Isobaric Spin and Dipole States in Nuclei

It has been known for a long time that the charge independence of nuclear forces leads to conservation of isobaric (isotopic) spin in nuclei. Energy levels of light nuclei may be labelled by isobaric spin quantum numbers and many nuclear properties depend only on these quantum numbers and are independent of the detailed structure of the states involved. The Coulomb force begins to play a dominant role in nuclei beyond calcium and heavy nuclei all have a large neutron excess. Before 1961 it had been assumed that Coulomb effects would destroy the symmetries resulting from charge independence and that isobaric spin would not be a useful concept in heavy nuclei. In an earlier contribution to "Comments" Feshbach and Kerman[1] have discussed how the discovery of isobaric analogue states changed this view. It seems now that the effects of charge independence persist even in heavy nuclei. We discuss the consequences for collective dipole states in nuclei.

The "dipole state" can be observed as a resonance in γ-ray absorption experiments and in γ–p and γ–n reactions. It seems to exist in all nuclei throughout the periodic table. In 1948 Goldhaber and Teller[2] suggested that the dipole state could result from a collective mode of oscillation in a nucleus in which the neutron and proton clouds vibrated against one another. Such a vibration would have a large electric-dipole matrix element with the nuclear ground state. The Goldhaber–Teller collective mode can be described in the shell model as a coherent superposition of single particle excitations. The particle–hole interaction tends to combine the single particle excitations so as to produce a dipole state at a high excitation energy.[3] This state carries a large fraction of the electric-dipole transition strength from the ground state.

The ground state of a self-conjugate nucleus like O^{16} has isobaric spin $T = 0$. A $T = 0$ to $T = 0$ electric-dipole transition is forbidden by isobaric-spin selection rules and the dipole state of such a nucleus is an eigenstate of isobaric spin with $T = 1$. The ground state of a heavier nucleus with a neutron excess will have isobaric spin equal to half the neutron excess, $T_0 = \frac{1}{2}(N - Z)$. Absorption of γ-rays in an electric-dipole transition can lead to excited states with isobaric spin T_0 and $T_0 + 1$. Several authors[4] have pointed out that a single particle–hole state is not an eigenstate of isobaric spin in a nucleus with a neutron excess. The residual particle–hole interaction produces a coupling between one-particle–one-hole states and two-particle–two-hole states, and this interaction splits the particle–hole state into two isobaric-spin components. The higher component has isobaric spin $T_0 + 1$ and is an analogue state, while the lower component has $T = T_0$ and is a modified version of the original particle–hole state. The energy difference between the two states is related to the nuclear symmetry energy. Thus in a heavy nucleus there should be two dipole states separated by an energy about 7 MeV.

The two components of the dipole state in a heavy nucleus do not have equal electric-dipole transition matrix elements to the ground state. Simple considerations suggest that the $T = T_0$ state should carry most of the strength and that the ratio of the transition strengths from the ground state should be

$$G(T_0 + 1)/G(T_0) \cong 2/(N - Z).$$

More accurate estimates give an even smaller value for $G(T_0 + 1)$. It is therefore unlikely that the two components of the dipole state could be observed in very heavy nuclei. It is best to look in a region of the periodic table where $N > Z$ but not too much greater. There is some experimental evidence[5] for the existence of the two components in Zr^{90} as a result of studies of p–γ reactions.

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