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The electromagnetic and hadronic diffractive dissociation of ^{16}O ions

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Abstract: Events which satisfy the kinematics of $p(^{16}O, C\,He\,p)$, with low excitation energy in the (C He) system and a low-energy recoil proton, have been identified in the interactions of 200 GeV/nucleon ^{16}O ions with nuclear emulsion. An eikonal DWIA estimate of the target A-dependence of strong-interaction diffractive dissociation suggests that, on the basis of these hydrogen data, most of the (C He) final states, previously ascribed to electromagnetic dissociation on heavy nuclei, might rather be hadronic in character. This contamination is very much less important in the dominant (N H) channel.

1. Introduction

A previous work [1]) showed that events for which all that was observed was the low energy break-up of the projectile accounted for a significant fraction of the interactions of ultra-relativistic heavy ions in their passage through nuclear emulsions. At 200 GeV per nucleon these were 11% of the total in the case of ^{16}O and 18% for ^{32}S. These events were ascribed to electromagnetic dissociation (EMD) processes in the Coulomb field of the target nuclei within the emulsion.

Charge and angular measurements allowed these events to be categorised into various break-up channels and the excitation energies of the final nucleus to be estimated. By

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assuming a virtual photon spectrum given by the prescription of Weiszäcker and Williams [2-4]) and corresponding to the nuclear elements in the emulsion, it was then possible to compare the cross sections for various channels with the results obtained from real photon events, where available. Whereas there was good agreement for both the ^{16}O and ^{32}S results for (γ, p) processes, especially in the giant dipole region, the EMD cross sections for (γ, α) processes were an order of magnitude larger than expected. It was argued [1]) that a possible explanation for this discrepancy could be in terms of a contribution from multiphoton processes. It should be borne in mind though that conventional estimates of these processes suggest that they should in general be small [5]).

However, events have been observed, which seem to have all the features ascribed to electromagnetic break-up, except that at the point of dissociation there is also a track of a very low energy charged particle. Indeed, on measurement, some of the events were found to be consistent with diffractive dissociation on free protons within the emulsion. It is highly unlikely, because of the proton's small charge, that these could in fact be electromagnetic in origin. They must thus be induced by the strong interaction. In view of this, a careful search was performed on a much extended sample of 200 GeV per nucleon ^{16}O ion interactions to establish the extent of such processes, particularly those giving rise to (CHe) and (NH) final states of the ^{16}O nucleus. Since we have no isotope identification in the emulsion it is impossible to separate ^{1}H from ^{2}H or ^{3}He from ^{4}He. However it is expected that most of the H and He in the final states will be protons and ^{4}He (α-particles), respectively. The procedures and results of this search are presented in sect. 2, where it is shown that about 12% of the (CHe) final states are consistent with being produced on hydrogen whereas for (NH) the figure is less than 1%.

Similar coherent hadronic processes occurring on nuclei other than hydrogen in the emulsion would produce no recognisable recoil and so such events would thus be kinematically indistinguishable from those originally classified as being electromagnetic.

On the other hand, it is very difficult to make an *a priori* theoretical estimate of the hadronic diffractive dissociation cross section because of the complexity of the nuclear physics of ^{16}O at high (10–20 MeV) excitation energies. Not only would one need a good description of the transition form factor to the various nuclear levels, the results are also heavily dependent on their branching ratios into the (CHe) final state. There is, however, sufficient information to make reliable estimates of the excitation of the 2^+ level of ^{16}O at 11.52 MeV for both the hydrogen and complex nuclear targets. The calculations, described in detail in sect. 3, show that in the hydrogen case about 13% of the observed events would be expected to excite this one particular nuclear level. The resulting predicted target dependence is quite close to the $A^{1/3}$ expected from production by a rim around the nucleus. As a consequence, about 11% of the events previously classified as EMD on emulsion nuclei are likely to arise from strong-interaction excitation of this specific level.

Since it is impractical to make reliable estimates for the other levels and the continuum, we must make the simplifying assumption that this particular level is typical of all the levels produced by diffractive dissociation. In particular we assume that the A-dependence is as given in the model calculation for the 2^+ state so that we can estimate the number of strong interaction events to be expected in the emulsion by using this A-dependence to scale from our hydrogen results. It is shown in the conclusions of sect. 4 that such a scaling predicts a number of (C He) events close to what we have observed experimentally! It appears therefore that there is a very large hadronic contribution to (C He) final states in the diffractive break-up of relativistic ^{16}O ions on nuclei but that this contamination is far less serious for the dominant (N H) final states.

2. Experimental procedures and results

The experimental set-up and the line-scanning procedures used to locate interactions of ^{16}O ions in emulsion and the measurements made are fully described by Baroni *et al.* [6]). The particular selection made to establish the electromagnetic sample of events is given in ref. [1]). However, additional scanning has been done, in some plates for all classes of interactions and in others for only those satisfying the EMD classification [1]). As a consequence, the various classes of events discussed in this paper are obtained from the different track length samples given in table 1. Thus a further 508 m of 200A·GeV ^{16}O track, have been added to those obtained from the original 349 m used earlier [1]), resulting in 85 and 503 events classified as EMD candidates for (C He) and (N H) final states, respectively, with estimated excitation energies of less than 150 MeV. These estimates of the total centre-of-mass kinetic energy E released in the interactions were made assuming isotropy as in ref. [1]).

Interactions leading to hadronic dissociation of ^{16}O on hydrogen are to be found among the sample scanned for nuclear interactions. They have a topology characteristic of an EMD event plus a track of a low-energy singly charged particle at the interaction

TABLE 1

Number of events and associated track lengths for various classes of events

Class	Total track length examined (m)	Number of events
^{16}O(nucleus) → C He(nucleus)	857.2	85
^{16}O(nucleus) → N H (nucleus)	857.2	503
^{16}O + p → C + He + p	635.3	11 [a])
^{16}O + p → N H + p	463.0	9 [b])

[a]) See qualifications in table 2.

[b]) See qualifications in table 3.

vertex. The direction of such a track with respect to the primary beam was measured as was, where possible, its range. The method of development and subsequent sticking of the emulsion pellicles on glass may result in local distortions which can affect the determination of the track angles, particularly those of steeply inclined tracks. If this effect were observed to be present for any event, the coordinates of the points measured on the 'proton' track were corrected following an extension of the method of Apostolakis and Major [7]) and the emission angles re-determined. Such distortions do not affect the measurements of the small opening angle between the particles from the breakup of the ^{16}O ion. In some cases the range could not be measured as the proton left the emulsion stack before coming to rest. However, in each case it was judged from an examination of its ionization and scattering, to be close to rest. Consequently, only a small underestimate of the proton's momentum is incurred by using the observed track length. An estimate of the total centre-of-mass kinetic energy E released in the break-up of the ^{16}O was also made.

Eleven examples of the topology (C He+ a low-energy 'proton') were located. The details of these events are listed in table 2. To be kinematically consistent with the diffractive dissociation of an ^{16}O ion on a free proton within the emulsion, the magnitude of the "proton" momentum q and its emission angle θ with respect to the

TABLE 2

Events satisfying the C He p topology. The nine above the horizontal line satisfy the kinematics of $^{16}\mathrm{O} + \mathrm{p} \to {}^{12}\mathrm{C} + \alpha + \mathrm{p}$

Proton range (μm)	Proton momentum (MeV/c)	Observed emission angle (deg.)	Predicted emission angle (deg.)	Energy above ^{12}C + α threshold (MeV)
294	112	83.3 ± 2.8	86.6	8.7
1636	185	84.3 ± 2.2	84.3	18.6
>7322 [a])	$\gtrsim 286$	81.1 ± 0.9	$\lesssim 81.3$	11.8
173	95	81.2 ± 3.3	87.1	8.4
> 10200 [a])	$\gtrsim 315$	74.4 ± 2.2	$\lesssim 80.3$	17.6
2401	207	85.1 ± 1.5	83.7	2.2
>1154 [a])	$\gtrsim 167$	82.4 ± 1.4	$\lesssim 84.9$	28.0
>4500 [a])	$\gtrsim 248$	85.6 ± 2.6	$\lesssim 82.4$	6.5
2125	200	82.9 ± 2.1	83.9	7.2
381	121	147.0 ± 2.2	86.3	16.3
208	101	107.4 ± 3.1	86.9	1.9

[a]) In these events the proton leaves the emulsion but it is already close to rest. The estimated residual range is less than 1 mm, which would imply only a small increase in the initial proton momentum.

beam direction should satisfy, to a good approximation, the relation

$$\cos(\theta) = \frac{q}{2m}, \tag{2.1}$$

where m is the mass of the struck proton. The nine events satisfying this condition also have a centre-of-mass kinetic energy spectrum similar to that of the 85 events classified as EMD (C He) candidates as shown in fig. 1a. The other two events, which do not satisfy the free hydrogen criterion, may correspond to the knock-out of a proton from a heavier nucleus in the emulsion. The kinematic relation of eq. (2.1) would then be modified by both the Fermi motion of the proton in the nucleus and its multiple scattering whilst emerging therefrom.

The situation with regards to the so-called (N H + a low energy 'proton') events is far less clear because in this case one cannot distinguish between the tracks of a forward-going fast proton and a produced charged pion on the basis of ionization alone. Nevertheless, nine events with the correct scanning topology were found. The details of these events are given in table 3. Six of them were kinematically consistent with production on free hydrogen. It is, however, only in two cases that the opening angle between the nitrogen and the supposed forward-going proton is such as to give an excitation energy in the ^{16}O system of less than about 50 MeV, the region in which 96% of our EMD (N H) candidates lie, as clearly demonstrated by fig. 1b. The remainder

TABLE 3

Events satisfying the N H p topology. Only the two above the horizontal line satisfy the kinematics of $^{16}O + p \to {}^{15}N + pp$ with a value of the excitation energy compatible with electromagnetic dissociation.

Proton range (μm)	Proton momentum (MeV/c)	Observed emission angle (deg.)	Predicted emission angle (deg.)	Energy above ^{15}Np threshold (MeV)
425	125	92.6 ± 3.0	86.2	6.8
3170	224	84.0 ± 1.5	83.1	20.1
>4693 [a]	$\gtrsim 251$	79.9 ± 0.8	$\lesssim 82.3$	51.0
>9345 [a]	$\gtrsim 307$	79.6 ± 1.2	$\lesssim 80.6$	90.9
>1820 [a]	$\gtrsim 191$	70.1 ± 2.3	$\lesssim 84.2$	106.9
12005	330	79.9 ± 1.0	79.9	122.7
442	126	91.3 ± 3.7	86.2	273.9
>12650 [b]	$\gtrsim 335$	87.4 ± 0.8	$\lesssim 79.7$	493.1
126	86	147.0 ± 4.5	87.4	908.8

[a]) In these events the proton leaves the emulsion but it is already close to rest. The estimated residual range is less than 1 mm, which would imply only a small increase in the initial proton momentum.

[b]) As footnote [a]) but the estimated residual range is less than 2 mm.

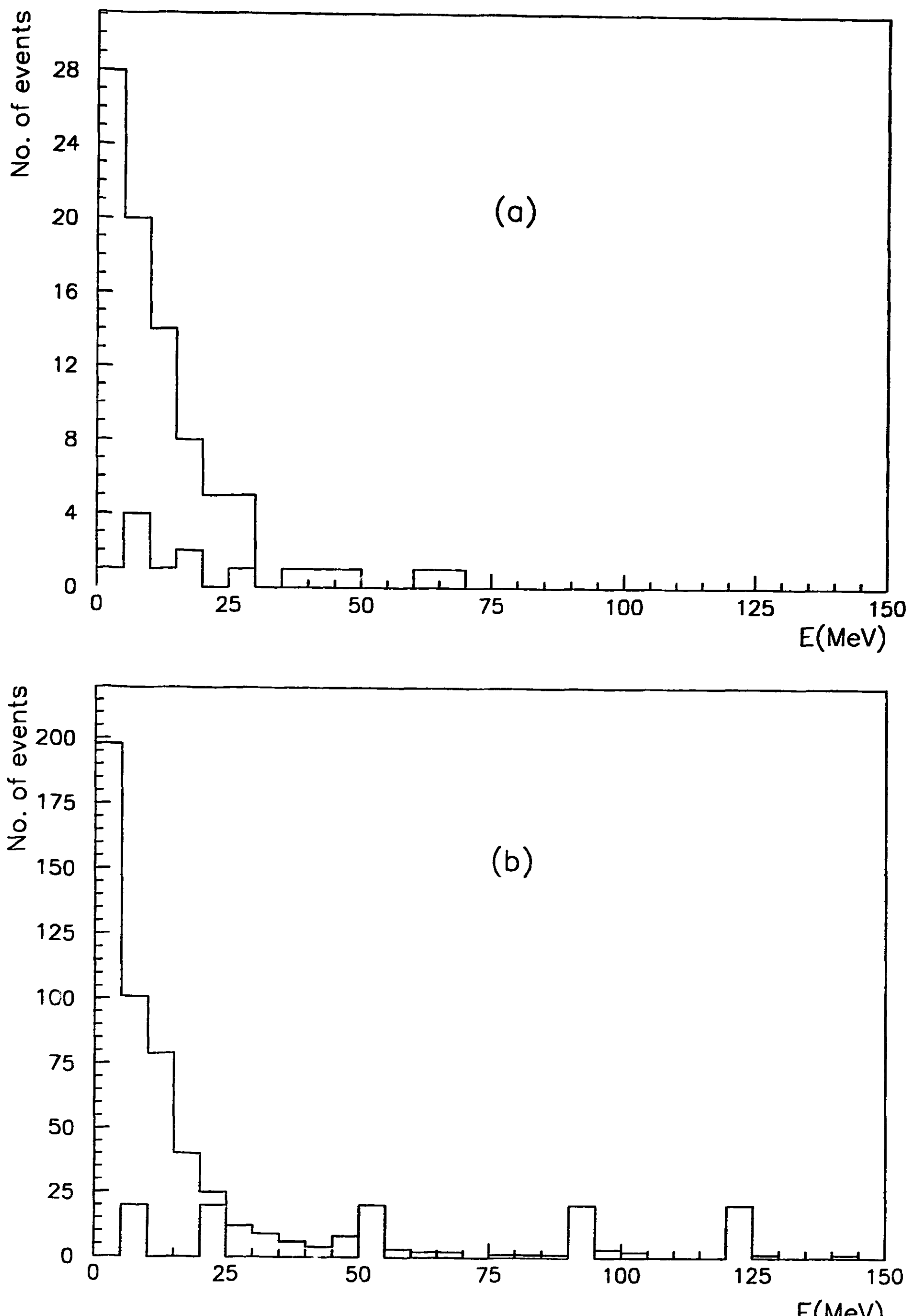

FIG. 1

Fig. 1. Centre-of-mass energy spectra of candidates for EMD (open histogram) and hadronic diffraction on free protons (shaded histogram) of (a) (CHe) and (b) (NH) final states. For clarity, the ordinate for the (NHp) events has been scaled by a factor 20.

of the events, therefore, do not appear typical for electromagnetic dissociation. It is in fact likely that in most of the these cases the minimum-ionising single-charged particle is actually a pion rather than a stripped projectile proton, since at large outgoing angles a 200 GeV proton would have a larger than expected transverse momentum.

3. Theoretical predictions

3.1. FORMALISM

In the distorted-wave impulse approximation (DWIA) for the excitation of nucleus B in the reaction $A + B \to A + B^*$, the transition from the ground to excited state is assumed to take place in a single step but with purely elastic distortion coming before and after the transition. At high energies it is legitimate to evaluate such distortion in the eikonal approximation [8,9]), the resulting amplitude then corresponding to the dominant subset of terms given by the Glauber theory [10]).

If we neglect the spin and isospin dependence of the high-energy nucleon–nucleon amplitudes $f_{NN}(q)$ then the amplitude for the excitation of a state of angular momentum l and projection m in nucleus B is

$$F_{lm}(\boldsymbol{q}) = \sqrt{4\pi} f_{NN}(0) \int e^{i\boldsymbol{q}\cdot\boldsymbol{r}} D(b) Y_{lm}(\hat{r}) \rho_l^{tr}(r)\, d^3r, \quad (3.1)$$

where it is assumed that both A and B are of spin zero.

In the eikonal approximation the trajectory is a straight line at constant impact parameter vector $\boldsymbol{b}$ so that in the integration $\boldsymbol{r} = (\boldsymbol{b}, z)$. The distortion factor

$$D(b) = e^{i\chi(b)}, \quad (3.2)$$

is then given by an integral over the momentum transfer $\boldsymbol{q}$,

$$\chi(b) = \frac{AB}{2\pi^{3/2}} \int e^{-i\boldsymbol{q}\cdot\boldsymbol{b}} S_A(q) S_B(q) f_{NN}(q)\, d^2q. \quad (3.3)$$

Here S_A and S_B are the ground-state point matter form factors of the two nuclei with A and B nucleons, respectively.

To avoid frame transformations the amplitudes are normalised to the momentum transfer such that

$$\left(\frac{d\sigma}{dq^2}\right)_{lm} = |F_{lm}(\boldsymbol{q})|^2. \quad (3.4)$$

In the absence of distortion, $D(b) = 1$, it is convenient to quantise along the direction of the momentum transfer vector $\boldsymbol{q}$ and in this limit one recovers the plane-wave impulse approximation result

$$F_{lm}^{\text{p.w.}}(q) = AB\sqrt{2l+1}\, i^{-l} S_A(q) S_B^{tr}(q) f_{NN}(q) \delta_{m,0}, \quad (3.5)$$

where $S_B^{tr}(q)$ is the transition matter form factor to the excited state.

The comparison of eqs. (3.1) and (3.5) allows us to evaluate the effective nuclear transition density

$$\rho_l^{\rm tr}(r) = \frac{\sqrt{4\pi}}{(2\pi)^3} AB \int S_A(q) S_B^{\rm tr}(q) \frac{f_{\rm NN}(q)}{f_{\rm NN}(0)} j_l(qr) q^2 \, {\rm d}q \,, \tag{3.6}$$

which therefore depends upon the shape of the nucleon–nucleon amplitude as well as nuclear structure information.

At high energies the nucleon–nucleon amplitude is dominated by the imaginary part and the diffraction peak may be parameterised as

$$f_{\rm NN}(q) = \frac{i\sigma_{\rm NN}}{4\sqrt{\pi}} {\rm e}^{-\beta^2 q^2/2} \,, \tag{3.7}$$

where, with the normalisation of eq. (3.4), $\sigma_{\rm NN}$ is the total nucleon–nucleon cross section.

3.2. APPLICATION TO ^{16}O SCATTERING

It has been shown that the elastic ^{16}O form factor is well described by harmonic-oscillator wave functions with an r.m.s. charge radius of 2.72 fm [ref. [11])]. In the inelastic case there are three low-lying 2^+ states of ^{16}O whose transition form factors have been well measured in electron scattering [12]). The 2_1^+ and 2_3^+ levels at 6.92 and 11.52 MeV, respectively, have form factors which are almost identical in shape, corresponding to surface-peaked transition densities, though the amplitude of the latter is about $1/\sqrt{2}$ smaller. After removing the proton size the form factors can be parameterised as

$$\begin{aligned} S2_1^+(q) &= 0.1844 q^2 (1 - q^2/1.935^2) {\rm e}^{-0.80 q^2} \,, \\ S2_3^+(q) &= 0.1217 q^2 (1 - q^2/1.970^2) e^{-0.72 q^2} \,. \end{aligned} \tag{3.8}$$

On the other hand, the overlap for the 2_2^+ state at 9.85 MeV is peaked in the interior so that its B2 moment is quite small and we shall not consider it further. Since the threshold for α-decay is at 7.16 MeV, the 2_1^+ cannot be seen in the (^{12}Cα) mode, whereas the 2_3^+ decays essentially 100% in this way and might therefore be seen in our experiment.

The factor of two between the 6.92 and 11.52 MeV levels is also seen in proton scattering at 200 and 500 MeV [refs. [13,14])], where the shapes of the two cross sections are found to be very similar.

Experimental data exist on the excitation of only the (lower) 2_1^+ level by proton scattering at 800 MeV [ref. [15])]. The eikonal DWIA formalism outlined above should be equally valid for proton scattering providing the nuclear form factor $S_A(q)$ is put equal to unity. The parameters are a little ambiguous in view of the neglect of the spin and isospin dependence as well as the real part of the NN amplitudes at such a low energy. Nevertheless, taking $\sigma_{\rm NN} = 4.0$ fm^2 and $\beta^2 = 0.2$ fm^2, the very satisfactory agreement shown in fig. 2 is obtained. This reproduces well both the shape

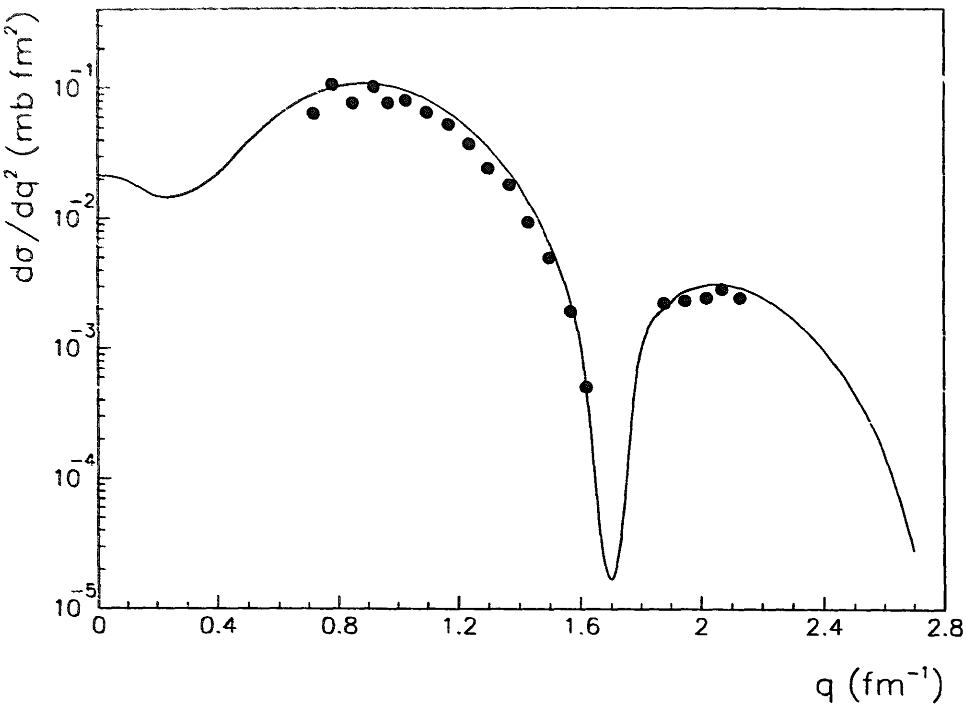

Fig. 2. Experimental cross sections for $p + {}^{16}O \rightarrow p' + {}^{16}O^*(6.92)$ at 800 MeV [ref. [15])] are compared with the predictions of the eikonal DWIA calculation described in sect. 3.

and the absolute normalisation of the cross section and confirms that both the reaction mechanism and nuclear structure information are sufficiently well understood to make reliable estimates for *both* 2^+ levels.

The validity of the eikonal DWIA model should improve with energy and when applied at our energy of 200 GeV per nucleon using $\sigma_{NN} = 3.9\ \mathrm{fm}^2$ and $\beta^2 = 0.44\ \mathrm{fm}^2$ [ref. [16])] it predicts an integrated cross section for the 11.52 MeV level of

$$\sigma({}^{16}O + p \rightarrow {}^{16}O^*(11.52) + p) = 0.52\ \mathrm{mb}. \qquad (3.9)$$

which would be seen finally in the ${}^{12}C + \alpha$ channel. The shape of the distribution in q^2 is broadly similar to the lower energy results of fig. 2 with an r.m.s. value of $\langle q^2 \rangle^{1/2} = 200\ \mathrm{MeV}/c$. The corresponding figure for the 9 hydrogen events shown in table 1 is $213 \pm 76\ \mathrm{MeV}/c$.

We would expect, on the basis of this cross section estimate and the path length scanned, to have 1.2 events where the final ${}^{16}O$ nucleus is found in this one excited state. The total cross section deduced from the nine events listed in table 2 is 4.0 ± 1.4 mb. Thus this particular 2^+ level accounts for about 13% of the (CHep) events that were discussed in sect. 2. Such a modest figure is not surprising in view of the myriad of higher energy ${}^{16}O$ levels which have significant branching ratios to $({}^{12}C\alpha)$ [ref. [17])].

Turning now to the interaction of the oxygen ions with the heavier components in the emulsion, the calculations proceed identically except that the elastic form factor for the target nucleus $S_A(q)$ has to be included. Evaluating this with harmonic oscillator densities for the light (C, N, O) nuclei and Woods–Saxon densities for the heavy (Br, Ag), the predicted integrated cross sections for $\sigma(^{16}O + A \rightarrow ^{16}O^* + A)$ where the target nucleus A is left in its ground state are shown in fig. 3. Such events should have a rather steeper q-dependence than for hydrogen but any such coherent recoils would be completely unrecognisable in the emulsion. In view of the strong damping and the large nuclear sizes only the rim of the nucleus should contribute to such excitations so that a behaviour of roughly $A^{1/3}$ would be expected. In fact a log–log fit to the results of our calculations in fig. 3 is quite close to this with

$$\sigma(^{16}O + A \rightarrow {^{16}O^*} + A) = 0.865A^{0.29} = 1.65\sigma_p A^{0.29}\ \text{mb}. \qquad (3.10)$$

There is of course no reason for this form to be valid for hydrogen since the rim there encompasses the majority of the target!

From the proportions of the different nuclear species in our emulsion stack given in reference [6]), it is straightforward to derive from eq. (3.10) the relative number of events expected on medium/heavy nuclei as compared to those on hydrogen. This turns out to be

$$\frac{N(A>1)}{N(A=1)} = 6.1. \qquad (3.11)$$

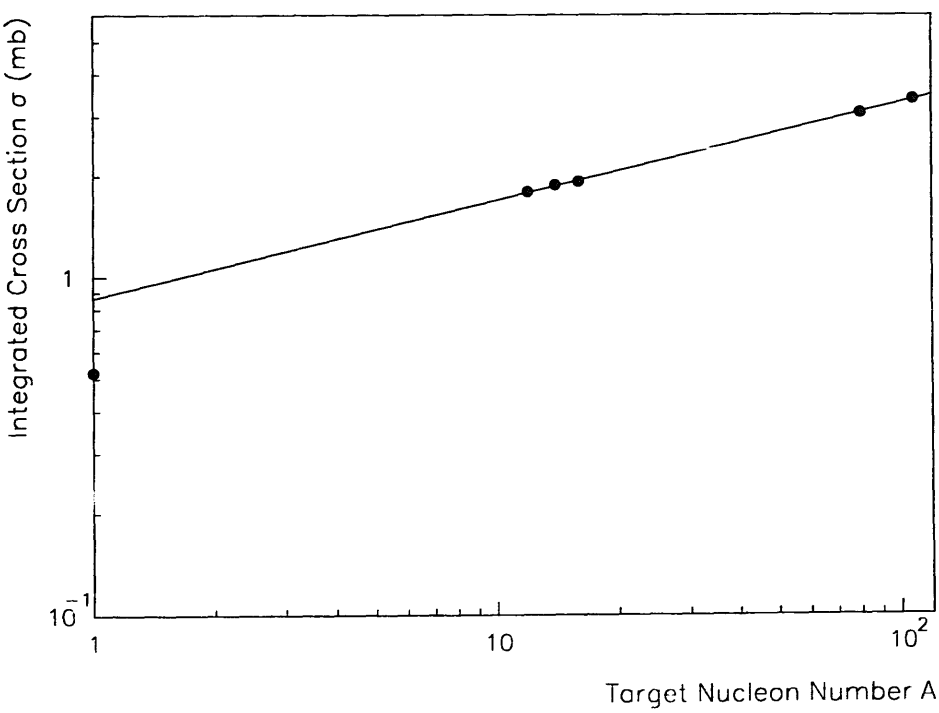

Fig. 3. Predicted integrated cross section for $^{16}O + A \rightarrow {^{16}O^*}(11.52) + A$ on various emulsion nuclei at 200 GeV per nucleon. The parameters of the straight line log–log fit are given in eq. (3.10).

There should therefore be about 10 events corresponding to the excitation of this single nuclear level via the *strong* interactions where the elastically recoiling target nucleus would not have been recognised.

From an inspection of the distribution of the c.m. energy E of the (C He) events given in fig. 1a it is seen that there are cases where the kinetic energy in the α–^{12}C system is of the order of 4 MeV so that they could correspond to this level. However the majority are at higher excitation energies where there is no immediate prospect of evaluating DWIA cross sections since the corresponding electromagnetic form factors have not been studied in detail for ^{16}O excitation energies above 12.1 MeV [ref. [12])].

4. Conclusions

We have shown in the previous section that, within the framework of an eikonal DWIA analysis, a significant fraction of the low excitation (C He) events produced on either hydrogen or heavier nuclei may be associated with the 11.52 MeV level in ^{16}O. However lack of nuclear structure information precludes a similar estimation of the excitation of higher nuclear levels. In view of this impasse, the simplest hypothesis that we can make is that these higher levels behave broadly similarly to the 2^+ ones and in particular that the A-dependence is given by eq. (3.10). In that case we can take the number of events that we have observed on free hydrogen (assuming that due to the small charge these are *not* of electromagnetic origin) and scale to the other target nuclei using the factor 6.1 of eq. (3.11). This scaling might still be reasonable if some of the events that we observe correspond, for example, to the production of ^{3}He rather than ^{4}He.

The predicted number of hadronic events where there is no observable low-energy recoil should be

$$N(C + He) = (9 \pm 3) \times \frac{6.1}{0.74} = 74 \pm 25, \tag{4.1}$$

where the denominator 0.74 arises from the fraction of the track length scanned for these events. The quoted error is only statistical, arising purely from the number of hydrogen events. This scaling suggests that the bulk of the 85 EMD candidates in this channel described in sect. 2 should in fact be of strong interaction origin. In addition though, there are likely to be cases where the nucleus A is excited through the strong interactions and the final two knock-out events of table 1 look like examples of this category. After these subtractions have been made our results would not be in disagreement with an estimate based on data from real photons which predicts about 9 events [1]). In principle there should be interference terms between the electromagnetic and hadronic excitation but these are probably very small due to the latter being dominantly imaginary with the former being dominantly real.

In the case of the (N H) events we have found only two events on hydrogen which could satisfy the EMD criteria, corresponding to a cross section of 1.2 ± 0.8 mb. On the basis of this we would only expect of the order of $2 \times 6.1/0.54 = 23 \pm 16$ events on the complex nuclei in the emulsion. This is small compared to the 503 events reported in sect. 2 and so changes little the plausible agreement with real (γ, p) data shown in ref. [1]). Hence there seems to be little in these two-body break-up channels which is not to be expected on the basis of low-energy nuclear physics information.

It has been shown, from studies of the shape of the excitation energy spectrum [19]) in the stripping of 2.1 GeV per nucleon ^{16}O ions by uranium, that the fraction of (N p) events which correspond to hadronic excitation is about 8%. It is clear that hadronic events are much more important here than at our energy. However our result is consistent with their observation when account is taken of the higher atomic and mass number of their target and the expected logarithmic rise of the Coulomb excitation cross section with energy.

It is very hard to devise useful criteria for the selection of EMD events but at high energies the strong interactions will only populate the isospin $T = 0$ states of ^{16}O. This is to be contrasted to the case of electromagnetic excitation which can lead to those with both $T = 0$ *and* $T = 1$. Coupled with the relatively small cross section for the reaction p(^{16}O, N H p) compared to p(^{16}O,C He p) this suggests that the states of ^{16}O which decay into ^{15}N p must be mainly of isospin 1 or otherwise we would have found more (N H p) events. However one must bear in mind that experimentally we have no isotope identification or efficient neutron detection and theoretically there are a multitude of low-lying energy levels in ^{16}O. This precludes detailed nuclear physics calculations of the relative proportion of these excited states decaying via the (C He) and (N H) channels.

Experimentally, we have not considered a detailed examination of events of the type ^{32}S + p $\rightarrow$ ^{28}Si + He + p worthwhile as we have not been able to augment our sample of 27 (Si He) EMD candidates of reference [1]). In addition, the low excitation (Si He) states of ^{32}S cannot be studied theoretically in the same manner as for the ^{16}O ones because of the poor knowledge of the electromagnetic transition form factors for the ^{32}S nucleus. However, despite this inability to predict the absolute cross section for this process, its dependence on target mass is expected to be similar to that of ^{16}O projectiles which, when expressed as a function of target charge Z is of the form $Z^{0.31}$. This is markedly different from the Z^2 behaviour expected for pure EMD processes. This difference, which arises from the much longer range at high energies of electromagnetic as compared to hadronic excitation, can be explored in our current experiment EMU09 [18]) which detects EMD reactions from a variety of foil targets of widely different atomic numbers.

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References

1) G.Baroni *et al.*, Nucl. Phys. **A516** (1990) 673
2) C.F.von Weiszäcker, Zeit. Phys. **88** (1934) 612
3) E.J.Williams, Phys. Rev. **45** (1934) 729
4) J.D.Jackson, Classical electrodynamics, 2nd ed. (Wiley, New York, 1975)
5) C.A.Bertulani and G.Baur, Phys. Lett. **B174** (1986) 23
6) G.Baroni *et al.*, Nucl. Phys. **A531** (1991) 691
7) A.J.Apostolakis and J.V.Major, Brit. J. Appl. Phys **8** (1957) 9
8) H.K.Lee and H.McManus, Phys. Rev. Lett. **20** (1968) 337
9) C.Rogers and C.Wilkin, Nuovo Cim. Lett. **1** (1971) 575
10) R.J.Glauber in Lectures in theoretical physics, vol.1, ed. W.E. Brittin (Interscience, New York, 1959) p. 315
11) C.Hyde-Wright *et al.*, Phys. Rev. **C35** (1987) 880
12) T.N.Buti *et al.*, Phys. Rev. **C33** (1986) 755
13) J.J.Kelly *et al.*, Phys. Rev. **C41** (1990) 2504
14) B.S.Flanders *et al.*, Phys. Rev. **C43** (1991) 2103
15) G.S.Adams *et al.*, Phys. Rev. Lett. **43** (1979) 421
16) M.K.Carter, P.D.B.Collins and M.R.Whalley, Rutherford Appleton Laboratory compilation RAL-86-002 (1986)
17) F.Ajzenberg-Selove, Nucl. Phys. **A460** (1986) 1
18) N.Armenise *et al.*, (EMU09 Collaboration), Proposal CERN/SPSC/89-1, P-243 (1989)
19) D.L.Olson *et al.*, Phys. Rev.**C44** (1991) 1862