論文の内容の要旨

Collapse of the N=28 shell closure: single-particle structure of ^{43}S
(中性子数 28 における閉殻の消失: ^{43}S の単一粒子構造)

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Thanks to the improvement of techniques to produce the unstable nuclei far from the valley of stability, the erosion of the magic numbers proposed around the stability line and emergence of new ones in the atomic nuclei have been observed. The magic number 28 is the first magic number made by the strong spin-orbit interaction. For the neutron side, this is well established around the doubly magic nuclei ^{48}Ca. South of this nuclei, however, the erosion of this magic number has been discussed through the decreasing excitation energy of the first 2^+ state and the increasing $E2$ transition matrix element between the first 2^+ state and the ground state, $B(E2; 2^+ \rightarrow 0^+)$, in the even-even nuclei on the $N = 28$ isotone line. These experimental results implies the quenching of the $N = 28$ shell gap. In the shell model framework the reduction of the $N = 28$ shell gap is explained by the tensor force whose effect becomes large in the region with the exotic N/Z ratio. The quenching of this shell gap can then trigger the quadrupole correlation between $\nu f_{7/2}$-$\nu p_{3/2}$ and $\pi d_{3/2}$-$\pi s_{1/2}$ orbits around ^{44}S region, resulting in the deformation of these nuclei. Especially about ^{44}S and ^{43}S, not only the deformation of the ground state but also the coexistence of the different shapes and the mixing/coexistence of the different neutron configurations in the wave function have been discussed both experimentally and theoretically.

Though there are many structural studies about the deformation of ^{44}S or ^{43}S, the mechanism of the structural change between the doubly-magic ^{48}Ca and these sulfur isotopes has been still unclear. To reveal the quenching of the $N = 28$ shell gap and its importance on the structure and deformation of these nuclei, an in-beam γ-ray spectroscopy of one-neutron knockout reaction from ^{44}S to ^{43}S was

performed. This reaction can selectively populate neutron single-hole states. Their excitation energies and production cross sections reflect the shell evolution of the neutron single-particle orbits.

One of the specific problems on ^{43}S is its low-lying isomeric state at 320 keV with 415 ns half-life. Because of this state, it is difficult to distinguish if the observed prompt γ-rays emitted from the excited states of ^{43}S correspond to the de-excitation onto the ground state or onto this isomeric state. To solve this problem, an additional γ-ray detector was placed at the very end of the beam line to measure the γ-ray from the isomeric state.

The experiment was performed at the Coupled Cyclotron Facility at the National Superconducting Cyclotron Facility at Michigan State University. A secondary beam of ^{44}S was produced by the fragmentation reaction of a ^{48}Ca primary beam by utilizing the cyclotron complex of K500 and K1200 and separated by the A1900 fragment separator. The reaction of interest was taken place at the ^{9}Be reaction target at the pivot position of the S800 spectrograph. The magnetic rigidity of the S800 was centered on the one-neutron knockout residue. In some runs, unreacted beam particles were centered for the calibration of the intensity and the purity of the incoming beam and for the deduction of the resolution of momentum measurement. De-excitation γ-rays were observed by a combination of the GRETINA array of high-purity germanium detectors, surrounding the reaction target, and the IsoTagger array of CsI(Na) detectors, placed at the end of the S800. The delayed coincidence between the GRETINA and the IsoTagger makes it possible to distinguish which prompt γ-rays decay onto the isomeric state. At the S800 spectrometer, the particle identification of the reaction residue was performed by the measurement of the time-of-flight and the energy deposition in the ionization chamber. Its momentum was also reconstructed by the measurement of the particle trajectory at the end of the S800.

Thanks to the high energy resolution and the high detection efficiency of the GRETINA, not only the previously reported γ-rays but also the new ones were measured with high statistics. This made it possible to performe the γ-γ coincidence analysis within the GRETINA array. Especially, the γ-ray decay scheme and the band structure of the excited states of ^{43}S was analyzed in detail by utilizing the simulated response function of the GRETINA, whose accuracy was confirmed by comparing the efficiency of the response function with those experimentally measured by the standard radiation sources. With the delayed coincidence information with the IsoTagger mentioned above, the full level scheme of the ^{43}S was constructed below the neutron threshold of ^{43}S around 2.6 MeV. Especially, the coincidence of an excited state decaying to the isomeric state at 320 keV was observed for the first time. By analyzing the parallel momentum distribution of ^{43}S produced by one-neutron knockout reaction and comparing it with the eikonal reaction calculation, the assignment of the spin-parity to each final state was also attempted. One of the interesting result worth noting is that there was an excited state best explained by the neutron knockout from $l = 2$ orbit. Considering all the analysis mentioned above, the level scheme of ^{43}S and the cross section of each state were successfully deduced.

To discuss the structure of the ^{44}S and ^{43}S in more detail, some theoretical calculations were performed. For the reaction side, the eikonal reaction calculation mentioned above was done to calculate the momentum distribution and the single-particle knockout cross section for the deduction of the spectroscopic factors experimentally. For the structure side, the shell model calculations with SDPF-U and SDPF-MU effective interactions were performed. By comparing the experimentally deduced level scheme and the cross sections with those calculated by the shell model, the band structure of ^{43}S was discussed. Theoretically the ground state of ^{43}S is predicted as prolate deformed state and the rotational band with specific order of spins as $3/2^- \rightarrow 1/2^- \rightarrow 7/2^- \rightarrow 5/2^-$ is suggested. In the present experiment, it was difficult to populate such kind of collective state via one-neutron knockout reaction but the tentative assignment of the rotational members by comparing the excitation energies was attempted. Besides the rotational band on the ground state and the state on the isomeric state, there was a candidate of the third band above 1.1 MeV.

After constructing the level scheme of ^{43}S, the spectroscopic factor of each state in this reaction was compared with one in the shell model calculations. One of the major difference between them is that there was a concentration of the strength of neutron knockout from $l = 1$ orbit around 1.2 MeV in the experimental data. Considering these experimentally deduced spectroscopic factors were normalized by the center-of-mass factor and the empirical reduction factor of the knockout reaction, they can be naively compared to the occupation number of the neutron single-particle orbits in the ground state of ^{44}S. As the sum of the spectroscopic factors of neutron knockout from $l = 1$ orbit amounts to about 1.6, this result can be interpreted as about 1.6 neutrons occupy the $p_{3/2}$ or $p_{1/2}$ orbits in the ground state of ^{44}S. This is the direct observation of the quenching of the $N = 28$ shell gap microscopically. Another interesting result is that the experimental strength of neutron knockout from $l = 3$ orbit above 2 MeV was smaller than that of corresponding state in the shell model calculations. This can be interpreted that a part of the strength of neutron knockout from the $f_{7/2}$ orbit can be fragmented above the neutron threshold of ^{43}S. This would be supported by the shell model calculations predicting that the wave functions of a few $7/2^-$ states in the higher excitation energies have the large component of both the neutron $1p1h$ and $2p2h$ configurations beyond the $N = 28$ shell gap. Such kind of competition of the wave function components and the small structural change could result in the drastic change of the cross sections producing corresponding states. Finally, the energy centroids of the $7/2^-$ and $3/2^-$ states weighted by the experimentally deduced spectroscopic factors were systematically analyzed with the experimental data of one-neutron knockout experiments of $^{46}\mathrm{Ar}\rightarrow^{45}\mathrm{Ar}$ and $^{48}\mathrm{Ca}\rightarrow^{47}\mathrm{Ca}$ channels. Though such kind of analysis works properly only when the full strength of the neutron knockout are observed in the bound states, the systematics of the experimental data would be interpreted as the rapid decrease of the $\nu p_{3/2}$-$f_{7/2}$ spacing.

Experimentally, the obvious next steps in this investigation would be the search of excited states predicted in the theoretical work but not observed in this work. For this purpose, not only taking a benefit of high statistics, but also utilizing the different reaction probes could be powerful methods. For example, the (p, p') reaction can excite both the single-particle and the collective states simultaneously. By this thesis work, a large part of the structure of ^{43}S was revealed. In this stage, such kind of reaction producing all kinds of states can be useful to search the missing transitions in this work. Other than the ground state band, a band above the 1155 keV state can be the candidate of the third band predicted in shell model and AMD calculations. Because these calculations predict controversial deformation of this band, experimental measurement of the deformation parameters of this band is one of the fascinating subject. Though such kind of measurement should be tough and quite high statistics must be necessary, one of the possible tool could be the sub-barrier Coulomb excitation experiment, which can be sensitive to the sign of the quadrupole moment of each state. When we can achieve very neutron-rich phosphor isotopes with $N \geq 29$, another interesting experiment could be the observation of β and β-n decays, which would give us the opportunity to distinguish the unnatural parity state by comparing the observed decay scheme in these two channels. This information would shed light to the change of occupation in the neutron *sd* shell.