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Berkeley, California

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Nuclear Physics

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ISOBARIC SPIN NON-CONSERVATION IN THE DELAYED ALPHA DECAY OF Na^{20}

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Isobaric Spin Non-Conservation In
The Delayed Alpha Decay of Na²⁰

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Abstract: The delayed alpha emitter, Na²⁰, was produced in bombardments of Ne²⁰ ions with various targets by what may be a neutron-proton exchange reaction. The alpha particle spectrum associated with the β^+ -decay of Na²⁰ was measured and four alpha groups were observed corresponding to transitions from known 2⁺ states in Ne²⁰ at 7.40, 7.82, 9.48, and 10.28 MeV to the ground state of O¹⁶. Evidence was obtained giving support to the suggestion that the 10.28 MeV level is the lowest lying T = 1 state of Ne²⁰. The effect of isobaric spin admixing on enhancing beta decay transition rates and hindering alpha decay transitions is clearly seen in this study.

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1. Introduction

The delayed alpha emitter, Na^{20} , was first observed by Alvarez¹ and confirmed shortly afterward by Shelton². This nucleide decays by β^+ -emission, with a half-life of 0.385 sec³ to alpha particle unstable states of Ne^{20} at excitation energies of 8-10 MeV. Prior to the work reported here, high resolution measurements had not been made of the alpha particle spectrum.

We have measured the alpha particle spectrum associated with Na^{20} decay and have found that each of the groups observed can be correlated with previously measured 2^+ levels of Ne^{20} . Of particular interest is a 2^+ , $T = 1$ state at 10.28 MeV in Ne^{20} which is significantly populated in Na^{20} β^+ -decay and which alpha decays to the ground state of O^{16} , a transition which does not conserve isobaric spin.

2. Experimental Procedure

Bombardments were made with the heavy ion beams of the Berkeley heavy ion linear accelerator (HILAC) and using a target assembly and detection system designed for studying short-lived alpha emitters. The details of this system are described elsewhere⁴. A gold-surface barrier solid state detector was used in obtaining particle spectra. The energy of the heavy ions was varied using Ni degrading foils placed close to the targets. The range-energy curves of Roll and Steigert were used to obtain the residual energy of the degraded beam⁵.

Some simple dE/dx experiments were performed in order to identify the particles detected. A thin Al leaf absorber of known thickness was placed between the source and the detector, and the decrease in the energies of the various groups was measured and compared with the expected attenuation for different types of charged particles.

Calibration of the system for alpha particle energy was made using U^{234} [4.75 MeV (average)]⁶, Am^{241} (5.48 MeV)⁷ and Dy^{150} (4.23 MeV)⁸. Points below 4 MeV were obtained using a calibrated pulse generator.

3. Results

3.1 Ne^{20} bombardments

Our first observation of Na^{20} delayed alpha activity was in measurements of the alpha particle spectra of the products of $Ru^{96} + Ne^{20}$ and $Pd^{102} + Ne^{20}$ reactions using 80 to 200 MeV Ne^{20} ions. We had been using these reactions to produce very neutron deficient Te and Sb isotopes in order to determine whether alpha or proton emitters could be detected in this region. With both the Ru^{96} and Pd^{102} targets, we observed alpha groups (established by dE/dx experiments) at 2.14, 2.49, 3.80, and 4.44 MeV (lab). Further bombardments using Al, Ni, and Cu targets and Ne^{20} as the projectile, also produced these alpha groups with the same relative intensities. This meant that the activity was associated with the Ne^{20} projectile and not with any particular target. This was confirmed by bombarding the same targets with O^{16} and F^{19} ions where only a very small amount of the alpha activity was observed. Meaningful excitation functions could not be obtained since both the target and absorber used to degrade the beam energy contributed to the production of this alpha activity. The most likely nuclide which could give rise to these alpha groups appeared to be Na^{20} , a nuclide which decays by β^+ -emission to alpha particle unstable states of Ne^{20} . Alvarez¹ established that the alpha particles had an energy greater than 2 MeV but a detailed spectrum has never been measured.

Half-life measurements of the stronger groups (2.14 and 4.44 MeV) when the activity was produced by the reaction $Al^{27} + Ne^{20}$, yielded a value of

0.62 \pm 0.06 sec., which is not in agreement with the reported value of the half-life of Na²⁰.

Alpha particle spectrum taken for the products of a Ne²⁰ + Al²⁷ reaction for a long bombarding time is shown in fig. 1. In addition to the four groups mentioned above, there was an indication of a group or groups between 4.6 and 5.2 MeV but the intensities of these were too low to establish their existence with certainty. Nothing was observed in the energy range 1 - 2 MeV where the background was still low enough to detect weak groups.

3.2 B¹⁰ and B¹¹ bombardments

In order to determine whether the alpha activity observed in the Ne²⁰ bombardments was due to Na²⁰, the alpha particle spectrum of this nuclide was measured when it was produced by simple compound nucleus reactions. The reactions studied were C¹²(B¹⁰, 2n) Na²⁰, C¹²(B¹¹, 3n) Na²⁰, and B¹¹ + B¹⁰. The products of the first two reactions yielded alpha particle spectra which contained groups with the same energy and relative intensity observed in the Ne²⁰ bombardments and which decayed with a half-life of 0.39 \pm 0.05 sec., a value in agreement with the reported half-life of Na²⁰. The B¹¹ + B¹⁰ reaction did not produce this alpha activity over a broad range of bombarding energies [36 - 112 MeV (lab)]. This established that the activity was due to an isotope of Na. Excitation functions were obtained using the intensities of the more prominent 2.14 and 4.44 MeV alpha groups to determine the relative yield. The shapes of the excitation functions, shown in fig. 2, are characteristic of compound nucleus reactions. For both the C¹² + B¹¹ and C¹² + B¹⁰ reactions, the activity was not detected at low energies but became measurable at energies near and above threshold energies for the C¹²(B¹¹, 3n) Na²⁰ and

$C^{12}(B^{10}, Zn)Na^{20}$ reactions (23.8 and 12.4 MeV respectively)⁹. The relative intensities of the alpha groups were independent of bombarding energy. These results showed that the alpha groups were associated with the same nuclide and also established that this nuclide was Na^{20} .

4. Discussion

4.1 Interpretation of the half-life measurement on Na^{20} . The half-life of Mg^{20}

That the apparent half-life of Na^{20} was longer than the true half-life when Na^{20} was produced in $Al^{27} + Ne^{20}$ bombardments was interpreted to mean that some Mg^{20} was also produced and a good fraction of the Na^{20} was in a state of transient equilibrium with this nuclide. If this is the case, the apparent half-life obtained for Na^{20} (0.62 sec.) is actually the half-life for Mg^{20} decay. No experimental information has been reported for this nuclide but predictions have been made concerning its existence. Zeldovich reported that it should be stable toward proton decay, have an E_{β^+} of 9.4 MeV and decay with a half-life of 0.7 sec.¹⁰

4.2 Mechanism of Na^{20} formation in Ne^{20} reactions

For the $Ne^{20} + Al^{27}$ bombardments, Na^{20} (plus other nucleides which eventually β^+ decay to Na^{20}) can be produced as a spallation product of the target and projectile. When higher Z targets far removed from Na^{20} are used, it appears that Na^{20} is produced mainly from the Ne^{20} projectile. Simple energy considerations suggest that the most plausible mechanism of formation is a proton-neutron exchange between the target nucleus and projectile. Measurements of the angular distribution and kinetic energies of the Na^{20} product would show whether this was indeed the mechanism.

4.3 Delayed alpha decay scheme of Na^{20}

The values for the alpha particle energies and their relative intensities are listed in table 1.

Using these Q -values and the alpha particle binding of Ne^{20} (4.730 MeV)¹¹ the energies of the alpha decaying levels in Ne^{20} can be calculated. These are compared in table 2 with previously measured energy levels of Ne^{20} which coincide in energy together with their spins and parities. A partial decay scheme showing the alpha transitions is given in fig. 3.

With the exception of the 10.28 MeV level, the total widths of the levels which are significantly populated in the β^+ decay of Na^{20} have been previously measured by nuclear reaction studies¹¹. In each case the total width is essentially equal to the alpha width because the partial widths for radiative transitions at this excitation energy should not be more than ~ 100 ev. This is based on single particle estimates of the lifetime of an unhindered EI transition. The relative intensities of the alpha groups then, are directly related to the beta branching fraction to these levels.

As shown in table 2, the major levels of Ne^{20} which are populated by the β^+ decay of Na^{20} and which alpha decay are all 2^+ levels. The ground state spin and parity of Na^{20} are not known. However, the most probable assignment based on F^{20} measurements¹¹ is that it is 2^+ . Positron decay from Na^{20} to the 2^+ levels of Ne^{20} should then fall into the classification of allowed unfavoured transitions. To determine whether this is consistent with our data, we obtained estimates of $\log ft$ values for the transitions which involve delayed alpha particle emission. The nuclide F^{20} decays 100% to the 2^+ level of Ne^{20} at 1.63 MeV and the $\log ft$ for this transition is 5.1. We assigned this same $\log ft$ value to

Na^{20} decay to the 1.63 MeV level and to the 7.40 MeV 2^+ level which is alpha particle unstable. No levels are known between these two 2^+ levels which would be populated by an allowed beta transition from Na^{20} . From the intensities of the alpha groups decaying from the 7.82, 9.48, and 10.28 MeV levels relative to the intensity from the 7.40 MeV level, log ft values and beta branching fractions were calculated. These are listed in table 3. The log ft values for the transitions to the 7.82, 9.48, and 10.28 MeV levels are consistent with the values observed for allowed unfavoured transitions.

Errors in our estimates of these log ft values and beta branching fractions could arise from the presence of 1^+ and 3^+ levels below 10 MeV since these would also be populated in Na^{20} decay by allowed transitions but would have extremely small alpha widths for decay to the ground state of O^{16} . No 1^+ or 3^+ levels have been observed but the techniques which have been used for studying the levels of Ne^{20} may have been fairly insensitive to the detection of these levels. The presence of a quadrupole γ -vibrational band below 10 MeV for example could give rise to a highly excited 3^+ level. If this level were significantly populated in Na^{20} decay a search for alpha decay from this level to the ground state of O^{16} would provide one of the strongest tests of parity conservation in strong interactions.

Analysis of the low-lying energy levels of Ne^{20} by Litherland¹², Hunt¹³, Pearson¹⁴, and Kuehner¹⁵, has shown that they can be ascribed to well-defined sets of rotational levels associated with various modes of vibration of the Ne^{20} nucleus. The alpha decaying states at 7.40, 7.82, and 9.50 MeV have been assigned to different rotational bands.

4.4 The 2^+ level at 10.28 MeV

Isobaric spin assignment

This level was first reported by Pearson and Spear¹⁶ who detected it by the reaction $O^{16}(\alpha, \gamma)Ne^{20}$. They assigned a spin and parity of 2^+ to this state and postulated that it was the lowest lying $T = 1$ state of Ne^{20} on the basis of radiative width measurements.

Levels in this region of excitation have also been extensively studied by Hunt using the $O^{16}(\alpha, \alpha)O^{16}$ reaction¹³. He did not observe this level but this is the result to be expected if the state is indeed $T = 1$. Alpha particle elastic scattering from this state could only arise from the very small isobaric impurity component of the ground state of O^{16} . Reactions of the type $O^{16}(\alpha, \gamma)Ne^{20}$, however, can proceed via $T = 1$ states of Ne^{20} because the isobaric spin impurity component of the highly-excited intermediate state can be quite large.

Our results show that the β^+ decay of Na^{20} to the 10.28 MeV level of Ne^{20} is highly favoured over transitions to lower lying states having the same spin and parity and to states just above the 10.28 MeV level. The reason for this enhanced beta transition is undoubtedly due to the fact that the 10.28 MeV level is the lowest lying $T = 1$ state of Ne^{20} and is the $T_z = 0$ state of the mass 20 isobaric triplet.

The presence of a $T = 1, 2^+$ level at 10.28 MeV affects the properties of the 2^+ level at 9.50 MeV, as one would expect. This level elastically scatters alpha particles so it must, therefore, have a large $T = 0$ component. However, our results show that it is preferentially populated over lower lying 2^+ states in $Na^{20} \beta^+$ decay which indicates the presence of a significant $T = 1$ impurity component from the 10.28 MeV.

4.5 Comparison of the calculated and experimental energy of the first $T = 1$ state of Ne^{20}

Wilkinson has developed a method for calculating the position of the first $T = 1$ state of self conjugate nuclei making use of experimentally determined ground state mass differences of the $T_z = +1$ and $T_z = 0$ isobars of mass number A , and the mass differences of the $(A-1)$ mirror pairs to obtain the Coulomb energy correction¹⁷. The difference between the calculated and experimental energy (Δ) has been interpreted by Wilkinson as being due to a measure of the relative strengths of the n-n and n-p singlet forces.

For Ne^{20} , the necessary atomic masses needed for the calculation are known with a high degree of precision⁹. The assignment of the first $T = 1$ state is now known with certainty and its position has been measured with relatively high precision. From these data, a precise value of Δ for Ne^{20} can be obtained. The value of Δ is defined as:

$$\Delta = E_{T=1}(\text{calc}) - E_{T=1}(\text{exp})$$

Using the mass tables of König et al⁹, and making the necessary corrections for the difference between the neutron and proton masses, and effect of nuclear radius on the Coulomb energy, a value of 10.219 ± 0.005 is obtained for $E_{T=1}(\text{calc})$. Comparing this with the experimental energy, a value for Δ of -0.06 ± 0.011 MeV is calculated. The experimental energy and the calculated result are quite close as it was in the cases considered by Wilkinson. This agreement is, of course, a reflection of the well-established charge independence of nuclear forces. The value of Δ for Ne^{20} is negative, however, whereas for the nucleides considered by Wilkinson, an average

positive value was obtained, an indication that the n-p force is slightly stronger than the n-n force. It would be difficult to determine the reasons for the negative Δ for Ne^{20} . Another nucleide in this region, F^{18} , also has a negative Δ (-0.046 ± 0.014) so that there may be some effect peculiar to the region around Ne^{20} . The fact that some nucleides in this region are now known to be deformed may have some bearing since deformation will alter the nuclear Coulomb energy.

4.6 Alpha widths

The total widths (essentially the alpha widths) of the 7.40, 7.82, and 9.48 MeV 2^+ levels which are populated in Na^{20} β^+ decay, are known from previous work and are listed in table 3¹⁰. From our measurements we conclude that the width of the 10.28 MeV level is < 10 keV. The Coulomb barrier is mainly responsible for the low values of \int for the 7.40 and 7.82 MeV levels. For levels above ~ 8 MeV, the alpha barrier-penetrability factor approaches unity and the widths for several levels above this energy approach 1 MeV. The width of the 9.48 MeV 2^+ level (24 keV) is quite low and must be due to the $T = 1$ impurity admixture from the 10.28 MeV level. Calculations made following the procedure used by Wilkinson¹⁸ show that the alpha width of the $T = 0$ level at 9.48 MeV should be reduced to ~ 16 keV due to the presence of a 2^+ , $T = 1$ state at 10.28 MeV.

The 10.28 MeV $T = 1$ level is in a region of excitation where large isobaric spin impurities of levels may be expected due to the high density of states. The origin of the $T = 0$ impurity of the 10.28 MeV which allows it to alpha decay to the ground state of O^{16} may be the 2^+ level at 9.50 MeV or higher lying 2^+ levels which have not been identified.

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Table 1

Summary of Results of Alpha Energy Measurements

E_{α} (MeV) lab	Q_{α} (MeV) c. m.	Relative Intensity*
2.14 ± 0.02	2.67 ± 0.02	100
2.49 ± 0.03	3.09 ± 0.03	5
3.80 ± 0.03	4.75 ± 0.03	1.6
4.44 ± 0.01	5.55 ± 0.01	21

* Normalized to the intensity of the 2.14 MeV group which was arbitrarily set equal to 100

Table 2

Assignment of Alpha Groups to Known Levels of Ne²⁰

Ne ²⁰ Excitation Energy (MeV) (from alpha energy measurements)	Known Levels of Ne ²⁰ which coincide in energy ¹¹		
	<u>Energy</u>	<u>J^π</u>	<u>(keV)</u>
7.40 ± 0.02	7.43	2 ⁺	8
7.82 ± 0.03	7.84	2 ⁺	2
9.48 ± 0.03	9.50	2 ⁺	24
10.28 ± 0.01	10.27	2 ⁺ (T=1)	< 10

Table 3

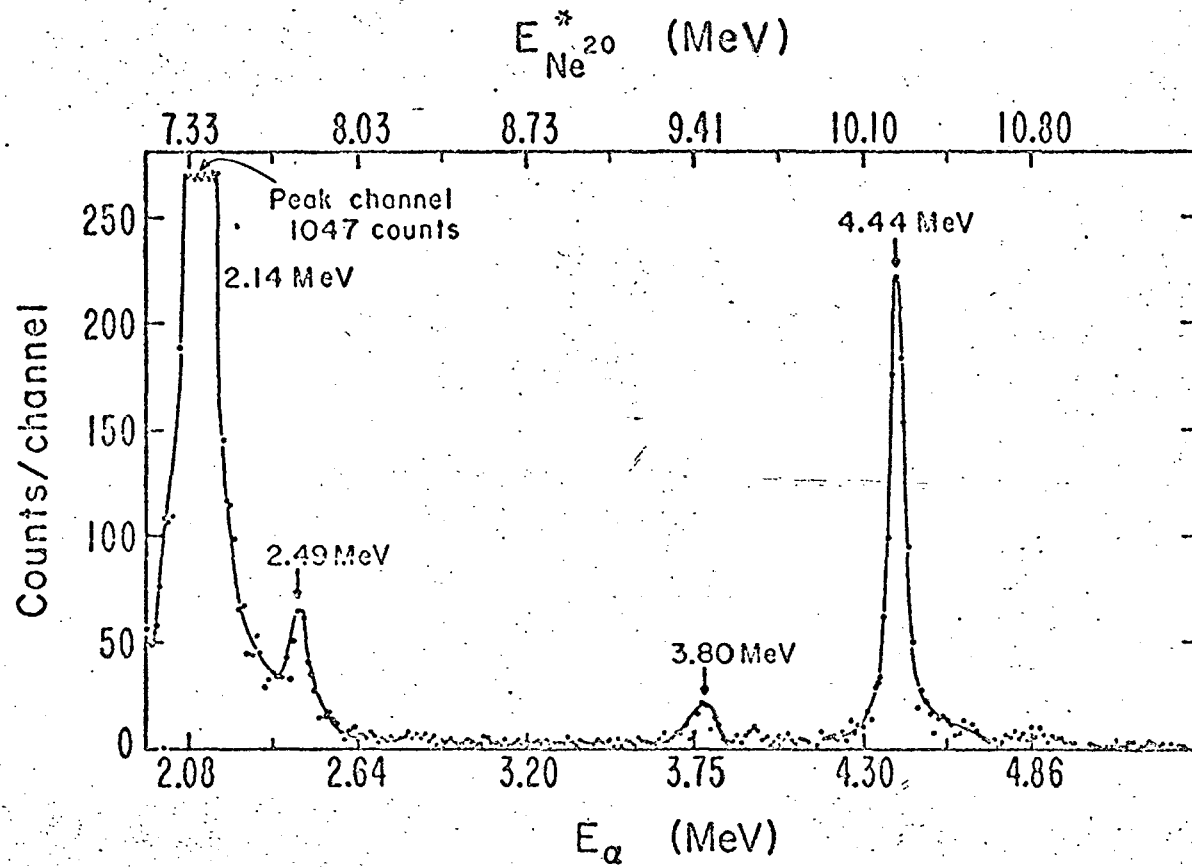
Estimated Log ft Values and Beta Branching Fractions Related to the Na²⁰ Decay Scheme

Transition	Level (Ne ²⁰)	E _{β⁺} max	Partial t _{1/2} (Sec)	Log ft	Beta Branching Fraction
Na ²⁰ (2 ⁺) → 2 ⁺	1.63 MeV	12.7 MeV	0.41	5.1*	0.94
→ 2 ⁺	7.40	6.9	~8	5.1*	~0.047
→ 2 ⁺	7.82	6.5	~160	6.3	~0.002
→ 2 ⁺	9.48	4.8	~500	6.1	~0.0008
→ 2 ⁺	10.28	4.0	~38	4.7	~0.01

* Assumed value taken from F²⁰ decay

Figure Captions

- Figure 1 The alpha particle spectrum associated with the delayed alpha decay of Na^{20}
- Figure 2 Excitation functions for the production of Na^{20} by $\text{C}^{12} + \text{B}^{10}$ and $\text{C}^{12} + \text{B}^{11}$ reactions. E_B refers to the centre-of-mass energy of the B^{10} and B^{11} projectiles
- Figure 3 Partial decay scheme for Na^{20} showing the transitions which involve alpha decay to the ground state of O^{16} .



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Figure 1



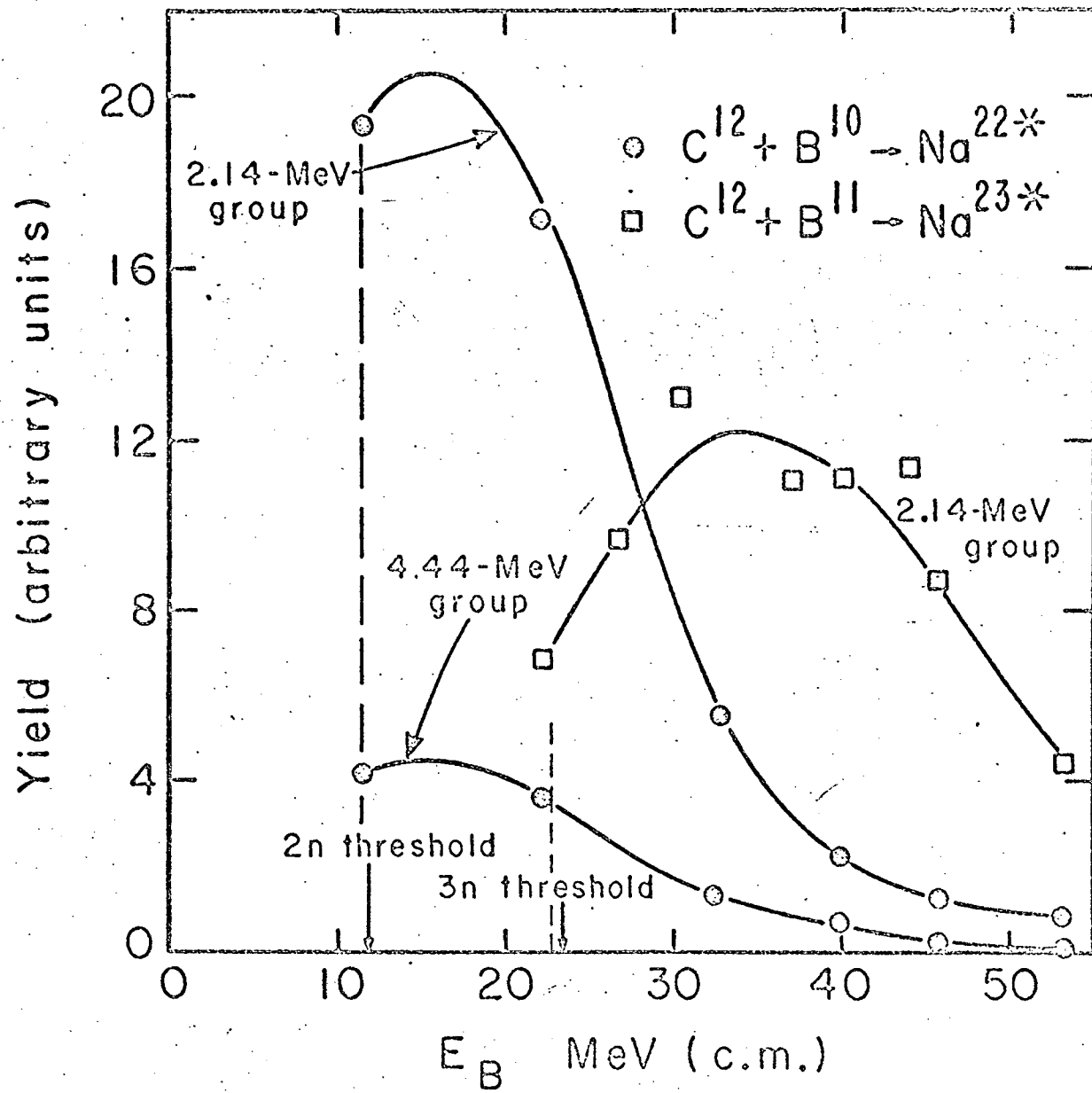
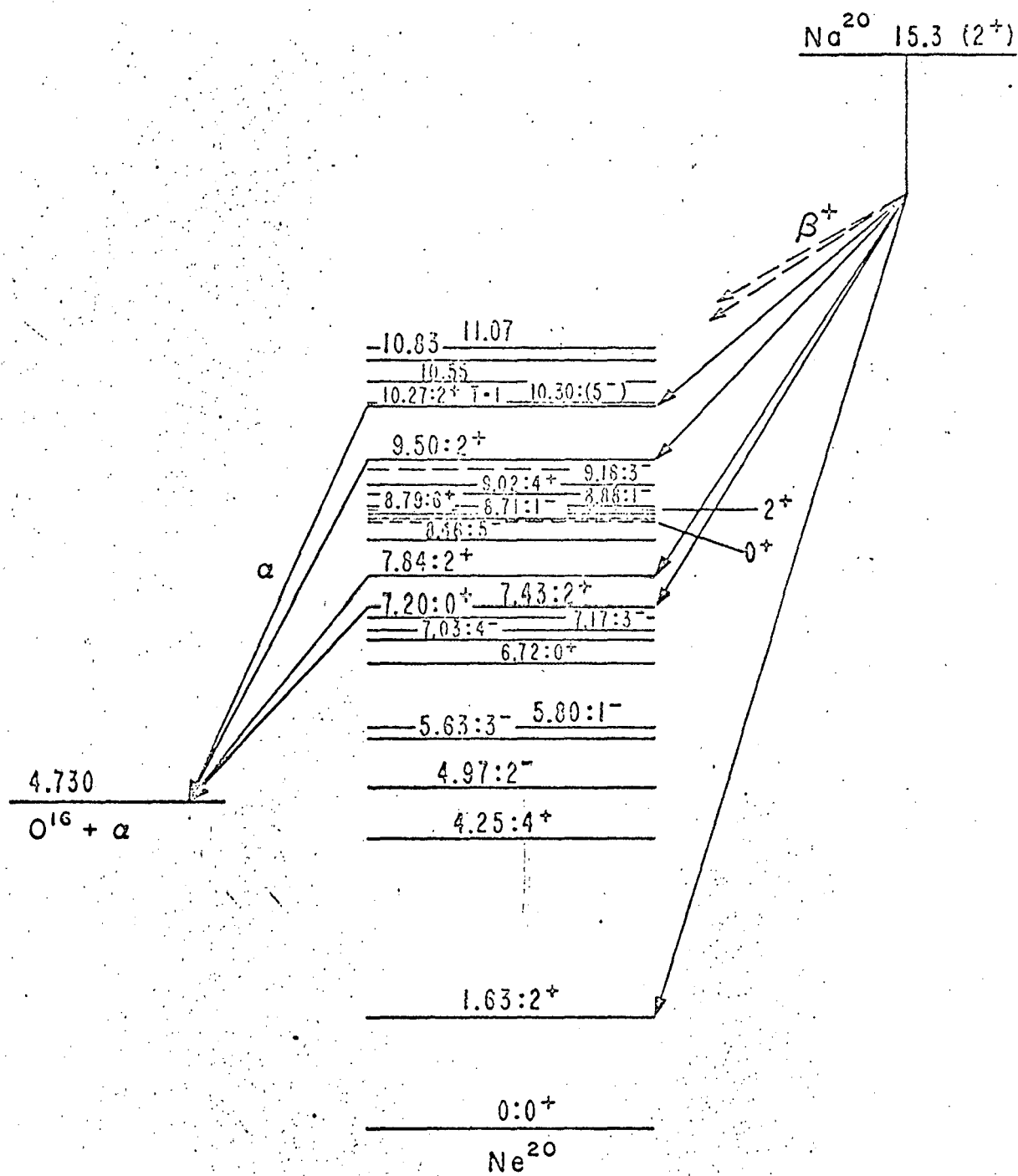


Figure 2

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Figure 3

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