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## STUDIES OF ISOSPIN QUINTETS AND NEUTRON-DEFICIENT INDIUM ISOTOPES WITH THE ON-LINE MASS ANALYSIS SYSTEM RAMA

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# STUDIES OF ISOSPIN QUINTETS AND NEUTRON-DEFICIENT INDIUM ISOTOPES WITH THE ON-LINE MASS ANALYSIS SYSTEM RAMA*

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## I. INTRODUCTION

The characterization of the nuclidic mass in those regions which are far removed from the line of beta stability is of fundamental importance for testing and improving mass theories. An increasing component of our knowledge on nuclear properties of light exotic nuclei is derived from the analysis of mass-separated radioactivity, complementing the much more extensive investigations by this technique of heavy nuclei off the stability line.[1] Such studies provide new insights into the limits of nuclear stability, the behavior of nuclear shapes and the onset of new radioactive decay modes.

The success of the isobaric multiplet mass equation in relating mass-excesses of members of light isospin quartets has permitted it to play a significant role in predicting ground state masses of highly proton-rich 1f2p shell nuclides. In addition, the extensive studies of complete isospin quartets[2] plus more recent research on isospin quintets provide valuable nuclear structure information as well as deepening our basic understanding of charge-dependent effects in the interactions between nucleons.

This report in part gives an overview of an experimental program that was developed to study the most proton rich members of high isospin multiplets through their radioactive decay. In experiments on light nuclei far from stability, the capability for on-line mass analysis of nuclides of many chemical elements with half-lives as short as 50 ms is clearly of importance. In order to accomplish this, an instrument known as RAMA, for Recoil Atom

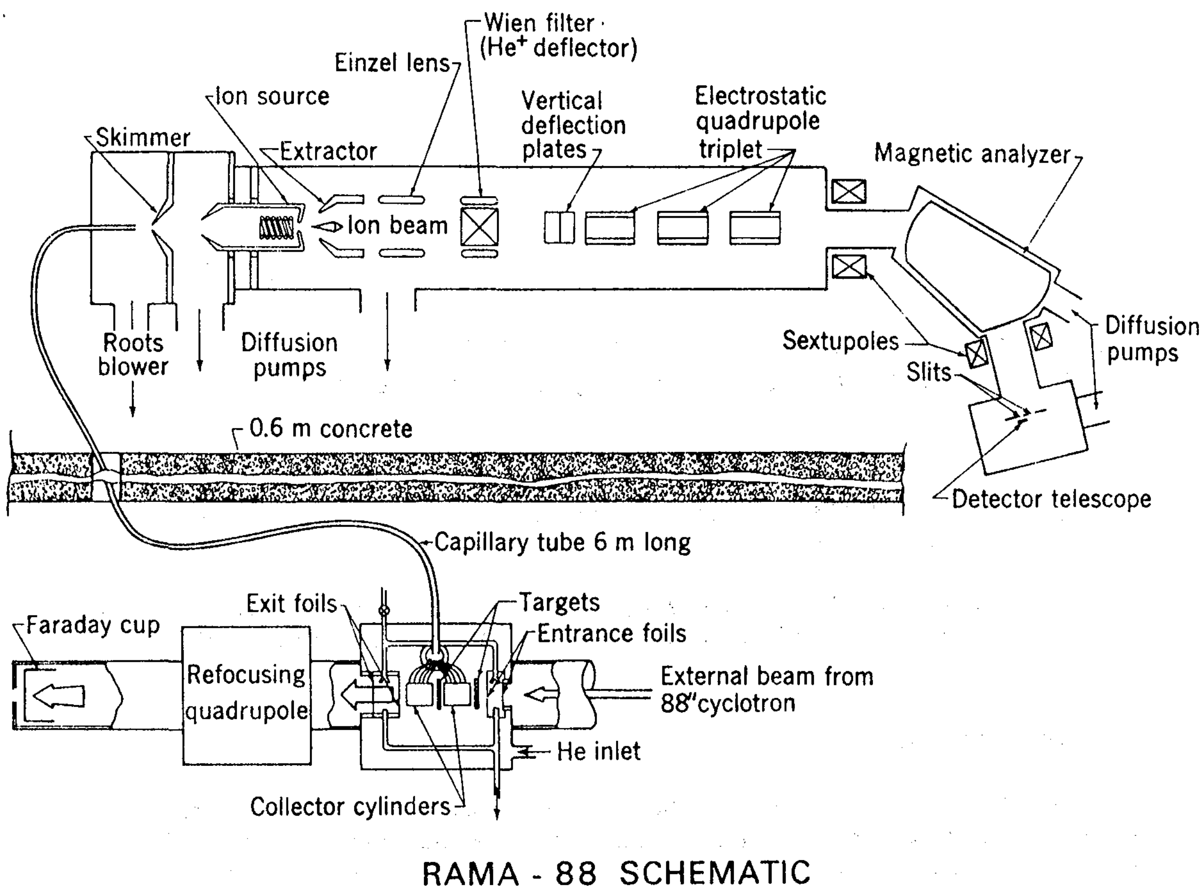


Fig. 1 Schematic view of the on-line mass separator RAMA.

Mass Analyzer, has been constructed and will be briefly described below.[3]

Another part of our program in studying nuclei far from stability is the initiation of a series of experiments to determine total decay energies of isotopes in the vicinity of the doubly-magic nucleus $^{100}_{50}Sn$. Mass-excess determinations for nuclides in this region should highlight the influence of the closed shells on the decay energies and establish whether such proton-rich magic nuclei follow the same mass systematics as do those nearer to or at stability. In the following we give preliminary results of experiments determining the total decay energies, and hence mass-excesses, of $^{103}_{49}In$ and $^{105}_{49}In$.

## II. DESCRIPTION OF THE RAMA SYSTEM

Figure 1 presents the experimental lay-out of the on-line mass analysis system RAMA at the Lawrence Berkeley Laboratory 88-inch cyclotron. RAMA employs a helium jet to transport activity from the target area to a Sidenius-type hollow cathode ion source which is coupled to a mass separator. A special multiple target and multiple capillary system was constructed to provide optimal yield. Reaction recoils are thermalized inside a cylinder and are collected by a set of capillaries spaced evenly over the distance of a maximum recoil range. A 6 m long stainless steel capillary is then fed by the multiple capillary system, transporting the activity to the skimmer-ion source region. Ethylene glycol is employed as an additive in the helium to build up high molecular weight aerosols; nuclides attached to these aerosols possess excellent transport and skimming properties. After skimming, the reaction products are ionized in the ion source which is operating at temperatures up to 2000 °C. Singly charged ions are extracted at 18 kV and mass analyzed as shown in Fig. 1. Overall efficiencies for RAMA currently range from 0.1-0.5% for such elements as Na, Mg, Si, Ca, In, Te, Cs, Ho, Er and At. The shortest half-lives observed to date have been ∿100 ms.

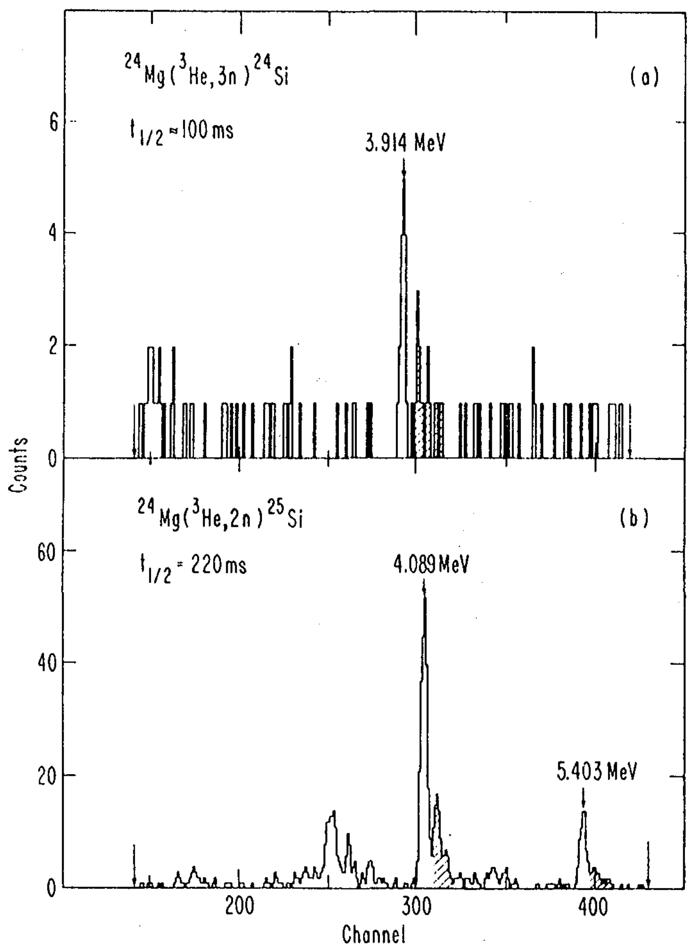


Fig. 2 Spectra of beta-delayed protons from a) $^{24}$Si and b) $^{25}$Si obtained at 70 and 41 MeV beam energy, respectively. Shaded areas in both spectra are due to a pile-up effect.

Detection systems for beta-delayed proton spectroscopy as well as for beta-, gamma-, and X-ray spectroscopy have been developed. Nuclides with short half-lives (∿100-500 ms) are observed by electrostatically deflecting the mass analyzed ion beam from one to another of a pair of vertically positioned detector systems placed about the RAMA focal plane. This technique gives half-life information as well as particle identification and energy measurements. For the beta-delayed proton studies, solid-state counter telescopes were employed which were protected from the ion beam by a 50 μg/cm$^2$ carbon foil. Investigation of the longer-lived, beta-gamma emitting indium isotopes was accomplished by collecting the mass analyzed ions on common magnetic computer tape; this tape can be moved at a speed of 75 cm/s from air into and out of the evacuated focal plane region via two differentially-pumped vacuum chambers. Singles and coincident beta-gamma spectra were obtained by high geometry viewing of the collected activity.

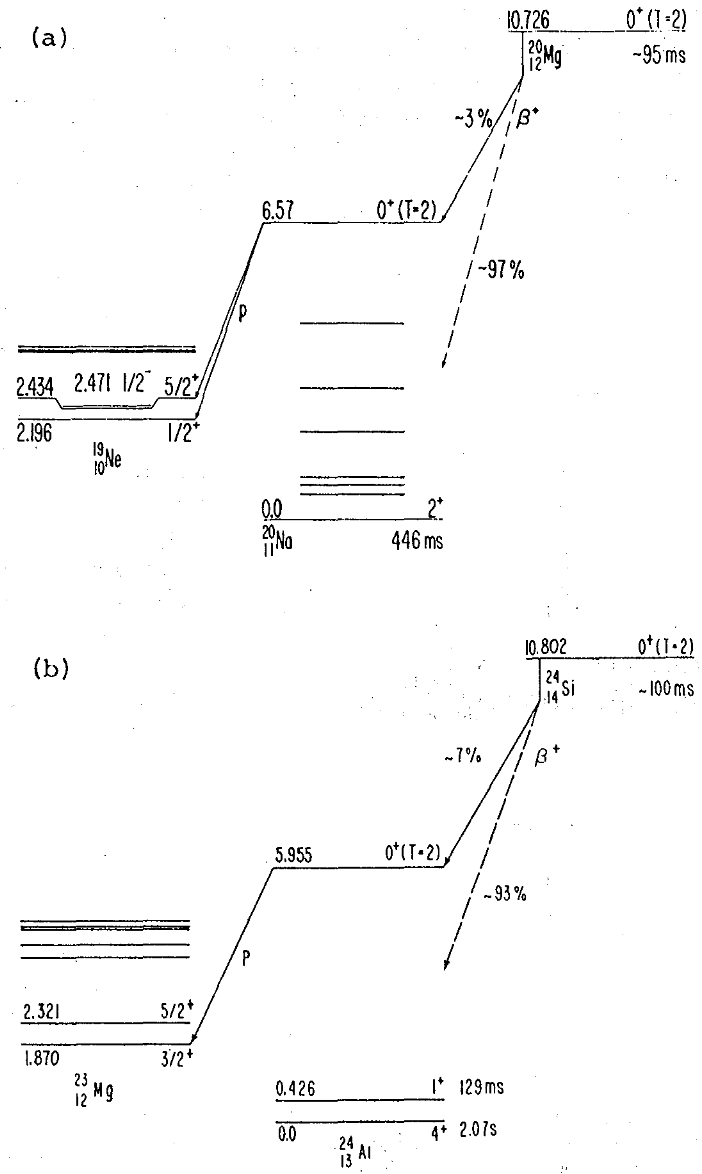


Fig. 3(a) Proposed decay scheme of $^{20}$Mg.
(b) Proposed decay scheme of $^{24}$Si.
The $^{24}$Al-$^{24}$Si mass difference was taken from the quadratic IMME prediction.

## III. ISOSPIN QUINTETS

The masses of the 2T+1 members of an isospin multiplet are given in first order by the isobaric multiplet mass equation (IMME) as

$$M(A,T,T_z) = a(A,T) + b(A,T)\cdot T_z + c(A,T)\cdot T_z^2 \ .$$

This equation results from the assumptions that the wavefunctions of analog states in an isospin multiplet are identical and that charge-dependent forces (Coulomb plus nuclear) are of two-body character and may be treated as perturbations. Although this quadratic form of the IMME fits the vast majority of the data on isospin quartets, a persistent deviation has been reported in the mass 9 quartet.[2] In addition the mass 8 isospin quintet also shows a deviation from the simple IMME,[4] so that tests at higher masses have become imperative to establish comparable systematics for quintets. Deviations from the quadratic form are generally represented by additional terms $d(A,T)\cdot T_z^3$ and $e(A,T)\cdot T_z^4$, in which the d and e coefficients can be derived from second order perturbation theory.

At present, experimental data on isospin quintets are almost exclusively limited to the A = 4n series. Although mass excesses of the $T_z$ = + 2, + 1 and 0 members are well known from A = 8 to A = 40, progress with regard to mass determinations of the $T_z$ = -1 and -2 members has been much slower. Probably the most general approach for locating the analog states in the $T_z$ = -1 nuclei is through investigation of decays of the $T_z$ = -2 nuclei,[5] while the ($^4$He,$^8$He) four-neutron transfer reaction is commonly employed to determine the ground state mass of the $T_z$ = -2 member.

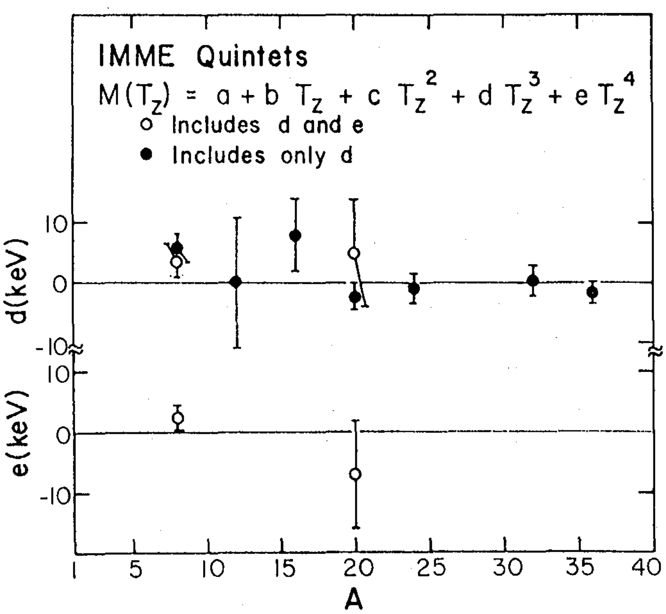


Fig. 4 A summary of the d and e coefficents of the IMME required to fit $0^+$, T = 2 multiplets in which four or more members are known.

One of the initial scientific motivations for the construction of RAMA was to exploit its properties to permit observation of the $T = 2$ states in the $T_Z = -1$ nuclei via the beta-delayed proton decay of the mass-separated $T_Z = -2$ nuclei. So far we have observed the decays of $^{20}Mg$ [6] and $^{24}Si$,[7] completing the mass 20 isospin quintet and determining the mass-excess of the fourth member, $^{24}Al$, of the mass 24 quintet. $^{20}Mg$ is the lightest nucleon-stable member of the series of beta-delayed proton emitters, since $^{12}O$ and $^{16}Ne$ are known[8] to have unbound ground states.

As an example, the beta-delayed proton spectrum arising from the decay of mass-separated $^{24}Si$ is shown in Fig. 2(a). The single peak evident in the spectrum occurs at a laboratory energy of 3.914±0.009 MeV and results from the isospin-forbidden proton decay of the lowest $T = 2$ state in $^{24}Al$. The decay of $^{25}Si$ provides a convenient proton-energy calibration as is shown in Fig. 2(b). Similar beta-delayed proton spectra were also obtained for $^{20}Mg$ and $^{21}Mg$. Decay schemes for $^{20}Mg$ and $^{24}Si$ are shown in Fig. 3(a) and 3(b), respectively. The mass excesses of the lowest $T = 2$ states in $^{20}Na$ and $^{24}Al$, as calculated from the observed proton energies, are 13.42±0.05 and 5.903±0.009 MeV, respectively. For both these multiplets, an excellent fit to the mass-excesses is obtained by using only the quadratic form of the isobaric multiplet mass equation.

A summary of the present experimental situation regarding fits via the IMME for studies of isospin quintets in which four or more members are known[4-9] is presented in Fig. 4. Here the d coefficient has been determined for each multiplet as well as the d and e coefficients for the complete quintets at masses 8 and 20.

The only deviations from the quadratic form of the IMME that have been observed arise in the mass 8 [4] and mass 16 [8] quintets with the latter being less statistically significant. In the case of the mass 8 quintet, the nonzero d and e coefficients have been attributed to the strong Coulombic repulsion associated with its particle-unbound members, in addition to the effect of isospin mixing in the $T_Z = 0$ member of this multiplet. [All members of the complete mass 20 quintet are stable toward isospin-allowed particle decay.] Generally, however, the results on isospin quintets together with the numerous measurements on isospin quartets support the validity of the simple quadratic mass equation and provide no evidence for substantial higher-order, charge-dependent effects in the nuclear interaction.

Extension of these experiments to detect other unknown $T_Z = -2$ beta-delayed proton emitters, such as $^{28}S$ and $^{36}Ca$, is planned. Our greatest interest centers on the $A = 36$ quintet, since a determination of the $T = 2$ state in $^{36}K$ would complete the heaviest quintet possible with established techniques and stable targets.

IV. NEUTRON-DEFICIENT INDIUM ISOTOPES

Total decay energies of the indium isotopes of interest were determined by utilizing RAMA for mass separation together with $\beta^+ - \gamma$ coincidence techniques for data collection. Activity collected on magnetic tape on the focal plane was rapidly transported to a detection station. Isotopic identification and end point determinations were accomplished by gating a beta-telescope with known $\gamma$-rays of the daughter nucleus.

IV.1. Detector System

A telescope designed to measure $Q_\beta$ values up to 20 MeV was used for $\beta$-particle detection. It consisted of a 10 mm diameter and 1 mm thick NE 102 plastic scintillator as a $\Delta E$ detector [for $\gamma$-ray rejection] and a large cylindrical, 11.4 cm diameter and 11.4 cm long, NE 102 plastic scintillator as an E detector. Typical coincidence timing between the $\Delta E$ and E counters was 5 ns full width at half-maximum. Gamma-ray detection was accomplished using a large volume (15%) Ge(Li) counter with a resolution of 2.1 keV at 1332 keV. Due to the low yields of the nuclei of interest, a high geometry was employed between the $\beta$- and $\gamma$-counters; the coincidence resolution between them was 20 ns.

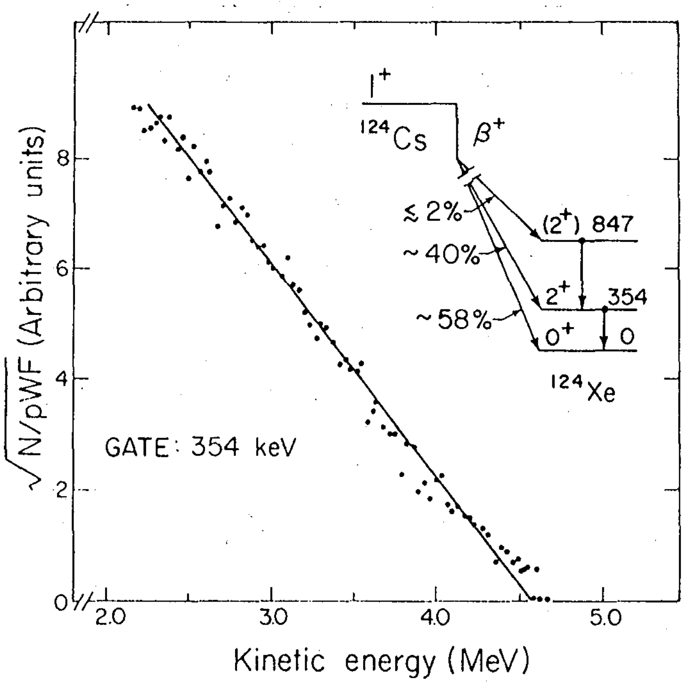


Fig. 5 Fermi-Kurie plot and partial decay scheme for $^{124}Cs$. Beta-branching ratios were obtained from the $\gamma$-spectrum in coincidence with positrons. Ground state branching was taken from Ref. 12.

The recorded positron spectra were distorted by energy-dependent effects, such as the finite energy resolution, back-scattering at the scintillation surface and pile-up by Compton recoil electrons arising from the annihilation radiation. However, in the rather narrow energy range of 2 to 5 MeV used in these experiments, the last two effects were of considerably less importance than the first in determining positron end-point energies.[10] As a result the measured $\beta^+$-spectra were corrected only for the resolution. Conversion electron measurements gave an energy resolution of

200 keV (FWHM) at ∿1 MeV and the response function of the E detector was then assumed to be a Gaussian curve whose width varied with energy as $\sqrt{E}$.[10] The overall energy calibration using this response function and employing known positron activities was found to provide a good linear fit.

## IV.2. Decay Energy Measurements

Energy calibration of the beta-telescope was based on the beta end points of the strongest allowed decay branches of $^{123}$Cs(3.410± 0.120 MeV--ref. 11,12); $^{124}$Cs(4.574±0.150 MeV--ref. 11,12); and $^{112}$Sb(4.750±0.050 MeV--ref.13) produced in $^{20}$Ne + Ag and $^{20}$Ne + Mo reactions at 150 MeV bombarding energy, respectively. As an example of these calibrations, the Fermi-Kurie plot of the response-function-corrected beta spectrum of $^{124}$Cs is given in Fig. 5. The weak $\beta^+$-decay component feeding the second $2^+$ state does not appear to affect the excellent straight line fit.

Indium isotopes were produced by bombarding 2 mg/cm$^2$ $^{102}$Pd targets with a beam of 200 MeV $^{14}$N ions; this relatively high beam energy was found to produce optimum yields of the isotopes of interest in our particular multiple target setup. Decay energies were measured for $^{103-106}$In. A typical result is shown in Fig. 6, which presents a similar Fermi-Kurie analysis of the positron spectrum of $^{105}$In that is in coincidence with the 131 keV γ transition in the $^{105}$Cd daughter. About 80% of the beta decay was found to feed this 131 keV level, while most of the remaining decay strength feeds levels at 196 and 260 keV which directly de-excite to the ground state.[12,14] As a result, the Fermi-Kurie plot is quite linear in the energy interval from 2.5 to 4.0 MeV.

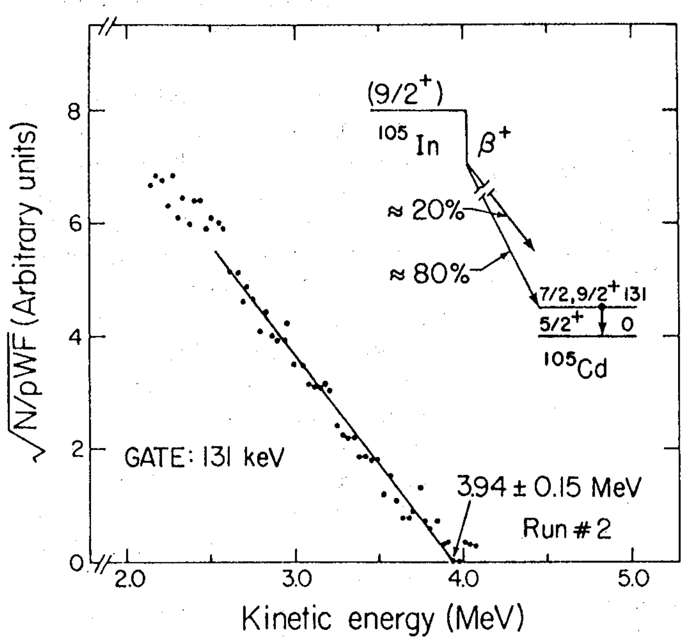


Fig. 6 Fermi-Kurie plot and partial decay scheme for $^{105}$In. Beta-branching ratios were determined from the γ-spectrum in coincidence with positrons.

The positron end point of the decay of

$^{103}In$ was obtained by gating the beta counter with the 188 keV, $7/2^+ \rightarrow 5/2^+$, ground state transition in the daughter $^{103}Cd$.[15] This 188 keV state is strongly fed in the beta-decay (∿80%) and only one additional transition--direct de-excitation of a level at 202 keV to the ground state--was observed. The resulting end point of 4.35±0.35 MeV is in reasonable agreement with the Louvain on-line isotope separator result.[15] [End point energies for $^{104,106}In$ were also determined; however, because of the unsatisfactory understanding of isomerism in these isotopes and substantial disagreement with previous results, additional studies appear to be necessary.] A summary of our measurements of the $^{103,105}In$ decay energies is given in Table I.

Table I. SUMMARY OF $Q_{EC}$ DETERMINATIONS

| NUCLIDE | GATE [keV] | LEVEL [keV] | DECAY ENERGY [MeV] THIS WORK | DECAY ENERGY [MeV] LITERATURE |
|---|---|---|---|---|
| $^{103}In$ | 188 | 188 | 5.56±0.35 | 5.8±0.5 a) |
| $^{105}In$ | 131 | 131 | 5.12±0.13 b) | - |

a) ref. 15, b) average of two measurements.

The mass excesses of $^{103}In$ and $^{105}In$ are presented in Table II.[16,17] Deviations of the experimental values from a semi-empirical shell model formula by Liran and Zeldes,[16a] from a Garvey-Kelson transverse equation,[16b] as well as from a droplet model calculation by Myers[16c] are given for comparison.

Table II. MASS EXCESSES OF $^{103}In$ and $^{105}In$
COMPARED TO DIFFERENT MASS PREDICTIONS

| NUCLIDE | MASS EXCESS [MeV] | Δ = ME(EXP)-ME(THEOR) [MeV] L-Z a) | G-K b) | Myers c) |
|---|---|---|---|---|
| $^{103}In$ | -75.04±0.38 d) | -1.00 | -0.61 | 0.87 |
| $^{105}In$ | -79.22±0.13 d) | 0.24 | 0.55 | 1.21 |

a) ref. 16a; b) ref. 16b; c) ref. 16c; d) mass-excesses of the $^{103,105}Cd$ daughters were taken from ref. 17.

In the main, these predicted masses agree fairly well with the experimental measurements--the observed deviations are of the same order of magnitude as were observed for the neutron-rich $^{120-129}$In isotopes.[18] An interesting disagreement of -1.0 MeV of the $^{103}$In mass excess from the Liran-Zeldes calculations[16a] is inconsistent with the good agreement of their approach in predicting the other experimentally known In mass excesses. Further systematic studies are required to understand both this behavior and whether it might have any possible relationship with a nearby double shell closure.

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Footnotes and References

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