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High Spin Spectroscopy Near The N=Z Line: Channel Selection and Excitation Energy Systematics

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The total γ-ray and charged-particle energies emitted in fusion-evaporation reactions leading to N=Z compound systems in the A = 50-70 mass region have been measured with the 8π γ-ray spectrometer and the miniball charged-particle detector array. A new method of channel selection has been developed which combines particle identification with these total energy measurements and greatly improves upon the selectivity possible with particle detection alone. In addition, the measurement of total γ-ray energies has allowed a determination of excitation energies following particle evaporation for a large number of channels in several reactions. The new channel selection procedure and excitation energy systematics are illustrated with data from the reaction of ^{24}Mg on ^{40}Ca at $E_{lab} = 80 MeV$.

1. Introduction

One of the major problems plaguing the high spin γ-ray spectroscopy of light ($A < 100$) proton-rich nuclei produced in fusion-evaporation reactions is the fragmentation of the total cross section into a large number of exit channels. A low Coulomb barrier in these systems, combined with strong pressures for decay towards stability, cause proton and alpha emission to dominate over neutron evaporation and the population of 10-20 nuclear species in a single reaction is common. In principle, the spectroscopic difficulties resulting from a large number of open exit channels can be solved by detecting the charged evaporation particles in coincidence with the γ rays [1–5]. In practice, however, channel selection by charged-particle detection is limited by the efficiency of the particle detection system. Even with near 4π coverage by the particle detector array, some fraction of the charged evaporation particles inevitably escape detection. The result is that low particle multiplicity gated spectra are contaminated by events from higher particle multiplicity channels. For example, a γ-spectrum in coincidence with the detection of 3 protons will contain not only real 3p events, but also 4p, α3p and 3pn events where the extra particle was not detected. If a low particle multiplicity channel of interest is populated very weakly in a reaction, while higher particle multiplicity channels have much larger cross-sections, the high particle multiplicity contaminants can completely dominate the low particle multiplicity gated spectra. In this situation, the channel selection provided by charged-particle gating is not sufficient to permit an accurate spectroscopic study of the low particle multiplicity channel.

2. Channel Selection Method

A detailed description of the new channel selection procedure has been given in [6]. Here we present a brief summary of the method. In order to discriminate between events from different channels for which the same charged particles are *detected*, we consider the different total energies available in the center of mass system for different exit channels:

$$E_{CM} = T_{CM} + Q \tag{1}$$

where T_{CM} is the kinetic energy of the collision in the center of mass system (the same for all channels) and Q is the Q-value for the specific reaction channel.

This total CM energy is emitted as γ-ray energy and particle kinetic energy:

$$E_{CM} = H_\gamma + T_{part} \tag{2}$$

where H_γ is the total γ-ray energy and T_{part} is the sum of the proton, alpha, and nuclear recoil kinetic energies in the CM system.

The BGO ball of the 8π spectrometer acts as an efficient γ-ray calorimeter to measure H_γ for each fusion reaction, and the miniball [1] charged-particle detector array gives T_{part} on an event by event basis. The position of each event can thus be plotted in a Total Energy Plane (TEP) where H_γ is the x coordinate and T_{part} is the y coordinate of the event. If we ignore loss of beam energy in the target for the moment, E_{CM} is a constant for a given channel and thus equation (2) constrains all events from this channel to lie on a line of constant energy in the TEP (ie. a line with slope negative one and x and y intercepts equal to E_{CM}).

For channel selection purposes, we are concerned with events in which one or more particles escape detection. Consider a 3-proton particle gated data set. As noted above, the real 3p events in this data must all lie on a line of constant energy in the TEP. Now, consider a 4p event that appears in the 3p-gated data because one of the protons was missed. Firstly, the Q-value for the 4p channel is less than for the 3p channel by the binding energy of the fourth proton and thus there is less total CM energy available in the 4p channel. Secondly, the kinetic energy of the missed proton is absent from the sum in equation (2). These two effects add constructively and permit discrimination between 4p events in which a proton is missed and real 3p events. Similar arguments apply for the α3p and 3pn events in the 3p-gated data. Given a 3p-gated TEP plot like that shown in Fig. 1, the channel selection achieved by charged-particle gating alone can be greatly improved by setting a two-dimensional gate in the TEP around the 3p line and taking the real 3p events inside this gate, while eliminating the background from the higher particle multiplicity channels that appear in the data set because particles were missed.

3. Channel Selection Results

In order to illustrate the effectiveness of the Total Energy Plane method of channel selection, we present here results from an experiment at TASCC in which a beam of ^{24}Mg at $E_{lab} = 80MeV$ was directed onto a self-supporting $\sim 460\mu g/cm^2$ target of ^{40}Ca enriched to 99.8% purity. In Fig. 2 a) we show a portion of the γ-spectrum in coincidence with the detection of 3 protons. Due to the imperfect particle detection efficiencies (the proton and alpha detection efficiencies in this experiment were $\epsilon_p = 0.56$ and $\epsilon_\alpha = 0.42$ respectively) strong peaks appear in this spectrum from all of the 3p, 4p, α3p, and 3pn exit channels. The channel selection achieved with particle coincidence gating can be improved significantly, however, using the Total Energy Plane method. In Fig. 1 we show a shading contour plot in the TEP for all events in which 3 protons were detected. The real 3p events have considerably larger total detected energy and are cleanly separated from the contaminating 4p, α3p, and 3pn events. As noted in Section 2, channel selection is achieved by taking a two-dimensional gate in the TEP that includes the majority of the events from the desired channel but little contamination from the higher particle multiplicity channels. In Fig. 2 b) we show a γ-spectrum produced by taking a gate in the 3-proton TEP around the real 3p events. All of the strong peaks in this spectrum are now from the real 3p channel (^{61}Cu). While 90% of the real 3p events pass the TEP gate, only 14% of the 4p events survive, and both the α3p and 3pn contaminants are almost completely eliminated - less than 4% of these events pass the TEP gate. While real 3p events constitute only 53% of the 3-proton gated spectrum (Fig 2a), the TEP gated spectrum (Fig. 2b) is 95% pure 3p channel.

In the above, the 3-proton gated data, in which the desired channel, 3p, as well as the contaminating channels (4p, α3p, and 3pn) were all strongly populated, has been used to illustrate clearly the effectiveness of the TEP method of channel selection. The real power of this method, however, lies in the isolation of very weakly populated low particle multiplicity channels - the channels which leave the nucleus with the highest spin and excitation energy. For example, in our reaction of ^{24}Mg on ^{40}Ca at $E_{lab} = 80MeV$ the nucleus observed with the most excitation energy was ^{62}Zn. This nucleus, populated via the 2p exit channel, constituted only $\sim 0.3\%$ of the total reaction cross section. In Fig. 4a) we show the γ-spectrum in coincidence with the detection of 2 protons. Due to the very weak population of the 2p channel and the imperfect particle detection efficiencies, this spectrum is completely dominated by contamination from much more strongly populated higher particle multiplicity channels (4p, α3p, α2pn, 2α2p, 3pn, 3p, α2p, and 2pn). Of the transitions in ^{62}Zn only the $2^+ \rightarrow 0^+$ at 954 keV is visible in the 2p-gated spectrum, and this peak is an order of magnitude smaller than those from the contaminating channels.

In Fig. 3 we show the Total Energy Plane for all events in which 2 protons were detected. Although the 2p channel is sufficiently weak compared to the contaminating channels that it does not show up as a peak in this plot, the calculated line of constant energy for the 2p channel focuses our attention on the high energy "bulge" in this TEP that is produced by the real 2p events. Taking the gate shown in Fig. 3 around this bulge we obtain a γ-spectrum dominated by real 2p events. Using the higher particle multiplicity gated spectra to subtract the remaining small contaminating peaks we obtain the γ-spectrum shown in Fig 4 b).

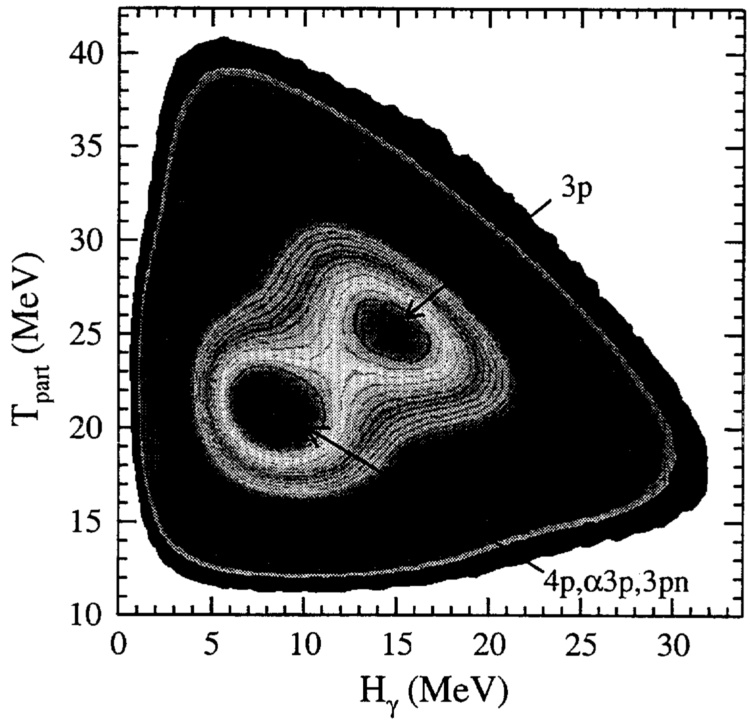

Fig. 1. Total Energy Plane contour plot for all events in which 3 protons were detected. The real 3p events are cleanly separated from the contaminating four-particle channels.

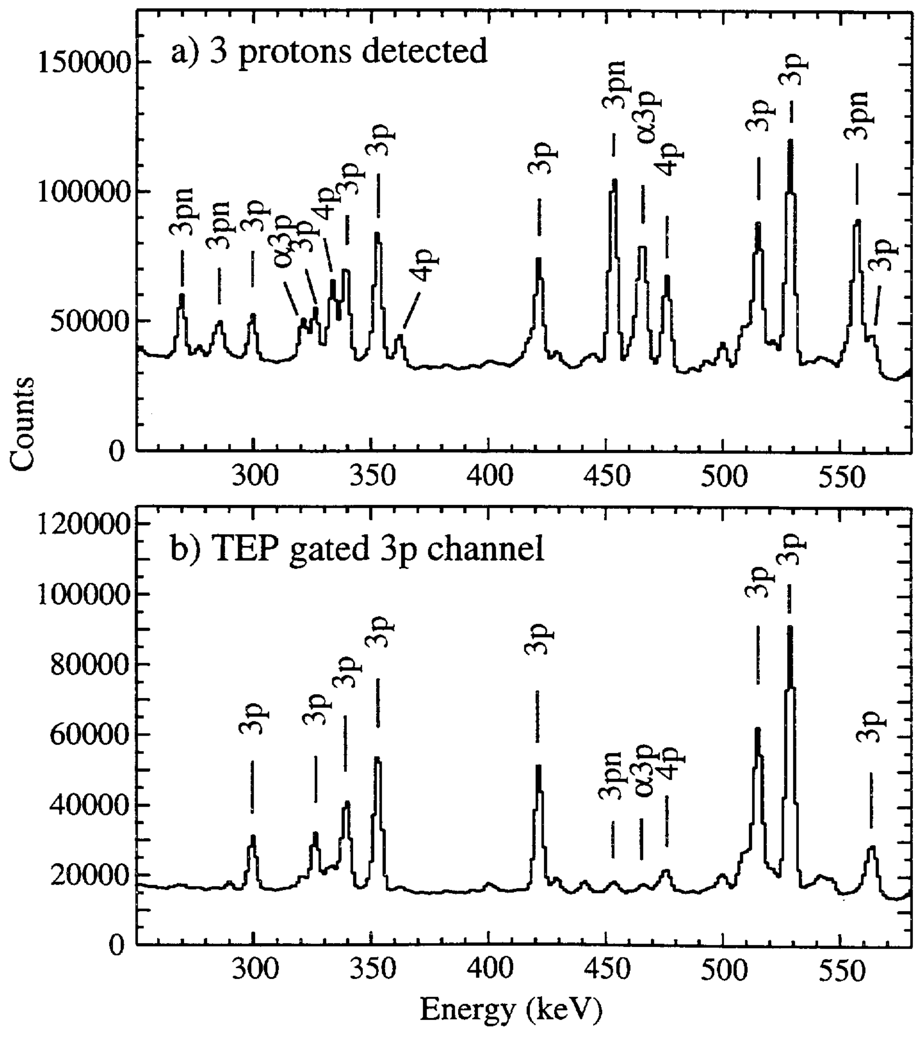

Fig. 2. Portion of the γ-spectra produced by a) gating on 3 detected protons, and b) setting a gate around the real 3p region of the 3p gated Total Energy Plane (Fig.1).

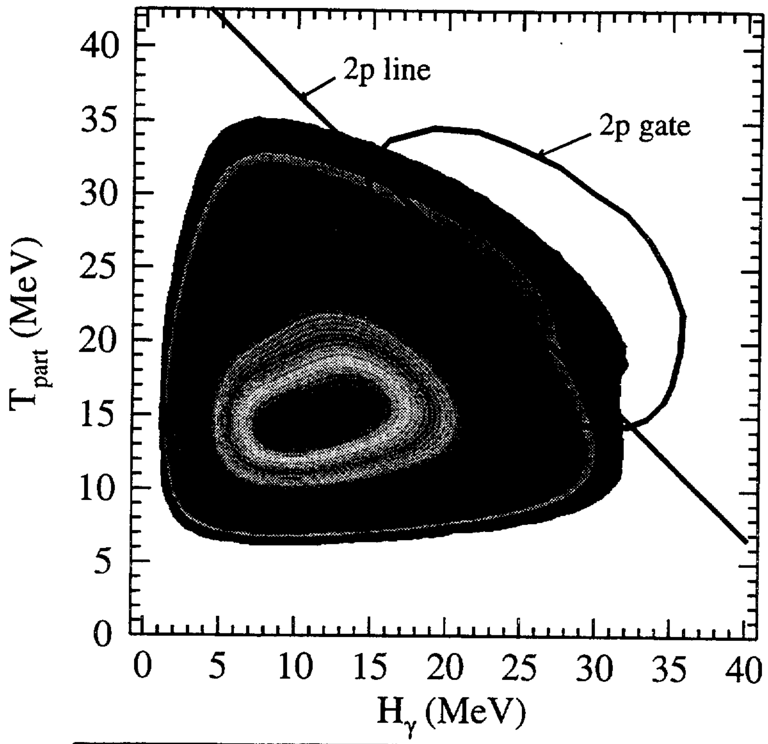

Fig. 3. Total Energy Plane plot for all events in which 2 protons were detected. The high energy "bulge" is produced by events from the very weakly populated 2p channel.

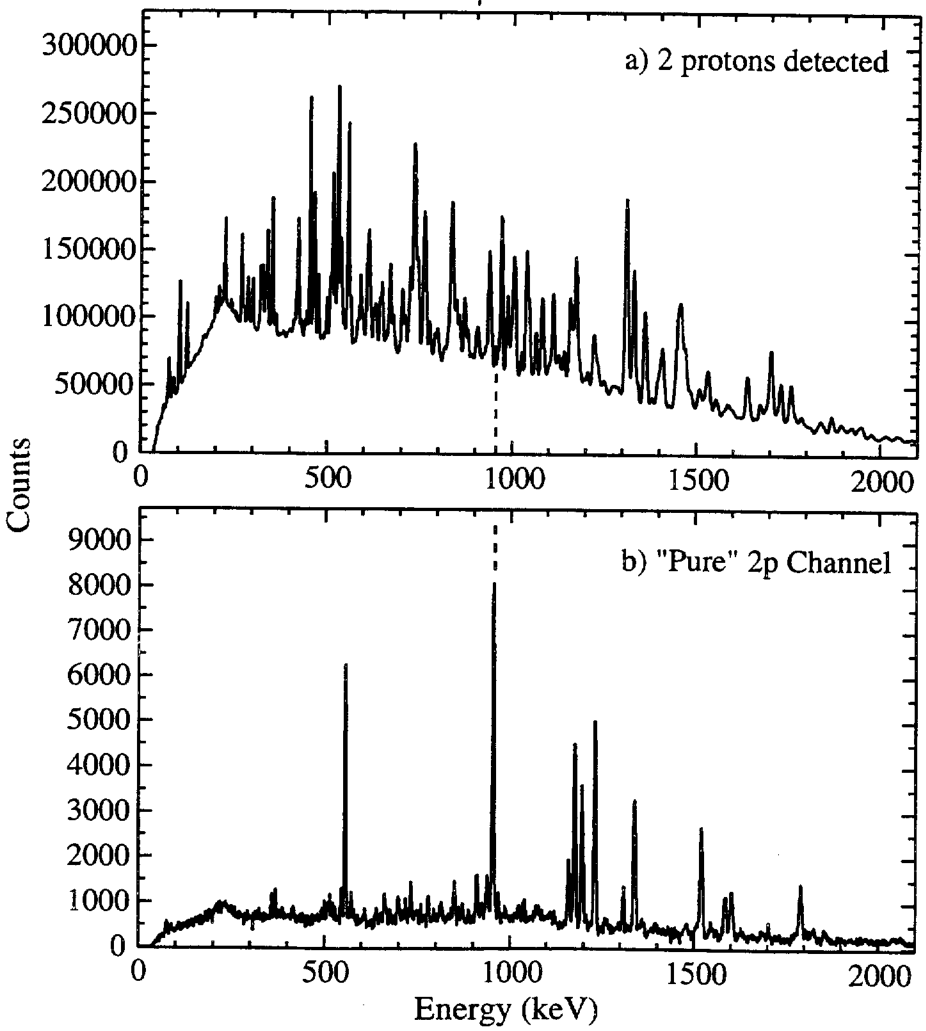

Fig. 4. Comparison of a) the γ-spectrum in coincidence with the detection of 2 protons, and, b) a "pure" 2p channel (^{62}Zn) spectrum produced by gating in the TEP (Fig.3) and then subtracting remaining contaminants.

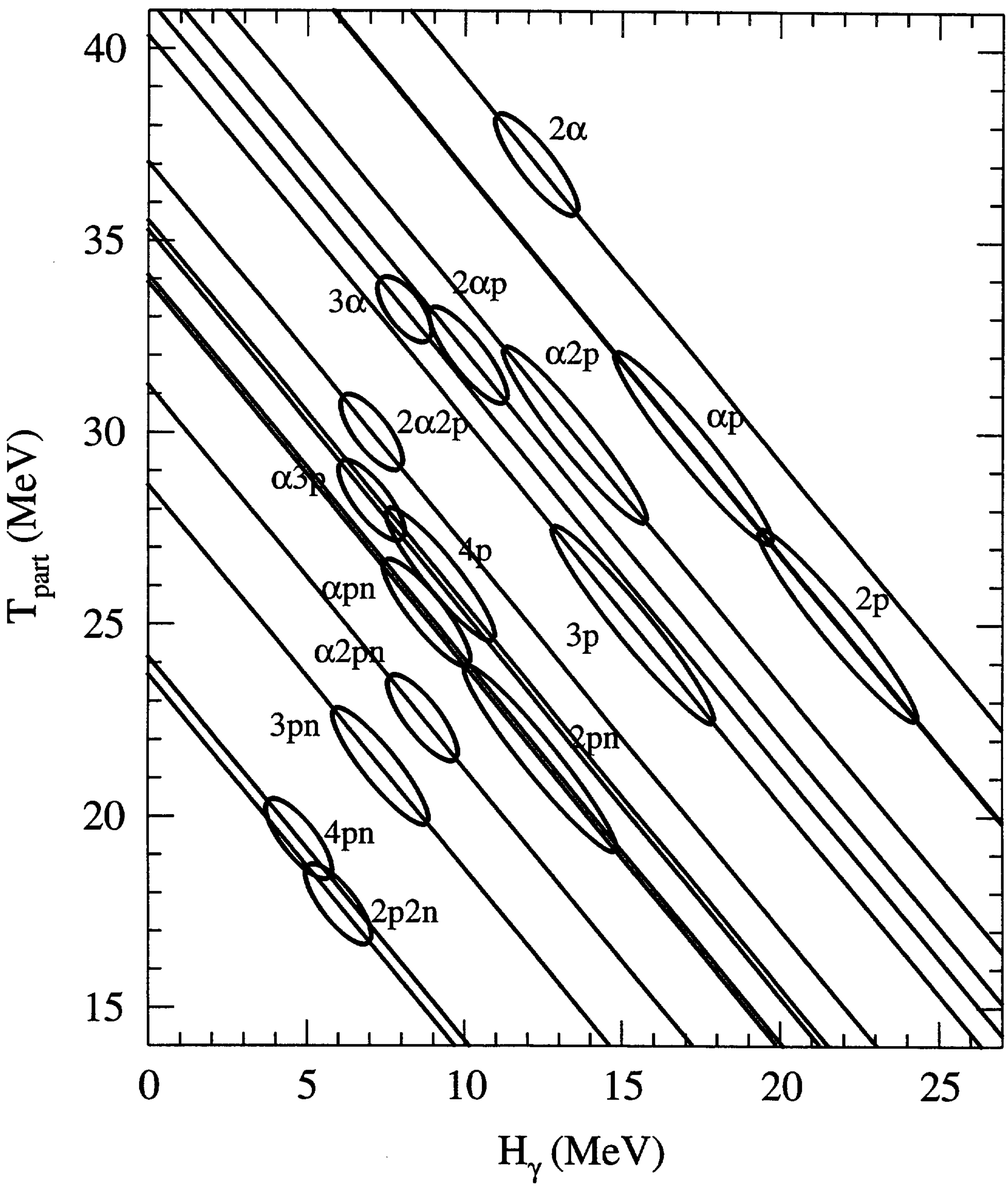

Fig. 5. Entry regions in the Total Energy Plane for the 16 exit channels observed in the reaction of ^{24}Mg on ^{40}Ca at E_{lab} = 80 MeV. See text for details.

All of the peaks in this spectrum belong to the real 2p channel (^{62}Zn). The TEP gate (before subtraction) improves the channel-to-total ratio for the real 2p channel by a factor of 46 over that obtained by gating on 2 detected protons. With this huge improvement in channel selection, spectroscopic study of this very weakly populated channel becomes possible.

4. Excitation Energy Systematics

In Section 2 it was noted that the real 3p events in the 3-proton gated Total Energy Plane must all lie on a line of constant total energy. These events will not, of course, be uniformly distributed along this line. The division of the total CM energy between the kinetic energies of the evaporation particles and the excitation energy left in the final nucleus is determined by the statistical pressures which govern the decay of the compound nucleus. In Fig. 1 we see that the peak in the entry distribution for ^{61}Cu (the 3p channel) is at a total particle kinetic energy $T_{part} = 25.0MeV$ and a final nucleus excitation energy $H_\gamma = 15.3MeV$. By making TEP plots similar to Fig 1 for all exit channels (gates on discrete γ-ray transitions are required for weaker channels) the division of the total CM energy can be mapped out for all nuclei produced.

In Fig. 5 we show entry regions in the TEP for all 16 exit channels observed in the ^{24}Mg + ^{40}Ca experiment. The diagonal lines are the lines of constant total energy for the 16 channels. The semimajor axes of the ellipses (corrected for T_{part} and H_γ resolutions) are such that 68% of the channel populations are enclosed, and the semiminor axes represent the spreads in total available CM energy due to beam loss through the target. One interesting feature that is immediately apparent from Fig. 5 is that the sum of the particle kinetic energies is almost identical for the 2p,3p, and 4p exit channels. In other words, the differences in excitation energy left in the final nucleus for these channels are simply the binding energies of the last proton removed. This pattern is also observed for the αp, α2p, α3p and 2pn, 3pn, 4pn exit channel chains. Fig. 5 also shows that of the four N=Z exit channels observed in this experiment (2p2n, αpn, 3α, and 2α) the 2α exit channel leaves the final nucleus with the greatest excitation energy. Although the cross sections are low for pure alpha exit channels in these systems, alpha particles are often emitted from the highest angular momentum components of the compound system [8,9] and these channels provide the best opportunity to study high spin states in even-even N=Z nuclei using stable beams and targets.

5. Summary and Outlook

In addition to mapping out excitation energy systematics, the Total Energy Plane has been shown to provide a powerful method for improving channel selection in reactions where charged-particle evaporation from the compound system dominates. This method is presently being employed in the analysis of a series of experiments conducted at the TASCC facility producing the even-even N=Z compound systems in the A = 50-70 mass region. Although this method has been developed to take advantage of the total energy measuring capabilities of the 8π spectrometer + miniball charged-particle detector array, it is also applicable to other large γ-ray spectrometer + charged-particle detector arrays. The method could be employed in the analysis of data taken with GASP + ISIS [3], and when combined with the sensitivity of GAMMASPHERE + the microball [2] and the H_γ response of GAMMASPHERE with the Hevimet shielding removed [7], the Total Energy Plane method will provide a powerful tool to increase the sensitivity of high spin spectroscopic studies of very proton-rich nuclei far from β-stability.

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