess value [4] as well as spin-parity assignment [5] and half-life determination [6] of the first excited 0^+ state at 1.77 MeV. Later experiments performed with the same reaction [7] located tentatively few more states in the ^{68}Ni and suggested the 2^+ assignment for the level at 2.2(4) MeV estimated excitation energy. The assignments of two other states at 2.70(4) MeV (0^+, 2^+) and 3.28(5) MeV (2^+, 4^+) were assumed based on the comparison with theoretical calculations. The extended Hartree-Fock-Bogoliubov calculations [7] indicated that the first excited 0^+ state may be a shape isomer inviting efforts to check those predictions in experiment. On the other hand, the ^{68}Ni nucleus draws considerable interest from groups involved in the calculation of rapid neutron-capture (r-process) nucleosynthesis. This aspect was extensively discussed by Kratz *et al.* [8], who pointed out that the nuclear properties of neutron-rich Ni isotopes may be crucial to progress in the understanding of the $A \approx 80$ solar r-abundance puzzle. The spectroscopic study of the ^{68}Ni, involving higher-spin states and testing the significance of the $N = 40$ subshell closure, appeared to be an attractive experimental challenge and a necessary step to enter the investigation of the even more neutron-rich region. In our effort to identify excited states in ^{68}Ni, we used deep-inelastic reactions of ^{64}Ni projectiles on heavy target nuclei.

Recently we exploited such processes to study the neutron-rich Ni isotopes produced in ^{208}Pb + 350 MeV ^{64}Ni collisions [9]. Some important aspects of the experimental method were described previously for other colliding systems [10,11], and some details concerning the ^{208}Pb + ^{64}Ni reactions were given in Ref. [12]. The γ-γ coincidences measured with the OSIRIS array at the Hahn-Meitner-Institut Berlin allowed us to extend significantly the level schemes of $A = 64$ to 67 nickel isotopes. Isotopic identifications were based on the observation of

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cross coincidences between the γ rays of two product nuclei present in the reaction exit channel. The observed pattern of the accompanying heavy products, in that case the well known Pb isotopes, indicated that certain strong gamma lines must be associated with a specific Ni isotope. In that experiment the production of ^{68}Ni was clearly indicated, but no γ ray could be positively identified with this isotope due to insufficient statistics. To improve the experimental conditions we performed at the INFN Legnaro a similar measurement for the ^{130}Te + ^{64}Ni system, using the much more powerful GASP multidetector array. The 275 MeV ^{64}Ni beam bombarded a 1.2 mg/cm^2 ^{130}Te target located in the array center and placed on a 14 mg/cm^2 ^{208}Pb backing to stop all reaction products. The γ-γ coincidences were stored without any restriction on the multiplicity and the beam was pulsed with 200 ns repetition time in order to separate the prompt and delayed events. The scope of the experiment was much broader and the data obtained were analyzed in different ways, emphasizing various spectroscopy and reaction mechanism points of interest. Here we report this part of the analysis which led to the positive identification of the ^{68}Ni excited states.

In our search we were guided by simple shell model expectations that the ^{68}Ni level spectrum, like that of ^{90}Zr, should feature a long-lived 5^- isomer as well as a significant increase of the 2^+ excitation energy as compared to the lighter Ni isotopes. Inspection of the appropriate energy region of the γ-γ coincidence data revealed a cascade of two coincident transitions of 814 and 2033 keV energy, which matched expectations perfectly for the $5^- \rightarrow 2^+ \rightarrow 0^+$ yrast cascade in ^{68}Ni. Both transitions follow the decay of the long-lived isomer and they appeared in both the ^{208}Pb and ^{130}Te target experiments, with intensities consistent with the expected production yields of the ^{68}Ni isotope. In order to clinch the isotopic identification, we performed a γ-γ cross-coincidence analysis of the superior-statistics GASP data for the ^{130}Te + ^{64}Ni reaction system, and the key results are presented in Fig. 1. When a gate was set on a known strong transition of a specific Ni product, the coincidence spectrum showed not only other γ rays of that Ni nucleus but also known γ rays belonging to various Te partner products occurring simultaneously in the exit channel. Approximate yields of the Te products could be estimated from the γ–ray intensities. For example, at the top of Fig. 1 the tellurium isotope yields in coincidence with the ^{64}Ni 1346 keV γ ray demonstrate, apart from the predominant inelastic scattering process, that ^{64}Ni appears frequently in the exit channel accompanied by Te partners lighter than ^{130}Te; apparently, processes involving up to four neutron evaporation contribute substantially. Moving down in Fig. 1, for each heavier Ni isotope, the pattern of tellurium reaction partners shifts towards lighter mass with a characteristic sharp cutoff at the high mass end in line with the $A = 194$ total mass of the system. For ^{68}Ni, shown at the bottom, the long-lived isomer restricts the cross coincidences observed to events in which the direct, prompt population of the presumed 2033 keV 2^+ state takes place. Nevertheless, the high statistics of the GASP data for the ^{130}Te + ^{64}Ni system allowed us to establish prompt coincidences between the 2033 keV line and several transitions of Te isotopes with mass numbers $A = 126$ to 122. This pattern of Te partner products settles the assignment of the 2033 keV transition to the ^{68}Ni nucleus, which is formed by a transfer of at least four neutrons to the ^{64}Ni projectile and subsequent evaporation of zero to four neutrons from the primary products.

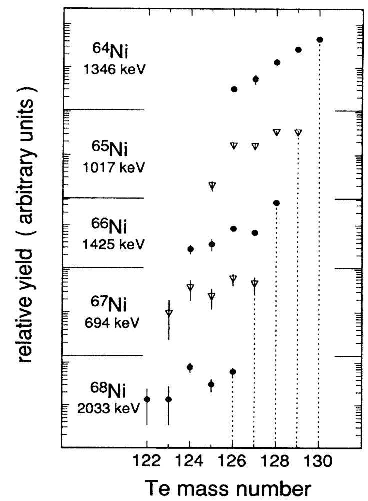

FIG. 1. Distributions of Te isotopes established from γ cross coincidences with the indicated gamma lines from ^{64}Ni to ^{68}Ni. The points show the relative, normalized separately for each Ni isotope, intensity of strongest lines in Te partner nuclei seen in coincidence with the indicated transition. The vertical lines mark the limits defined by the $A = 194$ total mass of the system.

The above result establishes also the ordering in the 814–2033 keV isomeric decay cascade; the 814 keV must be the expected $5^- \rightarrow 2^+$ $E3$ isomeric transition. In order to clarify this assignment we performed a separate experiment to measure the half-life of the isomer. This experiment was also performed with the GASP array at the INFN Legnaro, using the same ^{130}Te + ^{64}Ni system and the beam pulsing in the range from micro- to milliseconds. Along with the γ-γ coincidence data, single counts from all detectors were stored in the off-beam periods as a function of time. These singles data were clean enough to observe the isomeric decay and to select the beam pulsing condition (3 ms on, 10 ms off) for the main run used in the half-life determination. The off-beam spectrum enhancing the isomeric decay is displayed in the lower part of Fig. 2. The 814 and 2033 keV lines appear with a similar intensity, and both show the same decay displayed in the upper part of Fig. 2. The weighted average gave the isomeric half-life of

$$T_{1/2} = 0.86(5)\ \text{ms},$$

which indicates the 46 times retarded 814 keV $E3$ transition and practically excludes the $M2$, $M3$, or higher mul-

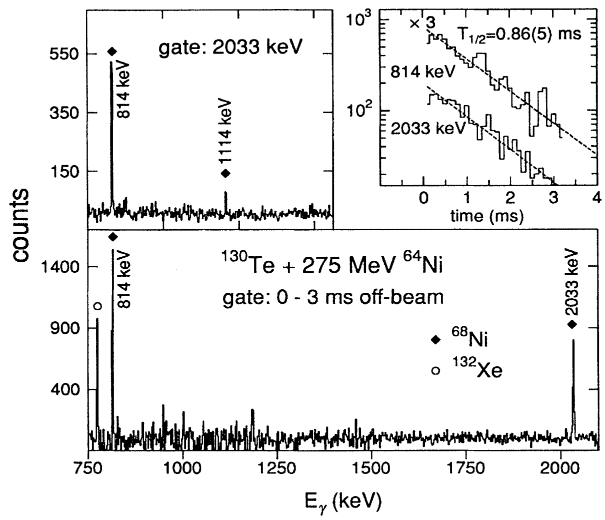

FIG. 2. Selected experimental results for ^{68}Ni isotope. A part of the off-beam single-gamma spectrum, taken in the time range enhancing the ^{68}Ni isomer decay (radioactivity background subtracted), is shown at the bottom. The prompt coincidence spectrum with the 2033 keV gate (upper left) shows the 1114 keV line, which establishes the 3147 keV level. The time decay of the two-gamma transitions from the 5^- isomer is shown in the upper right part.

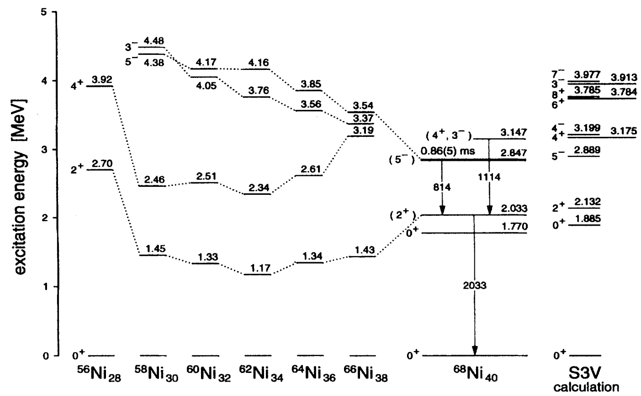

FIG. 3. Systematics of selected states in even Ni isotopes. The ^{68}Ni results are prominently displayed and compared with the S3V shell model calculations (see text).

tipolarity assignments. In all energy ranges there was no other line which could be attributed to the same isomer decay; specifically the upper limit of 3% was set for the intensity of a possible $E5$ crossover transition.

Whereas a more direct spin-parity assignment would demand a special effort, we conclude that the present results with high probability establish the expected 5^- isomer in ^{68}Ni decaying by a two transition $E3$-$E2$ cascade to the 0^+ ground state.

The high energy section of the prompt coincidence spectrum taken with the 2033 keV gate and shown in the upper part of Fig. 2 revealed the 1114 keV line; it is much weaker than the strong 814 keV isomeric transition, but clearly belongs to the nucleus and was also observed in the ^{208}Pb target experiment. It establishes another state in ^{68}Ni lying 300 keV above the 5^- isomer. From the systematics we assign tentatively this state as a 4^+ excitation, although a 3^- assignment cannot be excluded.

It is difficult to make a straightforward correlation of the three levels established now in ^{68}Ni with earlier ones given in Ref. [7]. Whereas the 2.033 MeV 2^+ level naturally falls in the range defined by the large energy uncertainty of the 2.2(4) MeV 2^+ level given previously, the suggested (0^+, 2^+) assignment for the 2.70(4) MeV state hardly allows to make the correspondence with the present 2.847 MeV 5^- state. On the other hand, the 3.28(5) MeV 2^+ or 4^+ states of Ref. [7] can well correspond to the presently observed 3.147 MeV 4^+ state, if one allows for small energy correction.

In Fig. 3 the systematics of the lowest excited states in even nickel isotopes is displayed. The present results for the ^{68}Ni isotope are outlined and compared with the shell model calculations shown to the right. The observed increase of the ^{68}Ni 2^+ state energy, by more than 600 keV compared to the ^{66}Ni, indicates a significant subshell closure at the neutron number $N = 40$. The 5^- excitation, attributed predominantly to the $p_{1/2}^{-1}g_{9/2}$ configuration, moves down in energy when the subsequent neutron pairs shift the Fermi level towards the $g_{9/2}$ orbital. As expected it attains the minimum energy at $N = 40$ and becomes isomeric, which is very well reproduced by the calculations. The 4^+ state energy increase observed in the ^{66}Ni isotope is naturally explained by completion of the filling of the $f_{5/2}$ neutron orbital at $N = 38$, which eliminates an easy way to form the 4^+ excitation from the coupling of two $f_{5/2}$ neutrons. This situation does not change when the next pair of neutrons fills the $p_{1/2}$ orbital at $N = 40$. Therefore the 3147 keV state in ^{68}Ni is most likely the 4^+ state lying at nearly the same excitation energy as in ^{66}Ni. Another possible characterization indicated for this state in Fig. 3, the 3^- assignment, cannot be excluded. The $p_{3/2}^{-1}g_{9/2}$ particle-hole excitation must play an important role in this state structure, since such a component should be particularly effective in building up the collective octupole vibration. It explains well the observed energy lowering of the 3^- level from ^{58}Ni to ^{66}Ni, and the downward trend might well extend to the ^{68}Ni isotope. However, a fast $E1$ transition [10^{-3} Weisskopf units (W.u.)] usually connects the collective 3^- and 2^+ states, and the expected lifetime of the 3^- state would be rather short. The observation of the 1114 keV transition as a narrow line in the coincidence spectrum of Fig. 2 indicates a picosecond range for the 3147 keV state lifetime, which is more compatible with the 4^+ assignment.

The shell model calculations shown in Fig. 3 are discussed in detail in Ref. [9]. In a truncated model space consisting of an inert ^{56}Ni core and $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, $g_{9/2}$ shells two approaches were used, one with a schematic modified surface delta interaction (MSDI) and the other

(S3V) with realistic two-body matrix elements derived by Sinatkas *et al.* [13]. The results of the S3V approach generally better agree with the experimental levels, and for ^{68}Ni they are presented in Fig. 3. The observed excellent agreement of the four known experimental levels with calculated ones nicely supports our spin-parity assignments. The S3V calculations also produce a low-lying 4^- level and push upwards the 3^- state; a similar but less pronounced feature is observed in the MSDI approach. Nevertheless we exclude the 4^- assignment for the 3147 keV state since such a level would decay predominantly by an $M1$ transition to the 5^- isomer, hardly allowing for an $M2$ branch to the lowest 2^+ state. The high excitation energy calculated for the 3^- state is due to the limited model space, which does not take into account a collective strength. The calculated wave function is dominated by the $g_{9/2}f_{5/2}^{-1}$ configuration with 73% , whereas the expected important $g_{9/2}p_{3/2}^{-1}$ component amounts to only 4%. A significant contribution of the collective 3^- amplitude would be needed to push this state down in energy to the observed 3147 keV level. This reinforces our preference of the 4^+ assignment discussed above. It is worthwhile to mention that the calculated lifetime of the 4^+ state at 3147 keV gives an estimate of 1.5 ps, which is in the range of a slowing down time for Ni ions in a Te, Pb target.

The calculated high spin 6^+, 8^+, and 7^- states give a clear warning affecting future experimental attempts to locate these states. The $g_{9/2}^2$ 8^+ state might well be a long-lived isomer, which would significantly complicate the identification procedure.

An important result of the present work is the measured half-life of the 5^- isomer, which gives the

$$B(E3,\ 5^- \rightarrow 2^+) = 6.0(3)\ e^2(\text{fm})^6 = 0.022\ \text{W.u.}$$

The calculated $B(E3)$ value within the S3V approach for the $E3$ neutron effective charge $1e$ gives the value of 0.023 W.u., which agrees with experiment almost perfectly, although the extreme closeness of the agreement is probably not significant. A similar $E3$ transition known in the ^{90}Zr is 10 times faster with $B(E3) = 0.22$ W.u. [1]; the explanation of this difference calls for special considerations. For comparison we have performed a shell model calculation for ^{90}Zr using the same $T = 1$ two-body matrix elements and single particle energies from Ref. [13]. The truncation of the model space was chosen consistently with the Ni calculations [9]. Inspection of the 5^- and 2^+ state wave functions revealed almost identical structures for the 5^- states, with the main configuration $g_{9/2}p_{1/2}^{-1}$ amounting to 83% in ^{90}Zr and 79% in ^{68}Ni. The remaining strength is scattered over several configurations with less than 10% each. On the other hand, the strongly mixed 2^+ states are quite different in ^{90}Zr and ^{66}Ni, which can be ascribed to the difference in single particle energies. The leading components are the $g_{9/2}^2p_{1/2}^{-2}$ with 47% in ^{90}Zr and 26% in ^{68}Ni, but the most important for the $E3$ transition, the $g_{9/2}^2p_{1/2}^{-1}p_{3/2}^{-1}$ amplitudes are rather close and contribute 13% and 10% correspondingly. This yields, probably accidentally, almost identical $B(E3)$ values calculated using the same $E3$ effective charge of $1e$ for protons and neutrons. The extraction of single particle effective $E3$ charges from experiment is hindered by varying the 3^- admixture in the single particle states and by the fact that most single particle $B(E3)$ values are reduced due to a particle to hole transition. From the remaining limited data set we extracted $e_{\text{eff}} = 1.0$ and 2.0 for neutrons and protons, respectively. This implies a factor of 4 enhancement for ^{90}Zr relative to ^{68}Ni. The remaining difference must be sought in different collective $3^- \otimes 2^+$ components in the 5^- state. The lower energy of the 3^- state in ^{66}Ni (3.37 MeV) than in its valence mirror ^{88}Sr (2.73 MeV) indicates well such a possibility. Future refined shell model calculations may also indicate delicate changes in the composition of states, which can also contribute to the explanation of the discussed difference in the $E3$ transition speed.

In summary, we have identified three new states in the ^{68}Ni, which establish this isotope as the spherical shell model nucleus and indicate a significant subshell closure at the $N = 40$ neutron number.

Further analysis in progress and future experiments are now directed towards a search for higher lying states in ^{68}Ni and an attempt to locate the 8^+ $g_{9/2}^2$ excitation. The perspectives to extend the search to the ^{70}Ni isotope also look promising. The knowledge of the complete set of the $g_{9/2}$ matrix elements would allow for much more reliable extrapolations to the extremely neutron-rich ^{78}Ni isotope, which is important for astrophysical considerations.

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