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The Light Nuclei

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Being a highly subjective account of the last two decades of nuclear spectroswpy intended for a mixed audience of nuclear and non-nuclear physicists.

All of you who are not nuclear physicists are well aware of the more sensational developments in nuclear physics in the last 15 years; the role of beta-decay in the discovery of the non-conservation of parity, especially the work of Madame Wu and her collaborators, the beautiful Goldhaber-Grodzins-Sunyar experiment on the helicity of the neutrino, the Mossbauer effect. But, do you know as much about our major effort in time and interest – namely, the study of the structure of nuclei?

Today I would like to talk to you about the structure of the light nuclei, a subject which has seen a great deal of activity in the last few years and one which has been my work and play for 18 years. This will be both a very personal view and a very personal history. As always, the hope is that reflection on the past can help guide the future.

The major part of the nuclear spectroscopy in which I have been involved has used the 3.7-Mev Van de Graaff accelerator at Brookhaven National Laboratory. Because of the Coulomb barrier between target nuclei and projectile, our studies with the Van de Graaff have been limited to nuclei with rather low Z – those with mass numbers less than about 50. These we term the light nuclei.

Let me give you a brief history of research on the structure of the light nuclei. The initial work focussed largely on the nuclei lighter than oxygen. Following the development of the shell model by Mayer[1] and Jensen[2] in the late forties and early fifties, and the historic Rev. Mod. Phys. article of Inglis[3] in 1953, it was clear that the shell model had a high degree of applicability in the nuclei lighter than O^{16}. From Li^5 through O^{16} the 1p oscillator shell is filling and, as it fills, the relative importance of the $\mathbf{l}\cdot\mathbf{s}$ term increases so that the situation changes from predominantly LS-coupling to predominantly jj-coupling. This intermediate coupling situation was treated fairly successfully in the fifties and early sixties by Kurath, by Elliot and Flowers, and by Lane (to name a few). In the meantime, others (e.g., deShalit, Talmi, French) were pursuing fundamental studies of the shell model, developing theoretical techniques, and exploring to what extent the model was applicable to nuclei in the 2*s*, ld oscillator shells, that is, the nuclei with mass numbers between O^{16} and Ca^{40}. Even at his stage the shell model was much more sophisticated than the first primitive start of Mayer and Jensen. In the lp-shell there was a spherical core of He^4 and up to 12 valence nucleons with residual interactions with each other as well as with the core. Thus, the situation was a rather complicated many-body problem and not at all a simple one to solve. One feature that bothered all was that the interaction potential was a phenomenological one, and no one really knew how well it simulated nature. It was like doing atomic physics without knowing the Coulomb interaction.

Now, what about the experimental side? All these theoretical studies fed on what was, by today's standards, rather skimpy experimental knowledge. But, slowly the improving technology was affecting experimental nuclear spectroscopy. The advent of fast, large memory on-line pulse-height analyzers and computers, improvements in electronics and accelerators, and especially the development of semi-conductor particle and gama-ray detectors all seemed to mesh together and stimulate the creation of brand new and powerful techniques of analysis. (As an example of improvement note that the modern $Ge(Li)$ gamma-ray detector has a resolution of about 5 keV for a 5-MeV gamma-ray, while the pre-1964 $NaI(Tl)$ detector resolution was typically 200 keV for 5-MeV radiation, an improvement of a factor of approx. 40. In 1964, the technical revolution was well underway – our knowledge of nuclear structure had doubled in the previous 5 years and was to double twice more by 1970.

How did the situation look to lp-shell nuclear spectroscopist in 1964? He was producing new information about 10 times faster than 10 years before, but the theorists were not using this information, and our theoretical understanding of the lp-shell nuclei seemed not be changing. It was for a few years a rather gloomy time when we thought often of the possibility that we would become – like the popular image of atomic spectroscopists – nothing but data collectors.

And, then the bottleneck which had been stopping progress in theory came unstuck. It is hard, even in retrospect, to see what had stopped progress so thoroughly. I think that perhaps there was a large element of psychology involved and that all the uncertainties about the procedures used stifled the creative process. Looking back, it seems that it was necessary to amass a seemingly over-abundance of experimental data before theory had enough touchstones to support itself. Of course, it took some time to develop the techniques necessary to harness large memory computers to the problem.

A big step forward concerned the interaction potential between pairs of nucleons. Gerry Brown, his student, Tom Kuo, and others developed techniques for obtaining the two-body matrix elements, which represent the interaction, directly from free nucleon-nucleon scattering data or at least, from a potential which fits that data This procedure is immensely more reassuring than the old use of a phenomenological potential. Another procedure, pioneered by Talmi, is to treat these two-body matrix elements as free parameters in a least squares fit to experimental binding energies. When this was done by Cohen and Kurath[4] in the lp-shell, the good agreement of the 2-body matrix elements with those derived from nucleon-nucleon scattering was very reassuring, indeed.

Let me illustrate nuclear spectroscopy in the lp-shell by work done at Brookhaven on the nucleus N^{14}.

In 1957-8, H. J. Rose, E. N. Hatch and I studied[5] the energy levels of N^{14}, illustrated in Fig. 1 (by a level scheme taken from a 1970 compilation[6]). How does one study such a nucleus? One of the pleasant aspects of experimental nuclear physics is the richness of approaches possible to solve a given problem. To study the excited states of N^{14} we could use any of the following reactions:

$N^{14}(e, e')$, $N^{14}(p, p')$, $N^{14}(d, d')$ — inelastic scattering

$C^{14}(p, n)$, $C^{14}(He^3, t)$ — charge exchange

$N^{15}(p, d)$, $N^{15}(He^3, \alpha)$ — one-nucleon pickup

$O^{16}(d, \alpha)$ — two-nucleonpickup

$C^{13}(p, \gamma)$ — radiative capture

$C^{13}(d, n)$, $C^{13}(He^3, d)$ — one-nucleon stripping

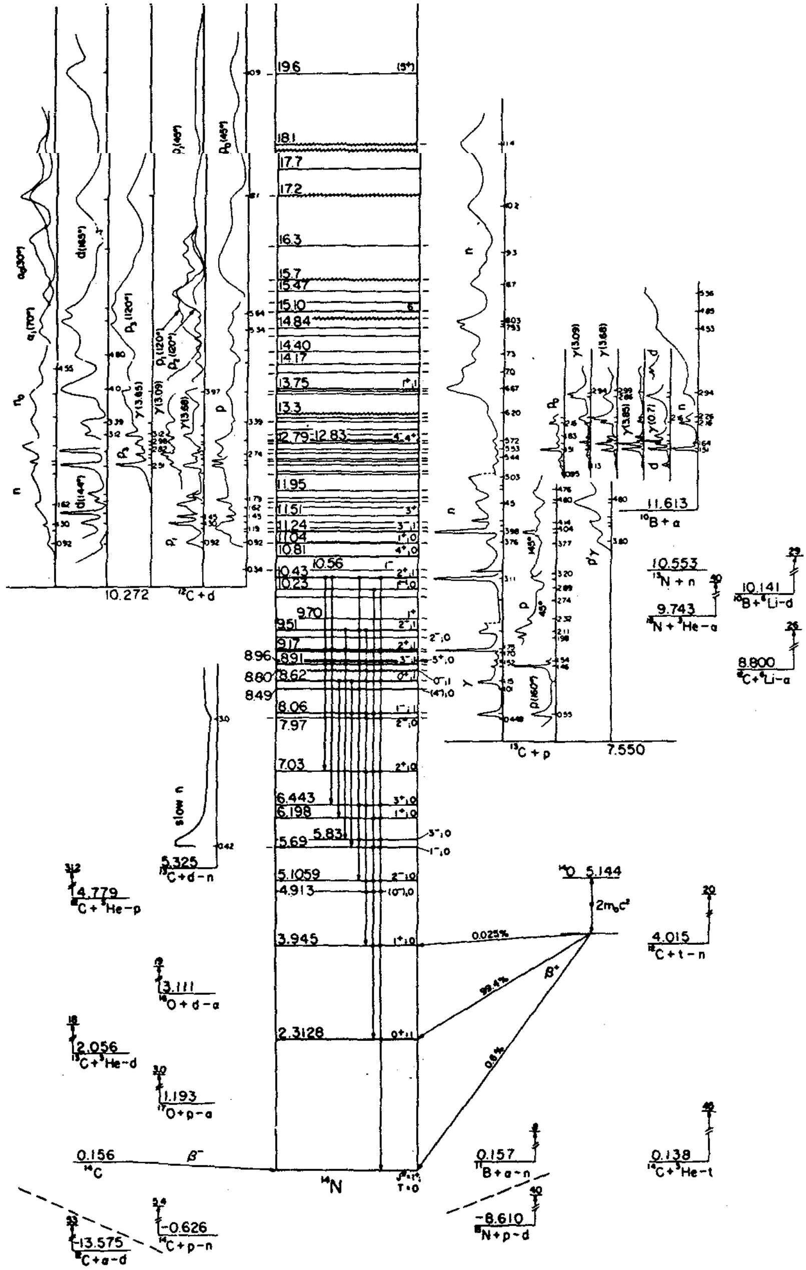

Fig. 1 - Energy level diagram for N^{14}. From Ref. 6.

$$\left.\begin{array}{l} C^{12}(He^3, p) \\ C^{12}(t, n) \end{array}\right\} \text{two-nucleon stripping}$$

$$\left.\begin{array}{l} B^{10}(Li^7, t) \\ B^{10}(Li^6, d) \end{array}\right\} \text{four-nucleon transfer}$$

etc.

What is one after? Besides excitation energies (binding energies) and spins and parities, we wich to determine the isospin and the electric quadrupole and magnetic dipole moments and transition rates (the transition rates coming from lifetime measurements) also particle reduced widths, that is, the probability that a state in a nucleus A can be described as a particle a coupled to a state in the nucleus A – a.

On the basis of electromagnetic transition rates and direct reaction cross-sections (reduced widths) and guided by theoretical work of Unna and Talmi[7] we concluded that three different types of energy levels were involved in the region within 10 MeV of the ground state.[8] 1) The even-parity s^4p^{10} states, 2) $s^4p^9(2s, 1d)$ states, and 3) $s^4p^8(2s, 1d)^2$ states, that is the normal 1p-shell states, states of odd-parity obtained by promoting a 1p nucleon to the 2s or 1d shell, and states of even-parity obtained by doubly-exciting two 1p-nucleons to the $(2s, 1d)$ shells. Note that states 1) and 3) can mix but neither mixes with 2) because of parity conservation.

This was one of the earliest studies of such depth in the 1p-shell. It was from investigations of this type that the trends and systematics of the static and dynamic properties of 1p-nuclei were exposed and this, in turn, prepared the way for the next stage of development – namely, multi-configurational calculations.

Let us now concentrate on the s^4p^{10} states of N^{14}. One of the most long-standing and intriguing puzzles in the $1p$-shell was the very long lifetime of C^{14} against beta decay to N^{14}. The Gamow-Teller matrix element essentially vanished, and a rigorous proof (Inglis[3]) could be given that this could not be achieved using s^4p^{10} wave functions generated from a central nucleon-nucleon interaction.

[Why not then ask for the coefficients in the expansion:

$$\psi(0^+,\ 1) = a\psi(p_{3/2}^{-1}) + b\psi(p_{1/2}^{-2}),$$
$$\psi(1^+,\ 0) = \alpha\psi(p_{3/2}^{-2}) + \beta\psi(p_{3/2}^{-1},\ p_{1/2}^{-1}) + \gamma\psi(p_{1/2}^{-2}).$$

We need three bits of independent data and the two normalization equations to solve for a, b, a, β, y. Why not

1) Beta decay between $(0^+,1)$ and $(1^+,0)$,
2)' $M1$ decay between (O ,1) and $(1^+,0)$,
3) $M1$ moment of $(1^+,0)$. 7

This gives a solution, but not a correct one. The difficulty is that $M1$ moments sufferfrom meson exchange currents **and** quenching effects of approx. *10-20%* **and,** in any case, p^{-2} wave functions only represent approx. 80% of the wave functions. Thus, neglecting the **small** admixtures **and/or** demanding an exact solution leads to misleading answers].

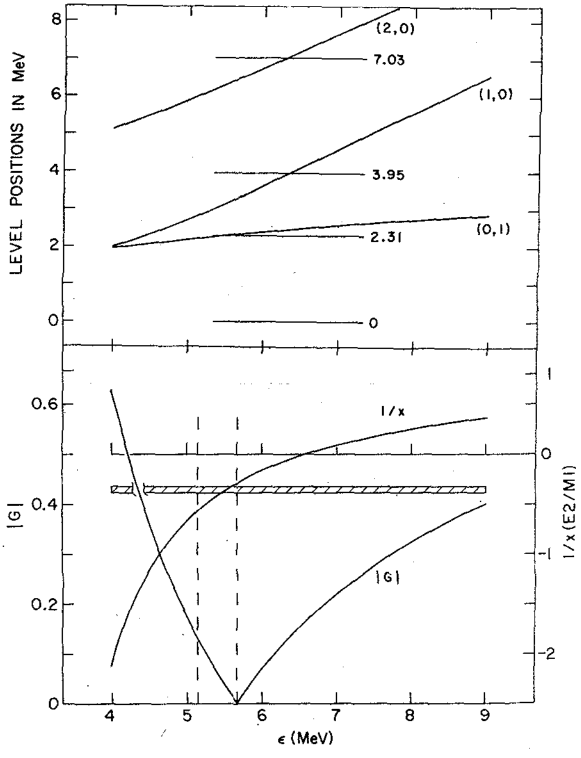

Fig. 2 - Results obtained from the (8-16)2BME **matrix** elements of **Ref.** 4. In the upper half of the figure the calculated **level** positions of ^{14}N are shown vs the $p_{3/2}-p_{1/2}$ splitting ε together with the experimental-level1 **scheme. In** the lower half $\langle G \rangle$ and the **reciprocal** of x(3.95 **MeV** $\rightarrow$ **gs)** is **plotted** vs ε. The hatched **area** corresponds to the experimental value $x = (2.87 \pm 0.27)$. The other possible value of x wrresponding to $-4.3 \lesssim 1/x \leq -2.3$ is not shown. The **meaning** of the dashed lines is explained in Ref. 9 from which the figure is taken.

The experimental information bearing on this problem was brought together in 1968 when H. J. Rose, O. Hausser and I made a comprehensive study[9] of all the electromagnetic transitions connecting the bound p^{10} states of N^{14} as well as the C^{14} beta decay, and achieved satisfactory agreement with experiment using slight modifications of existing wave functions, but including, importantly, the bits of $s^4p^8(2s, 1d)^2$ of approx. 5-10% mixed into the s^4p^{10} states. The results are shown partially in Fig. 2. The main point is that the longevity of C^{14} is due to cancellation within the s^4p^{10} contribution, and not between s^4p^{10} and $s^4p^8(2s, 1d)^2$, and is a natural consequence of the nucleon-nucleon force derived from free nucleon-nucleon scattering data. This force contains bits which are not central (in particular a tensor force is implied) thus allowing a solution. We would not have been sure of this explanation, which was prepared by many others before us, if we had not made a comprehensive comparison between theory and experiment.

Now, let us turn to another phenomena which puzzled us for many years, the collective enhancement of electric quadrupole transitions in lp-shell nuclei. The effect is quite large – giving us E2 rates approx. 4 times as large as calculated.[9] One can reproduce this effect quite well by endowing the neutrons with a charge of $(\frac{1}{2})$e and the protons an extra charge of $(\frac{1}{2})$e. This is illustrated in the table of Fig. 3, which shows a comparison between theory and experiment for E2 rates in N^{14}. We see collective enhancement is called for. The difficulty is to explain this enhancement (or the large effective charge, which amounts to the same thing) with the quite small quadrupole deformations present in lp-shell nuclei. The explanation has slowly emerged, due mainly to work by Kurath[10]: the quadrupole deformat-

Electric-quadrupole radiative widths (10^{-3} eV) connecting the four lowest s^4p^{10} states in ^{14}N.

	Transition						
	3.954		7.034		7.03→3.95		
Calculation	a	b*	a	b	a	b	7.03→2.31
Soper	1.47	5.89	18.46	73.84	0.16	0.62	1.33
Elliott	1.14	4.58	10.45	41.80	0.37	1.47	0.78
Visscher and Ferrell	1.33	5.32	6.58	26.30	0.20	0.81	0.94
Cohen and Kurath I	1.21	4.83	9.70	38.80	0.34	1.35	0.57
Cohen and Kurath II	1.11	4.43	8.35	33.40	0.37	1.47	0.50
Experiment	4.81f0.33		33±9		≤(1.1±0.3)		0.62±0.14

* The columns headed (a) have no collective enhancement of E2 rates. while those designated (b) have collective enhancement with $\alpha=0.5$.

Fig. 3 - Results of various shell-model calculations within the space s^4p^{10}. The references for both experiment and theory are given in Ref. 9 from which the table is taken.

ions, although small, mix into the 1p-shell bits of $1f$ and $2p$ configurations of approx. 5-10% intensity and, since these are mixed by a quadrupole force, they give a coherent effect on quadrupole matrix elements. We shall mention later another example of this type of specificity. It is rather amazing that we have only understood this in the last few years in spite of our excellent understanding of quadrupole deformations in rotational nuclei.

Now we consider a nucleus in the (2s, 1d) shell, F^{18}. This nucleus like N^{14} is close to my heart since we have studied it extensively at Brookhaven. Fig. 4 shows the experimental energy level scheme and theoretical results of Zuker, Buck and McGrory, (ZBM)[11], also carried out at BNL. This calculation explained our experimental work some six years after we accumulated it. Theory took awhile to catch up to experiment in this case. The ZBM work is a shell-model calculation involving an (assumed) $s^4p^8_{3/2}$ core of C^{12} and 6 particles free to roam in the $p_{1/2}$, $2s_{1/2}$ and $d_{5/2}$ shells. The force is fixed as one reproducing free nucleon-nucleon scattering with some corrections for core effects. This is truly a many-body calculation

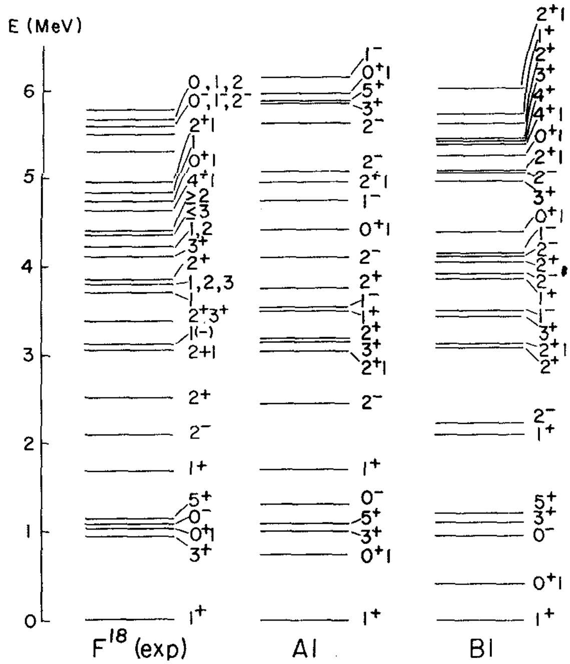

Fig. 4 - Shell-model calculations of Zuker, Buck, and McGrory (Ref. 11) compared to experiment.

and takes a large sophisticated computer program. The one used was provided by the Oak Ridge group of French, Halbert, McGrory and Wong. The output is the bindling energies of states of given spin, parity and isospin; the $M1$ and E2 matrix elements connecting these states, and some reduced widths. ZBM did similar calculations for masses 15-18 with startling success.

How does one test such a calculation? First, one compares the spectra of levels with given spin, parity, and isospin. Second, the results of various direct reactions are compared to the predictions of the calculation. As an example, the F^{18} calculation indicates that many of the low-lying states have simple parentage for neighboring nuclei. For instance, the 1.70-MeV, 2.52-MeV, and 3.35-MeV levels look remarkably like an alpha-particle coupled to the N^{14} ground state[12]. Thus, we expect them to be strongly formed in reactions which add an alpha to N^{14} such as $N^{14}(Li^7, t)$. In experiments by Middleton and collaborators at the University of Pennsylvania this was shown to be the case; and, in fact, the cross section for formation of these levels was observed to be larger than to any other. The lowest lying even-parity states look like two nucleons outside an O^{16} core. Thus, they are expected to be formed strongly by the $O^{16}(He^3, p)$ reaction This is also observed.

The third test is a comparison of electromagnetic transition rates. This is a sensitive test of the wave functions since there is, in the matrix elements, interference between the amplitudes of different contributions. The *ZBM* results give good agreement with experiment if the E2 rates are enhanced by a factor of approximately 4.

Let us now consider a nucleus in the region of the $(2s, 1d)$ shell where rotational effects are strong. This is the region from A = 19 to A = 25. The moment of inertia of an assumed rigid rotator has a local minimum at Na^{22} and the intrinsic quadrupole moment representing the deformation in shape of the nucleus also has a local maximum here. Thus, we expect to have some success in applying the Nilsson form of the rotational model to Na^{22}. (This model couples single-particle motions onto a deformed core). On the other hand, the properties of Na^{22} seem to be fairly well described by the shell model in calculations similar to those described for F^{18} but carried out at Oak Ridge. Among other things, the shell model calculations simulate the selection rules of the Nilsson model even though the shell model has a spherical basis. A word on the complexity of the shell model calculations – Na^{22} has 6 nucleons outside O^{16} and if we choose O^{16} as a core and only use the $s_{1/2}$ and $d_{5/2}$ shells (poor already!) then the Na^{22}, 3^+ ground state, has 29 terms – we must determine 435 interaction matrix elements and diagonalize the resulting 29 x 29 matrix in order to obtain the binding energy and wave function of the ground state.

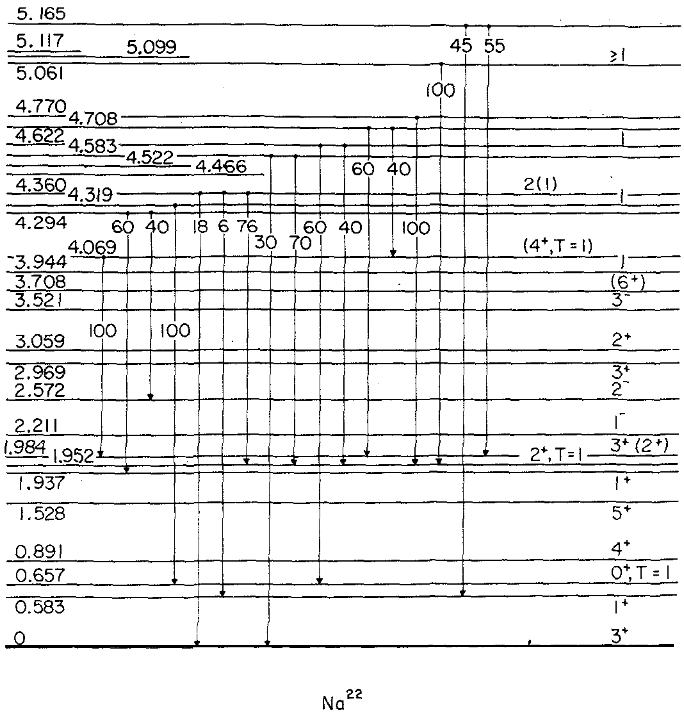

Fig. 5 - Summary of information on spins and parities for levels of ^{22}Na of E_x < 5.2 MeV. From Ref. 13.

The experimental level scheme of Na^{22} is shown in Fig. 5 and the rotational bands are illustrated in Figs. 6 and 7. This nucleus has been extensively studied in recent years with the bulk of the direct reaction studies performed at the University of Pennsylvania[14] and most of the y-ray work carried out at Brookhaven. From Fig. 6, we see that the energy levels of Na^{22} only approximate the J(J + 1) dependence expected for a rigid rotator. This is as expected for a light nucleus even though well described by the Nilsson form of the rotational model The important point is that the electromagnetic transitions within a band (see Fig. 7) follow rather closely the rotational model predictions and the selection rules for the intraband transitions are well obeyed.

So far'we have neglected experimental techniques. I would like to give three examples which illustrate the elegant **simplicity** with which nuclear **physics** research **can** be carried **out** today. Fig. 8 illustrates the **principle** of the "recoil **distance"** technique for **measuring** Iifetimes. This technique, suggested in its modern form by A. E. Litherland, **has** been applied to gamma-ray emitting states with **mean** lifetimes longer **than** 0.5 x 10^{-12} sec. Data for the ground-state decay of the third-excited state of Na^{Z2} is shown in Fig. 9. The time decay curve for **this level** and one other (obtained **si-multaneously**)are shown in Fig. 10. The lifetimes deduced from these data by Jones, Schwarzschild, Fossan and **myself**[15], are (14.4 $\pm$ 0.7) x 10^{-12} and (20.8 $\pm$ 1.0) x 10^{-12} sec., respectively.

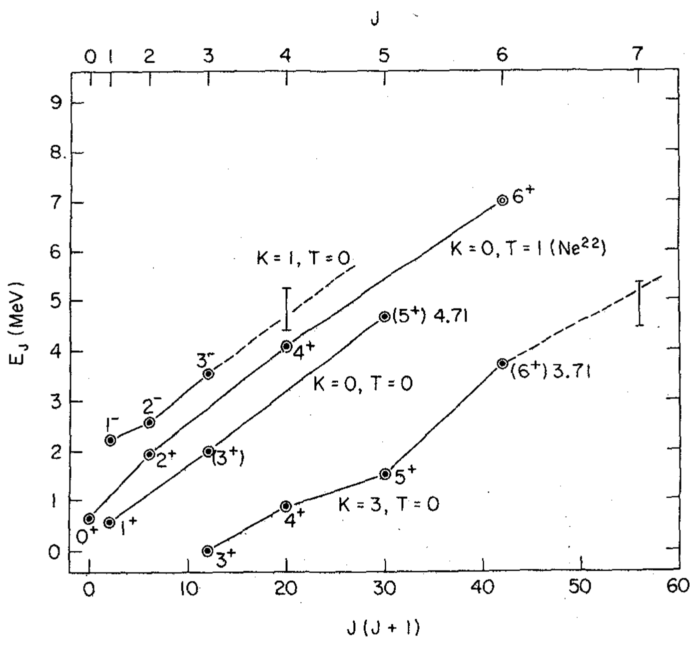

Fig. 6 - Plot of excitation energies E, **(in MeV)** for Na^{22} states with **spin** *J* **versus** J(J + 1) for those **levels** which have been **identified** with the **lowest-lying even-** and **odd-parity** bands of Na^{z2}, of the indicated intrinsic and **isotopic** spin (K, T). **Spin/parity** assignments which have not **been rigorously** determined, but **only** suggested, are enclosed in parentheses **Additionally**, **the** (*K*, T) = (0, 1) band **is** that of Ne^{zz} with the excitation energies **increased** by 0.66 **MeV.** From Ref. 13.

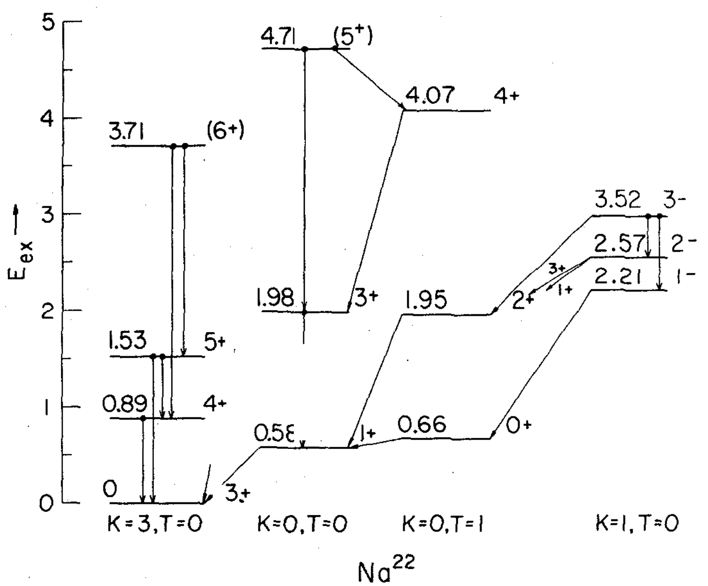

Fig. 7 - Intra- and inter-band gamma-ray transitions in Na^{22}.

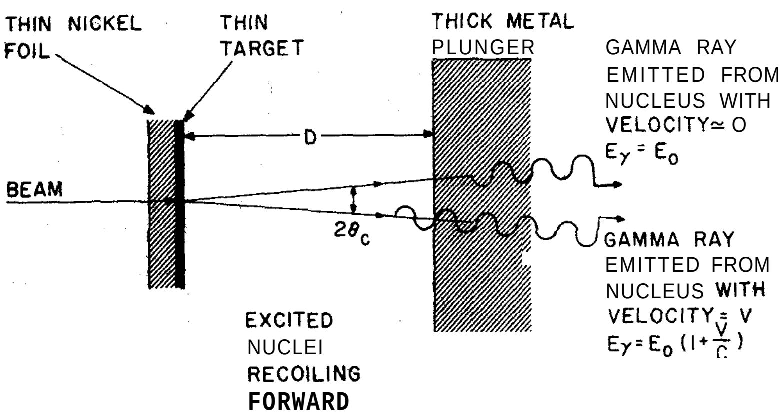

Fig. 8 - Recoil method of measunng lifetimes of excited states (from Ref. 15).

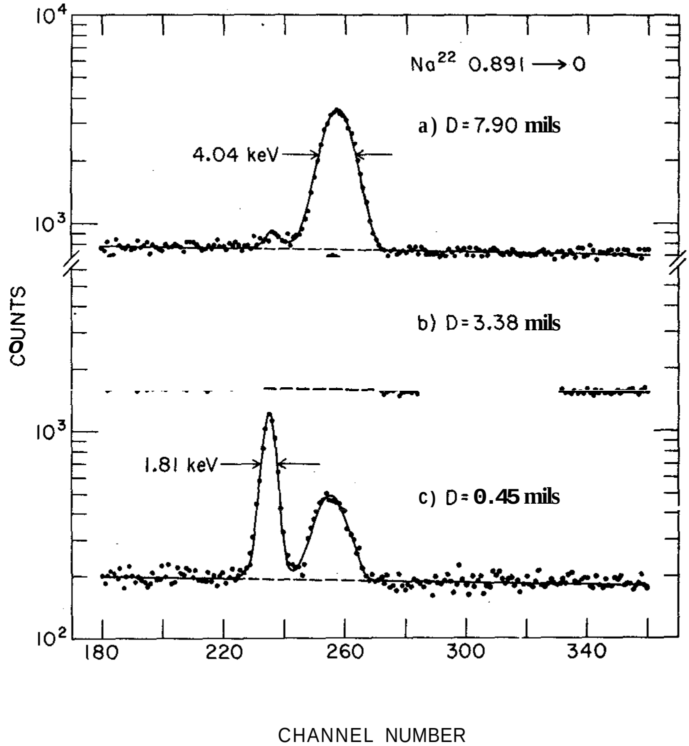

Fig 9 - The Na^{22}, *0.891* → *0* full-energy peak, viewed at 0° to the α beam in the $F^{19}(\alpha, n)Na^{21}$ reaction at $\bar{E}_\alpha = 5.5$ MeV. The presence of two γ-ray peaks with average energies E_0 and $E_0(1 + v/c)$ is evident as is the dependence of the relative intensities of these two peaks on the plunger displacement D. The energy dispersion is *0.33* KeV/channel *(1* mil = 25.4μ). From Ref. 5.

A related technique, also utilizing the Doppler shift of recoiling nuclei **is** to **form** the nuclei in a solid **medium** (the target) and allow them to slow **down** and stop in this **medium.** Some predictions for the resulting **distribution** of gamma-ray energies **observed** at 0" to the recoils are illustrated **in Fig. 11.** For lifetimes comparable to the time **taken** to stop the recoils, a lifetime measurement results as illustrated **in Fig. 12.** The stopping time for a typical solid **is** approximately 5 x 10^{-13} sec. This **method is good** to an **accuracy** of some **12%** for lifetimes between about 10^{-12} and 10^{-14} sec

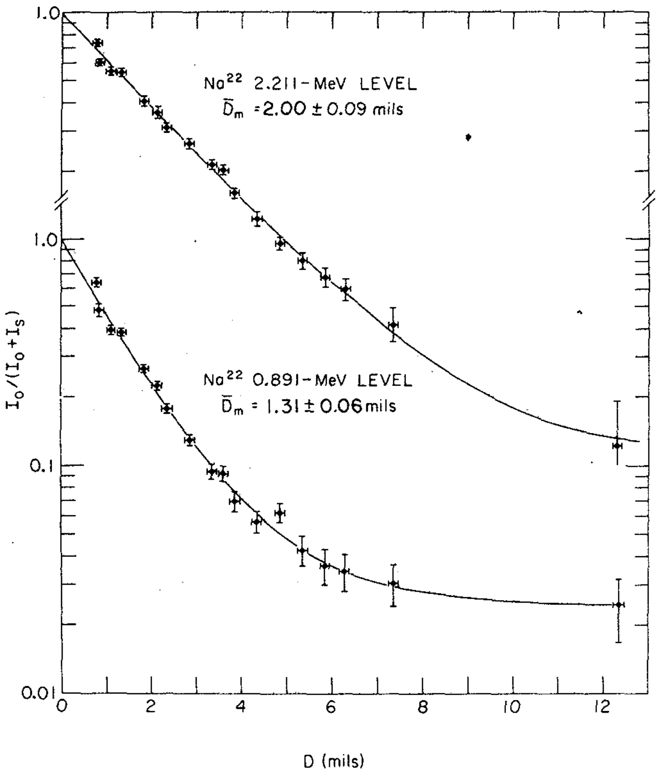

Fig. 10 - Decay curves for the Na^{22}, 0.891- and 2.21- MeV, levels The logarithm of the ratio $I_o/(I_o + I_s)$ is plotted *as* a function of the plunger displacement D. $\bar{D}_m$ is the mean displacement from which the mean lifetime is obtained (1 mil = 25.4μ). From Ref. 15.

The third technique I would like to mention utilizes our excellent knowledge of the electromagnetic interaction to determine the spins of nuclear levels by measurements of the spatial distribution of gamma-ray emission. Shown in Fig. 13 is the well-known case of a gamma-gamma cascade from a randomly populated (in this case J = 0) initial state. Now imagine the initial level to be populated by a nuclear reaction in a way that produces alignment (unequal magnetic substate populations). We now wish to do a spatial gamma-gamma correlation to determine the spin of the initial level (the other two being taken as J = 2 and 0) while we retain the degree of alignment as unknown and the beam axis as a further direction in space. The method is illustrated in Fig. 14 and data for Ne^{22} are shown in Fig. 15.

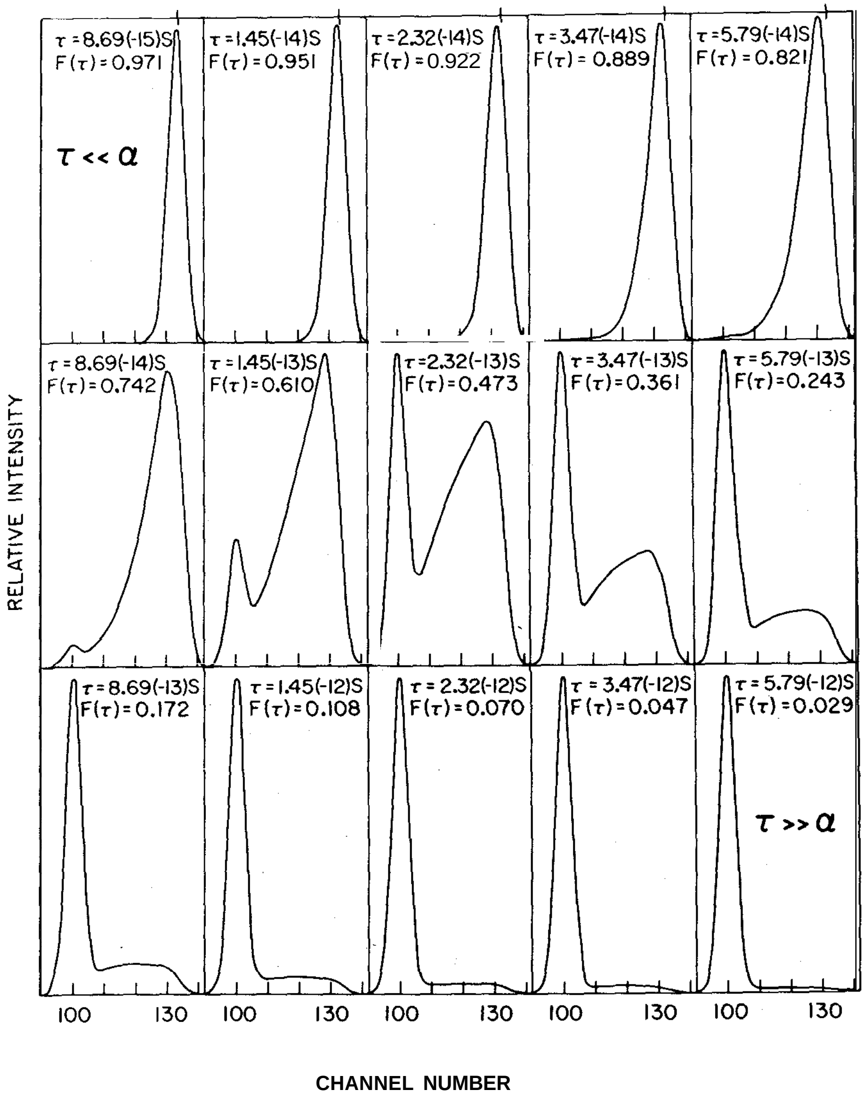

Fig. 11 - Hypothetical Doppler lineshapes as a function of assumed mean lifetime. $F(\tau)$ is the ratio of the average Doppler shift to the full shift for recoil into vacuum. From Ref. 16.

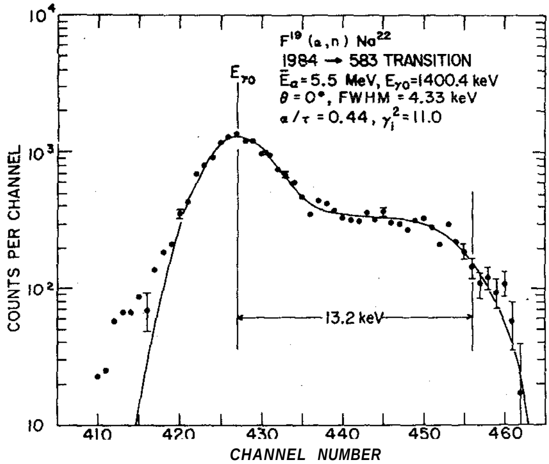

Fig. 12 - The **full-energy-loss peak** of the 1.400-MeV y-ray corresponding to the Na^{22}, 1.984 → 0.583 transition, observed at **0°** to the beam, resulting from direct feeding of the 1.984-MeV **level** in the $F^{19}(\alpha, n)Na^{22}$ reaction initiated in a 1.0-mg/cm² CaF_2 target. The spectrumis the sum of two obtained at E, = 5.4 and 5.6 **MeV**. Background has **been** subtracted The dispersion **is** 0.4542 **keV/channel**. The **solid** curve **is** a theoretical **fit** to the y-ray **line** shape as descnbed in Ref. 17 from which the figure **is** taken. The parameters **used** in the **theoretical** curve are **given** in the figure.

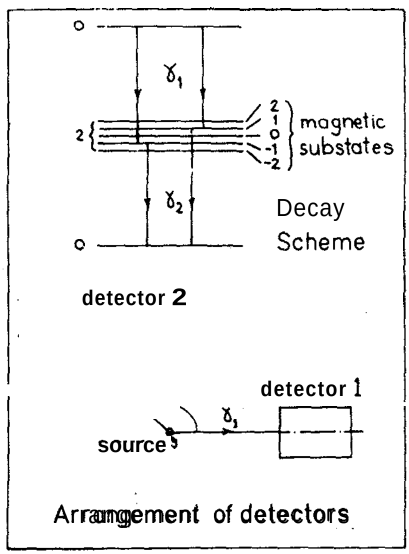

Fig. 13 - Schematic **illustrating** the gamma-gamma wrrelation from a **spin** zero **level**.

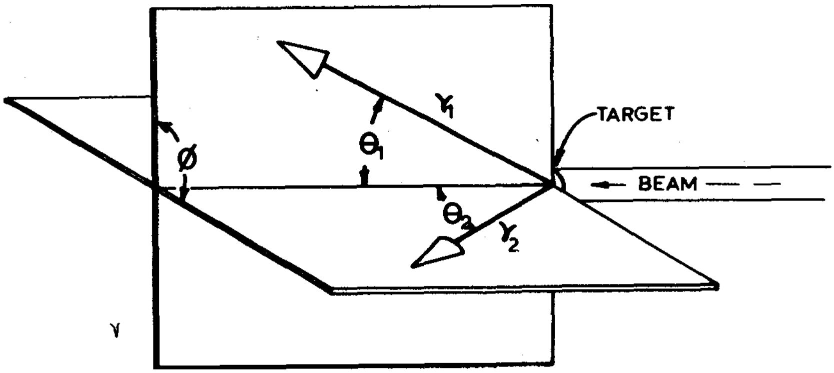

Fig. 14 - Schematic illustrating the gamma-gamma correlation from an aligned nucleus (initial spin $J \neq 0$).

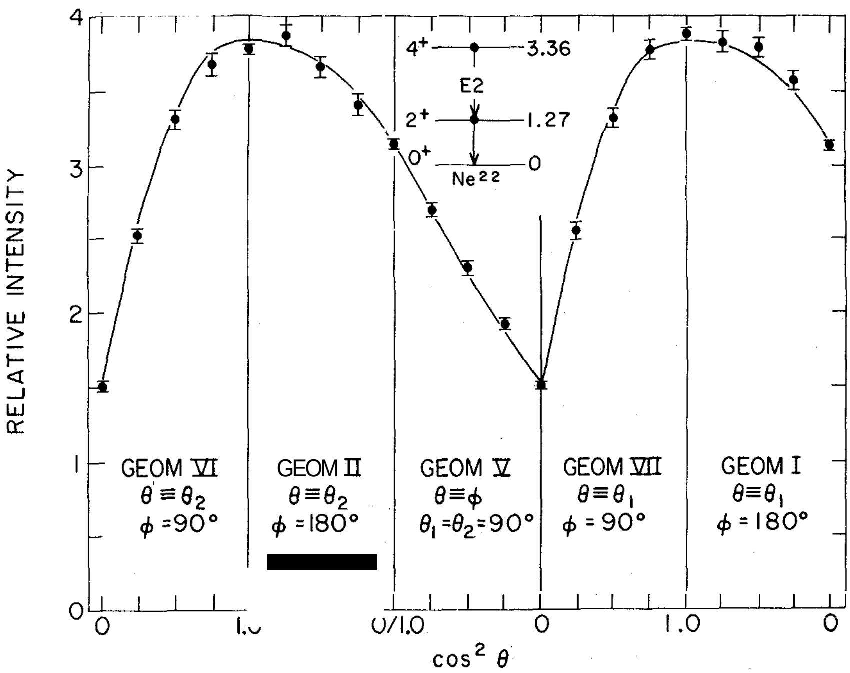

Fig. 15 - Results of a γ-γ triple correlation measurement for the Ne^{22}, $3.36 \rightarrow 1.27 \rightarrow 0$ cascade. The experimental points are shown for the five indicated geometries. The solid curve is the fit to the data for the spin values indicated in the level scheme and assuming both transitions are pure quadrupole. From Ref. 18.

We now ramble on to somewhat heavier nuclei in the (2s, 1d) shell and take up a little problem which illustrates another example of specificity and the extreme sensitivity of some nuclear phenomena to small bits of the nuclear wave function. One point I wish to illustrate here is that we now believe we can calculate rather well the bulk of a wave function – say 80%. The remaining parts we can estimate by various approximate measures. To investigate the reliability of this technique, we look for matrix elements sensitive to the small bits. The matrix element for unique first-forbidden beta decay is one such[19]. There are some 14 examples of this type of beta decay in the nuclei between S^{37} and Ca^{43}, all involve the change in orbit $d_{3/2} \leftrightarrow f_{7/2}$ to first order and all are about 10 times slower than predicted by a shell model assuming nucleons in the $d_{3/2}$ and $f_{7/2}$ orbits only. This discrepancy persists even for quite sophisticated calculations. The difficulty is due to the presence of small admixtures of other configurations, approx. 5%, which are admixed by a force which resembles the beta-decay operator and so the admixtures have a strong coherent effect on the beta matrix element – the 5% admixtures decreasing the decay rate by the necessary factor of about 10. The effect is similar to that for $E1$ decays where the giant resonance saps the strength of the other transitions. Thus we have here another example of specificity such as the enhancement of E2 rates and moments in the 1p shell.

So much for the past. What now of the future? The bulk of the information on the bound levels of light nuclei, particularly the electromagnetic properties with which I am mainly concerned, has been collected using electrostatic accelerators of the pre HVEC-MP variety. We now have available a new generation of accelerators of which the São Paulo Pelletron is an example. It is already clear that with these accelerators all the nuclei up to and even beyond lead are accessible to detailed studies of the type heretofore confined to the light nuclei, and such studies are underway. In addition, more details of higher-lying states of light nuclei are being obtained. A glance at a recent progress report[20] from the Chalk River MP tandem laboratory illustrates how beautifully the new accelerators can be utilized to study the electromagnetic properties of nuclear energy levels. In this report, covering a three-month period, levels in something like 15 nuclei between Li^6 and Bi^{209} are mentioned as being studied via Coulomb excitation, radiative capture or Doppler shift techniques. Specific investigations include Coulomb excitation of the first-excited state of Li^6, the determination of the radiative width of the 8^+ member of the Ne^{20} ground-state rotational band by means of the $He^4(O^{16}, \gamma)Ne^{20}$ reaction, and lifetime determinations in Bi^{209} via the Doppler shift attenuation method (DSAM) using $Pb^{208}(Li^7, \alpha 2n)Bi^{209}$ reaction.

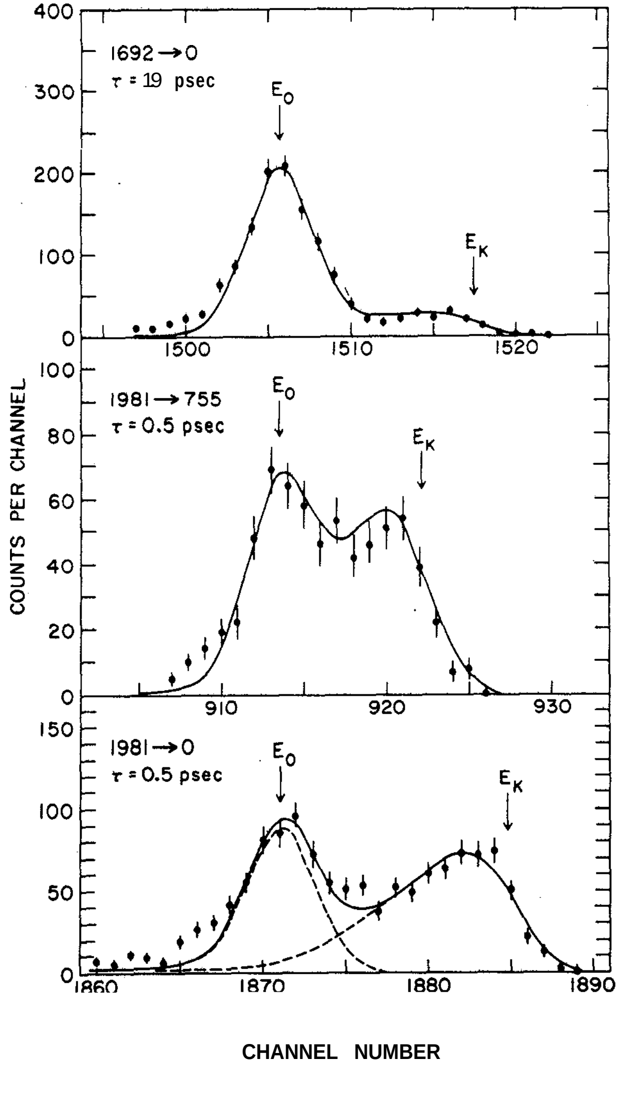

Fig. 16 - Doppler shift line-shapes observed in the $Cl^{37}(d, p\gamma)Cl^{38}$ reaction for γ-rays measured in coincidence with proton groups leading to the 1692- and 1981-keV states of Cl^{38}. These spectra were taken with the 40-cm^3 $Ge(Li)$ detector at 0°. The proton detector, centered at 180°, restricted the Cl^{38} ions to move in a forward wne with a half angle of 9°, with a velocity of about $v/c = 0.55\,\%$. The Cl^{38} ions are slowing down in $BaCl_2$ and Ta. A linear background has been subtracted from the data The solid curves are thwretical fits to the line shapes for the indicated value of the mean life. From Ref. 21.

The Doppler shift method for measuring nuclear lifetimes provides a good illustration of the adaptability of the tandem to investigations of the heavier nuclei. The accuracy and reliability of both the recoil distance method (Figs. **8-10)** and the **DSAM** (Figs. **11, 12)** falters when the Doppler shifts induced become small compared to the y-ray energy resolution. At the present time this means a limit of a few keV ($\sim$ **0.2%** for a 1-MeV transition). For $A_{Projectile} \ll A_{Target}$, the Doppler shift decreases inversely with A and for this and other reasons its usefulness decreases rapidly between A = 40 and 100. Heavy ion beams are the answer to this problem. First, there is the use of the inverse reactions with $A_{Projectile} \gg A_{Target}$, say $H^2(Cl^{37}, p\gamma)Cl^{38}$ instead of $Cl^{37}(d, p\gamma)Cl^{38}$. Doppler shifts obtained [21,22] with these two reactions at nearly the same center-of-mass energies are shown in Figs. 16 and 17. In the deuteron-beam reaction the recoiling Cl^{38} ions were selected in a forward cone of half-angle 9" by means of a proton coincidence condition in the backward direction. The Cl^{38} velocity was $v/c = 0.55\%$.

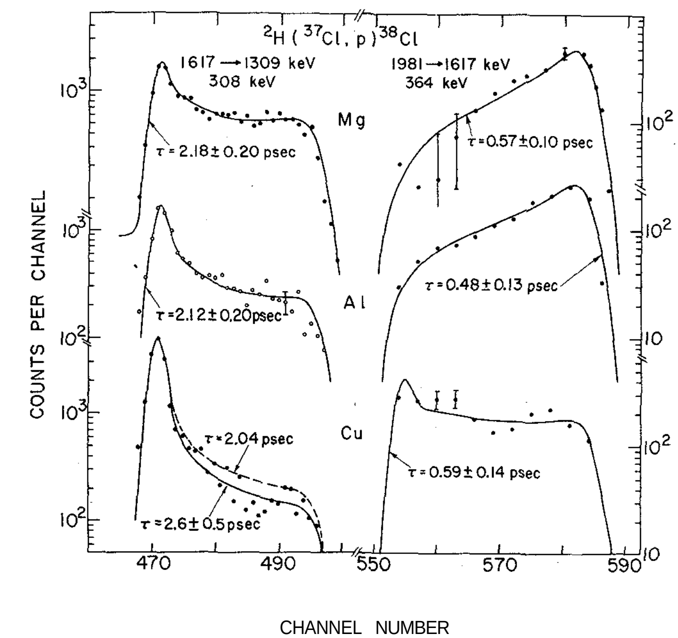

Fig. 17 - Doppler-shift line-shapes observed in the $H^2(Cl^{37}, p\gamma)Cl^{38}$ reactions The $Ge(Li)$ detector was at 0°. The kinematics are such that the Cl^{38} ions recoiled with a cone of half angle 2.8" with a mean velocity of $v/c = 5.4\%$. The background has been subtracted. The three line shapes correspond to the Cl^{38} ions slowing down in Mg, Al, and Cu backings with the indicated meanlives. From Ref. 22.

When using the Cl^{37} beam the kinematics force the recoiling Cl^{38} ions into a cone of half-angle 2.8" for a 60-MeV beam and so for the purpose of defining the recoiling ion direction no coincidence is necessary. Furthermore the Cl^{38} velocity is $v/c = 5.4\%$ – a gain of a factor of 10 in the magnitude of the Doppler shift. This method should be applicable to those heavier nuclei which can be accelerated in tandems.

For the general case with heavy-ion bombardment we do not have a narrow forward cone of recoiling ions such as is forced by A,,,,,, $\ll A_{Projectile}$ and either a coincidence condition is needed or the angular distribution of the reaction must be known and taken account of. An example of the former is provided by work at Yale on the Coulomb excitation of Nd^{150}

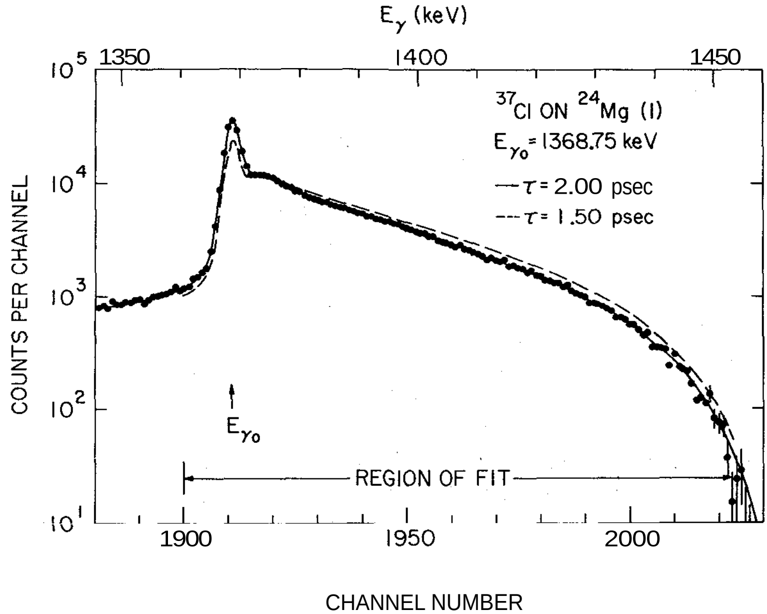

Fig. 18 - Doppler-shift line-shape observed for the ground-state decay of the 2^+, Mg^{24} first-excited state, formed via Coulomb excitation by a 53-MeV Cl^{37} beam. The target was natural Mg thick enough to stop the beam. The $Ge(Li)$ detector was at 0° to the beam and the maximum Doppler shift is $v/c = 6.8\%$. The solid and dashed curves are fits to the experimental line shape for the indicated meanlives. The least squares solution is $\tau = 2.0 \pm 0.3$ rsec. Input to the theoretical line shape includes the detector response function to monoenergetic y-rays, finite integration over the detector solid angle and the infinitely thick target, slowing down parameters for Cl^{37} and Mg^{24} in natural Mg, the theoretical Coulomb excitation particle-gamma correlations, quadrupole re-orientation effects, and various relativistic wrrections.

and Sm^{152} using O^{16} and S^{32} beams with coincidence detection of the inelastically scattered projectile in the backward direction[23]. The Doppler shifts were 1.7 and 3.0% for 60-MeV O^{16} and 110-MeV S^{32}, respectively. In this work nine lifetimes were measured by the DSAM in these two nuclei. An example of a DSAM lifetime obtained from Coulomb excitation without a coincidence condítion is gíven in Fig. 18. Here the line shape of the Mg^{24}, $1 \rightarrow 0$ transition, observed at 0° to the 53-MeV Cl^{37} beam is fitted[24] using the known theoretical angular distribution of the reaction to yield a lifetime of 2.0 ± 0.3 psec for the first-excited state of Mg^{24}. Another type of heavy ion reaction which shows great promise for use in recoil distance and DSAM lifetime work is the nucleon evaporative reaction; examples being $Sn^{120}(Ar^{40}, 4n)Er^{156}$, studied at Berkeley, and $Mg^{24}(O^{16}, np)Ar^{38}$, studied at Brookhaven. This type of reaction often has a relatively large cross section and it produces a narrow cone of recoiling nuclei suitable for Doppler shift work without the necessity of a coincidente condition. The $(Ar^{40}, 4n)$ work of Diamond, *et al.*[25] on rotational levels in $Er^{156,158,160}$ provides an example of its use with the recoil distance technique. Finally, I mention again work[20] at Chalk River on Bi^{209} which used a Li^7 beam on Pb^{208} and obtained Doppler shifts of $v/c \sim 0.5\%$. This $(Li^7, \alpha 2n)$ reaction appears to proceed like a (t, 2n) reaction with the α-particle acting only as a spectator, but for our purposes providing the extra momentum that makes DSAM work possible.

All this is intended to illustrate that we have at our disposal the means to extend to the whole periodic table the detailed picture of nuclear structure presently available for only the light nuclei. The amount of information as yet unknown is enormous and the job of gathering it will be long and difficult. There are bound to be periods when experiment and theory are out of touch and when our sense of direction and purpose is blunted. At these times we can turn to our previous experience in the light nuclei to reassure ourselves that these bad patches will pass – as the will. For I am convinced that a detailed omnibus knowledge of nuclear energy levels is vital to our understanding of the nucleus and, in fact, nuclear physics as a whole can only advance as fast as does nuclear spectroscopy.

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