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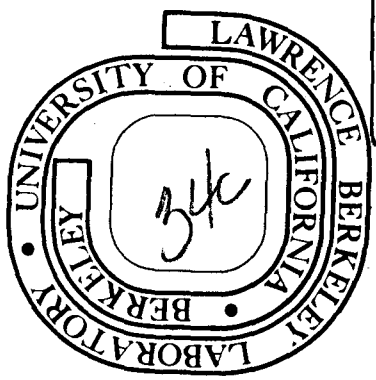

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DISCLAIMER

SPECTROSCOPY OF EXOTIC NUCLEI USING HEAVY-ION TRANSFER REACTIONS*

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September 1974

Abstract:

The reactions (^{11}B,^{8}B), (^{11}B,^{11}C) and (^{11}B,^{13}N) were studied at 86 MeV as a technique for the mass measurement and spectroscopy of exotic nuclei.

- - -

The known limit of particle stability of neutron-excess nuclei extends far beyond the region accessible to nuclear spectroscopy in conventional light-ion induced reactions.[1] With the (t,p) reaction, nuclei only two neutrons removed from stable targets can be studied, whereas on the neutron deficient side of stability three and four[1] neutron transfers are possible by the (^{3}He,^{6}He) and (^{4}He,^{8}He) reactions. Comparable transfers to neutron-excess nuclei are made possible by heavy-ion reactions. Here we present the first results on a reaction for 3n stripping - the (^{11}B,^{8}B) reaction - on targets of ^{26}Mg and ^{28}Si, both to provide a precise measurement of the mass-excess of the T_z = 5/2 nuclide ^{29}Mg for comparison with theoretical mass predictions, and to study the feasibility of using 3n transfer for studies of nuclear structure. The reactions ^{26}Mg(^{11}B,^{13}N)^{24}Ne and ^{26}Mg(^{11}B,^{11}C)^{26}Na also lead to exotic nuclei currently the object of nuclear model calculations,[2] and these were studied simultaneously.

Low yield, neutron deficient products such as ^{8}B, are difficult to detect with conventional counter telescopes because they are obscured[3] by spurious identifications arising from Landau fluctuations in the energy loss of more abundant reaction products, in this case ^{11}B and ^{10}B. Of the possible reactions for 3n transfer, (^{11}B,^{8}B) has the advantage that ^{9}B is particle unstable. Furthermore the break-up of ^{11}B into $^{7}Li + \alpha$ can simulate ^{8}B events[1] (this background may have confused the interpretation of earlier attempts to study this reaction.[4]) These problems are alleviated by using a magnetic spectrometer, which can give higher precision than counter telescopes for mass measurements. For the experiments reported here the Berkeley QSD spectrometer was used to detect the reaction products arising from the bombardment of ^{26}Mg and ^{28}Si targets of thickness 750 μg /cm^2 and 300 μg/cm^2, respectively, by a ^{11}B beam of 86 MeV from the LBL 88-inch cyclotron.

In this system[5,6] a measurement of the magnetic rigidity (Bρ) is made with a position-sensitive, Borkowski - Kopp proportional counter, which also yields a $(dE/dX)_1$ signal for ions in the region of ^{8}B with a resolution of 10%. A second thicker proportional counter, behind the first, provided an independent $(dE/dX)_2$ measurement with a superior resolution of 6%. In addition the time-of-flight (TOF) through the spectrometer was measured between an entrance "time-zero" detector consisting of a scintillator foil of NE111 250 μg/cm^2 thick, and a scintillator mounted behind the proportional counters. Flight times were typically 150 ns with a resolution of 3 ns. The plot of TOF vs $(dE/dX)_2$ in Fig. 1 shows the excellent separation of ^{8}B events. Plotting the data in this way, after correction of the TOF and dE/dX spectra for systematic variations along the focal surface, yields axes roughly proportional to M/Z and M^2.

The reliability of detection was further improved by comparing events in the independent TOF vs $(dE/dX)_1$ identification; this comparison almost completely eliminated spurious identifications in either (dE/dX) measurement.[3] All the parameters were stored on magnetic tape event by event for off-line analysis.

The prime objective of the present work was the precise mass measurement of ^{29}Mg. Although the masses of all $T_z = 5/2$ nuclides from ^{21}O to ^{35}P have recently been measured,[1] mainly by production in heavy-ion compound nuclear reactions followed by β-γ activity measurements, this technique was difficult to apply in the case of ^{29}Mg and resulted in a large error. The 3n transfer reaction is capable of high precision, but it is important to establish that the ground state of the reaction is populated. To clarify this point we studied the same reaction on ^{28}Si which differs from ^{26}Mg by the addition of a proton pair, and therefore the reaction might be expected to populate states with similar neutron structures. As Fig. 2b shows, the ground state of ^{31}Si is excited ($d\sigma/d\Omega \approx 80$ nb/sr), and we assume that the highest energy peak in the ^{29}Mg spectrum in Fig. 2(a) corresponds also to the ground state (here the cross section is only 15 nb/sr). The predicted location of the ground state from the mass-excess of Ref. 7 is also shown. Careful analysis of this peak, after corrections including energy losses in the target and "time-zero" foil, gave a Q-value of -19.72 ± 0.05 MeV, corresponding to a mass-excess for ^{29}Mg of -10.75 ± 0.05 MeV. The accuracy of the method, including the calibration of the magnetic field of the spectrometer, was checked using other reactions of known Q-value, e.g. (^{11}B, ^{13}N), which in some cases were measured with fields identical to that for the ^{26}Mg(^{11}B, ^{8}B)^{29}Mg reaction. Our result is within the error of the mass-excess quoted in Ref. 7, of -10.589 ± 0.400 MeV, differs by 0.83 MeV from the revised Garvey-Kelson prediction,[8] and is in excellent

agreement (within 50 keV) with the results of the modified shell-model predictive scheme of Jelley et al.[1,9]

The low cross section for 3n transfer follows the trend of high energy heavy-ion reactions of favoring the transfer of bound clusters.[3] However the selectivity of the reaction shows that some correlation is still present. For example, in ^{31}Si only two states are populated in the first 4 MeV of excitation: the ground state,which has dominant structure $(s_{1/2})^2$ $(d_{3/2})$ both in the simple and the extended shell-model calculations,[10] and a state at 3.15 MeV of dominant structure $(s_{1/2})^2$ $f_{7/2}$. These two states are also favoured in the ^{30}Si(d,p)^{31}Si reaction.[11] The reaction appears to proceed by direct transfer of a 2n cluster in an internal l = 0, S = 0, T = 1 state, with the transfer of the third neutron to the lowest available orbitals. This interpretation is consistent with the absence of the 0.75 ($1/2^+$) and 1.70 MeV ($5/2^+$) states, which are accessible in direct 3n transfer only by the $(s_{1/2})$ $(d_{3/2})^2$ components[10] in the wave functions, for which the 2n cluster component is smaller. The selectivity may imply that the contribution of sequential transfer is less important, unless the selection rules turn out to be identical. The sequential transfer process is, however, believed to be important theoretically in 2n transfer.[12] At higher excitation, in a region of level density greater than 15 levels/ MeV, the few strongly observed states are likely to be associated with higher shell-model orbitals, and other cluster configurations.

The spectrum for ^{29}Mg in Fig. 2(a) has excited states at 1.38, 2.34, 3.07 and 4.27 MeV. (± 90 keV). A recent calculation[2] of energy spectra of exotic nuclei in the sd-shell predicts positive parity configurations in ^{29}Mg of $J^\pi = 1/2^+, 5/2^+, 7/2^+$ and $3/2^+$ at 0.02, 1.89, 2.53 and 3.19 MeV respectively. If the observed level at

1.38 MeV corresponds to the $5/2^+$ configuration, its strong excitation in ^{29}Mg compared to ^{31}Si implies that the overlap of the three neutrons with the ^{26}Mg and ^{28}Si is very different. Since ^{26}Mg and ^{28}Si have opposite deformations,[13] an alternative interpretation is that of transfer to different Nilsson orbitals. In order to clarify these aspects of the 3n transfer, further studies must be undertaken on pairs of nuclei such as ^{18}O and ^{20}Ne in which the deformations have the same sign. At the present time the (^{11}B, ^{8}B) reaction appears to be the most feasible method of reaching the nuclide ^{29}Mg, and it will be interesting to obtain further data in order to locate the excited $1/2^+$ state. The predicted excitation of 0.02 MeV is much lower than the known position[11] of this state in the related nuclei ^{31}Si, ^{33}S and ^{35}Ar (0.75, 0.84 and 1.18 MeV. respectively), but the prediction is highly sensitive to small changes in the interaction. Although this excitation could not be observed with the present resolution, on the basis of the ^{31}Si data we anticipate that it will be excited very weakly, and therefore its presence is unlikely to affect significantly the measured mass-excess of ^{29}Mg.

In addition to ^{8}B, the reaction products ^{11}C and ^{13}N were clearly identified (see Fig. 1) and the Q-values permitted all three ground states to be encompassed by the 25% energy bite of the focal plane detector. A spectrum for the $^{26}Mg(^{11}B, ^{13}N)^{24}Ne$ reaction is shown in Fig. 3(b). Since ^{13}N has no particle stable excited states the reaction is favorable for spectroscopic studies of 2p pick-up. The cross section (80μb/sr for the g.s.) is also substantially greater than that of the (^{6}Li, ^{8}B) reaction.[1] On account of these advantages, and because the reaction is unusual in having comparable amplitudes for transfer of two protons in spatially symmetric and antisymmetric states,[14] this reaction may be suitable for determining the importance of the antisymmetric states.

Their theoretical importance in heavy-ion reactions has long been emphasized.[15]

The spectrum for the $^{26}Mg(^{11}B,^{11}C)^{26}Na$ reaction in Fig. 3(a) exhibits excited states at 0.23, 2.10, and 4.79 MeV. (± 150 keV), although the latter two are somewhat ambiguous owing to the close proximity of ^{11}C excited states at 1.995 and 4.794 MeV. The selectivity of the reaction appears to be similar to that[16] of $(^{7}Li,^{7}Be)$ and quite different from the $(t,^{3}He)$ reaction,[17] which established excited states at 88, 241 and 420 keV. Although the detailed mechanism of these rearrangement reactions is poorly understood at present, it appears that the heavy-ion case preferentially excites high spin states.[18] A comparison of the quadruplet of levels near the ground state, excited in light-and heavy-ion induced reactions could possibly be used to infer the spin sequence, thereby distinguishing between rotational and shell model interpretations of ^{26}Na.

The data reported here illustrate some of the unique features and the diversity characteristic of using heavy ion reactions for the study of exotic nuclei. As the identification systems on the new generation of large solid angle magnetic spectrometers in use at high resolution, high energy accelerators are improved, heavy-ion transfer reactions are likely to become an important means of extending our knowledge of nuclei far from stability.

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FOOTNOTES AND REFERENCES

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FIGURE CAPTIONS

Fig. 1. Identification of particles produced by the reaction of ^{11}B ions of 86 MeV on a ^{28}Si target at 11°. On the vertical axis is plotted the time-of-flight, which is approximately proportional to (M/Z), since $TOF \propto 1/v \propto \sqrt{\frac{M}{E}} \propto \frac{M}{Z}\left(\frac{1}{B\rho}\right)$. The horizontal axis is the differential energy los's, dE/dX, proportional to $\frac{MZ^2}{E}$, or $M^2\left(\frac{1}{B\rho}\right)^2$

Fig. 2. Energy spectra for the reactions (a) $^{26}Mg(^{11}B, {}^{8}B)^{29}Mg$ and (b) $^{28}Si(^{11}B, {}^{8}B)^{31}Si$ induced by 86 MeV ^{11}B ions at 11°. The cut-off at $\approx$ 5MeV excitation in ^{29}Mg is instrumental. The ground state predicted from the mass excess for ^{29}Mg in reference 7 is shown in (a).

Fig. 3. Energy spectra for the reactions (a) $^{26}Mg(^{11}B, {}^{11}C)^{26}Na$ and (b) $^{26}Mg(^{11}B, {}^{13}N)^{24}Ne$ induced by 86 MeV ^{11}B ions at 11°.

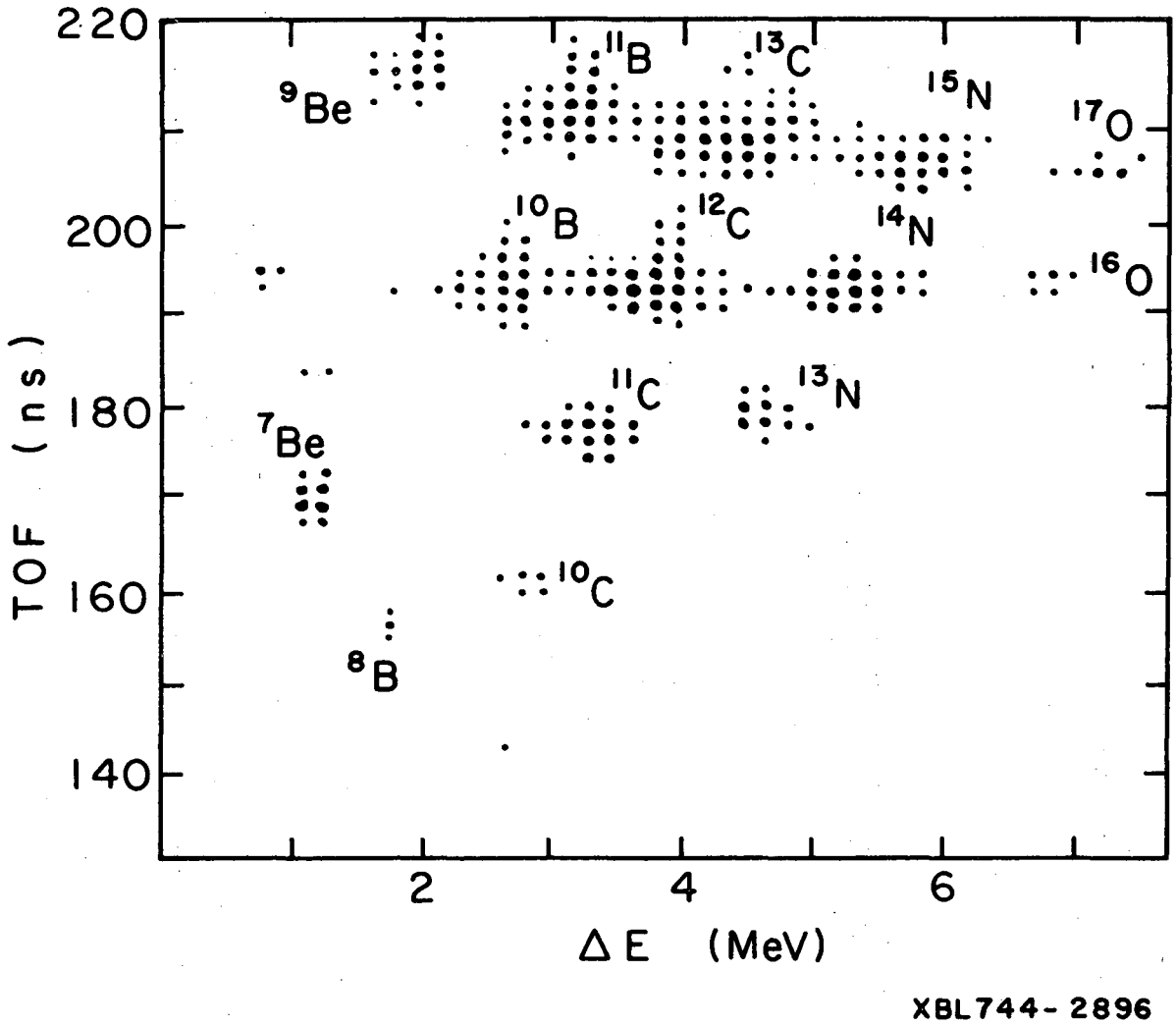

220
200
180
160
140
TOF (ns)
2
4
6
ΔE (MeV)
^{9}Be
^{11}B
^{13}C
^{15}N
^{17}O
^{10}B
^{12}C
^{14}N
^{16}O
^{7}Be
^{11}C
^{13}N
^{10}C
^{8}B
XBL744-2896

Fig. 1

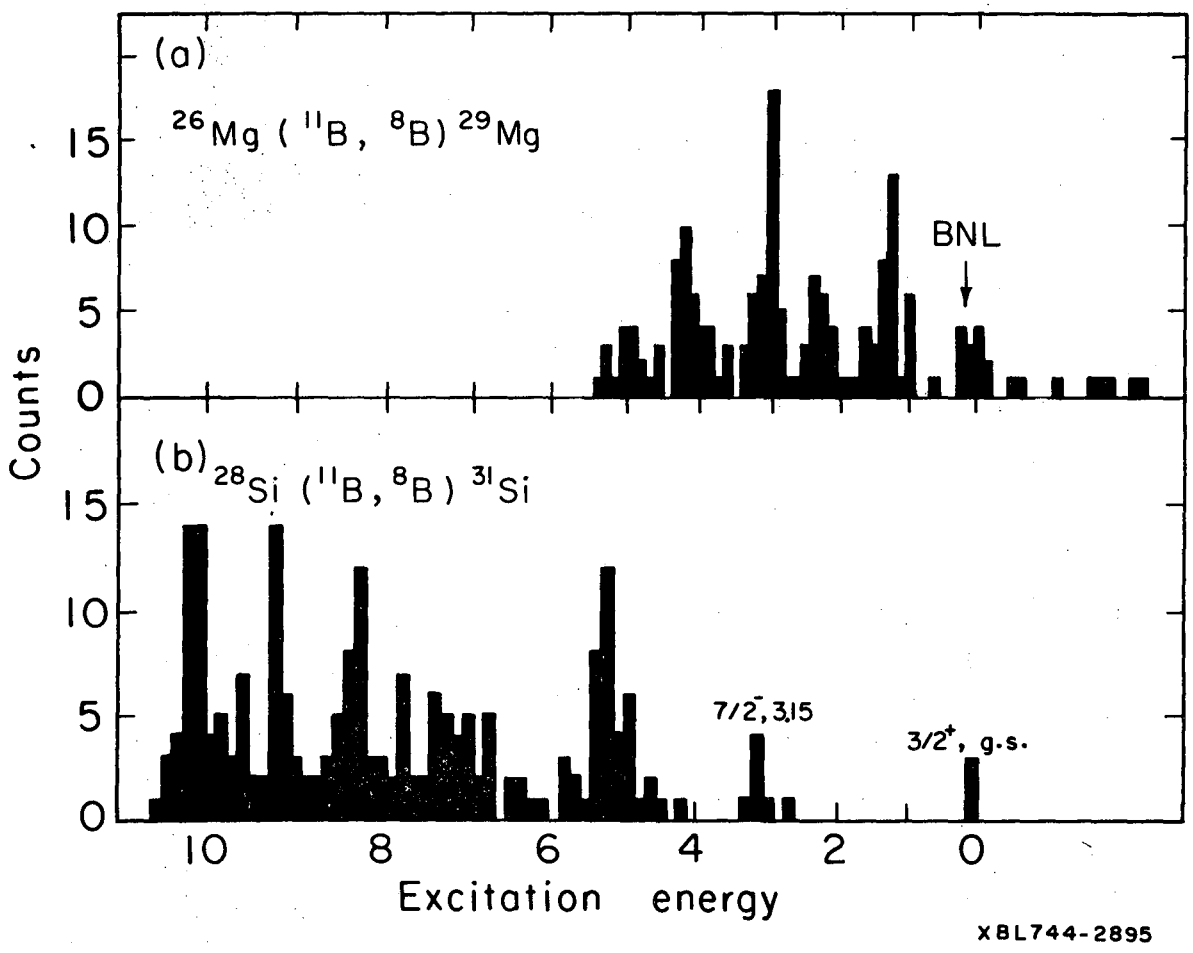
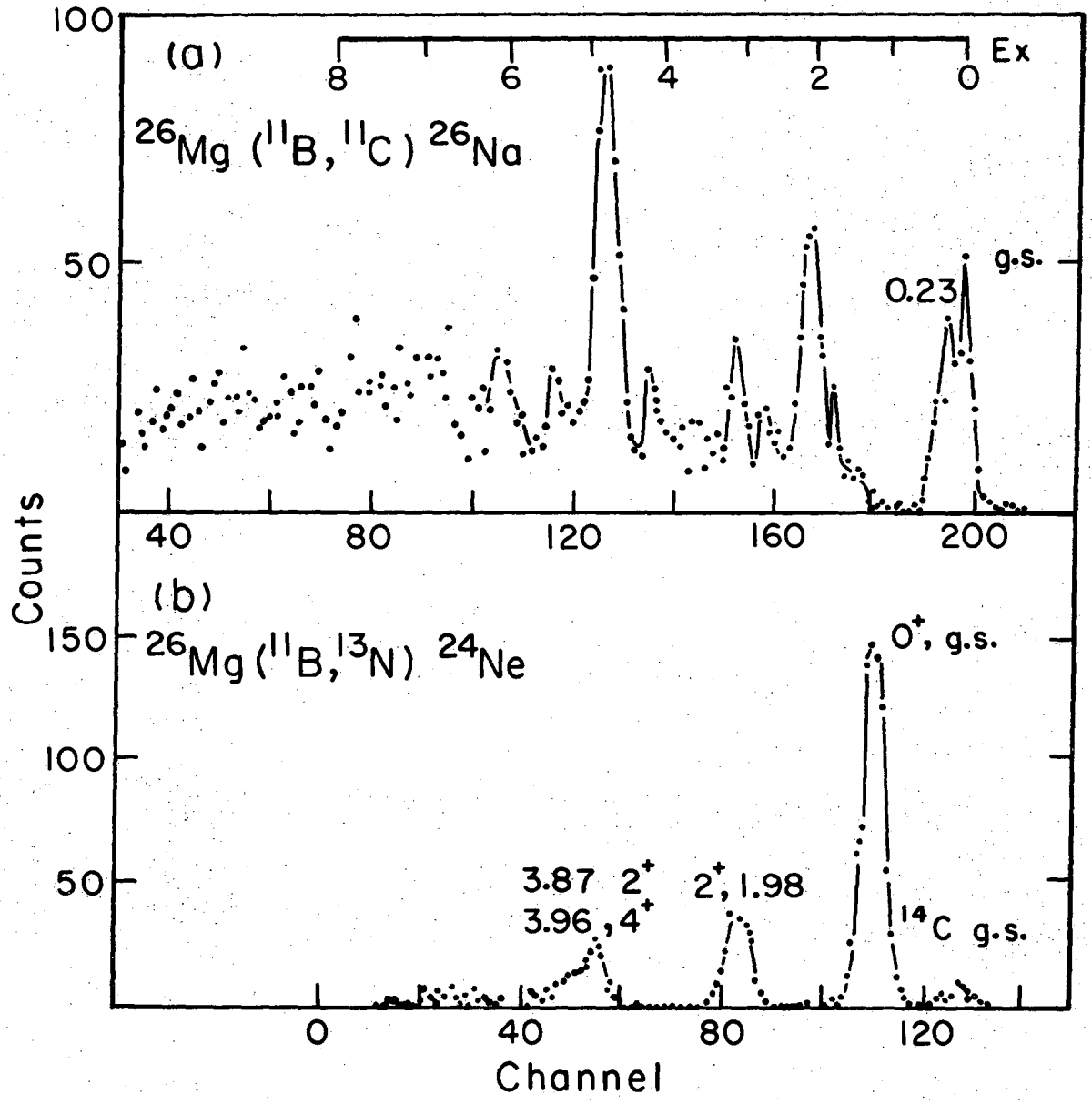

(a)
^{26}Mg (^{11}B, ^{8}B) ^{29}Mg
BNL
(b) ^{28}Si (^{11}B, ^{8}B) ^{31}Si
7/2⁻, 3.15
3/2⁺, g.s.
Counts
Excitation energy
XBL744-2895

Fig. 2



XBL 744-2897

Fig. 3

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