DECAY STUDIES OF NUCLEI NEAR ^{78}Ni

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Significant progress have been made over the last decade in experimental investigation of the ^{78}Ni and its neighbors. Nuclear decay studies achieved lifetime measurement of the doubly-magic ^{78}Ni and provided excitation energies of low lying levels up to ^{76}Ni, establishing the "baseline" systematics of the nuclear structure knowledge for this region of nuclear chart. Perspective studies which will build on this research are presented. One major goal is determine, if ^{78}Ni is a good double closed-shell nucleus. The answer to this question may have profound consequences for astrophysics and also our understanding of the nuclear models describing properties of very neutron rich nuclei.

1. Introduction

One current focus of nuclear structure studies is the search for modifications of traditional shell structure in neutron-rich systems. The region around ^{78}Ni is an important milestone when moving towards heavier nuclear systems. The possible erosion of the N=50 and Z=28 shell gaps will have important consequences for the modeling of the astrophysical r-process.[1]

If the magicity is eroded for ^{78}Ni, and there is a body of research, which suggests this, the future task is to experimentally establish the nature of these changes in an unambiguous way, quantify their extent, and determine the reasons behind them on a microscopic level. In consequence, will any of this fundamentally change the outcome of the r-process reaction network? Can the "business as usual" scenario be applied, where extension of conventional knowledge can be applied to follow usual systematics. Although not being completely out of reach experimentally, ^{78}Ni and its neighbors are eluding very detailed studies, because their nuclear and atomic properties make them very difficult to produce in sufficient quantities.[2,3] Despite the difficulties posed by the inconveniently low production rates, there is steady progress in investigations of nuclei near ^{78}Ni enabled by advances in experimental techniques which are overcoming the production rate limitations. Such progress is evidential in such landmark discoveries as the identification[2] of ^{78}Ni and the investigations of its lifetime[3] in relativistic fission of ^{238}U and heavy ion fragmentation of ^{86}Kr beams. The experimental data are still quite patchy and their interpretation is complicated by the usual insufficient statistics limiting the quality of the observable. The small mass and atomic number of ^{78}Ni makes difficult the effective use of the ^{238}U fission as the method for its production. This isotope is also too distant from any of the stable isotopes, which can be used as primary beams, to be abundantly produced in fragmentation reaction. Electron induced fission,[4] which is much 'cooler' and multi-nucleon transfer on nuclei with radioactive beams[5] could be the alternative production techniques of the future, when stable beam ion beam facilities exhaust their capabilities.

A complete description of this complicated region can be obtained through the efforts to measure excited states near this doubly-magic nucleus in order to understand the role of neutron excess and its true influence on magicity. Various methods of gamma-ray measurements have been employed.[6–16] The data reveal the relatively complicated nature of the nuclei in this region. Neutron-rich nickel isotopes seem to survive as closed shell nuclei, evidenced for example by a strong change in beta-decay lifetimes across the Z=28 line and the relatively high excitations of 2^+ states. There are however significant signs of the nickel core breaking shown by a steady decline of the 2^+ level energies with increasing neutron number,[15] and the disappearance of the 8^+ isomers[12] which are prevalent in the region. Not much is known experimentally about the true nature of ^{78}Ni itself, apart from the above mentioned circumstantial evidence obtained by studies of its less exotic neighbors. The theory of choice to describe excited states in these nuclei, nuclear shell-model, is facing computational difficulties, due to the possible effects of the ^{56}Ni core breaking, hence an exploding number of configurations in the model space, which in addition to $f_{5/2}$, $p_{3/2}$, $p_{1/2}$ and $g_{9/2}$ will have to include nucleons in the $f_{7/2}$ orbital. Although it is rather difficult, much more accurate experimental data are required, exploring a wider range of observables in order to constrain the theoretical predictions. With the decreasing neutron separation energy, gamma-ray spectroscopy techniques will not suffice to study nuclear properties in this region. Mass measurements are currently feasible. Difficult neutron energy measurements have to be adopted in this region. Many more challenging reaction experiments with radioactive beams have to be performed. In this manuscript we will address briefly some of the near future experimental plans to investigate experimentally the unsolved problems in ^{78}Ni region.

2. The disappearing isomers

The intriguing disappearance[12,17] of 8^+ isomers in ^{72,74}Ni has baffled us for almost a decade, and we still do not know for sure how trivial or fundamental is the answer from the point of view of detailed structure theory. There is a suggested theoretical explanation,[18,19] which may indicate some fundamental changes happening in this region. The disappearance of the elsewhere very robust isomerism is thought to be due to the lowering of the seniority $\nu = 4$, $J^\pi = 6^+$ state below the $\nu = 2, J^\pi = 8^+$ state which causes the isomeric lifetime to be too short to be observable in a fragmentation-type experiment. Previous calculations,[12] using a set of realistic residual interactions,[20] predicted this state to be excited 300 keV above the $\nu = 2$ $J^\pi = 6^+$ in ^{72}Ni, thus making it energetically unavailable for the isomeric decay. In Listestkiy's calculations, there is a link between the disappearance of isomerism and the 2^+ excitation energy. The new shell-model calculations,[18] which explain the isomer non-observation, also predict correctly lower than expected position of the 2^+ states, compared for instance with S3V estimates. These systematics of the 2^+ levels have been determined experimentally for the even-even nickel isotopes from ^{70}Ni to ^{76}Ni. In calculations by Lisetskiy,[18] the particularly low diagonal $(\nu g_{9/2})^2$ two-body matrix element (TBME) seems to be responsible for this effect. This TBME causes the lowering of the energy of the 2^+ levels and introduces a significant amount of configuration mixing with the fp-shell neutrons. Such a TBME renormalization was necessary only for neutron states. This apparent modification of residual interactions is most likely due to a too small model space, most likely $f_{7/2}$ proton excitations, which in this case implies ^{56}Ni core breaking.

Although the recent experiments have been successful in their findings, they do not give a definite confirmation of theory predictions[18,19] yet, because the $\nu = 4$ states have not been identified unambiguously. In this contribution we will present the possible candidate for a transition, which could be one of the unobserved 4^+ states which is conspicuously close in energy to the one predicted by theory.

To verify experimentally the validity of the new SM, additional observables can be exploited: the transition probabilities. According to the SM calculations, the transitions between seniority $\nu = 4$ and $\nu = 2$ states will be enhanced, while transitions between states of the same seniority will be retarded relative to the Weisskopf lifetime estimates: These variations in B(E2) values may offer a possibility to test experimentally the predictions of the theory.

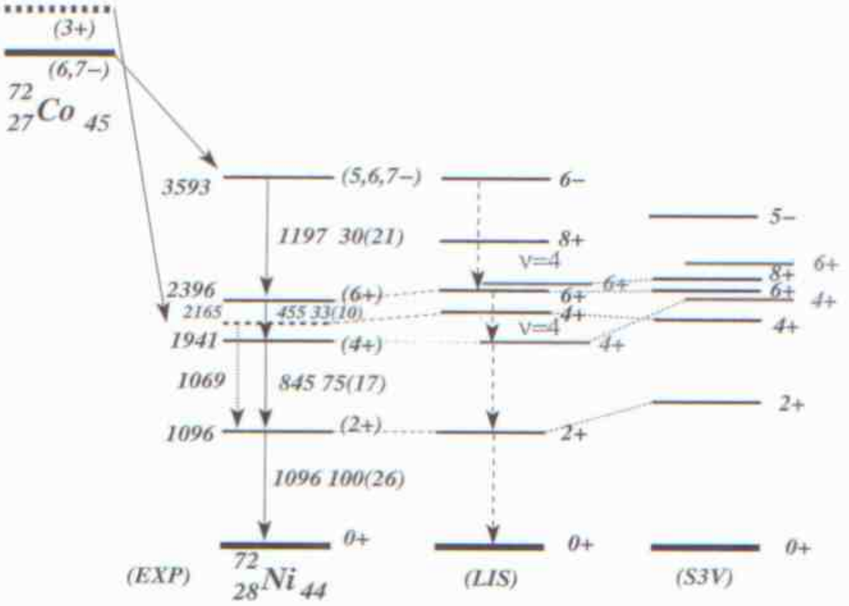

Fig. 1. The decay scheme of ^{72}Co populating excited levels in ^{72}Ni[12] (EXP). The theoretical predictions for lowest excited states of ^{72}Ni (LIS)[18] and (S3V).[12] Seniority ν=4 states are shifted to the right.

It should be easy to determine the dominant seniority of the state experimentally as the estimated lifetimes are measurable for example with the delayed gamma(beta)-gamma coincidence technique.[21] Beta decays of ^{72}Co, which is produced in sufficient quantities in present day fragmentation facilities, can be used to verify the above hypothesis for ^{72}Ni. As observed for the decay of ^{70}Co by Mueller at al.[11] the odd-odd cobalt isotopes will exhibit two close-lying states, with the following proton-neutron configurations $J^\pi = (6,7)^- \; \nu g_{9/2} \, \pi f^{-1}_{7/1}$ and $J^\pi = (3)^+ \; \nu p_{1/2} \, \pi f^{-1}_{7/1}$. The decay of the negative parity, high spin states will populate in the subsequent cascade, one of the $J^\pi = 6^+$ states in ^{72}Ni, thus enabling the study of its properties.

Transition probabilities are observables which will enable us to distinguish the nature of states with dominating ν=4 and ν=2 seniority. For example the $\Delta\nu$=2 transition between $J^{\pi}_{\nu} = 6^{+}_{2}$ and $J^{\pi}_{\nu} = 4^{+}_{4}$ is predicted with B(E2)$\approx$29 $e^2 fm^4$, compared with a B(E2)$\approx$3.8 $e^2 fm^4$ for the $J^{\pi}_{\nu} = 6^{+}_{2}$ and $J^{\pi}_{\nu} = 4^{+}_{2}$ $\Delta\nu$=0 transition (1 W.u. = 17.8 $e^2 fm^4$).

If there are indeed low lying $\nu = 4$ states the model predicts the following strong cascade $6^{+}_{\nu=2} \rightarrow 4^{+}_{\nu=4} \rightarrow 2^{+}_{\nu=2} \rightarrow 0^{+}_{\nu=0}$ cascade. All transitions will have strong B(E2) values and the measured lifetimes will be short.

If there are no low lying 4^{+} $\nu = 4$ states, the B(E2) will be small and the measured lifetimes will be long because the de-excitation will have to occur via $\Delta\nu = 0$ transitions. The difference between observed lifetimes will be large ($\sim 200ps$ vs $\sim$ 700 ps) and will show as a very clear signature to distinguish between the two scenarios.

Another interesting possibility could arise from the observation of the decay of the $J^{\pi} = 3^{+}$ state in ^{72}Co. In this case it is most likely that the $J^{\pi}_{\nu} = 4^{+}_{\nu=2}$ state would be populated via the Gamow-Teller transition and this could reveal information about the predicted alternate cascade. In a recent experiment performed at the NSCL[22] we have accumulated much higher statistics data on the decay of $^{71-74}$Co isotopes than in previous measurements. This allowed us to have a more thorough look at the cascades populated in ^{72}Ni, through beta-gamma-gamma coincidences. Interestingly we have identified a gamma ray with energy of 1069 keV which is in coincidence with a 1096 keV gamma-ray, attributed to the $2^{+} \rightarrow 0^{+}$ transition. Despite the higher detection efficiency for other low energy gamma-rays, we could not identify any other coincidence, hence we place the 1069 keV gamma-ray at 2165 keV in a separate cascade with the 1096 keV ground state transition. This state is very close in energy (E=2276) to the $J^{\pi}_{\nu} = 4^{+}_{\nu=4}$ state expected from Lisetskiy's calculations.

At this moment it appears, that the only chance to directly observe the 8^{+} isomers in ^{72}Ni and ^{74}Ni is thorough the use of Deep Inelastic Collisions (DIC) in conjunction with in-beam type techniques because of their lifetimes in the nanosecond range. In DIC experiments the reaction may populate states with higher spin than those populated in beta-decay studies. This method has been used successfully with stable beams of the most neutron-rich isotopes on neutron-rich targets,[6,7,23] but it seem to be reaching its limits due to the rapidly decreasing production cross-sections. Radioactive beams of accelerated ^{238}U fission products offer a way to investigate the structure of isotopes near ^{78}Ni. Such studies have been proposed to be performed at HRIBF.[5] The proposed new generation experiments with RIBs will add to the somewhat sketchy knowledge on the nuclear structure near ^{78}Ni obtained from beta-decay and microsecond-isomer studies. Study of yrast states in neutron-rich Copper ($Z = 28 + 1$) isotopes populated in the DIC will be a central focus of these initial studies. In the first *proof of principle* experiments we will use the technique of *isomer-scope* similar to that used by Ishii *et al.*[24] in a series of very successful measurements[7,25] using DIC with combinations of stable neutron-rich beams and targets. This method is very sensitive to isomers with lifetimes ranging from one to hundreds of nanoseconds. We intend to use this technique with RIBs in order to gain information about the neutron-rich isotopes through the discovery of new nanosecond isomers. We plan to examine $^{73-76}$Cu isotopes for nanosecond isomers. The yrast configurations with $(\nu g_{9/2})\ \ ^{2}$ component in ^{73}Cu and ^{75}Cu could be isomeric, however the lifetimes will be short, for reasons similar to those outlined in Ref.[18] for ^{72}Ni and ^{74}Ni, but also because the coupling with $p_{3/2}$ or $f_{5/2}$ protons will make the level scheme richer and add new decay channels. From fragmentation experiments we know that these configurations are most likely short lived ($t_{1/2} < 100$ ns). Radioactive ion beams of A=78,80 gallium and germanium isotopes are foreseen to perform these studies. In the longer term future after all experimental conditions are recognized it may be possible to directly investigate the nickel isotopes.

3. Beta-delayed neutron spectroscopy

Beta-decay studies provide a sensitive and selective means for investigating neutron-rich nuclei, allowing one to probe for a deeper understanding of the underlying nuclear structure in this region while attempting to verify a multitude of theoretical models. Even in a strictly astrophysical sense, a better understanding of the beta decay strength function is needed not only in order to properly describe nuclear lifetimes for the r-process nuclei, but also to model more exotic electron-capture or neutrino-induced nucleosynthesis scenarios.[26] However, a detailed determination of the beta-decay strength is a daunting task both experimentally and theoretically. For the nuclei closer to stability, total absorption gamma-ray spectoscopy should be employed to determine the strength of the transitions below the neutron separation energy in the daughter nucleus. In more exotic nuclei the $Q_\beta - S_n$ becomes wide open and neutron emission will become strong if not dominating channel.

So far, for the heavy neutron-rich nuclei, the focus was on measurement of the neutron emission branching ratios.[27] With current and future advances in detector technology and access to more intense beams of rare isotopes it is time to revisit these important measurements. Far from stability the increasing decay Q_β values causes a larger portion of the strength to become experimentally available. In consequence, the family of states populated in a decay daughter nucleus increases and those above the neutron and two-neutron separation energy become involved, giving rise to the emission of beta-delayed neutrons. This delayed neutron emission becomes ever more important because of the consecutive decrease of neutron separation energy which could be as low as 1-2 MeV .

The decay of very neutron rich cobalt isotopes have been investigated for beta-delayed neutron emission by Hosmer at al.[28] using a ^{3}He neutron detector and by our group[29] employing information from beta-neutron delayed gamma-ray studies. The latter technique gives the lower limit for the branching ratio. The numbers obtained for decay of cobalt isotopes are rather crude but remarkably consistent with each other. The large branching ratio for b_n in the case of ^{74}Co decay is unexpected, both measurements give the result to be about 30 % while the QRPA calculation gives $b_n \sim 10\%$ consistent with the results for neighboring isotopes. The decay of cobalt isotopes is dominated by the allowed Gamow-Teller transformation of the $f_{7/2}$ neutron into $f_{5/2}$ proton, hence decays to the neutron bound states should dominate, because the $f_{5/2}$ state is readily available. One possible explanation could be the proton core breaking resulting in partial proton occupation of the $f_{5/2}$. This would block the high-energy Gamow-Teller transitions, shifting the strength to states above neutron separation energy, or more probably, what is observed is a decay from the isomeric state and spin selection rules push the Gamow-Teller strength above the neutron separation energy in ^{74}Ni.

Ultimately, in order to clearly understand the role of nuclear structure in beta-delayed neutron emission, it is necessary to measure the energy distribution of the emitted neutrons, which determines the branching ratios and can be more directly compared to theoretical predictions. Such studies are possible with detectors capable of measuring neutron energy via time of flight, like those used to study beta delayed neutron emission in light nuclei.[30–32] The required improvements of detection efficiency and energy detection threshold has to be met.

In summary, the view on the near future of decay studies has been outlined aiming at more thorough studies of the structure of neutron-rich nickel isotopes. These are studies which could be performed soon with present day facilities. The next step, to move beyond ^{78}Ni will require radical improvements in beam intensities.

Acknowledgment

This work was supported under US DOE grants DE-AC05-00OR22725 and inpartby the NNSA through DOE Cooperative Agreement DE-FC03-03NA00143.

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