ENERGY SYSTEMATICS OF THE GIANT GAMOW-TELLER RESONANCE AND A CHARGE-EXCHANGE DIPOLE SPIN-FLIP RESONANCE

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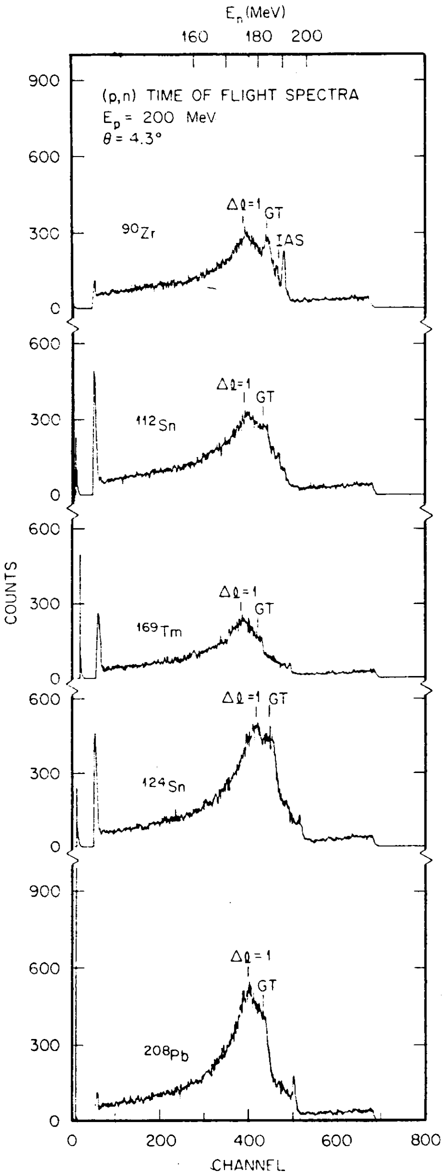
In a series of papers$^{1-5)}$ in the early 1960's, Fujita, Ikeda and Fujii explored the description of isobaric analogue states (IAS) in terms of proton particle-neutron hole pairs ($p\bar{n}$) and subsequently hypothesized the existence of a collective giant Gamow-Teller (GT) resonance to explain the hindrance of GT transitions in beta decay. These workers$^{2-4)}$ also pointed out the probable existence of additional collective resonances of the type $\Delta\ell>0$ and $\Delta S=1$. Bohr and Mottelson$^{6)}$ have discussed the general features of collective modes of excitation involving spin degrees of freedom. The first experimental observation of a giant resonance for N > Z nuclei was reported by Doering et al.$^{7)}$ from a study of the (p,n) reaction using incident energies of 25 to 45 MeV. In this work we report energy systematics for the giant GT resonance as well as a new resonance excited via a L=1, S=1 interaction.

Calculations have shown$^{8,9)}$ that the strength of the central spin-isospin component relative to the central isospin component increases by more than a factor of two with increasing proton energy between E_p=100 and 200 MeV. From measurements of zero-degree cross sections at 120 MeV,$^{10)}$ values have been deduced for the volume integrals of the central isospin and central spin-isospin potentials which agree within about 20% with the theoretical$^{9)}$ calculations. L=1 resonances have been observed in ^{90}Zr(p,n)^{90}Nb at E_p=120 MeV$^{11)}$ and in ^{208}Pb(p,n)^{208}Bi at E_p=120 and 160 MeV. The cross section of the L=1 resonance at the first maximum was found to be comparable to that of the giant GT resonance at 0° and behaved similarly as a function of proton energy. Since the GT resonance is excited via the spin-isospin component of the effective interaction, it was argued$^{11)}$ that excitation of the L=1 resonance also involves S=1. This then implies that the L=1 resonance is of a charge-exchange dipole mode with spin flip and, hence, could have $J^{\pi} = 0^-$, 1^- or 2^-.

We have used the beam-swinger facility$^{13)}$ at IUCF, protons with incident energies of 120, 160, and 200 MeV, and neutron flight paths of 60-70m to study the energetics of the GT and L=1 resonances for a number of targets with A > 90. For some targets, angular distributions were measured in 2.5° intervals out to about 15°, while for others 5° intervals were used. Targets studied included ^{90,92,94}Zr, ^{112,116,124}Sn, ^{169}Tm, and ^{208}Pb. The targets were in the form of self-supporting metallic foils with thicknesses between 40-180 mg/cm^2. Neutron time-of-flight spectra for θ = 4.5°, i.e., near a maximum[11,12] in the differential cross section for $\Delta\ell$=1, are shown in Fig. 1. The results of detailed analyses of these data will be given elsewhere. Here, we focus attention on the energy systematics of the GT and L=1 resonances.



In Fig. 2 we have plotted versus (N-Z)/A the energy differences between the giant GT and L=1 resonances, respectively, and the IAS. The energies of the IAS and GT resonances have been determined from 0° spectra, and those for the L=1 resonance from preliminary analyses of the 4.5° spectra. The uncertainties for $E_{GT}-E_{IAS}$ are less than 0.4 MeV, and those for $E_{\Delta\ell=1}-E_{IAS}$ are estimated to be <1 MeV. As can be seen from the figure, to first order both energy differences can be represented by linear functions of (N-Z)/A which have about the same slope. From Fig. 2, we find the energy differences in MeV

$$E_{GT} - E_{IAS} = -30.00(N-Z)/A + 6.7 \qquad (1a)$$

and

$$E_{\Delta\ell=1} - E_{IAS} = -33.0(N-Z)/A + 13.6 \qquad (1b)$$

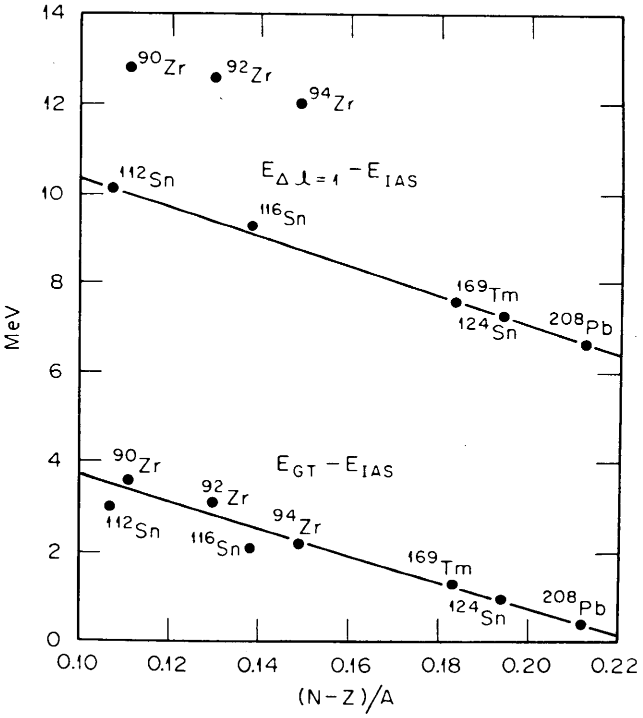


Figure 1. Time-of-flight spectra at 4.3° for the (p,n) reaction at E_p = 200 MeV for targets of ^{90}Zr, ^{112}Sn, ^{169}Tm, ^{124}Sn, and ^{208}Pb.

Figure 2. Plots of ($E_{GT}-E_{IAS}$) and ($E_{\Delta\ell=1}-E_{IAS}$) versus (N-Z)/A.

The GT-type excitations with L=0, S=1 involve mainly $p\bar{n}$ excitations in which there is no change of radial wavefunctions, i.e., excitations within the same oscillator shell. The energies of these would lie close to those for the IAS except that an important contribution to the GT comes from transitions of the type $(j=\ell+1/2) \rightarrow (j=\ell-1/2)$. Consequently, the GT energy is shifted up relative to the IAS by an amount typical of this spin-orbit splitting. This accounts for the constant term in equation (1a). Now the residual p-n interactions introduce a further shift which Fujita et al.3) estimated to be about $-30(N-Z)/A$, in good agreement with what is observed. Gapanov and Lyutostanskii14) have made microscopic calculations of the excitation energies and strengths of the IAS and GT resonances for a number of nuclei from arsenic to lanthanum. Their predicted energy differences, $E_{GT}-E_{IAS}$, for ^{116}Sn and ^{124}Sn are in excellent agreement with our data (i.e., within 0.3 MeV); however, those for ^{90,92,94}Zr fall on a parallel line about 2 MeV higher than our measured values.14) The calculated energies14) for the IAS resonances for both the Zr and Sn isotopes agree within a few tenths of an MeV with observed values. Hence, the discrepancy between the calculated values of E_{GT}.

A striking feature in Fig. 2 is that the values of $E_{\Delta\ell=1}-E_{IAS}$ for the Zr isotopes lie about 3 MeV above the curve formed by the other elements. Since at present there are no detailed calculations of a L=1, S=1 resonance available for the Zr isotopes, one can only speculate as to the reasons for this. One might be that the distribution of strength among the J-components for the Zr isotopes differs from that for the other elements. Or, possibly, the effective energy for shell crossing in Zr is greater. (This might not be unreasonable from shell-model considerations).

In this work we have presented phenomenological systematics of the GT and a giant L=1 resonance (both of which involve spin flip) for the medium to heavy mass region. Some agreement with calculations using finite Fermi systems has been found. However, much additional investigation remains before detailed comparisons can be made.

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GENERAL FEATURES OF THE GAMOW-TELLER RESONANCES

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A striking feature of the (p,n) reaction in the IUCF energy range is that the 0° neutron spectra are so strongly dominated by Gamow-Teller (GT) transitions that these spectra provide an instant snapshot of GT strength distributions. This feature of the (p,n) reaction is understood1) on the grounds that at 0°, where there is no transverse momentum transfer and the longitudinal momentum transfer is small, most terms in the projectile-nucleus interaction do not contribute, and the only important terms are $V_\tau(\tau_p \cdot \tau_i)$ and $V_{\sigma\tau}(\sigma_p \cdot \sigma_i)(\tau_p \cdot \tau_i)$, where σ and τ are spin and isospin operators, the subscript p refers to the projectile proton and the subscript i refers to the ith nucleon in the nucleus. A summation over nucleons is implied. The (p,n) results also show that V_τ is much smaller than $V_{\sigma\tau}$ for E_p ~200 MeV.

In interpreting the data on GT strength distributions it is useful to think in terms of how a nucleus with a neutron excess responds to the transformation of a neutron to a proton. This is easily representable in an independent-particle model. Each nuclear state is represented as an occupancy pattern of a set of single-particle states appropriate to the specific model. The neutrons, of course, are indistinguishable from each other, so that the transformation of a neutron into a proton implies a summation over all neutrons. The relevant operator is $\tau_p^+ \tau_i^-(\sigma_p \cdot \sigma_i)$. The result of operating on the target ground state yields a fictitious state that we may call the collective Gamow-Teller (CGT) state. The Gamow-