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Author
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Publication Date
1979-09-01

Peer reviewed
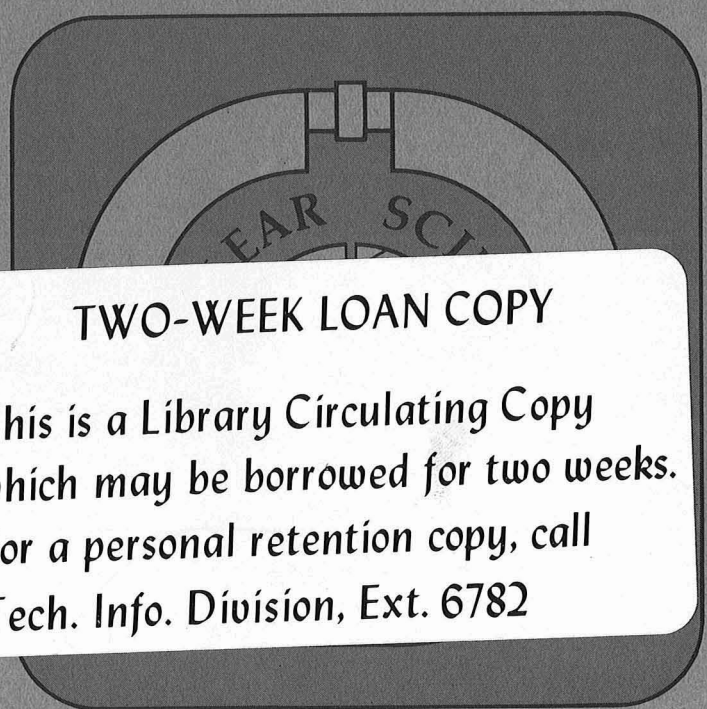
Lawrence Berkeley Laboratory
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Presented at the International Symposium on Future
Directions in Studies of Nuclei Far from Stability,
Vanderbilt University, Nashville, TN, September 10-13, 1979

CURRENT AND FUTURE DIRECTIONS IN THE STUDY OF LIGHT
NUCLEI EMPLOYING AN ON-LINE MASS SEPARATOR

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September 1979

CURRENT AND FUTURE DIRECTIONS IN THE STUDY OF LIGHT
NUCLEI EMPLOYING AN ON-LINE MASS SEPARATOR.*

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Recent work on isospin quintets utilizing the on-line mass
analysis system, RAMA, is described. Possibilities for future
studies of both proton-rich and neutron-rich light nuclides
towards the limits of nuclear stability are discussed.

I. INTRODUCTION

Our knowledge about nuclear properties in regions far from stable nuclei has
increased substantially with recent developments of accelerators and instrumen-
tation techniques[1]. Studies of exotic light nuclei have provided important and
sometimes unexpected information on the limits of nuclear stability, on nuclear
shapes and on the appearance of new decay modes.

Isobaric multiplets play a significant role in predicting masses of highly proton-
rich nuclides in addition to contributing to our basic understanding of charge
dependent effects in nuclear forces. Extension of studies of isobaric multi-
plets to isospin quintets (and possibly sextets) beyond the by now well-known
quartets[2] is of considerable interest. The most proton-rich members of these
multiplets frequently decay by beta-delayed proton emission; nuclei decaying
by more exotic modes such as two proton radioactivity and beta-delayed ^{3}He decay
are being sought. This report presents an overview of experiments initiated to
study proton rich members of high isospin multiplets through their radioactive
decay. To accomplish this, an on-line system capable of mass-analyzing nuclides
of many chemical elements with half-lives as short as 50 ms is clearly of great
utility. An instrument known as RAMA, for Recoil Atom Mass Analyzer, has been
constructed for this purpose and will be briefly described below[3].

Although the present experiments exploit the (^{3}He,xn) and (HI,xn) reactions to
study proton rich nuclei, RAMA has a pronounced potential for the investigation
of highly neutron-rich light nuclei, produced via deeply inelastic scattering
reactions of heavy ion beams. The proposed Electron Beam Ion Source (EBIS) for
the 88-inch cyclotron would enhance these latter studies by providing high-
intensity beams from silicon to calcium at energies of 10 MeV/nucleon and above.
Future research could focus on beta-gamma coincidence techniques to determine
masses and spectroscopic properties of very neutron excess nuclei, comparable
to the unique experiments on the sodium isotopes[4].

II. DESCRIPTION OF THE RAMA-SYSTEM

The experimental set-up for the on-line mass analysis system RAMA is shown in
Figure 1. RAMA consists of a helium-jet system, an ion source, ion optics
combined with mass analysis and a detection station. A special multiple-target
and capillary system was constructed to optimize the recoil yield from the
reactions. Recoils are thermalized in a collection cylinder, and are collected
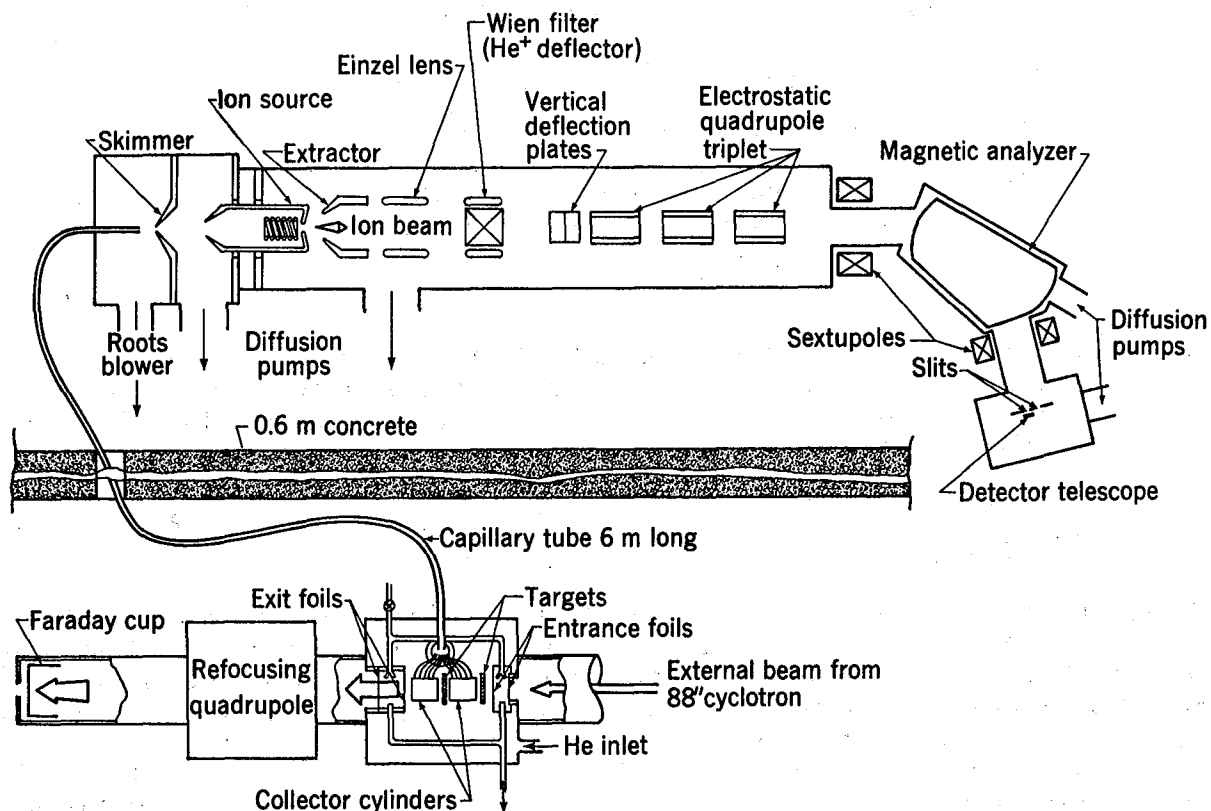
Figure 1
Schematic view of the on-line mass separator RAMA.

by a set of adjacent capillaries spaced evenly over a distance corresponding to
a maximum recoil range. This multiple capillary system feeds a single, 6 m long
stainless steel capillary which transports 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 a hollow cathode ion source operated at temperatures up
to 2000 °C. Ionized nuclides are subsequently extracted and accelerated to 18
keV for magnetic mass separation. Detection systems for both beta-delayed
particle spectroscopy as well as for beta-, gamma-, and X-ray- spectroscopy have
been developed.

At present, total efficiencies of 0.1 - 0.5 % have been obtained for a variety
of light elements, such as Na, Mg, Al, Si, P, K, and Ca as well as for various
heavier elements including high melting point rare earths. The shortest observed
half-lives for various elements have been in the 100 ms region.


III. CURRENT STUDIES ON ISOSPIN QUINTETS

The masses of analog states in 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 relation results from the assumptions that the spatial wave functions of
the members of an isospin multiplet are identical and that all charge-dependent
forces between nucleons are only of two body character. Although this quadratic
form of the IMME with its a, b and c coefficients fits the vast majority of 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[5], 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 $d(A,T)T_z^3$ and $e(A,T)T_z^4$, in which
the d and e coefficients can be derived from second order perturbation theory.

Present experimental information on isospin quintets is almost exclusively limited
to the A = 4n series. Although the mass excesses of T = 2 states in T_z = +2, +1
and 0 nuclei are well known from A = 8 to A = 40, experimental difficulties are
associated with mass determinations of T = 2 states in the T_z = -1 and -2 nuclei.
There are two possible procedures for determining mass excesses of T = 2 states
in the T_z = -1 members. One is the use of the (^{3}He,^{6}He) transfer reaction, which
satisfies the isospin selection rule. However, a lack of selectivity in popula-
ting the T = 2 state in a high background of T = 1 states makes the use of this
reaction difficult; an exception to date is the A = 8 quintet, in which the T = 2
(T_z = -1) state is easily recognizable as a peak on a continuum of T = 1 states.
The other general approach, followed here and discussed below, is the investiga-
tion of decays of the T_z = -2 nuclei[6]. Finally, to complete the quintet, the
mass of the T_z = -2 member can be measured by utilizing the (^{4}He,^{8}He) four-
neutron transfer reaction.

Because of the difficulties in determining the mass excesses of T = 2 states in
the T_z = -1 members of the quintets, we have initiated a program to characterize
these states by observing the beta-delayed proton decay of the mass separated
T_z = -2 nuclei. So far we have completed the mass 20 isospin quintet by observ-
ing the decay of ^{20}Mg and determined the mass of the fourth member, ^{24}Al, of the
A = 24 quintet through the decay of a new isotope ^{24}Si[7,8].
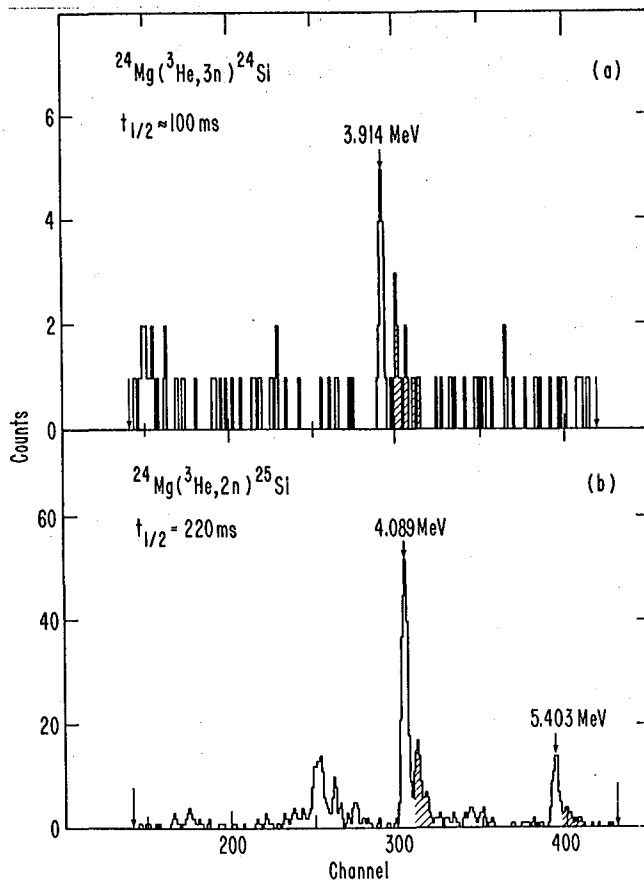
As an example, the beta-delayed
proton spectrum arising from the
decay of mass separated ^{24}Si
($T_{1/2}$ = 100 ms) is shown in Fig. 2a.
Only one peak is evident in the
spectrum; it occurs at a laboratory
energy of 3.914 ± 0.009 MeV and
results from the isospin-forbidden
proton decay of the lowest T = 2
state in ^{24}Al. A proton spectrum
arising from the decay of ^{25}Si
provided a convenient calibration
and is shown in Fig. 2b. Similar
spectra were also obtained for ^{20}Mg
and ^{21}Mg. Mass excesses of the
lowest T = 2 states in ^{20}Na and ^{24}Al,
as calculated from observed pro-
ton decay energies are 13.42 ± 0.05

Figure 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.

and 5.903 ± 0.009 MeV, respectively. For both multiplets discussed here, an
excellent fit to the IMME is obtained by using only the quadratic form. This
good agreement is contrary to that found in the mass-8 system, in which non-zero
d and e coefficients are obtained, a result attributed to the strong Coulomb
repulsion and isospin mixing effects. However, the data on the mass 20 and 24
nuclei coupled with numerous measurements on isospin quartets support the
validity of the simple quadratic mass equation and give no evidence for sub-
stantial higher-order charge-dependent effects.

Extension of these experiments to determine other unknown T = 2 states in T_z = -1
nuclei 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 and would thus have a
significant value in the systematic investigation of charge-dependent effects
in the nuclear interaction.

IV. FUTURE STUDIES

Figure 3 summarizes our present experimental knowledge about the existence of
nuclei up to titanium; it also shows those nuclei whose masses have been
measured. This figure demonstrates clearly that future studies on proton-rich
nuclei will concentrate on the proton-drip line and will be dealing with topics
such as high-isospin multiplets and possible new modes of radioactive decay.
On the neutron-rich side of this figure, experiments demonstrating the existence
of nuclei are far ahead of those determining decay modes and accurate masses.
Future studies of light neutron-excess nuclei will have to employ new techniques
to permit these spectroscopic measurements. Possible future plans utilizing
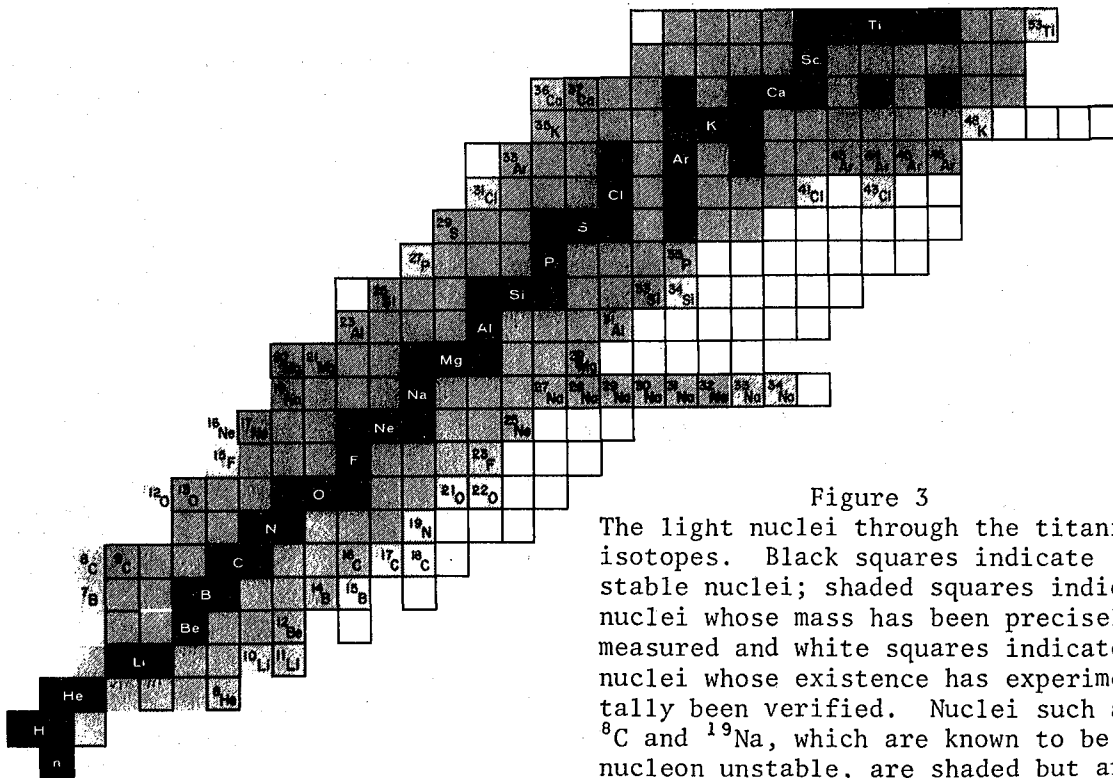both light- and heavy-ion beams and on-line mass analysis are covered below.

Figure 3
The light nuclei through the titanium
isotopes. Black squares indicate
stable nuclei; shaded squares indicate
nuclei whose mass has been precisely
measured and white squares indicate
nuclei whose existence has experimen-
tally been verified. Nuclei such as
^{8}C and ^{19}Na, which are known to be
nucleon unstable, are shaded but are
not included in a framed square.

IV.1. STUDIES NEAR THE PROTON DRIP LINE

Studies of proton-rich nuclei near the drip line will open up exciting possibilities such as exploring the IMME with isospin multiplets having T = 5/2 and could test predictions of two-proton radioactivity[9]). The beta-delayed particle decay of these nuclei would also be a rich source of information with which to examine nuclear model wavefunctions and isospin mixing effects. Specific investigations of interest are detailed below:

a) Although isospin quartets are very well-known, there remain two bound $T_Z = -3/2$ nuclei, ^{27}P and ^{31}Cl, whose radioactive decays have not yet been observed. These are expected to be weak delayed-proton emitters, mainly decaying via beta-γ decay. The difficulty of observing their decay in an intense background of other high energy positron emitters has made their detection difficult, but it should be possible with on-line mass analysis.

b) The family of isospin quintets with A = 4n+2 is very poorly known. Mass predictions from the untruncated 2s1d shell model calculations of Cole, Watt, and Whitehead[10]) as well as those of Jelley et al.[11]) using updated input masses in the Kelson-Garvey mass relations (based on the charge symmetry of nuclear forces) indicate that there is only one completely bound quintet in this series, namely that with A = 22. The $T_Z = -2$ member, ^{22}Al, is predicted to be bound only by about 100 keV. Experimental observation of ^{22}Al by on-line mass analysis as well as the determination of masses of other members of this quintet would be of substantial value.

c) Three $T_Z = -5/2$ nuclei are expected to be bound (but none with $T_Z = -3$). The updated Kelson-Garvey mass formula mentioned above predicts that ^{23}Si, ^{27}S and ^{35}Ca should exist and therefore be beta-delayed proton emitters. Observation of these nuclides and extension of experimental tests of the IMME to isospin sextets is an exciting area of future studies of proton-rich light nuclei. Experimentally, the most accessible sextet would probably be the one with A = 35. The mass of the $T_Z = +5/2$ member, ^{35}P, is already known to a precision of 75 keV[12]) and the T = 5/2 states in ^{35}S and ^{35}Cl could be located via isospin conserving (p,^{3}He) and (p,t) reactions, respectively. The multi-neutron transfer reactions (^{3}He,^{6}He) and (^{3}He,^{8}He) could in principle (but with well-known difficulties) be used to measure mass excesses of the T = 5/2 state in ^{35}Ar and of the ground state of ^{35}Ca, 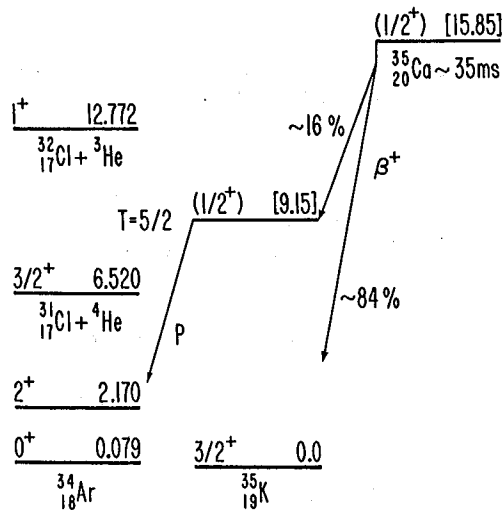respectively. Finally the T = 5/2 state in ^{35}K could be established by observing the beta-delayed proton decay of mass analyzed ^{35}Ca, produced in the $^{40}Ca(^3He,^4He4n)$ or $^{36}Ar(^3He,4n)$ reaction.

A predicted decay scheme for ^{35}Ca is shown in Fig. 4. The ground state mass of ^{35}Ca was calculated using the Kelson-Garvey relations; the T = 5/2 analog state in ^{35}K was obtained from a simple Coulomb displacement energy calculation. Branching ratios were obtained by assuming a log ft of 3.09 for the super-allowed beta decay and using the experimental information on the beta decay of the mirror-nucleus, ^{35}P[12]). Energetically, beta-delayed proton, alpha and ^{3}He-decay are possible, although branching ratios to the ^{3}He - emitting states would be very small.

Figure 4
Predicted decay of ^{35}Ca.

d) Among the light elements there are several candidates for nuclei decaying via two-proton radioactivity. The present mass predictions suggest that searches for the T_z = -5/2 nuclei ^{19}Mg (S_{2p} = -0.76 MeV), ^{31}Ar (S_{2p} = -0.08 MeV) and ^{39}Ti (S_{2p} = -0.74 MeV) or the T_z = -3 nucleus ^{22}Si (S_{2p} = -0.20 MeV) would appear to be promising, since all these nuclei are predicted to be bound against single proton emission. However, detection of these exotic nuclei would require new and highly specialized techniques due to the very short half-lives expected for their decay.

IV.2. NEUTRON-RICH NUCLEI

Substantial progress in establishing the existence of many new neutron-rich isotopes has occurred during the past several years. This information has mainly been obtained from bombardments of heavy neutron rich targets with high-energy protons[13], from products of deeply inelastic scattering reactions[14] and from projectile fragmentation of high energy heavy ion beams[15]. Interestingly, even with this progress, the predicted neutron-drip line has only been reached up to ^{14}Be.

Much work remains to be done in establishing mass and spectroscopic properties of very neutron-rich light isotopes. Heavy ion transfer and rearrangement reactions[16,17] as well as pion double charge exchange reactions[18] have had significant success in spectroscopic studies of most of the light T_z = 5/2 nuclei and several T_z = 3 nuclei. However, extension of such techniques to even more neutron-rich nuclei is limited by their very low cross sections. To circumvent this situation, a combination of deeply inelastic scattering reactions on neutron-rich targets coupled with on-line mass analysis utilizing the helium-jet technique could be a promising approach toward studying decays of very neutron-rich nuclei. As an example, ^{21}O and ^{22}O isotopes are produced in the deeply inelastic scattering of ^{22}Ne on ^{232}Th with total cross sections of 3.5 mb and 0.5 mb, respectively[14]; this value for ^{22}O is much higher than in the ^{18}O(^{18}O,^{14}O)^{22}O transfer reaction where it is $\sim$1 μb[16]. The experiments on sodium isotopes[4] produced by fragmentation reactions with high energy protons have indicated the unexpected onset of a new region of deformation near the N = 20 shell. It is clearly important to extend these studies to other neighboring nuclei to map out the systematics of this unusual behavior.

FOOTNOTES AND REFERENCES

†On leave from the University of Jyväskylä, Finland.

[1] Proc. Int. Conf. on Nuclei Far from Stability, Cargese, 1976, 3rd. Rep. CERN 76-13. and P. G. Hansen, to be published in Ann. Rev. Particle and Nuclear Science.

[2] W. Benenson and E. Kashy, to be published in Revs. Mod. Phys. (1979).

[3] J. Cerny et al., Proc. of the Isotope Separator On-Line workshop, ed. R. E. Chrien, BNL-50847 (1977) p. 57.

[4] C. Thibault, R. Klapisch, C. Rigaud, A. M. Poskanzer, R. Prieels, L. Lessard and W. Reisdorf, Phys. Rev. C12 (1975) 644.

[5] R. G. H. Robertson, W. Benenson, E. Kashy, and D. Mueller, Phys. Rev. C13 (1976) 1018; R. E. Tribble, R. A. Kenefick and R. L. Spross, Phys. Rev. C13 (1976) 50.

[6] E. Hagberg, P. G. Hansen, J. C. Hardy, A. Huck, B. Jonson, S. Mattson, H. L. Ravn, P. Tidemand -Petersson, and G. Walter, Phys. Rev. Lett. 39 (1977) 792.

[7] D. M. Moltz, J. Äystö, M. D. Cable, R. D. von Dincklage, R. F. Parry,
     J. M. Wouters, and J. Cerny, Phys. Rev. Lett. 42 (1979) 43.
[8] J. Äystö, D. M. Moltz, M. D. Cable, R. D. von Dincklage, R. F. Parry,
     J. M. Wouters and J. Cerny, Phys. Lett. 88B (1979) 43.
[9] V. I. Goldansky, Ann. Rev. Nucl. Sci. 16 (1966) 1.
[10] B. J. Cole, A. Watt, and R. R. Whitehead, J. of Phys. A7 (1974) 1399.
[11] N. A. Jelley, J. Cerny, D. P. Stahel, and K. H. Wilcox, Phys. Rev. C11
     (1975) 2049 and Lawrence Berkeley Laboratory Report no. 3414; I. Kelson
     and G. T. Garvey, Phys. Lett. 23 (1966) 689.
[12] D. R. Goosman and D. E. Alburger, Phys. Rev. C6 (1972) 820.
[13] G. W. Butler, D. G. Perry, L. D. Remsberg, A. M. Poskanzer, J. B. Natowitz,
     and F. Plasil, Phys. Rev. Lett. 38 (1977) 1380.
[14] V. V. Volkov, Phys. Rep. 44C (1978) 93.
[15] T. J. M. Symons, Y. P. Viyogi, G. D. Westfall, P. Doll, D. E. Greiner,
     H. Faraggi, D. J. Lindstrom, D. K. Scott, H. J. Crawford, and C. McParland,
     Phys. Rev. Lett. 42 (1979) 40.
[16] J. Cerny, p. 225 in ref. 1.
[17] D. E. Alburger, p. 289 in ref. 3.
[18] K. K. Seth, H. Nann, S. Iversen, M. Kaletka, J. Hird, and H. A. Thiessen,
     Phys. Rev. Lett. 41 (1978) 1589.